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Advancements and challenges in self-healing coatings for sustainable smart materials in industry applications

ABSTRACT

This review examines the developing fields of self-healing coatings and smart materials, emphasizing how they have the potential to transform a number of sectors by improving efficiency, sustainability, and durability. A growing number of self-healing coatings incorporate smart materials, which react to environmental stimuli like temperature, pressure, and electric fields, allowing damage to be repaired without the need for outside assistance. Even with some improvements in self-healing processes, there is still a great deal to learn about the long-term functionality and real-world uses of these materials, especially when paired with cutting-edge technology like nanomaterials. The most recent studies on self-healing coatings are summarized in this study, which also offers insights into the mechanisms underlying these advancements, such as vascular systems, reversible chemical bonding, and microencapsulation. It also emphasizes the various ways that smart materials are being used in sectors including construction, automotive, healthcare, and aerospace, showcasing their potential to save maintenance costs and enhance sustainability in general. This study discusses current issues and suggests future lines of inquiry that may propel the development and commercialization of these technologies for practical uses.

Keywords:Advanced coatings; industry applications; nanotechnology; self-healing coatings; smart coating systems; smart materials; sustainability*

1. INTRODUCTION

Smart materials are materials that have the ability to respond dynamically to external stimuli, such as mechanical, electrical, thermal, or chemical changes. These materials can adapt and modify their properties in response to environmental conditions, making them highly valuable in various technological applications. The growing interest in smart materials stems from their potential to enhance the performance, durability, and functionality of devices across numerous industries.One of the most inventive uses of smart materials is in self-healing coatings. The lifespan of the materials these coatings cover is increased since they are made to automatically fix damage brought on by mechanical wear or environmental conditions. Damage-induced alterations, like cracks, can activate self-healing coatings, which fix the harmed portions without the need for human assistance (Kessler, Sottos, & White, 2003).

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The basic idea is to incorporate micro- or nanocapsules that contain healing agents. These chemicals are released when the coating is destroyed, starting the repair process. Numerous sectors make extensive use of this idea, and material design and engineering have advanced significantly (Wang & Urban, 2020).

The potential for enhancing the durability and sustainability of different systems has led to an increase in the significance of smart materials and self-healing coatings. These materials are essential in situations when more conventional repair techniques would be expensive or difficult (Yu et al., 2023). Self-healing coatings, for instance, have the potential to save maintenance costs and enhance the performance of structural materials in the fields of civil engineering, automotive engineering, and aerospace (Zhang et al., 2018). They can also be used in protective coatings for metal surfaces, which can effectively prevent corrosion and drastically cut down on the frequency of repairs or replacements (Zhang et al., 2020).Many different industries have showed promise in self-healing materials, particularly coatings (Kim et al., 2024). These materials contribute to increased vehicle and aircraft durability in the automotive and aerospace industries (MohdJani et al., 2014). Additionally, they can be applied to electronics to create protective layers for circuits and components, increasing their dependability and prolonging their useful lives (Sekine&Nakao, 2023). Moreover, the application of self-healing coatings to building elements like steel and concrete has the potential to completely transform infrastructure maintenance. Long-term advantages include less maintenance needs, less of an influence on the environment, and more economical material management (Achal& Mukherjee, 2015; Jonkers et al., 2010).

Research on self-healing coatings is progressing quickly, with a focus on a variety of mechanisms, including stimuli-responsive materials, intrinsic healing polymers, and microcapsule-based systems (Rivero et al., 2014). These advancements hold the potential to improve self-healing systems' adaptability and effectiveness, enabling them to satisfy the demands of harsher and more complicated situations (Zhang et al., 2020). Self-healing coatings continue to develop as a game-changing technology by fusing nanotechnology, polymers, and composite materials (Kim et al., 2024).Self-healing systems' capacity to fix themselves, frequently without outside assistance, has significant ramifications for upcoming materials science applications. Performance and sustainability could be greatly enhanced in a number of industries by incorporating smart materials into commonplace products (Venkata Chalapathi et al., 2023). These materials provide a sustainable substitute for conventional techniques, altering not just the way goods are created but also the approach to upkeep, durability, and repair (Yang & Urban, 2013; Wang & Urban, 2020).

An important knowledge gap about the long-term performance and practical uses of smart materials is highlighted by the paucity of prior studies in the field of sophisticated self-healing coatings. The integration of these coatings with cutting-edge technology, such nanomaterials, and their employment in many industries have received little attention, despite some research into self-healing processes. Comprehensive assessments that evaluate the latest developments, difficulties, and possibilities for scaling up these technologies in real-world settings are also lacking. This review is unique in that it synthesizes the most recent advancements in self-healing coatings and smart materials, offering a current viewpoint on the underlying principles, inventions, and applications that are now influencing the sector. It also provides fresh perspectives on future research avenues that might get past current obstacles and help create material systems that are more effective, long-lasting, and sustainable.

This review's primary goals are: (i) Smart materials alter their characteristics in a regulated manner in response to outside stimuli like pressure or temperature; (ii) Self-healing coatings, which frequently use microcapsules or polymers that release healing chemicals, are a sort of smart material that can mend itself when injured; (iii) Shape memory alloys (SMAs), electroactive polymers (EAPs), and piezoelectric materials are important categories of smart materials, each with specialized uses in flexible electronics, sensors, and actuators; (iv) Nanotechnology and real-time monitoring systems are used in recent developments in self-healing coatings to improve their functionality and efficiency; and (v) These materials improve durability, lower maintenance costs, and enable more sustainable solutions in a variety of industries, including construction, automotive, healthcare, and aerospace.

2. FUNDAMENTALS OF SMART MATERIALS

Smart materials are engineered to respond to external stimuli, enabling adaptive and innovative applications across fields. This section explores key types such as piezoelectric materials, SMAs, and EAPs, their unique properties, and how they interact with environmental factors for optimized performance.

