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Self-healing materials for potential use in textile and clothing applications

Alena Dannehl[1], Amelie Buhr[1], Angela Sanchez Leyton[1], Lennart Hellweg[1], Mathias Beer[1], Lilia Sabantina[1,2*]

[1] *Faculty of Textile and Clothing Technology, Niederrhein University of Applied Sciences, 41065 Mönchengladbach, Germany*

[2] *School of Design and Culture, Berlin University of Applied Sciences (HTW Berlin), 12459 Berlin, Germany*

*Corresponding author *E-mail address:* lilia.sabantina@fh-bielefeld.de

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ABSTRACT

Self-regenerating, polymer-based textiles emulate living organisms' ability to heal broken skin and other lesser injuries. To achieve this effect, either intrinsic or extrinsic methods of having polymeric compounds mend these damages can be employed. Depending on the method used, the handling and results of the self-regenerating effect differ. This allows for different areas of application. The focus of this paper is to discuss some of these potential textile applications as well as related research and developments in the area of self-healing materials.

1 Introduction

With the advancement of technical textiles, new possibilities in the field of textile research arise. One such possibility is self-healing materials. Mimicking a living organism's ability to mend injuries it sustains, these fabrics, too, are made to restore a damaged area's integrity without further interference [1]. On a very literal level, the self-regenerating polymer compounds that serve as the basis for self-healing tissues can be used, for example, to heal chronic skin wounds [2]. The use of polymers with these properties is not limited to textiles, but can also be used as coatings, for example, to repel water etc. [3]. The materials such as metals/alloys, plastics/polymers, paints/coatings, or ceramics/concrete involve self-healing mechanisms such as release of healing agents or reversible crosslinking for the development of self-healing materials [4-8]. In addition, technologies such as electrohydrodynamics, shape memory effect or migration of nanoparticles and co-deposition also play a major role in the development of self-healing strategies [4,5,9,10]. Textiles, ranging from linear textile structures such as fiber yarns to textile structures such as woven, knitted, braided, stitch-bonded, nonwoven or tubular fabrics etc. with self-healing properties are important for extending the product life cycle of the defined semi-finished products and products on the one hand and for sustainability aspects in order to protect the environment on the other hand [11-14].

In this review, the mechanisms underlying self-healing principles are discussed. The main part of this review focuses on different application areas for self-regenerating polymers. The emphasis is on textile-related applications, although brief excursions into non-textile areas may also be of interest. In addition, discussion of potential applications is provided, particularly in the fields of aerospace and protective clothing.

2 Functionality and classification

Self-healing is known for living organisms and plays a great role in preservation of life as well as its prolongation [15]. Inspired by nature, researchers have come up with the idea of self-healing materials to extend the lifetime of synthetic materials that are susceptible to damage, and at the same time reduce the environmental impact of synthetic materials [16-18]. Self-healing materials are material systems or substances that can partially or completely recover from mechanical damage and regain their original properties. The self-healing of a material is the ability to restore damage automatically and autonomously. The terms such as self-repair, autonomous healing or autonomous repair are used for this purpose. In order to induce self-healing properties of the artificial materials, external triggers are necessary to generate the self-healing effect [19].

Self-healing materials can be categorized into two different methods – intrinsic and extrinsic as well as autonomous and non-autonomous [20]. Fig. 1 shows the classification of self-healing mechanisms [21-23].

