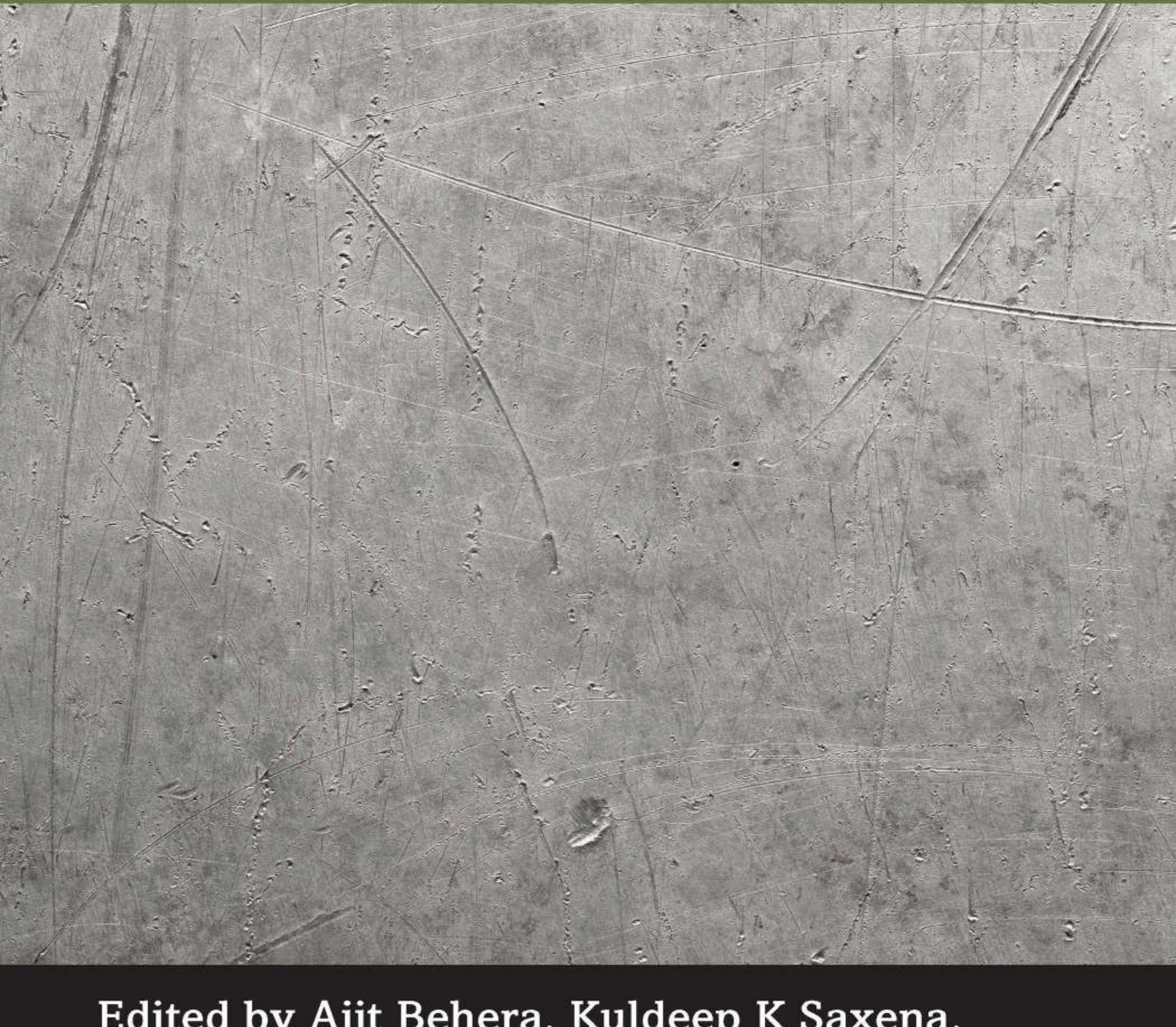
EMERGING MATERIALS AND TECHNOLOGIES

Multi-scale and Multifunctional Coatings and Interfaces for Tribological Contacts



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Multi-scale and Multifunctional Coatings and Interfaces for Tribological Contacts

This book covers developments in multi-scale and multifunctional coatings, including strategies in the preparation, characterization, and properties of both thin and thick multifunctional coatings along with their corresponding application. Various technologies for processing, characterization, and tribology effects of various coating surfaces and interfaces are discussed. It describes smart surfaces like piezoelectric materials, shape memory alloys, shape memory ceramics, magnetostrictive materials, electrostrictive materials, dielectric materials, and advanced ceramics.

- Explains multifunctional materials with respect to their tribology behavior at surface and interface.
- Covers analysis techniques for multifunctional surfaces and interfaces.
- Discusses emerging applications of multifunctional surfaces.
- Explores multifunctionality of thin films as well as thick coatings.

