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Self-Healing Materials: Innovations and Applications

Ngugi Mwaura J.

School of Natural and Applied Sciences Kampala International University Uganda

ABSTRACT

The advent of self-healing materials (SHMs) has presented a revolutionary advancement, with the capacity to independently mend harm, thus prolonging the lifetime and improving the dependability of diverse items and systems. This review examines current progress in self-healing materials (SHMs), specifically highlighting innovative methods including self-healing elastomers, gels, and thermosets, along with the incorporation of healing additives and stimuli-responsive processes. Advancements in capillary-driven recovery and biomimetic design, which draw inspiration from natural healing processes, are examined. A wide range of applications in coatings, electronics, and structural materials are emphasised, showcasing the revolutionary capacity of SHMs in industrial and technical sectors.

Keywords: Self-healing materials, elastomers, thermosets, biomimicry, capillary-driven recovery, stimuli-responsive materials.

INTRODUCTION

Traditional materials have allowed innovations and enhanced performance, but research on self-healing materials has also gained momentum. Self-healing can occur actively, passively, or by repairing crucial components. Most approaches integrate healing compounds or require excessive energy inputs, making them impractical. Novel approaches include self-healing elastomers, gelation, polymerization, and supramolecular bonds. Labyrinthine networks and porous substrates can be imbued with healing capabilities. Strategies using environmental changes like temperature or humidity have also emerged [1]. Alloys, oxides, and ceramics capable of healing under extreme conditions have been explored. Energy-oriented approaches, such as solar heating and reversible thermal processes, have been utilized. This field is rapidly evolving and encompasses various disciplines. This review focuses on novel self-healing elastomers, gels, and thermosets. Healing strategies and applications are briefly discussed. Industrially relevant materials are mentioned. Additional reading lists on various topics are provided [2].

FUNDAMENTALS OF SELF-HEALING MATERIALS

Self-healing materials (SHM) are a relatively new concept that has rapidly grown in recent years due to advances in polymer and material science. These materials can autonomously recognize and repair damage, providing both basic damage management and early defect monitoring. Incorporating specific chemicals, they can be triggered by external stimuli such as heat or moisture. Synthetic analogues of biological components can be designed and incorporated into SHM systems. These systems can be categorized based on the nature and mechanism of the healing process. Passive systems do not include external sensing/actuator elements, while active systems incorporate integrated sensing and/or actuating elements [3]. A passive response implies that a deflective response is present, but the shape is not recreated. This can happen with soft arrangements, such as foam or gel-like solid scaffolds, or be newly introduced (and operate within narrow and defined conditions). A structural foam will behave differently under the application of a force than a homogenous solid resulting in a deflection. Passive scaffolds, combined with an external analysis, can effectively monitor and classify cracks in structure without having the ability to recreate and reinforce the shape [4].

MECHANISMS OF SELF-HEALING

Nature can heal itself, from skin scratches to regenerating tissues and organs. Synthetic materials have been developed to mimic this ability. Strategies have been designed over the past 20 years to create self-healing materials, initially focusing on thermosetting polymers used in various industries. Polymers are macromolecules made of repeating subunits. However, they are vulnerable to degradation and have poor mechanical properties. Martinez and co-workers pioneered research on self-healing thermosetting polymers using urea-formaldehyde resin. This material can form covalent links and be healed with heat or moisture. Tensile and flexural tests showed 60% and 65% repair efficiency, respectively [5]. Martinez and co-workers' "first generation" research was followed by the proposals of "second generation" self-healing thermosetting polymeric materials composed of "empty" microcapsules filled with cycloaliphatic epoxides or dicyclopentadiene (DCPD). Once the thermosetting polymeric film was damaged, the healing agent, once triggered by a catalyst, would diffuse far and heal the damaged site. The materials showed 32-90 healing efficiencies depending on the topology of the damage [6]. The invention of self-healing materials was, in a material sense, the first approach found in large-scale industrial sensor-actuated strategies. However, on the nanometer scale, this was a biological approach already decades old.

