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REVIEW ARTICLE

State of Art Review on Applications and Mechanism of Self-Healing Materials and Structure

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Abstract

Self-healing materials (SHEM) have extensive characteristics that significantly influence structural and polymeric components' damage detection and healing behaviour. The composite materials with self-healing capabilities can automatically repair themselves after damage and lessen the economic losses. The present work aims to explore the recent successes in these endeavours from numerous kinds of research published over the last few years and focuses on methodologies/mechanisms, material types, and the excellent abilities of SHEM in various fields. The three objectives of the current article are: (i) to deliberate the motivation behind materials that can either extrinsically or intrinsically heal. (ii) investigate research on self-healing composites, emphasizing several healing systems or mechanisms. (iii) to review the most recent developments and applications of self-healing materials in different sectors. Additionally, some of the classifications, computational methods, and healing efficiency specific to self-healing materials have been reviewed, and the individual comparisons of self-healing techniques are discussed.

Keywords Composite materials · PolymersDamages (cracks and delamination) · Catalyst · Encapsulation (repair, coatings and corrosion protection) · Mechanical properties

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1 Introduction

Self-healing materials' ability to detect damage and repair on their own has drawn researchers' quest in recent years. Every year, numerous initiatives are made to create various self-healing systems and integrate them into large-scale manufacturing with the best possible property-cost relationship. The lightweight and high-toughness fiber-reinforced composites are becoming popular in automobiles, aerospace, wind turbines, high-performance engineering etc. The main problem of using these advanced materials with internal damages may lead to catastrophic/sudden failure and are difficult to detect early and/or repair. To overcome these unwanted issues and to improvise the structural durability by incorporating self-healing properties into the parent materials. This, in turn, allow these materials/structure to repair automatically and restore their final mechanical properties or strength. In natural biological systems, the human skin, bones, or other components can detect damage and self-heal accordingly. Hence, the self-healing is generally relating to the medical term like how wounds in plants and animals heal on their own. The own healing abilities of plants and animals have inspired the development of composite materials that can repair the damage. These SHEM have been created in response to increase durability, reliability, and safety demands. The fiber-reinforced composites with self-healing abilities are extensively used in aerospace [1], marine [2], biomedical [3], and structural [4] applications and advancing in several other fields. Applications of self-healing polymers and nanocomposites and their recent developments in various fields are discussed, and the product-based insights and future prospects of these materials are presented in [5]. Over the past two decades, many studies have been explored relating to the field of SHEM. The different studies anticipated that the self-healing will increase material life, reduce maintenance costs, and improve safety and endurance for artificial advanced structural materials (composites). Many concepts have been advanced to demonstrate the effectiveness of ceramic, polymer, and metal matrix composite materials for designing and creating SHEM. Self-healing polymers prolong a material's life span while improving its functionality. Incorporating extrinsic (capsular and vascular) self-healing mechanisms will indisputably change the characteristics of composite matrixes [6] .It is essential to comprehend such modifications to ensure that the SHEM functions better than the virgin material. Shape memory effects (SME) and healing characteristics of SMA are integrated to form novel composites like elastic structures embedded with nanobeams [7], multi-walled carbon nanotubes [8, 9], palm fibres composites [10], natural fibres composites [11], FGM skew-Nano plates [12–14], checkerboard reinforced composite [15], polyurea coated fibre reinforced composites [16], and piezoelectric skins [17]. Materials like FG porous silicon nanobeams [18], multifunctional foam plates [19], calcium carbonate nanoparticles [20], FGM truncated micro shells [21], and honeycomb sandwich beams [22] have been explored to an extent for the verification of each constituent to show their self-healing behaviour for an integrative healing agent. The unique sensitivity of nanobeams [23–26], plates [27], sheets [28, 29] and shells [30] to compression and temperature effects can also be exploited as a potential healing agent in composites. In recent years, a gap has arisen between capsule-based/vascular self-healing composites and intrinsic self-healing materials. Research on capsule/vascular based is generally focused on the rupture process, healing agents, mixing process, and micro-structure manufacturing techniques. The work first focused on the three primary self-healing methodologies and the significant issues and challenges to each approach. A literature review on the materials used as healing agents in recent years is provided. The present review discusses the classifications of self-healing materials most commonly utilized for various applications, i.e., intrinsic and extrinsic types of self-healing mechanisms. These types have been categorized into subdivisions based on different criteria such as mode of contact, healing agents, catalyst, etc. and discussed in the following sections. Therefore, the article's final section discusses the current developments and applications of self-healing materials in various areas.

2 Self-Healing Materials (SHEM): Overview

2.1 Classification of Self-Healing Materials (SHEM)

These materials currently use autonomous and non-autonomous systems as part of their healing processes. Non-autonomous materials typically need external stimulation to have the desired healing effect, such as light, heat, load, etc. However, autonomous SHEM can initiate the self-healing process without the aid of external triggers or stimuli. SHEM based on triggering can generally be classified into two types i.e., intrinsic self-healing (without any healing agents) and extrinsic healing systems (with healing agents) [31]. Detailed classification and generation-wise self-healing mechanisms are shown in Figs. 1 and 2.