This book is aimed at graduate students and researchers in metallurgical engineering, materials science, and nanosciences.

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Contents

Introduction

With leading technology we are going to miniaturization of systems. With these small volumes, knowledge of surfaces and their connected interface in systems is most important. In the operational life of a system, it is exposed to wear and tear. Hence, the study of tribological contacts is essential. This book focuses on the emerging development and various strategies in the preparation, characterization, and properties of both thin and thick multifunctional coatings along with their corresponding applications. This book covers the introduction to multi-scale and multifunctional coatings and the various multifunctional activities with respect to tribology behavior for thin and thick surfaces. Smart surfaces like piezoelectric materials, shape memory alloys, shape memory ceramics, magnetostrictive materials, electrostrictive materials, dielectric materials, and advanced ceramics are discussed. The cutting-edge technology-based additive manufactured multifunctional thin films and thick films, high-temperature behavior of multifunctional thin films, self-cleaning multifunctional thin films, antiviral thin surfaces, multifunctional porous coatings, and abradable coatings are also discussed in this book along with their classifications.

Preface

This book focuses on the emerging development and various strategies in the preparation, characterization, and properties of both thin and thick multifunctional coating along with their corresponding applications. Section 1 of this book covers the introductory part of multi-scale and multifunctional coatings. Here various technologies for processing, characterization, and tribology effects on various coating surfaces/interfaces are discussed. Section 2 and Section 3 cover the various multifunctional activities with respect to tribology behavior for thin and thick surfaces, respectively. Smart surfaces like piezoelectric materials, shape memory alloys, shape memory ceramics, magnetostrictive materials, electrostrictive materials, dielectric materials, and advanced ceramics are discussed. The cutting-edge technology based additive manufactured multifunctional thin films and thick films, high-temperature behavior of multifunctional thin films, self-cleaning multifunctional thin films, antiviral thin surfaces, multifunctional porous coatings, and abradable coatings are also discussed in this book along with their classifications. Section 4 of this book covers various emerging applications and associated tribology effects for thin films as well as thick films. Finally, some future trends and the prospects in these research areas are also discussed to explain the coatings of tailored corrosion protection materials that are of the utmost relevance to ensure the reliability and long-term performance of coated parts as well as the product value of the coated materials.

About the Editors

Dr. Ajit Behera currently works as an assistant professor in the Metallurgical & Materials Department at the National Institute of Technology, Rourkela. He was born in 1987 in Odisha. He completed his PhD from IIT-Kharagpur in 2016. He received the National IEI Young Engineer Award in 2022, the Yuva Rattan Award in 2020, the C.V. Raman Award in 2019, and the young faculty award in 2017. He has published more than 170 publications, including books, book chapters, and journal articles.

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Prof. Sehgal has served as guest editor of many esteemed SCIe indexed journals. His Scopus h-index is more than 18. He served as coordinator of three international conferences, ICAMSE2022, ICAMSE2021, and ICAMSE2020, held at Panjab University, Chandigarh, India. He has also been the coordinator of two international faculty development programs in the field of materials and 3D printing. He served as zonal vice president of the Association for Machines and Mechanisms from 2014 to 2018.

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Dr Rajak has made significant contributions in the field of mechanical and materials science engineering. He did his doctor of philosophy work in the research area of crashworthiness analysis of empty/foam-filled structures at the Indian Institute of Technology (ISM) Dhanbad, Jharkhand, India.

Dr Rajak has 10 years of teaching and research experience in mechanical and materials engineering, and he is a life member in many professional bodies. He has presented many guest lectures at national and international gatherings. His field of interest is the development of metallic foams/composites for different applications where low density and high specific energy absorption are required in the automotive, aerospace, and thermal management sectors.

Dr Rajak has received many prestigious awards, and he has published more than 100 research articles in esteemed national and international journals. He has also authored two books, 16 book chapters, 18 patents, two designs, and one copyright.