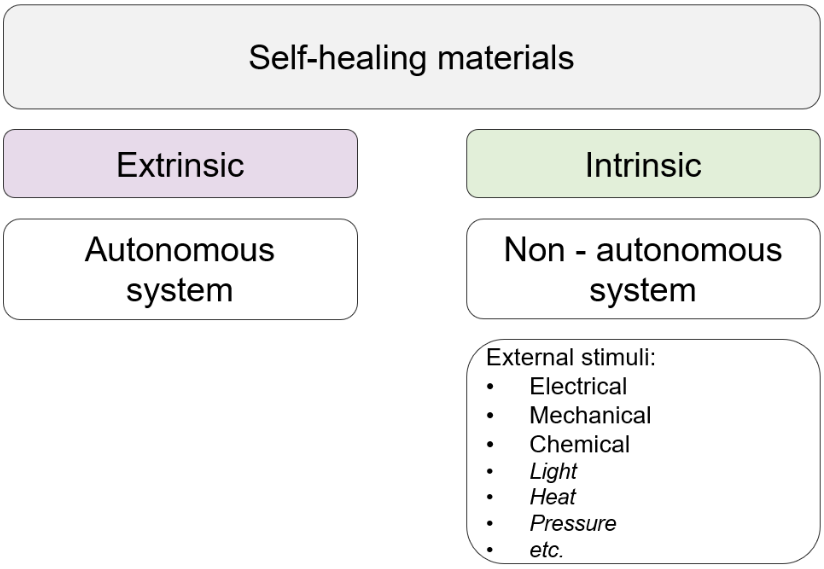
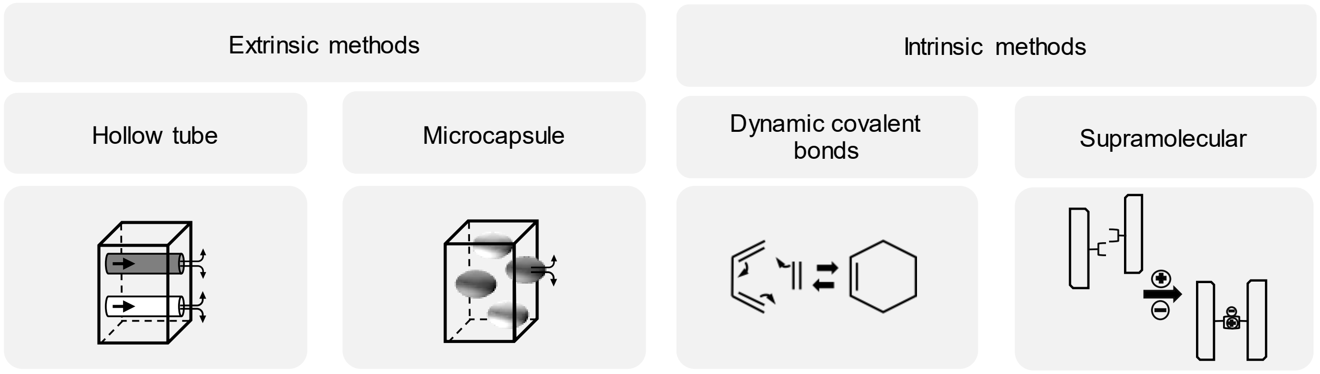


Fig. 1 Classification of self-healing materials.

Extrinsic self-healing materials are based on the encapsulation of a healing agent that is integrated into polymer matrix [24-26]. Upon damage, the encapsulated healing agent is released and self-healing is initiated [27]. In contrast, intrinsic self-healing materials contain specific reversible chemical bonds that allow multiple healing steps to occur at the same site upon damage, and the self-healing process takes place [28,29]. These bonds include, for example, the Diels-Alder reaction [30], radical-based systems [31], supramolecular interactions [32,33], ionic interactions [34], metal-ligand interactions [35] etc. Some examples of the extrinsic and intrinsic self-healing material methods are shown in Fig. 2.

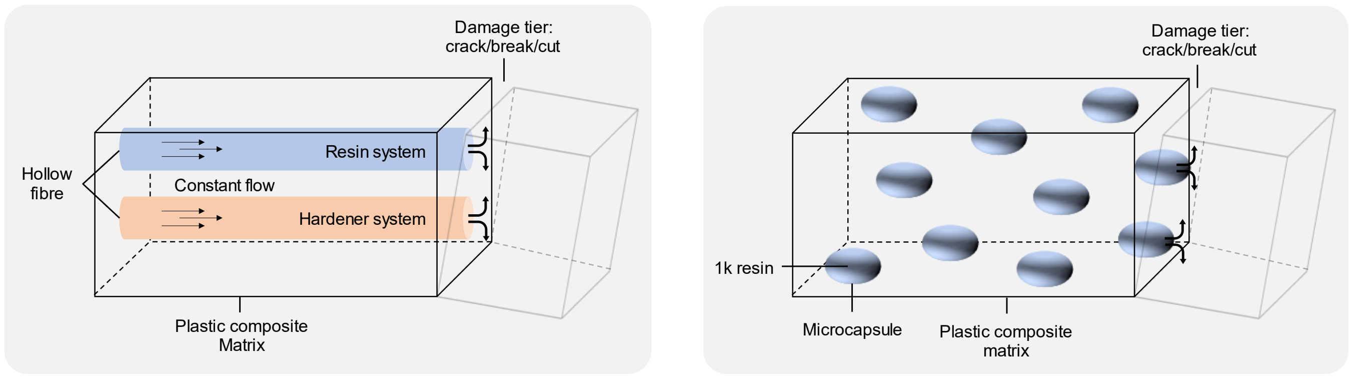


(**a**) (**b**)

*Fig. 2 (**a**) Extrinsic and (**b**) intrinsic self-healing material methods.*

2.1 Extrinsic methods

Extrinsic self-healing materials always work with a healing agent and a catalyst that is stored separately from the matrix. There are three different methods of this self-healing technique in the market. The self-healing mechanism of the hollow tube and microcapsules is shown schematically in Fig. 3.