Types of Smart Materials

Smart materials are engineered to respond to changes in their environment by altering their physical or chemical properties. These materials have been widely studied and implemented in various applications such as sensors, actuators, and self-healing systems. The following sections provide an overview of the most prominent types of smart materials:

1. Piezoelectric Materials: The ability to produce electrical charge under mechanical stress is a special property of piezoelectric materials. Applications such as EH, sensors, actuators, and transducers make extensive use of this feature. Technologies for EH and damage detection have greatly improved with the recent invention of carbon fiber-reinforced piezoelectric nanocomposites. These nanocomposites improve durability in harsh conditions and energy conversion efficiency by fusing the mechanical strength of carbon fibers with the piezoelectric qualities of certain polymers (Yu et al., 2023). Piezoelectric materials are indispensable in the civil engineering and aerospace sectors because they are essential to wireless sensor networks and devices that track the health of structures.
2. Shape Memory Alloys: Metallic compounds known as SMAs, a pre-programmed shape and revert to it in response to a certain heat stimulation. SMAs are especially helpful in applications like medical devices, robotics, and actuators that demand accuracy and reactivity. The most widely used SMAs are nickel-titanium (NiTi) alloys, which are distinguished by their exceptional capacity to experience reversible

phase changes. Research is still being done to improve their performance, such as making these alloys more fatigue resistant for longer service lives (Jani et al., 2014). Innovation in fields like micro-electro-mechanical systems (MEMS) and biomedical implants is being fueled by the incorporation of SMAs into flexible and compact systems. Furthermore, the use of SMAs in high-performance automotive and aerospace applications is growing as new models with wider operating temperature ranges are developed.

3. Thermochromic and Photochromic Materials: Materials that are thermochromic react to changes in temperature, but materials that are photochromic change colour when exposed to light, especially ultraviolet (UV) light. Applications for these materials are numerous and include smart packaging, car glass, clothing, and temperature-sensitive indicators. Thermochromic coatings have advanced to the point where they are used in energy-efficient windows. Depending on the ambient temperature, these coatings can either block or let solar radiation, helping to adjust temperature (Kuilla in 2010). Wearable electronics and sensors are incorporating photochromic materials to provide real-time input on environmental changes, like UV exposure (Kessler et al., 2003). The development of multicolourthermochromic materials is another area of innovation. These materials may find use in a variety of contexts, including thermometers, smart fabrics, and adaptive camouflage systems.
4. Electroactive Polymers: A type of intelligent materials known as EAPs undergoes deformation when exposed to an electric field. They are frequently referred to as "artificial muscles" because of their capacity to replicate the mechanical characteristics of real muscles. EAPs have clear advantages over conventional actuators since they are flexible, lightweight, and can function in a range of conditions, including space and underwater. Recent developments have produced conductive polymer composites for soft robotics (SR), in which electrical signals regulate movement and deformation (Wang & Urban, 2020). The ability of these materials to react to variations in electrical stimuli makes them a crucial part of next-generation medical, robotic, and automotive equipment. They are also being employed in adaptive optics (AO) and sensor applications.
5. Magnetostrictive Materials: Materials that undergo shape change in response to a magnetic field are known as magnetostrictive (MD) materials. The realignment of the material's magnetic domains under the effect of a magnetic field, which produces dimensional changes, is the mechanism underlying MD. Actuators, sensors, and EH devices frequently use these materials. One of the most well-known MD materials, terfenol-D (TFD) is an alloy of iron, terbium, and dysprosium that is frequently utilized in high-performance actuators (Zhang et al., 2020). Optimizing the material's speed, sensitivity, and efficiency for application in energy-harvesting systems and sophisticated sensors for structural health monitoring (SHM) has been the focus of recent advancements. Furthermore, multifunctional MD composites are being created to improve their mechanical and MD qualities, opening the door to better robotics and aerospace actuation systems.

Properties and Mechanisms of Smart Materials

Numerous characteristics of smart materials make them special and appropriate for a range of uses. Usually, these characteristics include the capacity to alter size, form, or colour in reaction to outside stimuli like heat, light, or mechanical force. Understanding the mechanisms underlying these changes is essential to comprehending how these materials function.An electric charge is produced by the displacement of charges brought on by mechanical stress in piezoelectric materials, for example, where the transformation takes place at the atomic level. Similarly, in SMAs, the material's form recovers when heated due to phase transitions between the austenitic and martensitic phases (Jani et al., 2014). However, when exposed to an electric field, electrostatic forces cause shape changes in EAPs, whereas MD materials create mechanical strain through domain reorientation brought on by magnetic fields (Wang & Urban, 2020).

These materials must be able to react reversibly to external stimuli in order to be used in devices that need adaptive functionality, such as actuators that move, sensors that respond to pressure changes, or self-healing materials that can repair themselves after being damaged (Sekine&Nakao, 2023).Certain smart materials can also heal themselves, allowing them to bounce back from damage on their own. This capability has been shown in a variety of polymers and composites, where damage triggers the release of microencapsulated healing agents, promoting material repair (Kessler et al., 2003). Chemical events, such as polymerization or other healing processes, are part of the mechanisms of self-healing and are brought on by outside stimuli like light or temperature.

Interaction between Smart Materials and Environmental Stimuli

The way smart materials react to external stimuli is their basic behaviour. When temperature, pressure, light, electric field, or magnetic field changes, these materials react by changing their properties or behaviour accordingly. To detect damage in buildings, for instance, piezoelectric materials are perfect since they can produce electrical signals and are sensitive to mechanical stress (Yu et al., 2023). SMAs react similarly to temperature fluctuations, recovering a certain shape when heated above a critical temperature.Temperature indicators and smart textiles frequently incorporate thermochromic and photochromic materials, such as thermochromic inks, which change colour in response to temperature changes (Kuilla et al., 2010). Photochromic materials react more readily to UV light, they can be used in adaptive eyeglasses and smart windows that change their tint in response to changes in the surrounding light (Kessler et al., 2003). Soft robotics, artificial muscles, and actuators can all benefit from the shape-changing properties of EAPs, which interact with electric fields (Wang & Urban, 2020). The intensity of the electric field determines the rate and magnitude of deformation that these polymers can undergo when subjected to an applied voltage.High sensitivity to magnetic fields causes dimensional changes in MD materials, which are used in actuators and sensors for high-precision applications like motion sensing and vibration control (Zhang et al., 2020). Furthermore, self-healing materials exhibit distinct interactions with environmental stimuli. For example, self-healing polymers release encapsulated healing chemicals that can fix the material on their own when it is mechanically damaged. The polymerization or healing events that restore material integrity are triggered by external cues such as heat or UV light in certain self-healing materials (Sekine & Nakao, 2023).