2.2 Modes of Healing (Interaction)

There are several mechanisms and approaches to obtaining the self-healing criteria to heal the material; basically, there are three modes of interaction between one material to another material, which are physical, chemical, and supramolecular [33].

2.3 Efficiency Of Healing

The factors which are considered for healing efficiency as per the mechanical testing are mechanical integrity, strength, fracture energy, elastic stiffness, and fracture toughness [34]. These parameters evaluate the effectiveness and consider how the material will perform after healing. Several tests are currently being used to estimate how efficiently the material will work after recovery [35]. The efficiency of healing (tensile) for the specimen is given in the following mathematical form as same as in the reference [36].

$$\eta_{(Tensile)} = \frac{K_{healed}}{K_{Virgin}} \times 100 \quad (1)$$

where, $\eta_{(Tensile)}$ is the total efficiency (%) and K is the tensile strength of the specimen.

2.4 Computational Methods of Self-Healing Materials

Further, the computational tool has been adopted by White et al. [37] to detect the damage and its healing

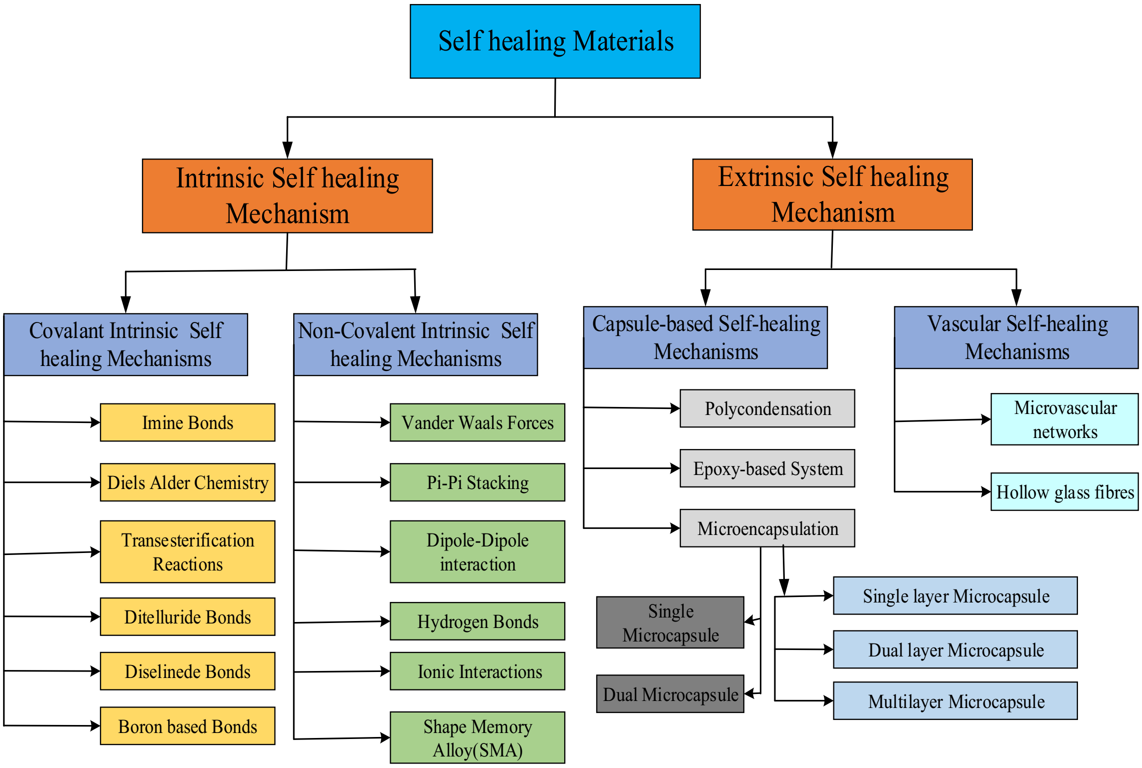
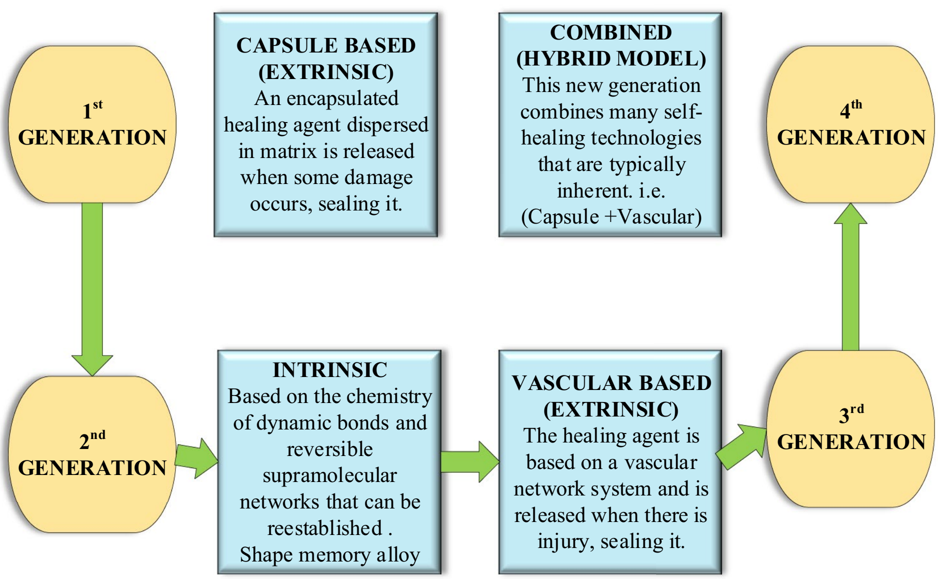