(**a**) (**b**)

*Fig. 3 Scheme of (**a**) the hollow tube and (**b**) the microcapsules' self-healing mechanism*

The first method is microvascular-based self-healing systems, which are very similar to the hollow tube approach (see Fig. 3a). Said methods have a constant feeding system and therefore the capacity to repair larger or multiple damages. The next method is microcapsule-based self-healing (see Fig. 3b). Microcapsule-based techniques have the catalyst and the healing agent already embedded in the matrix and constant feeding of those materials is therefore not possible. Only smaller damages can be healed that way. The best-known types of self-healing materials that use microcapsules are microcapsule-catalyst-based self-healing, dual/multi-capsule-based self-healing, microcapsule-latent functionality system based self-healing and self-healing using the processing method of capsule catalysts [36]. In the study by Xiang et al, isocyanate prepolymer microcapsules with self-healing properties were prepared. Isocyanate prepolymer for self-healing protective coatings served as the core material. In addition, a commercial polyurethane hardener (Bayer L-75) and 1,4-butanediol (BDO) as a chain extender in an emulsion solution were used for interfacial polymerization. It was found that addition of gum arabic (GA) reduced the adhesion phenomenon and improved microcapsule surface appearance by making them smoother [37]. Fig. 4 shows the scheme of microencapsulation preparation (see Fig. 4a) and self-healing mechanism of isocyanate prepolymer microcapsules (see Fig. 4b). When damage occurs in the coating, embedded microcapsules will release the isocyanate prepolymer after breakage, thus repairing the cracked area.

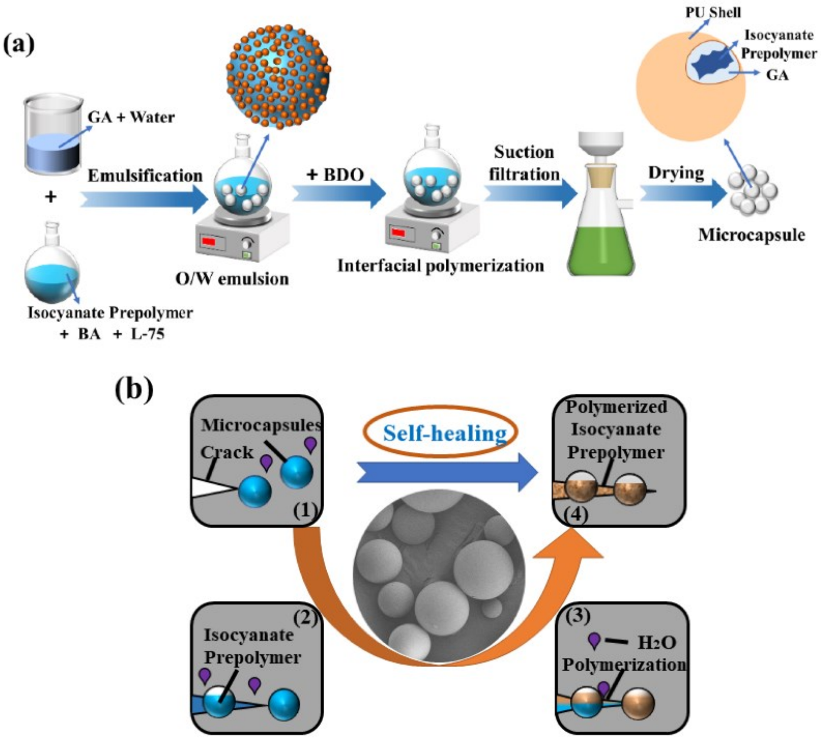


Fig. 4 Scheme of production of the microcapsules (a); Self-healing mechanism of isocyanate prepolymer microcapsules (b). Gum arabic (GA), butyl acetate (BA), polyurethane (PU), oil-water system (O/W). Adapted from [37], originally published under a CC-BY 4.0 license.

All extrinsic self-healing systems can achieve the virgin properties of the material after damage. When damage occurs, a trigger reaction takes place and the healing agent, which is inside the matrix or encapsulated and behaves as a catalyst, interacts and initiates a healing process. The newest method of extrinsic self-healing is a system that uses mesoporous networks. This microvascular method can be more easily explained as an optimized solution of the hollow tube approach. The hollow tubes are integrated into the matrix and look similar to veins in the human body. A constant feeding of healing agent is possible and the material can be repaired multiple times [36].

2.2 Intrinsic methods

Materials that heal through intrinsic systems can inherently restore their integrity. By comparison, they are not as autonomous as most extrinsic self-healing methods and normally need an external trigger to start the healing process [38,39]. These methods work with the individually defined properties of the materials. They can work with the properties and behaviors of the chemical and physical bonds or their behavior when getting in contact with heat or water. Intrinsic self-healing has three well-known systems.

The first system is based on reversible reactions. The most widely used reactions are Diels-Alder and retro-Diels-Alder. The next technique is based on ionomers. The most commonly used reactions of this technique are thermoreversible and physical interactions. Supramolecular-based systems are the last intrinsic method [40]. These systems function like metal coordination and/or hydrogen bonding [36]. Fig. 5 shows a simple, water-triggered self-healing coating suitable for various substrates by coalescence of the precipitated hydrogen-bonded complex of tannic acid (TA) and polyethylene glycol (PEG) in aqueous media [41,42]. As schematically shown in Fig. 5, formed assemblies are released quickly and combined through hydrogen bonds on the lower substrate to form a soft coating, which is able to repeatedly repair small cracks in the micrometer range [41].