Significant advancements have been made in the design and functionality of smart materials for a variety of applications, and innovation in this field is still developing quickly. EAPs give SR flexibility and adaptability, SMAs transform actuation systems, and piezoelectric materials facilitate effective EH and damage detection. MD materials improve actuation and sensor precision, while thermochromic and photochromic material innovations enable the development of systems that visually react to environmental changes. Certain smart materials' capacity for self-healing opens up new avenues for lifespan and endurance in structural applications. When taken as a whole, these developments show how smart materials are becoming more and more promising across a wide range of high-performance industries, such as robotics, healthcare, aerospace, automotive, and construction. Table 1 highlights the diverse range of smart materials, showcasing their properties, operational mechanisms, and wide-ranging applications in modern technologies. Each material type is tied to its core properties and innovations, indicating their ongoing importance in the development of adaptive and intelligent systems.

Table 1. Overview of Key Smart Materials, Properties, Mechanisms, and Applications

Type of Smart Material	Key Properties and Mechanisms	Applications	References
Piezoelectric Materials	Generate electrical charge under mechanical stress. React to mechanical forces by generating electric signals at the atomic level.	EH, sensors, actuators, damage detection, wireless sensor networks in civil engineering and aerospace sectors.	Yu et al., 2023
Shape Memory Alloys	Recover a pre-programmed shape when heated, transitioning between austenitic and martensitic phases.	Medical devices, robotics, actuators, MEMS, automotive, aerospace.	Jani et al., 2014
Thermochromic and Photochromic Materials	Change color in response to temperature (thermochromic) or UV light (photochromic).	Smart packaging, car glass, adaptive eyewear, energy-efficient windows, temperature-sensitive indicators.	Kuilla, 2010; Kessler et al., 2003
Electroactive Polymers	Undergo deformation when exposed to electric fields, acting as "artificial muscles".	Soft robotics, actuators, AO, biomedical devices, automotive systems.	Wang & Urban, 2020
Magnetostrictive Materials	Change shape in response to magnetic fields, caused by the reorientation of magnetic domains.	Actuators, sensors, EH, SHM, vibration control.	Zhang et al., 2020
Self-healing Materials	Materials that can repair themselves when damaged, triggered by external stimuli such as heat or UV light.	Self-healing composites, damage detection, structural applications.	Sekine&Nakao, 2023

3. UNDERSTANDING SELF-HEALING COATINGS

Self-healing coatings are innovative materials that can repair themselves after damage, restoring their protective and functional properties without external intervention. These coatings have become crucial in fields like corrosion protection, automotive applications, and infrastructure, offering notable improvements in material longevity and performance. This section explores self-healing coatings, their mechanisms, types, and applications.

Self-Healing Mechanisms

The purpose of self-healing coatings is to increase surface protection, save maintenance costs, and extend the lifespan of materials by automatically fixing mechanical damage such cracks and scratches (Acharya et al., 2021). These coatings are especially useful in settings like the automotive, marine, and aerospace industries where routine maintenance is expensive or impossible. Reactive agents, such as microcapsules or reversible chemical bonds, are usually embedded within the coatings' structure and triggered upon damage (Liu et al., 2012). Important mechanisms consist of:

1. Autonomous Self-Healing: Certain coatings have inherent qualities, such as reversible chemical bonds or molecular interactions that enable the material to mend itself under normal circumstances without the need for an outside trigger. Hydrogen bonds, for instance, can be broken and then reformed, offering effective and affordable repair for real-world uses (Liu et al., 2012).
2. Microencapsulation: This technique, which is one of the most studied self-healing systems, entails encasing healing chemicals (such as monomers or resins) in coated microcapsules. These capsules rupture when they are broken, releasing the healing chemicals that subsequently polymerize to repair damaged surfaces. This technique, which is frequently used in epoxy-based coatings, increases coating lifetime and decreases the requirement for manual repairs (Karaxi et al., 2019; Chen et al., 2023).
3. Vascular Systems: The coating's networks of microchannels carry healing materials to places that have been injured. These substances move to the crack site, simulating organic healing. This method works well for bigger cracks because it guarantees that the healing ingredients are distributed evenly (Sanyal et al., 2024).
4. Reversible Chemical Bonds: Diels-Alder reactions and other dynamic bonds are used in some coatings to enable the material to establish new bonds in response to particular stimuli, such as light or heat. These coatings are perfect for applications that need several healing cycles and long-term durability because this procedure can be repeated (Brunsveld et al., 2001; Hager et al., 2015).

Types of Self-Healing Coatings

Self-healing coatings vary by the materials used and healing mechanisms, each offering unique advantages for different applications:

1. Polymer-Based Coatings: These are among the most adaptable self-healing coatings; they are based on polymers, such as polyurethane or polyaniline composites, which have the ability to self-heal via processes like polymerization or hydrogen bonding. These coatings are appropriate for corrosion prevention and biodegradable applications due to recent advancements that include the use of graphene oxide and other nanomaterials to enhance mechanical qualities and healing effectiveness (Lei et al., 2020; Liu et al., 2022). They are frequently utilized in biodegradable materials, automotive, and aerospace (Ren et al., 2024).
2. Ceramic-Based Coatings: Despite their reputation for resilience to wear and high temperatures, ceramic coatings frequently suffer from brittleness. However, self-healing ceramics, including silica-based coatings that mend by silica condensation or hydrolytic bonding, have been made possible by developments in microcapsule embedding or the use of vascular systems. These coatings are perfect for high-temperature applications where traditional repairs are difficult, like thermal barriers for turbines and aircraft components (Zhang et al., 2018).
3. Hybrid Coatings: These coatings combine inorganic ceramics and organic polymers to provide both thermal stability and mechanical strength. These coatings produce improved mechanical, thermal, and self-healing capabilities by embedding nanostructured particles, such as carbon nanotubes, in polymer matrices. Applications in the automotive, aerospace, electronic, and marine industries benefit greatly from hybrid systems since they use a variety of processes, such as reversible bonding and microencapsulation (Wang et al., 2024).

Applications and Benefits

Self-healing coatings are gaining traction in industries that require high material integrity and where repairs are costly or impractical:

1. Corrosion Protection: These coatings shield metal surfaces from corrosive substances by patching fractures that may otherwise expose them to them. This is particularly helpful in

sectors where corrosion drastically shortens material lifespan, such as the automotive, aerospace, and marine industries (Banerjee et al., 2020).