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1 Introduction to Multifunctional Surfaces

Ajit Behera

1.1 INTRODUCTION

As the name suggests, multifunctional materials can perform multiple tasks and roles. They are supposed to be versatile and perform various tasks in order to meet various needs. In technology, biology, design, and other fields, these materials are being used more often. Multifunctional materials can be material, structures, or coatings that can be engineered to serve different useful functions. These materials can also be found in fields like material science, architecture, and engineering. Due to their versatility, these materials are applied in a wide range of fields and industries. Anticorrosion coatings and drag reduction surfaces can be used as multifunctional materials in aerospace and automobile sectors, respectively [1]. Anticorrosion coatings in metal surfaces increase lifespan in critical environments. So they can be very useful in aerospace and marine applications. Similarly, drag reduction surfaces reduce drag in aerospace applications, thus increasing performance and fuel efficiency of aerospace vehicles and automobiles. Self-healing surfaces, superhydrophobic surfaces, and anti-icing and antifogging surfaces are various surfaces that can be considered multifunctional surfaces [2]. Self-healing surfaces can repair minor damage in their surfaces, making them very useful for structural materials, coatings, and composites. Self-cleaning surfaces and superhydrophobic surfaces are used in car windshields, textiles, and building exteriors where self-cleaning is essential. To prevent the buildup of fog and ice, antifogging and anti-icing surfaces are used in transportation, optical devices, and aviation.

Multifunctional materials are also useful in the application of green building materials and air and water purification [3]. Multifunctional surfaces can remove contaminants and pollutants from water and air sources, thus proving to be environment friendly. Improvement of indoor air quality in buildings, temperature regulation, etc., can also be achieved by multifunctional materials, thus making them environmentally friendly and sustainable. Solar panels, antireflection coatings, and thermal management can also be done by multifunctional materials. Energy conversion efficiency can be increased, and heat dissipation can be enhanced in solar panels by use of multifunctional materials. Antireflection coatings made of multifunctional materials are very useful for optical lenses and solar cells. Multifunctional materials with enhanced thermal conductivity are used in electronic devices [4]. Smartphone and tablet screens, textiles, cookware, and kitchen appliances can be made of multifunctional materials. Anti-fingerprint, glare-reducing coatings and scratch-resistant features of multifunctional materials make them useful for smartphone applications. Easy-to-clean coatings and nonstick applications make them useful for kitchen appliances. Stain resistance, moisture wicking, and UV protection make them useful for the textile industry [5]. To maintain hygiene and prevent the spread of infections, multifunctional materials are used in health care. These materials can also be used in tissue engineering and drug delivery systems, and some materials compatible with biological tissues can be used as medical implants. To detect pathogens and molecules, these materials can also be used as biosensors [6]. Following are a few examples to illustrate the concept.

1.2 SMART SURFACES

Multifunctional materials can be embedded with actuators or sensors to form smart surfaces. The smart surfaces have greater efficiency and potency for various applications. Smart surfaces refer to materials or coatings that are designed to have enhanced functionalities beyond their traditional

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roles. In building design and architecture, smart surfaces change their properties in response to external stimuli. For example, we can observe that multifunctional materials can alter opacity or color with respect to light or temperature. This property allows for dynamic control and automatic shading.

In smart surfaces, the surface material is often made up of shape memory alloy (SMA) [7]. As the name indicates, the shape memory alloy can remember its original shape. If one deforms the alloy, the alloy can return to its original state. That means it can show pseudoelasticity and shape memory. This property is due to a reversible phase transformation that occurs within the material's crystalline structure. Shape memory alloy surfaces can be prepared by depositing shape memory material on the substrate surface. This can be achieved by sputtering, physical vapor deposition, chemical vapor deposition, and other coating techniques. Shape memory materials are broadly used in medical devices, aerospace components, and actuators. Smart surfaces are used in a range of applications where controlled shape change is desirable [8]. For instance, smart surfaces may be used in stents, where the surface can be compressed during insertion and expanded when in position. Adaptive wings are used in aircraft that may incorporate smart surface SMAs that can change shape as climatic conditions and flight conditions change. Shape memory surfaces also face various challenges such as fatigue over repeated cycles and degradation of materials.

Energy harvesting means capturing one form of energy and converting it to another form of energy. A chromogenic surface is a surface that gives indication or changes its optical properties when a source of energy (light) is incident upon it or its voltage changes [9]. The combination of chromogenic surfaces with energy-harvesting techniques has various applications, such as adaptive camouflage and smart windows. A smart window uses a chromogenic surface that converts its optical properties when temperature changes or light is incident upon it. The incorporation of energy-harvesting techniques such as solar cells in windows makes them useful for harvesting electricity for homes. From this electricity various electrical devices can be powered. Again, solar cells may be used with a chromogenic surface that can absorb only certain spectra of light. This property can enhance heat-absorbing capacity as compared to traditional materials in which all spectra of light are absorbed. This can enhance the efficiency of solar cells. In some military appliances, adaptive camouflage is needed that may use chromogenic surfaces. These surfaces can change color to match their surroundings. By integrating energy-harvesting components, the energy generated from ambient light could power sensors or communication devices. Wearable devices incorporating chromogenic materials could change color based on the wearer's preference or environmental conditions. These wearables could also integrate energy-harvesting mechanisms to power themselves using ambient light or body heat. Nowadays smart buildings are being built that incorporate chromogenic surfaces. These surfaces change color depending upon the intensity of sunlight or temperature. The building also utilizes energy-harvesting equipment in which the whole building system is powered by sunlight. Chromogenic materials could be used in large outdoor advertising displays that change color or appearance based on the time of day, weather conditions, or even user interactions. Energy harvesting could help power these displays, reducing the need for external power sources. Chromogenic sensors that change color in response to specific environmental factors (e.g., pollution levels, temperature) could be integrated with energy harvesting to create self-powered monitoring systems [10].