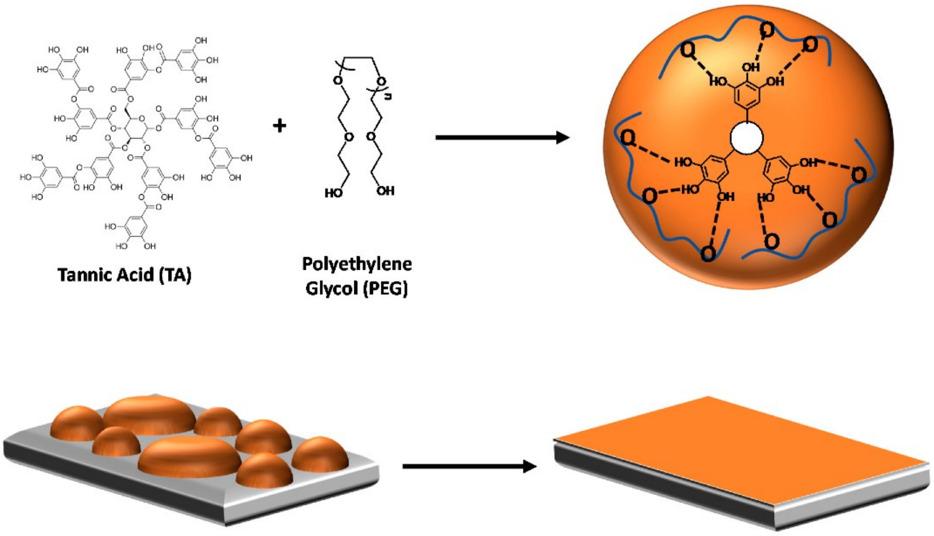


Fig. 5 Schematic representation of the formation of TA-PEG hydrogen-bonded complexes and the fabrication of the coating. Reprinted from [41], originally published under a CC-BY 4.0 license.

2.3 Levels of Autonomy

Various classifications of self-healing materials have already been undertaken [43]. Some are based on matrix materials (organic and inorganic) or the need for an external stimulus (autonomous or non-autonomous). Others are classified based on the underlying chemistry of the healing such as extrinsic or intrinsic or the type of healing agent such as metals and alloys, shape memory alloys, chemical catalysts and monomers or bacteria [43-47].

The degree of autonomy can be sorted into four different categories: increased durability, assisted healing, semi-autonomous healing and fully autonomous healing [48] (cf. Fig. 6).

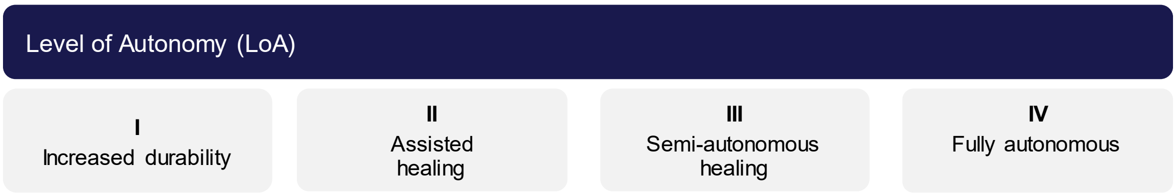


Fig. 6. Levels of autonomy.

Increased durability shows the lowest degree of autonomy. This level of autonomy will be made before the actual use of the product. The lifecycle will be prolonged through different methods, which are the individualization of the materials, the designs, and production steps [49,50]. The only aspect taken into consideration is the preparation and production of the product. The materials' properties do not change during the use of the product. No healing processes will take place and therefore no trigger response is needed. An example of increased durability is creating radiation-resistant metals by irradiation [48]. The next level of autonomy is assisted healing. It has the second-lowest degree of autonomy. On this level, a healing process is able to take place; therefore, a trigger response is needed. It uses an external trigger, which can for example be heat, radiation, or pressure [51-53]. Furthermore, a material or energy flow is needed to initiate a healing of the product [48]. Semi-autonomous healing has the second highest degree of autonomy. A healing process, as in assisted healing, will take place and therefore a trigger response is needed. The difference to assisted healing is that the trigger response is based on environmental factors, like for example heat (e.g. on a hot summer's day) or water [48].

The category with the highest degree of autonomy is fully autonomous healing. A healing process also takes place during the use, as it does with semi-autonomous healing or assisted healing. In this category, the trigger response that starts the healing process comes from the damage itself. Possible techniques to achieve fully autonomous healing are the already named vascular-based self-healing methods or microcapsule-based self-healing [48].

3 Applications of self-healing materials

Based on the principles of operation described above, the following section describes applications for self-healing textiles that are already available on the market or in research. The applications are divided into industrial applications, using aerospace as an example, and applications from the clothing industry.