Fig. 1 Classification of self-healing materials [31]

Fig. 2 Generation wise self-healing mechanisms [32]



characteristics using the molecular dynamic (MD) for the self-healed material. Similarly, studies reported the development of a self-healing model using commercial finite element simulation software like ABAQUS [38, 39]. Additionally, researchers have extended the innovative and effective computational methods for fracture/damage modelling limited to structural applications, i.e. extended finite element method (XFEM) [40–42] and cohesive zone approach [43], mesh free method [44, 45], cracking particle method [46] and screened Poisson's equation method [47].

2.5 Intrinsic Self-Healing (Without Any Healing Agents)

In contrast to the extrinsic mode, the intrinsic method is capable of multiple reversible self-healings without using a self-healing agent. It has a more stable and reliable capability than the extrinsic mode and avoids laborious dispersion and encapsulation steps [48]. Intrinsic mechanisms are further classified as covalent and non-covalent intrinsic self-healing mechanisms. In the present work, we have reviewed one of the most prominent non-covalent intrinsic types of self-healing method, which is used in damage detection and reversal of strength through shape memory alloy (SMA). As there are numerous methods in intrinsic self-healing mechanisms, this study mainly concentrated on the healing of structural applications with the incorporation of SMA.

2.5.1 Shape Memory Alloy (SMA)

The concept of healing on its own is becoming more popular in everyday life, and shape memory alloy fiber (SMA) for crack healing in composite structures are playing a vital role in commercial sectors. The smart material (SMA) can heal the material with its instinctive properties, which encourages researchers to conduct added research on these materials [49]. SMA wires are combined with a self-healing polymer for the first time, and their influence on the properties was examined [50]. The efficacy of these polymers with a healing agent is significantly enhanced by embedding SMA wires which closes the crack and activate them throughout the healing process [51]. Later, new accomplishments have been developed in self-healing using SMA have improved the efficiency and the quality of the healing. Neuser et al. [52] investigated solvent (ethyl phenylacetate, EPA) based SHEM combined with SMA and achieved 78% of healing efficiency and only 24%; for non-presence of SMA wires. The overview of SMA's healing mechanisms is deliberated in [49]. Burton et al. [39] aimed to model composite materials embedded with SMA wires through ABAQUS simulation software. The metal matrix composite is being loaded, which causes the crack to propagate through the material due to its brittle nature, and the crack also disrupts the SMA wires, changing its phase to martensite and allowing recovery stress to develop due to loading. which causes reversal of the crack and closes the damage because of its extensive shape memory effect. Crack propagation and subsequent self-damage healing is implemented. Xue et al.[53] investigated the self-healing behaviour of the cementitious materials using XFEM. Chen et al. [54] conducted an experimental analysis of smart composite materials under flexural loads to achieve crack healing ability. The intrinsic self-healing behaviour of carbon fibre reinforced polymer (CFRP) composite material is examined using ABAQUS modelling [55]. The structural strength improvement and damage enhancement is attained by SMA wires [56].

2.6 Extrinsic Healing Systems (With Healing Agents)

Extrinsic self-healing mechanisms are basically divided into two main categories i.e., capsule and vascular based self-healing materials.

2.6.1 Capsule-Based Self-Healing Structures

Microcapsules made of capsule-based materials contain healing agents. Damage causes the local microcapsules to rupture, letting the healing agent stream out and interact with a polymer's embedded catalyst to fill and heal the crack [57, 58]. Since capsules serve the dual purpose of storing the healing agent and drawing the damage, it is due to the reason that the interfacial region between the capsule and the polymer is the weak spot in the polymer-based mechanism. It is conclusive that self-healing polymer can initiate and carry out self-repair on its own with the help of capsules [59].

2.6.1.1 Microencapsulation Method/Ring-Opening Metathesis Polymerisation (ROMP) Over two decades ago, self-healing through microencapsulation was introduced by White et al. [60]. He presented an autonomic healing concept in composite materials, which attracted many researchers to work in this field. In a wide range of materials, microcapsule-based mechanisms have proven the most popular method of creating self-healing [59]. A healant is deposited in discrete microcapsules that are spread throughout the matrix [61]. Under the influences of damage, microcapsules present in the path of cracks rupture, which releases a healing agent and it reacts with hardener to make it heal and hard, as shown in Fig. 3. They achieved a very promising self-healing efficiency by embedding microcapsules using Grubbs' catalyst and healing agent; dicyclopentadiene (DCPD) at particles into a matrix material [62]. Further, many improvements have been made to this concept to coverup the drawbacks of an existing method [63]. The current approach only performs well with larger amounts of catalyst (2.5 wt%) for lower weight fractions, the performance is inefficient, and the catalyst dispersion rate is poor in epoxy. Thus, Grubbs' catalyst is embedded into the wax microspheres, tested for self-healing, and obtained better results in terms of healing and efficiency [64]. Additionally, many microencapsulation methods have been improved based on the healing agents, and numerous studies have undergone with the help of these mechanisms; some of the works based on the capsule-based mechanisms have been presented in Table 1. There are three types of encapsulation concerning layers are: Single layer microcapsule [65, 66],