2. Aerospace and Automotive: Self-healing coatings reduce maintenance requirements and increase the lifespan of automobiles and aircraft by providing resilience and damage resistance against environmental stressors such UV radiation, mechanical wear, and temperature fluctuations (Kontiza&Kartsonakis, 2024).
3. Smart electronics: Self-healing coatings increase the dependability of devices by shielding circuits and other parts from harm, extending their lifespan and reducing the need for replacements or repairs (Jung et al., 2023).
4. Sustainable and Biodegradable Coatings: Biodegradable self-healing coatings, which provide environmentally friendly substrate protection, have gained popularity as environmental concerns have grown. Green building materials and sustainable packaging are perfect for these coatings (Liu et al., 2012).

Materials science is being advanced by self-healing coatings, which solve problems like corrosion, wear, and durability on their own. These coatings drastically lower the requirement for maintenance by repairing damage on their own through the use of mechanisms including vascular networks, microencapsulation, and reversible bonding. Applications for coatings based on polymers, ceramics, and hybrids are growing in a variety of sectors, including electronics, automotive, aerospace, and sustainable technologies. The ongoing advancement of self-healing coatings demonstrates how they have the potential to completely transform durability and material maintenance in a variety of industries.

4. TECHNOLOGIES BEHIND SMART MATERIALS AND SELF-HEALING COATINGS

Smart materials and self-healing coatings are reshaping industries with their ability to adapt to environmental changes, damage, and wear. These technologies incorporate advanced manufacturing, nanotechnology, and real-time monitoring systems to enable dynamic responses to damage. This section outlines recent advancements in smart material and self-healing coating technologies.

Advanced Manufacturing Techniques for Smart Materials

The production of smart materials requires specialized techniques that embed responsive elements into materials at molecular or macroscopic scales. Methods like layer-by-layer deposition, sol-gel processing, and nanostructuring allow for precise control over material properties, enhancing their response to environmental stimuli. Nanostructured coatings, for instance, improve self-healing by allowing efficient diffusion and activation of healing agents (Wang et al., 2019; Li et al., 2024). These methods yield coatings resistant to corrosion, abrasion, and environmental degradation. Recent progress in 3D printing and additive manufacturing enables the design of complex coatings with self-healing capabilities, allowing precise control over material structure and facilitating the inclusion of mechanisms like microcapsules and vascular networks (Li et al., 2023). These methods produce customizable coatings suited to specific industry needs, including aerospace, marine, and automotive applications.

Nanotechnology in Self-Healing Coatings

Nanotechnology is pivotal in enhancing the durability and self-healing efficiency of coatings. Nanomaterials such as nanoparticles, nanocapsu-les, and nanotubes strengthen coatings at the nanoscale, improving both mechanical and chemical properties. For example, nanocapsules filled with healing agents like epoxy or resins are incorporated into polymeric coatings, releasing healing agents upon rupture to repair cracks and prevent further damage (Li et al., 2024; Liu et al., 2021). Additionally, carbon nanotubes and graphene create conductive networks that facilitate rapid self-repair in cases of mechanical failure (Xu et al., 2024). Materials like graphene oxide and lignin derivatives enhance anticorrosive properties, making them ideal for protecting metals in harsh environments. These nanomaterials improve adhesion, flexibility, and thermal stability, allowing self-healing coatings to endure extreme conditions while maintaining functionality.

Smart Coating Systems with Sensors and Real-Time Monitoring

Integrating sensors with self-healing coatings represents a major innovation in smart materials. These sensors allow coatings to detect and respond to damage, such as corrosion or cracks, by releasing healing agents as needed. Coatings with embedded corrosion sensors, for example, can detect wear onset and activate a protective response, making them especially valuable in aerospace, automotive, and marine applications (Li et al., 2023). Embedded sensors can detect changes in mechanical, thermal, or chemical conditions and even biofouling. These capabilities enable predictive maintenance by providing real-time data on potential failures before they become critical, enhancing the efficiency and longevity of protective coatings (Li et al., 2024).

Additive Manufacturing and 3d Printing of Smart Materials

Additive manufacturing and 3D printing enable the design of self-healing materials with intricate geometries and embedded functionalities. These methods support the integration of microchannels, capsules, or encapsulated healing agents directly into the material. For example, certain 3D-printed structures incorporate patterns that optimize the controlled release of healing agents upon damage (Wang et al., 2019). Furthermore, multi-material 3D printing allows the creation of layers with distinct functions, some providing mechanical strength, others containing healing agents. The customization offered by these techniques improves the performance of self-healing coatings across a range of applications, from aerospace to biomedical devices (Li et al., 2024; Liu et al., 2022).

Computational Modelling and Simulation of Self-Healing Processes

Computational modelling and simulations are crucial for optimizing self-healing coatings, allowing researchers to predict material behaviour under different conditions. Techniques like finite element analysis (FEA) and molecular dynamics (MD) simulations model interactions between healing agents, polymers, and nanoparticles in coatings (Li et al., 2023). Machine learning and Artificial Intelligence(AI) further support these advancements by predicting coating responses under various stresses. Simulation tools provide insights into healing kinetics, structural integrity, and lifetime predictions, allowing for precise fine-tuning of self-healing mechanisms before production (Li et al., 2024).

Smart materials and self-healing coatings are advancing industries by enabling autonomous damage repair, improved performance, and reduced maintenance costs. Innovations in advanced manufacturing, nanotechnology, sensor integration, and computational modelling make it possible to design coatings with highly specialized functions. Real-time monitoring capabilities and self-triggered healing processes provide a significant advantage for industries reliant on durable and efficient protective materials, including corrosion protection, aerospace, and automotive sectors. Table 2 summarizes the technologies behind smart materials and self-healing coatings, with relevant citations that highlight the innovative advancements shaping their development and applications.

Table 2. Technologies behind Smart Materials and Self-Healing Coatings

Technology	Description	Applications	References
Advanced Manufacturing Techniques	Methods like layer-by-layer deposition, sol-gel processing, and nanostructuring allow precise control over material properties.	Aerospace, automotive, marine applications, energy-efficient coatings, 3D printed smart materials.	Wang et al., 2019; Li et al., 2024
Nanotechnology	Utilizes nanomaterials such as nanoparticles, nanotubes, and nanocapsules to enhance mechanical, chemical, and self-healing properties.	Protection of metals, corrosion-resistant coatings, flexible coatings, conductive networks.	Li et al., 2024; Liu et al., 2021; Xu et al., 2024
Smart Coating Systems with Sensors	Coatings embedded with sensors that can detect damage, like cracks or corrosion, and trigger self-repair mechanisms.	Aerospace, automotive, marine applications, predictive maintenance, corrosion control.	Li et al., 2023; Li et al., 2024
Additive Manufacturing &3D Printing	Allows for intricate design and embedding of healing agents, microchannels, and capsules directly into the material.	Aerospace, biomedical devices, custom smart coatings, 3D printed self-healing systems.	Wang et al., 2019; Li et al., 2024; Liu et al., 2022
Computational Modelling & Simulation	Utilizes tools like FEA and MD simulations to predict material behavior, healing kinetics, and optimize coating designs.	Coating optimization, material behavior prediction, failure analysis, enhanced self-healing processes.	Li et al., 2023; Li et al., 2024

5. INNOVATIVE APPLICATIONS OF SMART MATERIALS AND SELF-HEALING COATINGS

Smart materials and self-healing coatings are increasingly applied across various industries, offering durable, low-maintenance, and safety-enhancing solutions. These materials self-repair damage in real time, ensuring sustained performance and protection in harsh environments. Below are the innovative applications of smart materials and self-healing coatings across multiple industries.