1.3 ENERGY-HARVESTING SURFACE

An energy-harvesting surface is a surface that can absorb one source of energy and convert it to another form of energy. These surfaces have many applications. The main objective of the surface is to utilize the energy that is wasted. Also, these surfaces are used where there is a limited supply of traditional source of energy. Energy-harvesting surfaces have the potential to power various types of devices, including sensors, wearable electronics, remote monitoring systems, and low-power electronic gadgets. They are particularly useful in scenarios where frequent battery replacement or access to power sources is impractical or costly. Some of the generalized energy-harvesting surfaces are discussed below.

Solar energy-harvesting surfaces: These surfaces are equipped with photovoltaic cells that capture sunlight and convert it into electrical energy. This is a common and important application of energy harvesting from sunlight [11].

Thermal energy-harvesting surfaces: The energy is harvested as a result of temperature difference between the surface and the surrounding environment to generate electricity through thermoelectric effects [12].

Vibration and mechanical energy-harvesting surfaces: These surfaces often use piezoelectric materials. They convert mechanical vibrations into electrical power [13].

Radio frequency (RF) energy-harvesting surfaces: Through rectifying circuits and specialized antennas, electrical energy is harvested from radio frequency electromagnetic waves, such as those from cellular networks or Wi-Fi signals [14].

Wind energy-harvesting surfaces: Wind energy harvesting can be done by the use of wind turbines. These are commonly used in applications where wind energy is available, but traditional wind turbines are not feasible due to size or location constraints [15].

It is important to note that the efficiency of energy-harvesting surfaces can vary depending on factors such as the energy source, the technology used, and the specific application. While they may not generate large amounts of power, they can extend the operational lifetime and reliability of devices that require low levels of energy.

Piezoelectric surfaces: Piezoelectric surfaces work as an energy-harvesting source in certain circumstances. In a piezoelectric surface, material is used that can harvest energy [16]. When a piezoelectric material is subjected to mechanical stress or strain, electricity is generated in its surface. Due to the mechanical stress, there is an alteration in crystal properties, as a result of which voltage is generated. Similarly, when electric current is provided to the piezoelectric material, the material gets deformed. The electricity produced can be stored in a battery. In the context of energy harvesting, a piezoelectric material is used to create a surface that can capture and convert mechanical energy from sources like vibrations, impacts, or even ambient movements into usable electrical energy. This technology has gained significant attention due to its potential to provide power for small electronic devices, sensors, and even remote or low-power applications where traditional power sources are impractical. The piezoelectric material is integrated into a structure that allows it to deform in response to mechanical vibrations or forces. This structure could be a beam, membrane, or other flexible component that can convert the mechanical energy into strain on the piezoelectric material. The piezoelectric surface is exposed to mechanical vibrations or deformations. These can come from a variety of sources, such as ambient vibrations, footsteps, machinery vibrations, or even from vehicles passing on a road. Piezoelectric energy harvesting has found applications in various fields such as wearable electronics, smart infrastructure, wireless sensor networks, Internet of things (IoT) and structural health monitoring [17].

Dielectric surfaces: A dielectric surface is another type of energy-harvesting device that plays great role in solar energy storage. These materials don't conduct electricity, but they can store energy in the form of an electric charge. Dielectric materials are embedded with or coated in solar panels. In this process, generally the dielectric material is coated on photovoltaic cells. The coated material efficiently traps the sunlight, absorbs it, and reduces reflection. Dielectric metasurfaces, which are patterned structures made of dielectric materials, can also be designed to manipulate the incoming light's direction, polarization, and wavelength, further increasing the efficiency of solar panels. When a light source is incident on the panel, the electricity generated by the dielectric material can be stored. Dielectric materials can also be used in energy storage applications. Capacitors, which consist of two conductive plates separated by a dielectric material, can store and release energy quickly compared to batteries. The greater the dielectric constant of the material, the more energy it can store and the more preferable in industry [18].