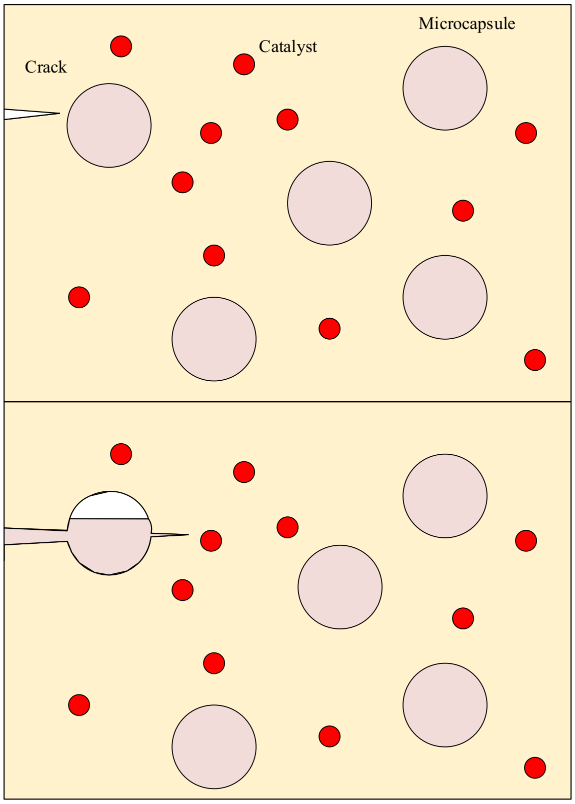


Fig. 3 Capsule based self-healing mechanism [60]

Dual layer microcapsule [67] and Multilayer microcapsule [68, 69].

2.6.1.2 Polycondensation To create a polymer, a process known as polycondensation links one or more types of monomers to form long chains, releasing water or another substance in the process [73]. Di-n-butyltin dilaurate (DBTL) was used by Cho et al. to develop a polycondensation-based mechanism with a mixture of hydroxyl end-functionalized poly(dimethylsiloxane)(HOPDMS) and poly(diethoxysiloxane) (PDES) serving as the healing agent [74]. The efficacy of this type is lesser compared to GRUBBS and DCPD catalysts. Though, it has a lower price, and a more comprehensive range of applications, making it more appropriate for actual use. by utilizing the polycondensation mechanism, self-healing coatings [75] and woven fiber-reinforced composites [76] have been developed.

2.6.1.3 Epoxy-Based System The epoxy resin and hardener are individually encapsulated and kept inside the composite matrix in this mechanism. Both forms of capsules erupt when a crack appears, and the epoxy and hardener that release out are combined to seal the crack [77]. Epoxy-solvent capsule healing systems for polymer composites have also been developed [78]. Due to their accessibility, epoxy-based mechanisms have surpassed ROMP reactions and polycondensation-based mechanisms in popularity. Liao et al. [79] examined and summarized the characterization and healing performance of the epoxy-based coating.

2.6.2 Vascular Self-Healing Structures

Vascular self-healing systems incorporate hollow microchannels filled with healing agents into the vessel design framework. Hollow microchannels can be designed to flow in one, two, or three axes referred to as 1D, 2D, or 3D vascular systems [80, 81] The interconnection is determined by how the vessels are constructed and organized within the composite matrix. They work likewise to capsular-based mechanisms in that the vessels break down at locally damaged zones, allowing the healing agent to be carried to the crack and then polymerized [82, 83]. Numerous studies were performed based on these networks based on SHEM; a few studies based on microvascular and hollo fibres have been reviewed and reported in Table 2.

2.6.2.1 Microvascular Networks Vascular SHEM replaces the microcapsules with a vascular structure resembling a network of tunnels through which numerous functional flu-

Table 1 Self-healing mechanisms based on microencapsulation method

Microcapsule type	Healing components and agents	Working temp. and curing time	Efficiency (%)	Tests conducted	Ref.
Single Microcapsule	*Healing component*: Polymeric matrix *Healing agent*: 5-ethylidene-2-norbornene (5E2N) with CNT and GRUBBS catalyst	ambient 24 h	82%	fracture test	[70]
Dual micro capsule	*Healing component*: Glass /Carbon fibers + Epoxy matrix *Healing agent*: Epoxy + Hardener	ambient 24 h	103.4% 101.8%	flexural tests	[71]
	Healing component: Epoxy resin *Healing agent*DGEBA (resin) + polyether amine (hardener)	ambient 24 h	84.5%	fracture test	[72]