INNOVATIONS IN SELF-HEALING MATERIALS

Since the advent of synthetic polymers in the early 20th century, efforts have been made to develop repair systems, both active and passive, because of their desirable properties. Among those proposed were particle migration and bond reformations at elevated temperatures. However, these approaches had their limitations, with passive systems offering limited functionality and active systems being more complicated, costly, and often limited by the low energy of polymer chains. This field, appearing to have stagnated, received renewed interest in the early 1990s following the discovery of biomimetic self-healing systems in nature that provided inspiration [7]. Self-healing systems can be designed to be passive or active. Passive systems tend to act as a protective measure by repairing a material when damage occurs, while active systems monitor the structural properties of a material, activate a healing mechanism in response to the detected damage, and maintain the properties over time. Active self-healing approaches typically require an external energy source (i.e., light) or the incorporation of a metallic matrix with embedded shape memory wires that contract upon a temperature change and close the crack. The latter structure enhances the matrix's stress transfer ability and mitigates the development of large cracks, while energy induced by welding helps with the healing process [8]. Self-healing materials are already being used across various fields. Biomimicry, the study and imitation of nature's designs, processes, and systems, is increasingly being considered by engineers and researchers when designing new materials. A prominent example would be lotus leaves due to their self-cleaning properties. Inspired by the geometric patterns of the leaf surfaces, numerous superhydrophobic surfaces have been researched. Other examples include structural coloration or strength from spider silk. Nature's design principles may guide the development of sustainable, environmentally friendly, and smart structures with low energy consumption [9]. Inspired by natural healing processes, various mechanisms have been explored to develop synthetic self-healing materials. Capillary-driven recovery has been made by localized filling of damage sites using low viscosity liquids in hollow channels with surface-tension-induced capillarity-driven flow. Polymeric coatings incorporating injectable microencapsulated healing agents and catalysts (Diels-Alder cycloaddition) recovered up to 65% of original mechanical properties on the second fracture. Swelling under solvent exposure of poly(ethylene-co-vinyl acetate) exposes more healing sites and recovered 91% tensile strength after immersion in toluene. Even bulk polymeric structures that completely healed cracks upon heating were developed. All these systems mimicked mechanisms found in nature but did not address the complex multi-stage responses seen in biological systems [10].

APPLICATIONS OF SELF-HEALING MATERIALS

Evoking an inalienable form of wonder, the prospect of materials that can autonomously repair damage reminds us of the extraordinary resilience inherent in life itself. In nature, healing mechanisms of great sophistication abound, from the repair of wind-blown broken trees to the robust revival of cracked desert plants after rain. Consequently, ingenious adaptive systems that utilize healing processes to achieve robustness and longevity can be observed at levels from proteins to tissues. These driving forces behind the development and evolution of such systems can inspire the creation of artificial, synthetic self-healing materials. Focused on macroscopic material properties, these intelligent synthetic materials emerge as an extension of 'living' cells, thus raising the question of what properties they might exhibit in the future [11]. Diverse types of (macro)scopic damage can take place in numerous settings, such as the breakage of the earth's crust in earthquakes, punctures and tears in fabrics, scratching and scuffing of coatings and optics, or the gradual deterioration of infrastructure due to corrosion, wear-and-tear, or fatigue. Persistent damage can easily compromise the function of a given system and, therefore, many approaches to 'fixing' such damage have become commonplace, such as plastering, sealing and gluing cracks in walls; stitching and patching the tears in fabrics; and resurfacing scratched optics. All of these concepts are passive, meaning they do not prevent the damage from occurring in the first place, besides being always labor-intensive, often time consuming, and not always as effective as hoped. In this context, a more active concept would be to implement protective/self-healing mechanisms in the damaged material [12]. Work is reviewed on the development of synthetic, man-made self-healing materials, which are explicitly designed to detect and repair damage without the need for external intervention. Importantly, these 'intelligent' materials deal with damage on a macroscopic scale (at the millimeter scale and beyond), as sought for applications in coatings, electronics, optics, and solar cells. To emulate life-like healing processes and strategies, synthetic materials have been developed that utilize a spectrum of different thermodynamic principles to remedy damage. Engineering the balance between those competing thermodynamic driving forces results in a broad range of distinctive healing mechanisms that can be tuned to achieve versatile protection and healing efficiencies in the desired setting [3].

CONCLUSION

The development of self-healing materials represents a significant leap forward in material science, with the potential to revolutionize numerous industries by providing materials that can autonomously detect and repair damage. These innovations not only improve the durability and safety of products but also contribute to sustainability by reducing waste and the need for frequent repairs. As research continues to advance, the integration of SHMs into various applications, from everyday consumer products to critical infrastructure, will likely become more widespread, paving the way for smarter, more resilient systems.

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