Magnetostrictive surfaces: A magnetostrictive surface for energy harvesting refers to a technology that utilizes the magnetostrictive effect to convert mechanical vibrations or strains in a material into electrical energy. The magnetostrictive effect is a property exhibited by certain materials that causes them to change their magnetic properties when subjected to a mechanical stress or strain [19]. The change in magnetic property can be utilized to produce electricity. The electricity is produced through electromagnetic induction. The changes in the magnetic properties of the magnetostrictive material induce an electromagnetic voltage in nearby coils or conductors according to Faraday's law of electromagnetic induction. This voltage can then be harvested and used as electrical energy. The induced voltage is often alternating current (AC). To make it usable for most applications, it needs to be converted into direct current (DC) using a rectifier. The harvested energy can then be stored in batteries or capacitors for later use or directly supplied to power electronic devices.

Solar-responsive surfaces: Certain surfaces can harness solar energy by incorporating photovoltaic materials. These surfaces can generate electricity from sunlight and be integrated into various structures, such as windows, roofs, and facades. Solar-responsive surfaces, often referred to as "smart surfaces" or "smart coatings," are materials designed to interact with and respond to sunlight or solar radiation in various ways. These surfaces are engineered to have specific properties that can enhance energy efficiency, comfort, or other functionalities in buildings, vehicles, or other applications. Here are a few examples of solar-responsive surfaces and their functions [20].

Photovoltaic surfaces: These surfaces are coated with solar cells that can convert sunlight directly into electricity. They are commonly used in solar panels to generate renewable energy for various applications, such as residential and commercial power generation [21].

Thermochromic surfaces: Thermochromic materials change color in response to temperature changes. These surfaces can be used in buildings to modulate heat gain or loss. For example, windows coated with thermochromic materials can darken to reduce sunlight and heat transmission during hot days, and become transparent again when it's cooler [22].

Photochromic surfaces: Photochromic materials change color when exposed to light, particularly UV light. These surfaces can be used in eyeglasses, windows, and other applications to automatically adjust their tint in response to sunlight, providing protection against glare and UV radiation [23].

Solar heat-reflective coatings: These coatings are designed to reflect a significant portion of sunlight and solar heat, reducing the amount of heat absorbed by surfaces. This can help keep buildings cooler and reduce the need for air conditioning, leading to energy savings [24].

Solar thermal absorbers: These surfaces are designed to absorb and retain solar heat, which can then be used for heating purposes. They are often used in solar water heaters and space heating systems [25].

Daylighting control surfaces: These surfaces are engineered to optimize natural daylighting in buildings while minimizing glare and excessive heat gain. They can enhance indoor lighting quality and reduce the need for artificial lighting during the day.

Solar-powered sensors: Some surfaces are integrated with sensors that are powered by solar energy. These sensors can be used for various purposes, such as environmental monitoring, security systems, and more [26].

- **Solar-powered ventilation:** Certain surfaces can be designed to automatically open or close in response to sunlight, facilitating passive ventilation in buildings and improving indoor air quality [27].

Heat-reflective coatings: Heat-reflective coatings are also called reflective roof coatings or cool roof coatings. The coating reflects the sun's rays, including infrared and ultraviolet rays. Mainly these coatings are used on rooftops for cooling purposes. These materials have high reflectivity and low emissivity. They include pigmented substances that can inhibit the transfer of heat through conduction. They are typically available in liquid form and can be sprayed or rolled onto the surface. They form a protective layer that reflects sunlight and prevents excessive heat absorption. This can be used mostly in hotter regions or in applications where cooling is necessary. These coatings can be applied to various surfaces, including roofs, walls, and even pavements. B reflecting a larger portion of the sun's energy, the building remains cooler, which can lead to energy savings and increased indoor comfort. Heat-reflective coatings are often available in light colors, such as white or light gray, because these colors have higher reflectivity. However, advancements in technology have led to the development of coatings with improved reflectivity even in darker colors [28]. Benefits are:

- **Energy efficiency:** By reducing the amount of heat absorbed by a building, heat-reflective coatings can lower the need for air conditioning and cooling systems, leading to energy savings.
- **Extended roof life:** Excessive heat can cause thermal stress and degrade roofing materials over time. Reflective coatings can help prolong the life of roofing materials by minimizing temperature-related wear and tear.
- **Indoor comfort:** Buildings with heat-reflective coatings often maintain a more comfortable indoor temperature, reducing the need for temperature control systems and enhancing occupant comfort.
- **Environmental impact:** Reduced energy consumption can lead to lower greenhouse gas emissions, contributing to environmental sustainability.

1.4 SELF-CLEANING SURFACES

Some surfaces are engineered to repel dirt, water, and other substances, effectively keeping themselves clean. This can be useful in environments where regular cleaning is impractical or challenging, such as in outdoor installations or on buildings. Self-cleaning surfaces are materials that have the ability to remove dirt, dust, microorganisms, and other contaminants from their surface without the need for manual cleaning or external intervention. These surfaces can maintain their cleanliness and appearance over time through various mechanisms that prevent the accumulation of unwanted substances. There are two main types of self-cleaning surfaces: hydrophobic (water-repellent) and photocatalytic.