Table 2 Self-healing mechanisms based on vascular type

Vascular type	Healing components and agents	Working temp. and curing time	Efficiency (%)	Tests conducted	Ref.
Hollow glass fibre / Hollow glass tube	*Healing component*: Bituminous composites *Healing agent*: oily rejuvenator	30℃ 24 h.	80%	The tensile strength tests	[88]
	Healing component: Epoxy + Glass fibre *Healing agent*: Grubbs catalyst + DCPD	Ambient 24 h.	60%	Controlled energy impact test	[99]
	Healing component: Glass fibers + epoxy composite *Healing agent*: Epoxy resin + hardener	70℃ 48 h.	42%	Tensile tests for different orientations	[100]
Microvascular networks	*Healing component*: Epoxy monomer + curing agent *Healing agent*: Infiltrating waterborne polyurethane matrix	Ambient 3 days	99.34%	Tafel polarization tests.	[101]
	3D Vascular network *Healing component*: Glass fiber reinforced epoxy composites *Healing agent*: Epoxy resin epichlorohydrin hardener	25℃ 7 days	89%	Tensile test and creep tests	[36]
	Healing component: Epoxy coating *Healing agent*: Grubbs catalyst and DCPD	25℃ 12 h	70%	Four-point bending, fracture toughness test	[81]

ids circulate. When a crack appears, and the vascular network is broken, these functional fluids will also occupy the gap. A healing agent is a constituent that is stored within a capsule or a vascular network [84]. The retrieval process and restoration of mechanical properties depend critically on the behavior and mechanism of healing agents. Capsule-based SHEM is suitable for the repair of small cracks, whereas larger damaged areas are healed with the help of vascular systems [85]. Toohey et al. [81] Implemented a new microvascular design based on interdigitated dual networks, which helped solve the problems related to the exhaustion of embedded catalysts and the requirement to replenish several healing agents inside these designs. Through the microvascular distribution of a two-part, epoxy-based self-healing mechanism, several healing cycles of a single crack in a brittle polymer covering are accomplished [86]. The characterization and potential of microvascular-based self-healing coatings using DCPD and Grubbs' catalyst are investigated [87]. A direct-tension mechanical experiment examines the bituminous material's potential to self-heal its microvascular damage using hollow fibers and an oily rejuvenator using a wet-spinning approach [88].

2.6.2.2 Hollow Glass Fibres Self-repairing, increased damage visibility biomimetic composite that offers a practical solution to regain mechanical strength and draw attention to concealed damage following impact damage has been developed [89]. Investigations are being conducted into a new fiber-reinforced plastic that uses a biomimetic strategy to perform its own repair and visual enhancement of impact damage by exploiting action from filled hollow fiber [90]. The use of self-healing hollow glass fibers (HGF) plies in both glass fiber, and carbon fiber epoxy laminates reduce damage and reinstate the mechanical strength. Initially, the researchers [82, 91, 92] focussed on the development of these microvascular networks like hollow glass tubes as containers preloaded with an epoxy-based healing agent and succeeded accordingly. After being subjected to quasi-static impact damage, Trask et al. [93] examined the effects of embedded HGF on the mechanical characteristics of the host laminates as well as the effectiveness of the laminates ability to heal. Flexural testing findings have demonstrated that the self-repairing ability of a healing resin housed within hollow fibers can recover a sizeable portion of flexural strength [94].

Further, hollow fibre networks were filled with polyester resin and the appropriate accelerator to enable self-repair as well as a UV fluorescent dye to detect sub-critical transverse impact damage. 3-point bending tests were used to illustrate the capability of self-repairing material, and SEM (scanning electron microscopy) analysis was utilized to verify the healing performance [95]. Fifo et al. [96] investigated the recovery after damage, i.e., post-damage recovery of 3D vascular channels within glass fibre or polyester laminated composites. In recent times this method has been further improvised by adding SMA wires; due to the produced recovery stress in the SMA, which causes fracture closing in the sample. The inclusion of SMA strips improved the healing effects of the composites with randomly oriented short HGF subjected to sudden loading [97]. It is more beneficial to store the healing agent in the hollow fibre of the composite material than in the microcapsule for the self-healing behavior of the epoxy polymers. This is due to hollow fiber containing more self-healing agents than the microcapsule, and the hollow fiber does not reduce the strength of epoxy polymers. Compared to the microcapsule approach, the hollow fiber technique has a more uniform spreading in the epoxy polymers, which aids in spreading the healing agent without disturbing the material's mechanical properties [98].

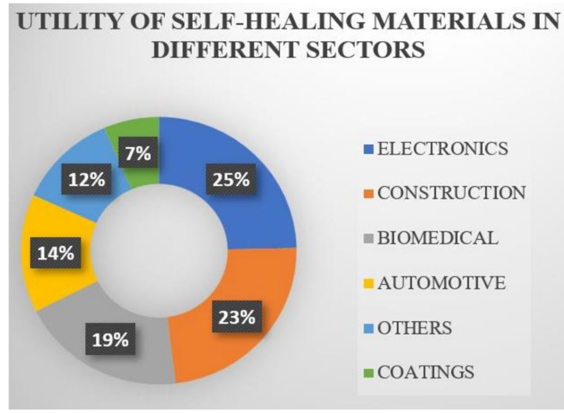


Fig. 4 Applications of self-healing materials [5]

3 Applications of Self-Healing Materials

Furthering research without a clear idea of its range of impact is as unfruitful as doing strenuous work without a distinct goal. Self-healing research began in 1970 due to the mending of polymer fractures [102]. Materials with self-healing properties are recently created sophisticated materials with prolonged lives that can fix themselves when they undergo injury without needing the physical intervention of any type [62, 103]. The development of SHEM is nothing more than an enhanced modification of conventional materials by introducing self-healing capabilities. Self-healing materials are used practically in every industry [89, 104], including construction/architecture, biomedical, coatings/paintings, aerospace/automotive [105], electronics, and textiles etc. These are utilized to minimize maintenance costs, extend durability and ensures safety. Although SHEM is one of the most promising approaches, they are yet ineffective in mending life-scaled damages [106]. Numerous advancements in the emerging technologies are explored in this section by assessing various fields of SHEM applications. The detailed utility based self-healing materials in various sectors are shown in Fig. 4.