Aerospace Industry: Protective Coatings for Aircraft and Satellites

Protective coatings are essential to the longevity and dependability of satellites and airplanes in the aerospace industry. Severe degradation is brought on by extreme circumstances like high-speed collisions, UV rays, and temperature changes. Self-healing coatings increase resistance to erosion, abrasion, and corrosion by fixing damage on their own. To prevent environmental degradation to aircraft surfaces, such as those made of aluminum and composite materials, nano-enabled self-healing coatings have been developed (Shakirzyanov et al., 2023; Zhang et al., 2018). These coatings contain microcapsules that automatically release healing chemicals to fix small cracks or abrasions. Embedded sensors in smart coatings provide real-time structural integrity monitoring, minimizing the need for expensive inspections and warning maintenance teams of possible damage early on (George et al., 2022). In aerospace applications, these technologies improve cost-effectiveness, durability, and safety.

Automotive Industry: Self-healing Paints and Materials for Vehicles

Automotive production is being revolutionized by self-healing materials, which can be used to create coatings that can fix tiny abrasions, cracks, and scratches. When a surface is damaged, these coatings' microcapsules or nanocontainers containing agents like epoxy or linseed oil activate, repairing the surface's appearance and providing protection from environmental elements like corrosion (Zhang et al., 2018; Morshed-Behbahani et al., 2022). Additionally, self-healing coatings are applied to car interiors to safeguard delicate electronic parts. Manufacturers improve car systems' dependability and safety by incorporating self-healing materials into electronics, protecting against environmental damage, wear, and moisture (George et al., 2022).

Construction Industry: Smart Coatings for Buildings and Infrastructure

Self-healing coatings are very advantageous to the construction sector for the upkeep of buildings and infrastructure. Smart coatings provide long-lasting defense against weathering, corrosion, and cracking when applied to steel, glass, and concrete. The self-healing concrete reduces the need for frequent repairs by containing bacteria or chemical agents that, when exposed to moisture, automatically mend cracks (Xia et al., 2022). These materials prolong the life of infrastructure and buildings, which promotes sustainability. Sensor-embedded intelligent coatings can track the health of the structure, giving maintenance crews up-to-date information on material quality and warning them of possible problems before they become serious.

Electronics and Sensors: Self-Healing coatings in consumer devices

Self-healing coatings improve the operation and longevity of consumer devices including wearables, tablets, and smartphones. These coatings frequently employ nanoencapsulation, which releases healing chemicals in response to damage, preventing problems from moisture, drops, or scratches (Li et al., 2017; Leal et al., 2018). Self-healing polymers are especially advantageous for flexible electronics, enabling wearable sensors and bendable screens to fix cracks without sacrificing functionality. These coatings will be more and more crucial for boosting the dependability and durability of electrical gadgets.

Energy Sector: Smart Materials in Renewable Energy Technologies

Self-healing coatings are used on wind turbines, solar panels, and storage devices in the energy sector to increase the lifetime of renewable technologies and combat environmental deterioration. The self-healing coatings on wind turbine blades fix impact damage, guaranteeing peak performance and lowering maintenance requirements (Erdogan et al., 2021). The reliability of renewable energy infrastructure is also supported by coatings on solar panels, which keep efficiency high by sealing fractures and keeping moisture out.

Healthcare and Biomedical Applications of Self-Healing Materials

Self-healing materials are used in the biomedical and healthcare sectors for devices, implants, and wound healing. In biomedical equipment like implants and prostheses, self-healing polymers fix themselves when they wear down, guaranteeing patient safety and lifespan. Self-healing hydrogel coatings in wound care protect and encourage tissue regeneration by simulating the skin's natural healing process (Behzadnasab et al., 2017). Self-healing materials, in which environmental factors induce the targeted release of medicines or healing agents, are also advantageous for drug delivery systems.

Marine and Offshore Applications: Protecting Structures in Harsh Environments

Materials that can withstand high pressure, harsh temperatures, and saltwater are necessary for the marine and offshore industries. Offshore platforms, ship hulls, and undersea structures are shielded from corrosion, abrasion, and biofouling by self-healing coatings. Offshore structures are coated to prevent corrosion, which lowers the need for repairs and increases the lifespan of the infrastructure (Hou et al., 2017). Marine coatings with antifouling and self-healing qualities keep organisms from building up, maintaining structural integrity and effectiveness (Erdogan et al., 2021).

Self-healing coatings and smart materials provide revolutionary solutions for a variety of sectors by boosting long-term performance in demanding settings, reducing maintenance, and improving durability. These developments, which tackle wear, deterioration, and environmental issues in fields ranging from healthcare to aerospace, highlight the promise of self-healing materials as crucial instruments for industrial resilience and efficiency as technology advances. Table 3 highlights the innovative applications of smart materials and self-healing coatings across various industries, from aerospace to healthcare. These technologies improve durability, reduce maintenance, and enhance performance in challenging environments.