Hydrophobic self-cleaning surfaces: Hydrophobic means repellent of water. Hydrophobic self-cleaning surface means the surface can repel water, and in that process it can remove dirt and other contaminants. The lotus leaf is a well-known natural example of this phenomenon, where its surface structure and chemical composition repel water and maintain its cleanliness. Like the lotus leaf, other surfaces have been developed by researchers that can clean their own surfaces. These materials often feature micro- or nanostructured surfaces that reduce the contact area between water and the surface, creating a "lotus effect." Coatings for outdoor surfaces, self-cleaning glass windows, and even clothing that resists staining are some of the best examples of hydrophobic self-cleaning surfaces [29].

Hydrophilic self-cleaning surfaces: Hydrophilic means affinity for water. The hydrophilic effect in cleaning refers to the phenomenon whereby cleaning or dirt removal is done by the substance. The hydrophilic material also can remove hydrophobic substances from surfaces. When hydrophilic material is added to a surface, the surface tension of water decreases. Hence water can spread out over the surface. This increased wetting helps to loosen and lift dirt and grime, making it easier to remove them during the cleaning process. This effect is crucial in various cleaning processes, from household cleaning to industrial applications [30].

Photocatalytic self-cleaning surfaces: Photocatalytic self-cleaning surfaces use a photocatalyst to clean a surface. In this surface, photocatalytic reactions take place that degrade pollutants and organic matter. When ultraviolet (UV) light is incident on the surface either from the sun or from any artificial source, photocatalytic action takes place in the presence of the photocatalyst. In photocatalytic action, reactive oxygen species are produced which degrade organic compounds and kill microorganisms on the surface. Titanium dioxide (TiO_2) is a common photocatalyst used in self-cleaning materials. This type of self-cleaning surface is mostly used in applications like air purification systems, building exteriors, and outdoor signage. It can help reduce the need for regular cleaning and maintenance while also contributing to improved air quality [31].

Anti-icing and antifogging surfaces are designed to prevent the accumulation of ice and fog on various surfaces, respectively. These technologies are especially important for safety and efficiency in various applications, including transportation, infrastructure, and everyday items.

Anti-icing surfaces: Anti-icing surfaces are engineered to prevent the buildup of ice on surfaces, which is crucial in environments where ice accumulation can lead to hazardous conditions and reduced performance. There are several ways to create anti-icing surfaces [32].

Hydrophobic coatings: These coatings repel water and ice by reducing the surface's ability to form ice crystals. They prevent ice adhesion and make it easier for ice to slide off surfaces [33].

Surface with **De-icing chemicals:** Some surfaces are treated with de-icing chemicals that can be released when the temperature drops. These chemicals can melt ice on contact or prevent ice formation altogether [34].

Microtextures on surface: Surfaces with microtextures or nanostructures can inhibit ice formation. These structures trap air, reducing the contact area between the surface and water droplets, which prevents ice from adhering [35].

Surface with h**eating elements:** In some cases, surfaces are equipped with embedded heating elements that can warm the surface to prevent ice accumulation. This is commonly seen in aircraft wings and wind turbine blades [36].

Antifogging surfaces: Antifogging surfaces are designed to prevent the formation of fog on surfaces, ensuring clear visibility in various conditions. Fog forms when warm, moist air comes into contact with a cooler surface. To prevent this, surfaces can be treated with:

Hydrophilic coatings: These coatings encourage the even spread of water droplets, preventing the formation of foggy patches. They promote the formation of a thin, transparent water layer that doesn't distort vision [37].

Antireflective coatings: These coatings reduce the reflection of light on the surface, which can reduce glare and the perception of foggy conditions [38].

Superhydrophilic surfaces: Similar to hydrophilic coatings, these surfaces have a high affinity for water, causing it to spread out and form a uniform layer instead of forming droplets that cause fog [39].

Both anti-icing and antifogging technologies have applications in various industries. For example, in aviation, anti-icing surfaces are crucial for maintaining the aerodynamic performance of aircraft, while antifogging technologies are essential for ensuring pilots have clear visibility. In transportation, such as in automobiles and trains, antifogging surfaces can improve driver visibility during inclement weather. In everyday products like eyeglasses and camera lenses, antifogging coatings can enhance usability.

1.5 SELF-HEALING SURFACES

Self-healing surfaces refer to materials or coatings that have the ability to repair damage to themselves without the need for external intervention. These surfaces have the potential to revolutionize various industries, including electronics, automotive, aerospace, and construction, by extending the lifespan of products, reducing maintenance costs, and improving overall durability. The concept is inspired by biological systems that can heal themselves, such as human skin healing from cuts or bruises. There are a few different mechanisms that researchers have explored to achieve self-healing properties in materials [40].