3.1 Electronics

Sensors, actuators, electronic skin, consumer electronic devices, and bioinspired robots are examples of electronics applications. Due to the significance of conducting materials in electronic devices like sensors, displays, and storage devices, conducting materials has been the subject of active research in recent years. A soft conductive material addresses the physical touch requirement that has been the focus of the recovery of conductive pathways for existing self-healing conductive materials [68]. The electronics and semiconductors industry is predicted to develop significantly by 2025. SHEM has been used in electronic devices such as mobile phones, laptop computers, and desktop computers by reputed electronic businesses.

Wearable health monitoring systems are gaining popularity due to their excellent possibilities for portable health monitoring devices and broad medical applications. Material stretchability is a feature that allows electrical equipment to adjust to irregular 3D structures, such as soft and moveable entities [107]. Intrinsic stretchy devices offer the potential benefit of providing a large area of surface coverage. Self-healing stretchable electronics can adapt to soft and nonplanar objects as well as align with the movements of biological tissues [107, 108]. This allows it to be used in microchip technology likely, bio-integrated sensors with optimized detecting efficiency and ease for implantable, wearable, and prosthetic applications, as well as providing an essential procedure for bio-inspired robots and modern user devices. Physical sensors are made of polymers to give flexibility and allow for monitoring pressure levels as low as a few pascals. At room temperature, these sensors are most sensitive [5]. There are several forms of self-healing polymeric sensors in addition to semi-conductive devices. There have been several reports on the potential use of these materials for different applications like transparent electrodes, electronic skins, and materials of battery electrode binders [109]. Wearable (non-invasive) and implantable devices are two prominent applications of plastic bioelectronics. Robust self-mending hydrogels are used in soft robotics, such as implantable or wearable biosensors because they increase mechanical performance and shelf life as a result of fatigue or damage repair. Haick et al. [107] have discussed a dynamic soft self-healing polymer material (PBPUU) that demonstrated good self-healing capabilities in complex underwater settings. Furthermore, the capacity to eliminate any leakages in electrically induced by underwater damage made PBPUU a greater option for the fabrication of electronic devices, which was critical for incorporating flexibility and self-healing ability in electronics [107]. Among the most recent hot material under discussion is Polyhedral Oligomeric Silsesquioxanes (POSS)- based SHEM. These SHEM are desirable for next-generation materials with better mechanical characteristics that are perfect for sensors because of the specific chemistry of the interactions that occur in these materials [105]. Cerdan et al. [110] explore the development of magnetic self-healing soft actuators whose movement or a magnetic field may regulate characteristics. Self-healing of soft robotics is a novel discipline that arises as a response to soft solids' essential susceptibility to extreme damage. Due to the capacity to repair micro/macro damages, which are exposed to a severe actuation environment, it increases the soft robot's performance lifespan and enhances dependability compared to traditional robotic systems [111]. They also considered merging shape memory with self-healing and magnetic characteristics to create improved SMASH (shape memory aided self-healing) actuators [112]. Light-emitting diodes (LEDs) could be repaired by exposure to a magnetic field, and magneto-electric self-healing supercapacitors for use as storage devices have also been mentioned [110].

3.2 Construction

In 2017, the most important applications for self-healing materials are building and construction in the whole industry, accounting for 27.4% of the total market as mentioned by Idumah [5]. Literature mentions the process of self-healing in concrete can be autogenous [113], based on optimal mix composition, or autonomous, when employing extra included micro/macro capsules carrying a healing agent and/or bacteria spore. Super absorbent polymers, Nano polymers, and shape memory alloys are examples of Nano-sized self-healing cementitious systems [105, 114, 115]. In 2017, the essential applications for self-healing materials were building and construction in the whole industry, accounting for 27.4% of the total market, as mentioned by Idumah [5]. Literature mentions the process of self-healing in concrete can be autogenous [113], based on optimal mix composition, or autonomous when employing extra included micro/macro capsules carrying a healing agent and/or bacteria spore. Super absorbent polymers, Nano polymers, and shape memory alloys are examples of Nano-sized self-healing cementitious systems [105, 114, 115].

3.2.1 Polymers

Polymer cement, which may be used to extract geothermal and fossil energy, is projected to replace conventional wellbore cement. These innovative polymer-cement composites have mechanical stability, ductility, and self-healing properties [5].

3.2.2 Cements

The growth of self-healing cementitious composites [116] that mimic/imitate the behavior of biological living systems has piqued the interest of global scientific researchers across a wide variety of technical and engineering disciplines, with the likely to transform the way concrete buildings are planned, designed, and built. The major goal of SHC is to decrease midway costs and prevent water intrusion [117].