Table 3. Innovative Applications of Smart Materials and Self-Healing Coatings

Industry	Application	Technology/Benefit	References
Aerospace	Protective Coatings for Aircraft and Satellites	Nano-enabled self-healing coatings with microcapsules that repair damage and embedded sensors for structural integrity	Shakirzyanov et al., 2023; Zhang et al., 2018
Automotive	Self-Healing Paints and Materials for Vehicles	Coatings that repair abrasions, cracks, and scratches using microcapsules containing epoxy or linseed oil	Zhang et al., 2018; Morshed-Behbahani et al., 2022
Construction	Smart Coatings for Buildings and Infrastructure	Self-healing concrete with bacteria or chemical agents to mend cracks and sensor-embedded coatings to monitor structural health	Xia et al., 2022
Electronics & Sensors	Self-Healing Coatings in Consumer Devices	Nanoencapsulation-based coatings for wearables, tablets, smartphones to prevent damage from moisture and scratches	Li et al., 2017; Leal et al., 2018
Energy	Smart Materials in Renewable Energy Technologies	Self-healing coatings for wind turbines and solar panels to repair damage and maintain efficiency	Erdogan et al., 2021
Healthcare	Biomedical Applications of Self-Healing Materials	Self-healing hydrogels for wound care and polymers for implants and prostheses	Behzadnasab et al., 2017
Marine & Offshore	Protecting Structures in Harsh Environments	Self-healing coatings for offshore platforms and ship hulls to resist corrosion and biofouling	Hou et al., 2017; Erdogan et al., 2021

6. CHALLENGES AND LIMITATIONS OF SMART MATERIALS AND SELF-HEALING COATINGS

Despite the many benefits of developing smart materials and self-healing coatings, a number of obstacles still stand in the way of their widespread use and efficacy. These difficulties cover a wide range of topics, including as integration with current infrastructure, environmental concerns, economic viability, scalability, and durability. For these materials to continue to improve in practical applications, these problems must be resolved.

Durability and Performance Under Extreme Conditions

Sustaining performance and durability under harsh conditions is a major problem for self-healing coatings. Variations in temperature, moisture content, and UV rays can all lower these materials' capacity for self-healing, which can occasionally result in partial or delayed recovery (Zhang et al., 2018). Mechanical wear can weaken coatings over time, reducing their capacity for self-healing. Researchers are looking into more durable choices, like graphene-based composites for corrosion protection and strong healing capabilities, to improve long-term performance (George et al., 2022).

Scaling up Production and Commercialization Challenges

Smart materials and self-healing coatings are still challenging to produce on a large scale. Despite their success in the lab, many self-healing coatings have difficulties in industrial manufacture because of intricate synthesis procedures (Samadzadeh et al., 2010). It can be difficult to maintain consistency over big batches, particularly for components that are nanoscale and susceptible to environmental changes. Technological advancements in nanoencapsulation may assist solve these scaling problems and increase production efficiency (Wang et al., 2017).

Cost and Economic Feasibility of Smart Coatings

The wider application of smart coatings is hampered by high production costs since sophisticated materials like graphene and nanoparticles are very expensive. Self-healing coatings can save maintenance costs, but because of their high initial cost, they are less accessible to cost-conscious industries like electronics and construction (George et al., 2022). Performance and economic viability must be balanced, especially in sectors where cost reduction is critical, such as renewable energy (Hou et al., 2017).

Environmental Impact and Sustainability Concerns

Smart materials' potential to contribute to plastic pollution raises concerns about their effects on the environment, especially those made of synthetic, non-biodegradable polymers. The environmental advantages of less maintenance may be outweighed by the energy-intensive manufacturing of nanoparticles (Xia et al., 2022). The development of biodegradable self-healing coatings and environmentally friendly encapsulation is promoted in order to improve sustainability (Grigoriev et al., 2017).

Integration with Existing Systems and Infrastructure

The integration of self-healing coatings with existing infrastructure presents an additional hurdle. Retrofitting efforts may be complicated by the incompatibility of modern coatings with traditional materials utilized in sectors such as construction (Leal et al., 2018). Furthermore, existing technological infrastructure must be modified in order to include these materials into sensor-based or automated maintenance systems (Dieleman et al., 2018).

Despite its potential, self-healing coatings and smart materials have problems with integration, scalability, cost, durability, and environmental effect. Innovations in sustainability, manufacturing, and materials science are needed to overcome these challenges. Future studies will probably concentrate on enhancing the effectiveness of self-healing, cutting production costs, and guaranteeing compatibility with a range of industrial applications.

7. RECENT INNOVATIONS IN SMART MATERIALS AND SELF-HEALING COATINGS

Recent developments in self-healing coatings and smart materials have produced important achievements, especially in enhancing usefulness, sustainability, and corrosion resistance. These developments are making it possible to create multifunctional coatings that react to a range of environmental stimuli in addition to improving the functionality of self-healing mechanisms.

Advances in Materials and Mechanisms for Self-Healing

The effectiveness of protective coatings has been greatly increased by recent developments in self-healing processes. The triple-stimuli-responsive nanocontainers, which react to light, moisture, and temperature stimuli to improve corrosion protection, have been created for anticorrosion coatings on aluminium alloys (Wang et al., 2019). Furthermore, to improve performance in harsh environments, dense Aluminium Oxide (Al_2O_3) sealing has been investigated as a means of preventing high hydrostatic pressure corrosion inChromium/Glassy Carbon(Cr/GLC) coatings (Li et al., 2024).

New Developments in Hybrid and Multi-functional Coatings

The creation of multipurpose coatings with improved qualities is the result of hybrid coatings, which combine several elements. Composite silicon dioxide and zinc oxide (SiO_2@ZnO) core-shell nanospheres have been shown to be used in polymer coatings that offer corrosion resistance and anti-fouling qualities for marine applications. Additionally, the use of porous microspheres in coatings has created new opportunities for active corrosion prevention and real-time damage detection (Li et al., 2023).

Advancements in Nano-enabled Self-Healing Coatings

More focused healing processes have been offered by developments in nano-enabled self-healing coatings. Liu et al. (2021) used nanoparticles to detect damage and initiate healing in order to create smart coatings with autonomous self-healing and early corrosion reporting capabilities. Waterborne polyurethane coatings containing chitosan-modified graphene oxide exhibit improved anti-corrosion and self-healing properties, making them perfect for extended outdoor use (Xie et al., 2022).

Role of Artificial Intelligence and Machine Learning in Material Design

Optimizing self-healing coatings is mostly dependent on machine learning and AI. Artificial intelligence algorithms simulate environmental conditions to help forecast material behavior and build more effective coatings (Li et al., 2024). Additionally, machine learning algorithms are employed to pinpoint performance trends and direct the creation of more resilient coatings.

Self-Healing Coatings for Extreme Environmental Applications

In challenging environmental applications where conventional coatings are ineffective, self-healing coatings are becoming more and more important. A mimosa-inspired anti-corrosive composite coating, for example, was created by Xu et al. (2024) and offers improved corrosion protection in challenging conditions. These developments hold the potential to completely transform industries by providing high-performing, environmentally friendly corrosion protection solutions.