3.1 Aerospace industry applications

Fiber-reinforced polymer composites with metal alloys or fiber-reinforced ceramic composites with integrated self-healing techniques are used in components such as aircraft fuselages and engines in the aerospace industry or in coatings [54-56]. Several problems in the aerospace industry can be solved by the mechanical, physical and chemical properties of self-regenerating systems. Spacecraft are typically coated with advanced polymer composites. They still sustain damages due to harsh environmental conditions like, for example, radiation, atomic oxygen, or collisions with space debris [57].

Modern aircraft use fiber-reinforced polymer composites for thermo-structural aerospace applications [58]. Currently used fiber-reinforced composites are susceptible to impact damage, and to remedy this deficiency, damage analysis methods based on the finite element (FE) method are used to predict the origin and development of damage as well as the load-bearing capacity [59]. Furthermore, they require further maintenance, as structural damage and integrity issues are difficult to detect. These materials have a very high application potential in terms of the use of hollow glass fiber epoxy composites. Hollow fiber reinforced composites have low weight and high mechanical performance and offer potential as encapsulation materials for self-healing, optical applications and good mechanical properties [60]. They have a strong recovery of up to 47% after healing damages from a three-point-bend impact stress and a strength recovery of about 97%. In addition to this, research on the preparation of ionomeric polymers suggests they have great self-healing abilities and a high velocity resistance. This preparation of ionomeric polymers can be an optimized replacement of aluminum alloys [61].

3.1.1 Coatings

The research on coatings of aerostructure plays an essential role in the development of self-healing coatings. They can be used as a protection of the aerostructures' wings, engine, cascade and many more parts from extreme conditions like heat or weather. Self-healing coatings can prevent dangerous errors from occurring due to damage. An example of these coatings is epoxy resin composites or self-healing vanadia composites, which are a good alternative to chromate coatings [61]. In another study, synergistic mechanism of self-healing of cracks with oxidation-induced healing and precipitation-induced healing mechanism was developed in Al-modified SiC coating with nitrogen heat treatment in a high-temperature oxidation environment [62]. A facile preparation of the highly transparent zwitterionic anti-fog coating of poly (SBMA-co-IA) with self-healing and with antifouling properties by (methacryloyloxy)ethyldimethyl-(3-sulfopropyl) (SBMA) and itaconic acid (IA) was developed and investigated in another study [63]. A novel microencapsulated hydrophobic amine and micro-encapsulated isocyanate in two-component structure for self-healing anti-corrosion coatings was developed and tested by Guo et al. Hydrophobic polyaspartic ester (PAE) and isophorone diisocyanate (IPDI) with melamine-formaldehyde (MF), which was microencapsulated by in-situ polymerization, served as the shell and self-healing tung oil (TO) dissolved in PAE served as the core material. True color confocal microscope (TCCM) micrographs confirmed the self-healing coating of two-component microcapsules and excellent self-repair performance at about 20 wt% content of two-component microcapsules in the epoxy coating [64]. Self-healing coating with and without self-healing microcapsules is shown in Fig. 7.

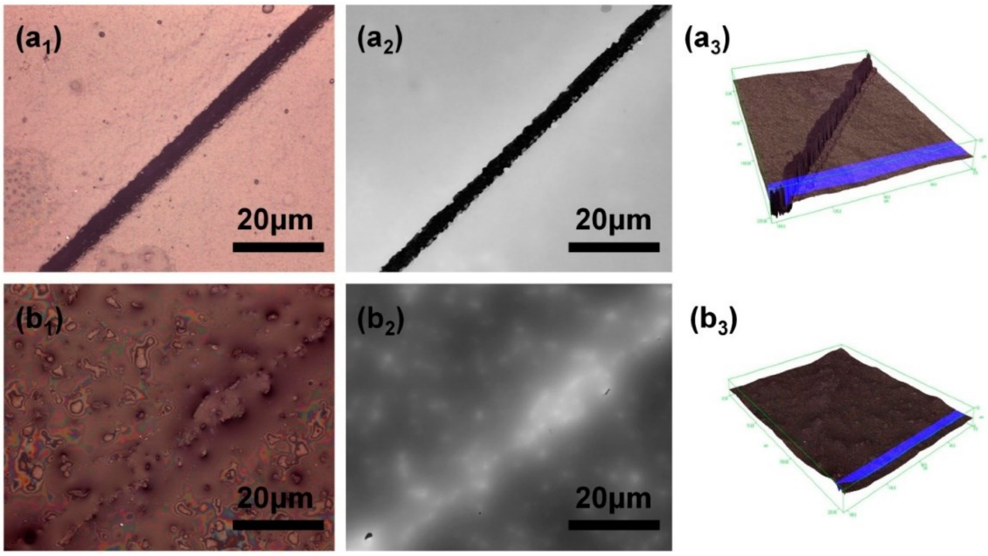


Fig. 7 TCCM images of scratched regions (a_1-a_3) control coating without self-healing microcapsules; (b_1-b_3) self-healing coating containing self-healing microcapsules. Reprinted from [64], originally published under a CC-BY 4.0 license.