3.3 Coatings

Tailoring the interaction and topography of droplet splattering and manipulation onto interfaces for the construction of non-wetting surfaces is an important phenomenon for building microfluidic devices, microreactors, and electronic refrigerators.

3.3.1 Polymers

Self-restoration of material properties is effectively done in polymer-based compositions, and coatings to the polymers are the more practical and sought commercial SHEM [104]. Because of the particular chemistry of certain of the interactions that occur in POSS-based SHEM, they are fascinating next-generation materials with better mechanical characteristics that are ideal for use in super hydrophobic coatings, according to Nowacka et al. [118]. Although it is highly desirable, it is still difficult to create epoxy resin paint systems that are mechanically durable, quickly healable, and recyclable. This sort of supramolecular polymer with distinct properties can also be used in ant frosting and anti-icing paints for Antarctic pole exploration [32].

3.3.2 Metals

Microcapsules that respond to UV dispersion coating are being developed for damage healing in space applications [119].

3.4 Biomedical

Membranes, micro-actuators, sensors, drug-delivery structures, and other specialized sophisticated micro-devices are made with self-healing microstructural polymers responsive to stimulus. Self-healing nanocomposites and natural fiber have also piqued the curiosity of researchers in the medical field are addressed [11]. This is due to their high potential as anticancer medication carriers [120]. Hydrogels show potential for various environmental and biological applications due to DNA biocompatibility. Self-mending hydrogels are classified as soft and resilient hydrogels with strong mechanical characteristics appropriate for minimally invasive (tissue engineering scaffolds, wound dressings, drugs, or cell delivery careers) biomedical applications [5]. To improve biomedical applications, self-mending hydrogels must overcome various hurdles, including the creation of these hydrogels with acceptable biocompatibility and mechanical qualities. Furthermore, adequate biodegradability control is critical in self-mending hydrogels used in tissue engineering and drug delivery [121, 122]. The unique properties of polyhedral silsesquioxnes make them apt raw materials for building self-healing and dynamic systems [118]. The topic of dynamically cross-linked hydrogels packed with magnetic particles, which has received little attention, has promising applications in chemotherapy, as well as controlled drug release and wound closing.

3.5 Aerospace

This sector requires long-lasting vehicle bodies and parts, heavy machinery, and fuel usage without sacrificing safety. The general features in demand include corrosion resistance, wear and tear resistance, and increased life. The self-healing metal matrix composites have great potential for use in sliding surfaces like cylinder liners, pistons, CV joints, and gears prone to damage from friction, creep, and wear between components [112]. Salowitz et al. examined a self-healing off-eutectic metal matrix alloy with integrated SMA fibers and numerous healing processes, including structural alignment (setting) and matrix soldering [123].

3.6 Textile

The progress of self-healing and chemical-resistant polymers with unique properties varies according to the applicability, such as superoleophobicity for underwater use. These kinds of composites offer good chemical infusion resistance, making this material appropriate for usage as self-healing electromagnetic interference cloaking fabric in barrier protection, with an increased lifespan [62, 124, 125].

3.7 Miscellaneous

Self-healing [126] (a) in polymers and their composites- avoids delamination failure in materials [127], (b) in cement-based materials- improves infrastructure structural performance, (c) in metals and metal matrix composites [128], and (d) in ceramics and ceramic composites- are beneficial in high temperature and corrosive situations, such as in IC engines [129]. These materials have also been pointed out as an apt option for raw materials for 3D printing [130]. Self-healing polymer nanocomposites have a wide range of applications in various tech industries, including armament, biomedical, and space exploration [5]. Graphene/polymer composites that self-heal are extremely promising intelligent/smart materials [131]. Because of its potential to undergo photothermal energy transition, graphene can show a significant part in the self-mending method as a component of self-mending composites. In this case, graphene serves as an absorbing agent (energy) for the speedy and effective translation of solar light to temperature energy, improving polymer chains' dispersion over the faulty interface and improving the self-mending mechanism. The fabrication of graphene-filled self-healing composites for various applications has been made possible by combining the characteristics of graphene, such as its immense specific surface area, ultrahigh conductivity, high antioxidation capabilities, thermal stability, and conductivity, and outstanding mechanical qualities [108, 125]. These materials are used in many applications such as turbine injectors, automobiles, spaceships, nuclear reactors, and specialized cutting devices. Magnetic self-healing hydrogels find applications as excellent underwater glues [110]. A polymethacrylamide-carbon composite mimics plant photosynthesis, and carbon fixation from the environment allows it to grow, strengthen, and self-repair. In the future, this polymer can be used in construction, restoration, or protective coverings, converting greenhouse gases into a carbon-based substance that self-reinforces [32]. SHEM has been demonstrated to be beneficial in lithium-ion batteries [132] Furthermore, researchers have explored all of the possibilities of SHEM in fields of applications using various methodologies, and some of the studies have been segregated individually based on the application and kind of materials used in SHEM, as shown in Fig. 5. The detailed analysis of the forms explored with respect to the sector-wise are given in Table 3.