Microcapsules: One approach involves embedding microcapsules filled with healing agents within the material. When damage occurs, such as a crack or scratch, these microcapsules rupture and release the healing agents into the damaged area, where they react and solidify to repair the material [41].

Vascular systems: Similar to the circulatory system in living organisms, some self-healing materials have vascular networks. When damage occurs, these vascular networks can deliver healing agents to the damaged area through channels or tubes [42].

Polymerization: Some materials are designed to have reversible polymerization properties. When the material is damaged, the polymer chains can rearrange and reconnect to restore the material's integrity [43].

Shape memory materials: Certain materials have the ability to "remember" their original shape and return to it after deformation. If a self-healing material with shape memory properties is damaged, it can revert to its original shape, effectively repairing the damage [44].

Chemical reactions: Some materials are engineered to have specific chemical reactions that can repair damage. For instance, a material might incorporate components that can react with each other to mend cracks or other types of damage [45].

Heat-induced healing: In this approach, materials are designed to heal themselves when exposed to heat. Damage causes the material to change its structure, and heating it can trigger a reversal of this change, effectively repairing the damage [46].

Light-activated healing: Materials that can be healed through exposure to specific wavelengths of light have also been explored. This involves incorporating light-sensitive compounds into the material that can initiate healing reactions upon exposure to light [47].

Electrochemical healing: Some self-healing materials rely on electrochemical reactions to repair damage. When damage occurs, the electrochemical reactions can be triggered to restore the material's structure [48].

Self-healing surfaces have applications in a wide range of industries. For example, in electronics, self-healing materials could lead to longer-lasting devices with reduced need for repairs. In the automotive and aerospace industries, self-healing coatings could help prevent corrosion and damage caused by environmental factors. In construction, self-healing materials could lead to more durable and longer-lasting structures.

1.6 NOISE-REDUCING SURFACES

Some surfaces are engineered to absorb or block sound waves, contributing to noise reduction in various environments. This can be particularly useful in urban areas or spaces where noise pollution is a concern. Noise-reducing surfaces, also known as acoustic surfaces or sound-absorbing materials, are designed to minimize or absorb sound waves in various environments. They are commonly used in architectural and interior design, industrial settings, and even in consumer products to improve acoustic comfort and reduce noise pollution. These surfaces work by converting sound energy into heat energy, thus decreasing the sound's intensity and preventing it from reflecting or echoing within a space.

Common types of noise-reducing surfaces are often made from materials like foam, fiberglass, or mineral wool. They are mounted on walls or ceilings to absorb sound and reduce echoes in a room. Acoustic panels are widely used in recording studios, theaters, offices, and other spaces where sound quality matters. These panels are installed in suspended ceilings to absorb sound and improve the acoustics of a room. They are commonly used in commercial spaces, schools, and offices. These panels consist of fabric stretched over a frame filled with sound-absorbing materials. They can be customized in terms of color and design to blend with the interior decor while also providing acoustic benefits. These suspended acoustic elements are often seen in large spaces like auditoriums and gymnasiums. They hang from the ceiling and help control sound reflections and noise levels. There are also wall coverings made from sound-absorbing materials. Similar to fabric panels, they can be textured or printed to match the aesthetic of a room. These are wallpapers designed with sound-absorbing properties. They can be used in residential and commercial spaces to reduce noise levels. Specialized flooring materials can absorb impact noise and footfall sounds, making them ideal for environments where noise from walking or movement is a concern.

Perforated panels: These are solid panels with small perforations that allow sound waves to pass through and be absorbed by sound-absorbing material behind them. They are often used in architectural design to integrate acoustic treatment with aesthetics.

Acoustic partitions: These are movable panels that can be used to create flexible spaces within a larger area. They also offer acoustic separation and noise reduction [49].

Green acoustic solutions: Some noise-reducing surfaces utilize natural materials like plants to absorb sound. Green walls or vertical gardens can act as both aesthetic features and acoustic treatments.

When considering noise-reducing surfaces, it's important to take into account factors such as the specific noise frequencies you want to address, the desired aesthetic, fire safety regulations, and the overall purpose of the space. Different materials and configurations are suitable for different applications, so consulting with an acoustic consultant or interior designer can help you choose the best solutions for your needs.

1.7 FLEXIBLE SURFACES

In materials science, there are surfaces that can change shape, texture, or flexibility in response to external factors like temperature, humidity, or pressure. These surfaces have applications in robotics, soft electronics, and adaptive structures. Flexible surfaces refer to materials or structures that can bend, deform, or change shape without breaking or losing their integrity. These surfaces are often designed to be adaptable, resilient, and capable of undergoing various forms of deformation while still maintaining their functionality. Flexible surfaces have a wide range of applications across different industries and technologies. Following are some examples and applications [50].