Fig. 7a_1-a_3 shows the sample with the control coating with a crack without the use of self-healing coating and sample 7b_1-b_3 with self-healing coating. It is clearly visible that the sample with the inclusion of microencapsulated IPDI and microencapsulated PAE/TO exhibits self-repair properties. The broken microcapsules release the repair agent and newly formed polyurea fills the microcrack. This self-healing coating with two-component microcapsules can be used in the anti-corrosion protection of metals as a quick repair for mechanical damages at early stages [64].

3.1.2 State of the art in aerostructures

Several aerospace composites consisting of epoxy resins that contain Diels-Alder furan and maleimide moieties are able to self-regenerate after getting in contact with heat sources. In epoxy amine systems that are blended with furfuryl and maleimide functional groups in addition to a concentration of binding, thermo-reversible cross-linkers balance the thermoset and thermoplastic behaviors. The Diels-Alder (DA) reaction involves reversibility and the advent of self-repair technology, and thus is a simple and scalable toolbox. Due to these properties, the use of the DA reaction is being discussed in both academic and industrial research [65-68]. Thermosetting epoxy resins containing DA adducts in the epoxy precursor belong to self-healing polymers and form the class of smart materials from which intrinsically self-repairing materials are produced. One of the properties of DA adducts is their ability to be reversibly cleaved and reformed under suitable thermal conditions [69]. The study by Zolghadr et al. investigated novel self-healing DA polymers and semi-interpenetrating polymer networks (semi-IPNs). They found that the self-healing efficiencies reached about 80% and 95% for semi-IPN and DA polyadducts, respectively, in terms of flexural strength [70]. In the study by Ehrhardt et al., furan-maleimide-Diels-Alder cycloadditions were investigated in polymer networks for ambient applications with self-healing property while maintaining mechanical robustness. The self-healing capacity of reversible polymer networks based on Diels-Alder cycloadditions were tested at temperatures between -40 °C and 85 °C and their potential application in photovoltaics as self-healing encapsulation material was confirmed [71].

Intrinsic self-healing technologies are particularly useful in high-risk or hot-spot regions where damage occurs more easily or frequently, and the new intrinsically self-healing materials with excellent mechanical properties are of great interest [72]. Said technologies can resist the extreme conditions these hot-spot regions have to undergo. Furthermore, a bulk material with a high healing efficiency was elaborated for the integration into fiber-reinforced polymer composites. The bulk material with the highest healing efficiency is a 20-pph bulk material derivative. Specialized polymers were developed, which are able to heal multiple times at very high temperatures.

3.2 Clothing industry

Within the clothing industry several different fields of application are existing. Besides traditional fashionable clothing applications, in specific technically focused applications like protective clothing and workwear are already addressed with solutions for self-healing textiles.

3.2.1 Protective clothing

The use of these self-healing polymeric materials is also highly attractive for protective clothing. Possible applications include armor, ground vehicles, and tactical structures [73]. Protective clothing is critical to the health and safety of police officers, firefighters, space travelers, fishermen, factory workers, etc. who face hazards from the environment. Protective clothing in general necessitates long-living, resilient products, textile or otherwise.

The durability of protective clothing can be improved by using self-regenerating polymer materials. An advantage here is that certain methods of applying self-healing materials, such as the solution process, are fairly simple. For example, textiles can incorporate a coating of microcapsules in a polymer matrix, which is the most practical extrinsic approach [74]. Using the solution as a coating, made from e.g. supramolecular polymers or rubber, also allows for the formation of a protective film across the treated surface. This is interesting in the context of fishermen's clothing, marine installations and ships, which are constantly exposed to the corrosive nature of seawater and UV-rays [75].

One of the most long-standing fields of research when it comes to self-regenerating polymers is that of ballistic protective gear. This applies not only to worn armor along the lines of Kevlar vests, but also to vehicular protection. The influence of ion content on the ballistic self-healing of poly(ethylene-co-methacrylic acid) copolymers and ionomers (EMAA) was investigated in the study by Kalista et al. These EMAA-copolymers demonstrate the ability to self-heal immediately after the impact of a ballistic projectile [76]. The integration of EMAA-copolymers can be promising for use in ballistic protection vests. In the study by Li and Gou, a multifunctional superamphiphobic cotton fabric with self-healing properties was produced by coating the surface of the cotton fabric with silica nanoparticles and further modifying it with 1H,1H,2H,2H-perfluorooctyltrichlorosilane (FOTS). The investigations demonstrated that the superamphiphobic cotton fabric possessed good chemical and mechanical resistance and exhibited self-cleaning and self-healing properties [77].