4 Conclusion

The comprehensive review based on the SHEM's mechanisms, applications, and classifications has been presented. Researchers have recently concentrated on automated healing processes for various benefits in the realm of applications, which has sparked interest in these smart materials. The current era of SHEM displays improvised performance, extended service life, and a smaller environmental impression, as evidenced by the growing capacity of self-healing polymers to get around material constraints and ensure repetitive recovery. These advancements were made possible by technological improvements and cutting-edge methods used in polymers' design, production, and characterization. The following points are deliberated in this study are:

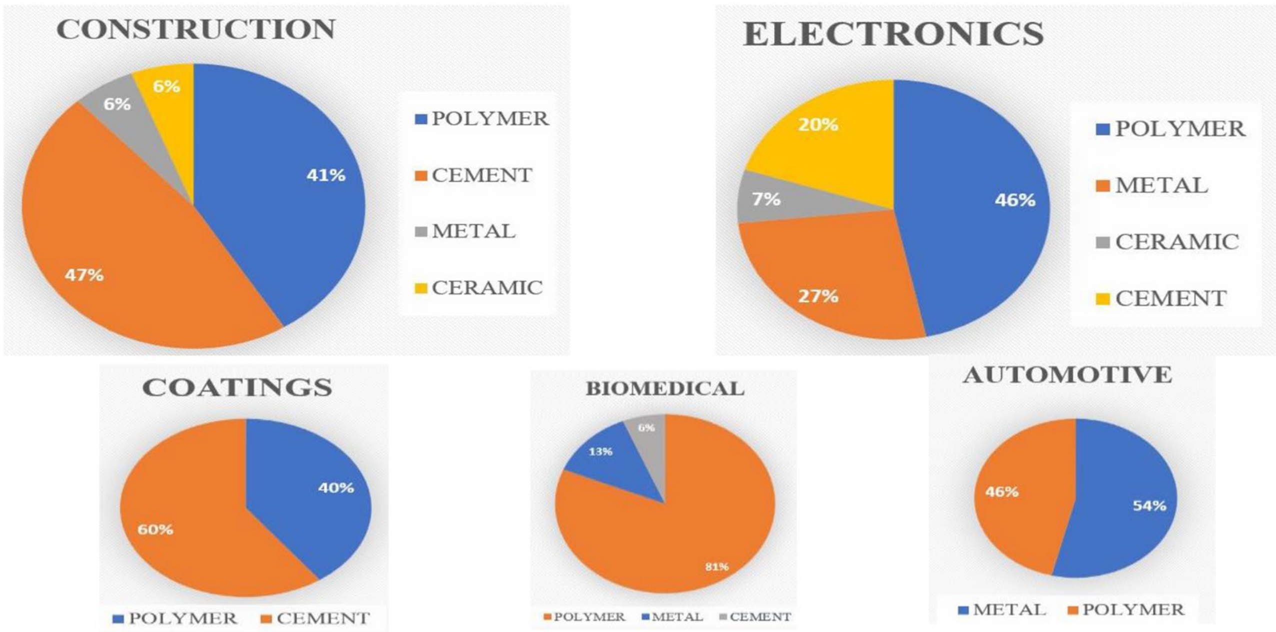


Fig. 5 Applications of self-healing materials (based on type of material) [5, 133]

Table 3 Applications of self-healing materials in various sectors

Sector	Forms Explored	References
Aerospace/Automotive/ Marine	Composite sandwich structures, Nanofibers, Polymer matrix, metal matrix	[31, 62, 66, 105, 119, 134–138]
Construction	Cementitious materials and composite, polymer matrix, Nano concrete	[4, 115, 117, 139–152]
Coatings	Metallic complexes, Polymers, Polymer matrix	[59, 133, 153–155]
Electronics	Polymer blends, Hydrogels, Metal reinforced rubbers, Nanocrystals reinforced polymers	[5, 33, 59, 62, 66, 107–111, 133, 156–163]
Biomedical	Rubbers, Hydrogels, Nanofibers, Polymers and polymer matrix	[31, 108, 110, 120–122, 133, 138, 164–170]
Textiles	Polymers, Nanofibers, Metal and nanocrystal reinforced polymers	[32, 124, 133, 138, 156, 159, 163, 166, 169]

a. SHEM with intrinsic type is simpler and easier to handle than the extrinsic type of healing mechanism, and the healing efficiency is higher than extrinsic.
b. The vascular self-healing system is preferable to the capsule-based mechanism because of its excellent uniform distribution of healing agents through network tubes, which also aids in maintaining consistent mechanical properties.
c. Shape memory alloys are the only intrinsic type of self-healing mechanism apt to the purpose, as they will not alter any mechanical property of the material in the healing process. A lot of work needs to be done in the future to accomplish effective utilization.
d. Currently, self-healing materials are becoming more common for a wide range of applications; however, there are specific areas of SHEM where researchers can work and conduct extensive research, such as increasing the efficiency of healing and improving healing agent movement toward the crack. These SHEM provide a clear insight into many areas where the applicability is more specific and has no limitations. The concept of SHEM has extended as time progresses, giving researchers more room to study their healing effectiveness and performance.
e. Finally, the research has been continuing in the field of extrinsic self-healing hybrid models (combination of vascular and microcapsule) and materials, which are the future of self-healing mechanisms (fourth generation models); however, very little literature have been published on these types of models, leaving room for future research.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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