Flexible displays: Flexible OLED (organic light-emitting diode) displays are becoming more common in smartphones, tablets, and even TVs. These displays can be curved, rolled, or folded without damaging the screen or affecting the image quality.

Wearable electronics: Wearable devices like smartwatches and fitness trackers often incorporate flexible surfaces to provide a comfortable fit and allow movement while maintaining the functionality of the electronics.

Flexible sensors: Sensors made from flexible materials can conform to irregular surfaces, enabling applications in robotics, health care, and environmental monitoring. For example, flexible pressure sensors can be used to measure touch or pressure on curved surfaces.

Textile electronics: Flexible electronics can be integrated into fabrics to create smart textiles. These textiles can have embedded sensors, LEDs, and even conductive threads for various applications, including fashion, sports, and medical wearables.

Medical devices: Flexible surfaces are used in medical applications such as catheters and endoscopes. These devices can navigate through complex anatomies while minimizing trauma to tissues.

Foldable furniture: Flexible materials can be used to create foldable furniture and space-saving solutions. For example, foldable chairs and tables are designed to be easily stored and transported.

Aerospace: Flexible surfaces can be used in aircraft to provide morphing wings that can change shape during flight, improving aerodynamics and fuel efficiency.

Packaging: Flexible packaging materials, such as pouches and bags, are used to protect and store various products. They can be easily manipulated and resealed, making them convenient for consumers.

Solar panels: Flexible solar panels can be integrated into a variety of surfaces, including roofs and backpacks, to generate renewable energy in a more versatile manner.

Automotive industry: Flexible materials are used in car interiors and exteriors. For instance, car seats with flexible components provide better comfort, and flexible displays can be integrated into dashboards.

Robotics: Soft robotics often utilize flexible materials to create robots that can move in complex ways, adapt to their environment, and interact more safely with humans.

Entertainment and gaming: Flexible surfaces can be used in interactive installations, such as flexible touch screens or projection screens that respond to touch or movement.

The development of flexible surfaces involves advancements in materials science, engineering, and design. Researchers and engineers work on creating materials that can withstand repeated deformations while maintaining their performance characteristics. These flexible materials often involve polymers, elastomers, and other innovative compounds.

1.8 ANTIMICROBIAL SURFACES

Antimicrobial surfaces refer to materials that are designed to inhibit or kill the growth of microorganisms, such as bacteria, viruses, fungi, and other harmful pathogens. These surfaces are particularly important in settings where hygiene and cleanliness are essential, such as health care facilities, food processing areas, and public spaces [51]. The goal of antimicrobial surfaces is to reduce the spread of infections and improve overall hygiene. There are several ways in which antimicrobial surfaces can be created or enhanced.

Chemical treatments: Some surfaces are treated with chemical agents that have antimicrobial properties. These agents can be embedded in the material or applied as coatings. Common antimicrobial agents include silver ions, copper, zinc, and various types of organic compounds.

Nanostructures: Nanotechnology has enabled the creation of surfaces with nanostructures that have inherent antimicrobial properties. These structures can physically damage the microorganisms by puncturing their cell walls or interfering with their metabolic processes.

Photocatalytic coatings: Some antimicrobial surfaces utilize photocatalytic coatings, often based on titanium dioxide (TiO_2), which can break down organic matter (including microbes) when exposed to light, such as ultraviolet (UV) light.

Electrostatic interactions: Some surfaces can be modified to have an electric charge that attracts and kills microorganisms. This can be achieved through the use of materials with inherent electrical properties or by applying specialized coatings.

Natural materials: Some natural materials, such as certain types of wood, have inherent antimicrobial properties. These materials can be used as surfaces without the need for additional chemical treatments.

Biological agents: Some antimicrobial surfaces incorporate biological agents like enzymes or peptides that have the ability to break down the cell walls of microorganisms.

It's important to note that while antimicrobial surfaces can play a role in reducing the spread of pathogens, they are not a replacement for proper cleaning and hygiene practices. Regular cleaning and disinfection are still crucial to maintain a safe and healthy environment. Additionally, there are ongoing discussions about the potential risks of relying heavily on antimicrobial surfaces, such as the development of antimicrobial resistance.

1.9 SUMMARY

This chapter has presented a brief introduction to the novel behaviors of the surfaces of multifunctional materials along with their specific requirements, processing, and applications. A huge research gap still exists regarding multifunctional material surface phenomena, which indicates that there is a new horizon for futuristic applications.

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