Both the need for technical staff to replace these damaged parts and the replacement itself are costly. Therefore, even ten to twenty years ago, self-regenerating materials were quite the prospective solution. For example, a patent application from 2011 describes an alternative approach to standard ceramic tile-based armor with the help of self-regenerating polymers [78]. In this invention, a self-healing ballistic armor protection structure was developed as a shell made of laminated fabric material with outer and inner lamella. Ballistic fabric served as outer shell and inner lamella is made of soft, conformable and self-healing rubber compound. In addition, the shell is filled with ceramic particles embedded in a liquid [78]. The authors explain that the invention arose against the backdrop of ceramic planes needing replacement upon breaking, which produced high costs, as well as the high weight stress ceramic armor puts on vehicles [78].

The state of the art at the time cited the requirements for self-healing materials as follows: "(1) the cleaved material faces must be in close physical contact, (2) sufficient time must be allowed for completion of the self-healing reactions, and (3) environmental conditions must be amenable to the self-healing chemistry" [79]. With the state of the art in 2006, the cracks in the material the self-healing fabric had mended [79] were already valuable enough a result.

Especially coatings and the healing of punctures are attractive for protective clothing for use by police officers. The study found that their material could restore a scratch-damaged coating to its initial functionality after two seconds of healing. Puncture damages (hole or point defects) were found to only restore relatively localized damages, seeing as the experiment used intrinsic healing methods and therefore was not able to deliver more healing material to the damaged areas. Using vascular or encapsulation self-healing methods could circumvent this issue. However, the damages that could be healed were restored after only one second by applying local heating. It is also suggested that patching the damaged area with new protein can help mend bigger holes [80].

3.2.2 Workwear

Working in environments where the human body is exposed to chemicals can be very detrimental to health. In agriculture, for instance, workers spend a great portion of their working hours handling chemicals and pesticides [81]. The need for protective clothing not only has to fulfill the basic functions, but also consider other scenarios in which workers can be exposed to dangerous situations, e.g. their clothes tearing apart or the presence of small gaps in the fabric. In the search for a solution, many investigators have decided on the application of self-healing composites for working garments.

A group of researchers from Pennsylvania State University worked on the development of a textile made from proteins together with a structure of polyelectrolyte multilayer (PEM) films. The protein is extracted from the squid ring teeth, and it presents valuable properties such as high-elastic modulus and healing properties as well [82]. The PEMs have been specially developed as a method to prevent bacterial adhesion to a material surface, and its manufacturing process mainly consists of the deposition of polyanions and polycations by coating the material through different methods [83]. These polyelectrolyte multilayers are already being used in the market, especially for medical textiles like cotton gauzes [84]. Both elements altogether reinforce protective functions against viruses or bacteria and the capability of self-regeneration in case of damage. Nevertheless, to ensure a high-protective performance, enzymes have been added to the textile’s structure. These will neutralize the chemicals from the outside and prevent the human skin from getting into direct contact with them.

Regarding the activation of the self-healing system, it works with the help of water. This element will stimulate the regeneration of components from the squid ring protein that is inside the textile. That way, new bonds are built and are completely tied up when the material is dried. An advantage of using this squid ring protein compared to other healing agents is the highly effective results, not just for regenerating the textile itself but also for preventing possible contact between pesticides or chemicals and the human skin. Moreover, apart from the great performance that it provides, the protein can be considered a more sustainable option. This technology of multilayer films coated with proteins and enzymes can be manufactured with conventional fibers such as cotton, wool, and linen. Therefore, it is very practical to apply it to different types of work garments. That way, the safety and health of people who are exposed to harsh conditions every day can be ensured. However, technologies with other approaches are also being developed in order to provide the healing fabric mechanism for different materials. This is the case with research focused on the manufacturing of worker gloves with high protective performance. The main healing composite is composed of methylvinyl silicone rubber containing hybrid molecules with an inorganic silsesquioxane, and the base fabric is made of cotton or polyamide fibers [85]. The results of several tests conclude that the textile shows great resistance to conditions such as penetration, abrasion, and puncture, which makes it very suitable to wear when working with hazardous chemicals.

Just as the two different technologies previously described, many scientists are on their way to develop methods that ensure the best protective conditions when working in difficult environments. The focus on the manufacturing of efficiently healing fabrics is one solution with countless alternative approaches to it, and over the passage of time, the interest in discovering new materials with high-performance properties will increase, just as there will be more proposals for techniques.

3.2.3 Fashionable clothing

The fashion industry is one of the most polluting consumer industries, and fast fashion means that cheap clothing is produced at a fast pace and disposed of just as quickly – most often after one season or earlier [86]. Moreover, the fashion industry generates around 92 million tons of waste per year [87,88]. The most common reason for disposing of garments is holes or tears in the fabric [89]. Different approaches are being developed to establish sustainable fashion and to extend the lifecycle of textiles and clothing. New approaches such as Zero Waste are established, which is intended to stop the unlimited pollution of the environment and involves social commitment of people in sustainability issues [90,91]. Consequently, self-healing fabrics can be considered as one way to avoid this problem by integrating its mechanism to everyday clothes such as T-shirts, jackets, jeans, hosiery, etc.