Industries that depend on durable corrosion protection are undergoing a revolution thanks to recent advancements in smart materials and self-healing coatings. More effective and sustainable coatings are being developed thanks to developments in nano-enabled coatings, multifunctional hybrid coatings, and the fusion of AI and machine intelligence. These developments hold the potential to tackle some of the most difficult corrosion prevention issues, providing solutions that are resilient to harsh environments and extend the life of vital infrastructure.

8. ENVIRONMENTAL IMPACT AND SUSTAINABILITY OF SMART MATERIALS

The environmental impact and sustainability of smart materials and self-healing coatings are critical considerations in their development and implementation. As these materials become more advanced, it is essential to evaluate their eco-friendliness, life cycle, and ability to contribute to more sustainable practices.

Eco-friendly Smart Materials and Sustainable Alternatives

Reducing the environmental impact of coatings is a key component of the growing trend toward eco-friendly smart materials. The creation of self-healing and self-lubricating nano-hybrid smart coatings, which provide greater durability while reducing the need for frequent replacements, was emphasized by Vafaeenezhad and Eslami-Farsani (2024). This method offers a more environmentally friendly substitute for conventional coatings, which frequently need more upkeep. Furthermore, because bio-based materials improve sustainability and lessen dependency on hazardous chemicals, their application in protective coatings is growing (Zhang et al., 2018).

Smart Coatings and Materials Life Cycle Assessment

Assessing the environmental impact of smart materials from manufacture to disposal requires life cycle assessment (LCA). Jung et al. (2023) discussed about how LCA can be used to optimize dual-function smart materials that combine self-healing and damage detection in order to reduce resource consumption. According to life cycle studies that contrast self-healing coatings with conventional coatings, the latter offer advantages for the environment by lowering the need for replacement and maintenance (Sabet-Bokati et al., 2024).

Recyclability and End-of-life Management of Self-Healing Materials

Recyclability and the handling of self-healing materials at the end of their useful lives are also aspects of sustainability. Intelligent anti-corrosion coatings that use recyclable and less hazardous ingredients were investigated by Liu et al. in 2024. Microcapsules containing natural polyelectrolytes in water-based polyurethane coatings are an example of a biodegradable material trend that enhances self-healing and recyclability while lowering environmental impact over the material's lifecycle (Li et al., 2022).

Role in Reducing Maintenance and Resource Consumption

Self-healing coatings minimize the usage of raw materials and the related environmental effects by reducing the need for frequent maintenance. Wang et al. (2019) showed how anticorrosion coatings using triple-stimuli-responsive smart nanocontainers improve long-term durability while using fewer resources. Similarly, active protection is integrated into porous microspheres with corrosion sensing, maximizing material efficiency and minimizing unnecessary resource use (Li et al., 2023).

By lowering resource consumption and environmental effects, self-healing coatings and smart materials are advancing sustainability in protective coatings. These coatings offer long-term cost benefits and support more sustainable business practices because to developments in eco-friendly materials, LCA, and recyclability.

9. FUTURE DIRECTIONS OF SMART MATERIALS AND SELF-HEALING COATINGS

The future of smart materials and self-healing coatings is marked by continuous innovation, which aims to enhance their performance, sustainability, and integration with advanced technologies. As these materials evolve, they are expected to play a pivotal role in next-generation protective systems and contribute significantly to sustainable development.

Innovations on the Horizon: New Materials and Technologies

Recent innovations in smart materials focus on enhancing self-healing properties and improving efficiency. Martin et al. (2014) highlighted the development of poly(urea-urethane) elastomers with aromatic disulfide bridges, which enable reversible crosslinking and improved self-healing performance, offering durability and flexibility. Liu et al. (2012) explored biodegradable poly(urea-urethane) elastomers, based on hydrogen bonding, providing both environmental benefits and self-healing capabilities, addressing sustainability concerns in industrial applications.

The Role of Smart Coatings in Sustainable Development

Smart coatings are increasingly crucial for promoting sustainability across industries. Rivero et al. (2014) introduced thermo-remendable shape memory polyurethanes, which reduce material waste by extending coating lifespan. Additionally, supramolecular polymers with dynamic bonds, as noted by Brunsveld et al. (2001), improve material durability and energy efficiency, contributing to long-term sustainability and reducing the frequency of coating replacements.

Integrating Artificial Intelligence, Internet of Things, and Smart Materials for Next-generation Protection Systems

Integrating AI and the IoT with smart materials is transforming protective systems. Hager et al. (2015) discussed the integration of shape memory polymers with AI-driven systems, enabling real-time damage detection and adaptive self-healing coatings. Lei et al. (2020) highlighted the potential of IoT sensors combined with corrosion inhibitors, offering advanced corrosion monitoring, predictive maintenance, and reduced manual inspections.

Potential Markets and Future Applications in Emerging Industries

Smart materials are expanding into industries like aerospace, automotive, and marine. Karaxi et al. (2019) assessed self-healing coatings for galvanized steel, highlighting their potential in high-durability sectors. Chen et al. (2023) reviewed self-healing coatings for magnesium alloys, indicating promising applications in lightweight automotive components and energy-efficient buildings, improving resource efficiency and reducing maintenance costs.

Challenges for Widespread Adoption and Scaling

Challenges remain in scaling self-healing materials. Acharya et al. (2021) identified cost and production complexity as barriers. Sanyal et al. (2024) emphasized the need for standardized testing protocols to ensure reliability and safety. Addressing these issues is crucial for the widespread adoption of smart materials across industries.

The future of smart materials and self-healing coatings is exciting, with innovations in materials, technology integration, and applications paving the way for more sustainable and efficient solutions. By embracing advancements in biodegradable materials, AI, and IoT, the next generation of smart coatings will offer enhanced performance, durability, and environmental benefits, supporting their widespread adoption across diverse industries.

10. RECOMMENDATION OF REVIEW

The field of self-healing coatings has made significant strides, but there are still key areas that require further research to enhance their functionality, scalability, and sustainability for real-world applications.

1. Integration with Emerging Technologies: To unlock the full potential of self-healing coatings, research should focus on integrating nanomaterials, real-time monitoring, and advanced sensors. Combining these technologies could enable coatings to not only heal but also detect and assess damage before it spreads, offering multifunctional protection within a single system (Zhao et al., 2020).

2. Enhancing Durability: Future research must address the challenge of maintaining long-term durability under harsh conditions, such as extreme temperatures and mechanical wear, especially in industries like aerospace, marine, and industrial applications. Developing coatings that retain their healing ability and protective performance over time is crucial for their practical deployment (White et al., 2016).

3. Development of Multifunctional and Sustainable Coatings: There is growing demand for coatings that offer multiple protective functions, such as corrosion resistance, fouling prevention, and SHM, in addition to healing damage. Future research should aim to combine these features in a single coating system, while also exploring eco-friendly and biodegradable materials that reduce environmental impact without compromising performance (Srinivasan&Pospisil, 2021; Liu & Zhang, 2021).

4. Advanced Manufacturing and Scalability: A significant barrier to the widespread adoption of self-healing coatings is the ability to produce them at scale. Cost-effective manufacturing methods, such as 3D printing and roll-to-roll processing, need to be explored to ensure these coatings can be mass-produced for commercial use without exorbitant costs (Song et al., 2023).

5. AI and IoT Integration for Real-time Monitoring: Integrating AI and IoT with self-healing coatings could enable autonomous monitoring and triggered healing at the optimal time. This integration could be especially beneficial in high-precision industries, such as aerospace or healthcare, where timely repairs are critical to safety (Chen et al., 2022).

Self-healing coatings show great promise but require further research to enhance functionality, scalability, and sustainability. Key areas for improvement include integrating emerging technologies, enhancing durability, developing multifunctional and sustainable coatings, advancing scalable manufacturing methods, and incorporating AI and IoT for real-time monitoring.

11. CONCLUSIONS

The development of smart materials, particularly self-healing coatings, has emerged as a groundbreaking innovation with significant advantages across industries such as aerospace, automotive, construction, and healthcare. These coatings, capable of repairing themselves when damaged, offer enhanced durability, reduced maintenance costs, and promote sustainability by extending the lifespan of materials. The integration of emerging technologies such as nanomaterials, AI, and real-time monitoring is crucial for optimizing the functionality of these coatings. Despite these promising advancements, challenges such as the lack of long-term performance data, scalability issues, and high manufacturing costs still need to be addressed.The future of self-healing coatings depends on the successful integration of nanotechnology, AI, and IoT. These technologies have the potential to enhance the responsiveness and efficiency of self-healing materials, enabling real-time monitoring and automated damage detection. Advanced nanomaterials, like nanoparticles and nanocapsules, could significantly improve the healing process by enabling faster and more efficient recovery from damage. Additionally, AI algorithms could optimize the self-healing process, adapting the coatings to different environments and conditions. This convergence of emerging technologies will not only improve the functionality of self-healing coatings but also expand their potential applications.However, for self-healing coatings to achieve widespread adoption and commercial success, several challenges must be overcome.

These include enhancing the coatings' durability under real-world conditions, making them cost-effective for mass production, and ensuring their scalability across various industries. Additionally, the development of multi-functional coatings that can offer self-healing, corrosion resistance, and other protective properties simultaneously presents another challenge. To make these coatings commercially viable, collaboration between researchers, engineers, manufacturers, and industry stakeholders will be essential. By addressing these challenges, self-healing coatings can transition from lab-based concepts to commercially viable solutions, revolutionizing material science and leading to more resilient, sustainable, and efficient industries.

Nomenclatures

AI	Artificial Intelligence
Al_2O_3	Aluminum Oxide
AO	Adaptive Optics
Cr/GLC	Chromium/Glassy Carbon
EAP	Electroactive Polymer
EH	Energy Harvesting
FEA	Finite Element Analysis
IoT	Internet of Things
LCA	Life Cycle Assessment
MEMS	Micro-Electro-Mechanical Systems
MD	Molecular Dynamics
MS	Magnetostrictive
NiTi	Nickel-Titanium
SMA	Shape Memory Alloy
SHM	Structural Health Monitoring
SiO_2	Silicon Dioxide
SR	Soft Robotics
TFD	Terfenol-D
UV	Ultraviolet
ZnO	Zinc Oxide

Statement and declaration

The research presented in this manuscript is original and has not been submitted or published elsewhere. All sources and references have been duly acknowledged, and the authors have taken all necessary steps to ensure the accuracy and integrity of the work.

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Highlights

1. Self-healing coatings enhance efficiency, sustainability, and durability by autonomously repairing damage in various industries.
2. Recent advancements include vascular systems, reversible bonding, and microencapsulation for autonomous damage repair.
3. Smart materials improve sustainability and reduce costs across sectors like construction, automotive, healthcare, and aerospace.
4. Challenges remain in long-term functionality, requiring further research on integrating nanomaterials and advanced technologies.

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IZVOD

NAPREDAK I IZAZOVI U SAMOZALEČIVIM PREMAZIMA ZA ODRŽIVE PAMETNE MATERIJALE U INDUSTRIJSKIM PRIMENAMA

Ovaj pregled ispituje razvoj oblasti samozalečivih premaza i pametnih materijala, naglašavajući kako oni imaju potencijal da transformišu brojne sektore poboljšanjem efikasnosti, održivosti i izdržljivosti. Sve veći broj samozalečivih premaza uključuje pametne materijale, koji reaguju na stimuluse iz okoline poput temperature, pritiska i električnih polja, omogućavajući popravku oštećenja bez potrebe za spoljnom pomoći. Čak i uz neka poboljšanja u procesima samozalečivosti, još uvek ima mnogo toga da se nauči o dugoročnoj funkcionalnosti i stvarnoj upotrebi ovih materijala, posebno kada se upare sa najsavremenijom tehnologijom poput nanomaterijala. Najnovije studije o samozalečivim premazima sumirane su u ovoj studiji, koja takođe nudi uvid u mehanizme koji leže u osnovi ovih napretka, kao što su vaskularni sistemi, reverzibilno hemijsko vezivanje i mikroenkapsulacija. Takođe naglašava različite načine na koje se pametni materijali koriste u sektorima, uključujući građevinarstvo, automobilsku industriju, zdravstvenu zaštitu i vazduhoplovstvo, pokazujući njihov potencijal da uštede troškove održavanja i poboljšaju održivost uopšte. Ova studija razmatra aktuelna pitanja i predlaže buduće pravce istraživanja koji bi mogli da podstaknu razvoj i komercijalizaciju ovih tehnologija za praktičnu upotrebu.

Ključne reči: *Napredni premazi; industrijske primene; nanotehnologija; samozalečivi premazi; pametni sistemi premaza; pametni materijali; održivost*

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