The first option for self-healing garments appearing in the market was a windbreaker designed in 2017 by the American apparel brand Imperial Motion that launched the outdoor jacket with its patented Nano Cure Tech (NCT) technology [92]. NCT is made from lightweight water-resistant nylon ripstop with resealing and repairing capabilities [93]. Ripstop is a woven structure that, thanks to the interlacing of threads in a crosshatch pattern, provides the fabric with a very high resistance against ripping and tearing [94], which improves the performance of the material under possible punctures. The mechanism behind this NCT material works because the interlaced threads are not broken when the fabric is perforated, only pushed apart (see Fig 8). Therefore, in order to repair the fabric, it is only necessary to rub the place in which the hole appeared with one's fingers. Imperial Motion developed a collection for outdoor apparel and accessories with this new technology, attracting not only customers but also different clothing manufacturers.

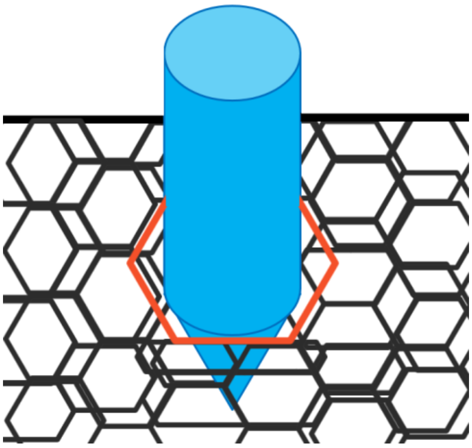


Fig. 8 Schematic representation of the interwoven threads during perforation of the fabric, which are pressed apart at the stitching point.

Consequently, the innovation for this new type of material can contribute to extending the lifecycle of garments, which will directly impact the supply chain of the fashion industry. If clothes can be mended easily, with a physical appearance as good as their original state, the need for buying new clothes will decrease. Less demand in the market means lower consumption of resources and fewer emissions into the environment. However, a major factor to consider is the quality level of the fabric once it has been repaired. It is important, especially in outdoor apparel, that the products can maintain their high performance capacity in order to provide efficient protection. In the case of water-repellent materials, the self-healing textiles can completely recover and maintain their hydrophobic behavior after suffering possible chemical and physical damage [95,96]. This occurs due to the presence of self-healing agents applied as coating layers to the textile, playing a key role in the development of self-regenerating materials.

There are now several companies offering products with self-healing properties. For example, Swiss start-up CompPair develops in-situ repair solutions for composite structures that heal damage by using intelligent prepregs and additional thermal heating to wind turbine blades, buildings and ship hulls [97]. The start-up SAS Nanotechnology (USA) develops intelligent coating consisting of microcapsules with efficient self-healing technology for corrosion protection. The polymer-based microcapsules release corrosion protection additives due to chemical and mechanical triggers and provide self-healing effect against corrosion [98]. In contrast, the US-based start-up company Tandem Repeat has developed programmable textiles with self-healing coating [99]. Microcapsules are also used for a self-healing effect by the company Autonomic Materials (AMI) (USA) [100].

4 Conclusions

The development of self-healing materials has gained great importance as a new solution for technical textiles. Relevant features are the compatibility with different materials such as polymers and natural fibers [101] and the flexibility of manufacturing methods and healing activation mechanisms. The integration of other techniques, such as multilayer films or the use of different resources as healing agents, demonstrates the capacity to continue generating more materials with self-healing properties in the future. Their application already takes place in many markets, ranging from technical areas, such as aerospace and military applications, to the fashion retail market. Moreover, the sustainability aspect that characterizes them makes the self-healing materials an attractive future trend for many industries. However, it will remain a constant challenge to preserve the original properties of the basic material when coming up with a new approach. Some investigations mention a toughening effect in composites resulting from the introduction of healing microcapsules [101,102]. To what extent this is relevant will depend on the final application and the user. Nevertheless, the impact generated by this technology is increasing exponentially and is turning into an attractive option for many companies.

Author Contributions

Alena Dannehl: conceptualization, methodology, investigation, resources, writing – original draft preparation, writing – review and editing, visualization; Amelie Buhr: conceptualization, methodology, investigation, resources, writing – original draft preparation, writing – review and editing, visualization; Angela Sanchez Leyton: conceptualization, methodology, investigation, resources, writing – original draft preparation, writing – review and editing, visualization; Lennart Hellweg: conceptualization, methodology, validation, formal analysis, writing – review and editing, visualization; Mathias Beer: methodology, validation, formal analysis, writing – review and editing, visualization, supervision; Lilia Sabantina: conceptualization, methodology, investigation, resources, writing – original draft preparation, writing – review and editing, visualization, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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