e-ISSN:2582-7219

INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH

IN SCIENCE, ENGINEERING AND TECHNOLOGY

Volume 7, Issue 12, December 2024

INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 7.521

ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 7.521| ESTD Year: 2018|

International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

Textiles of the Future: Exporting Self-Healing and Adaptive Fabrics

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ABSTRACT: The textile industry finds itself at the start of a new transformation in which self-repairing and adaptive fabrics might play a key role. These new materials have the ability to change the current approach towards the design, production and usage of textiles. Self-healing textiles aid in mending and restoring damaged materials automatically, thus decreasing waste and enhancing the shelf life of clothing. Adaptive fabrics, on the other hand, are fabrics that can actively change their properties as a result of environmental stimuli such as temperature or light. The focus of this paper is the overview of the development of self healing and adaptive fabrics technology, as well as the opportunities and when coupled with the challenges of marketing these products internationally. These fabrics are widely used in the fashion industry, healthcare, technical textiles industries. On the other hand, Adaptive fabrics, can also respond to external stimuli by changing their properties. They could, for instance, change the insulation properties of fabrics to help regulate the body's temperature or alter their colour in order to help conceal the wearer. Such adaptability increases comfort as well as makes it more effective in a variety of uses cases from sports wear to military wear. The advantages of self healing and adaptive fabrics are not restricted only to fashion and lifestyle. There are great prospects for these materials in industries such as healthcare, where they could be utilized in self cleaning wound dressing as well as adaptive therapeutic garments. These materials can also reshape the prospects in fields such as aerospace and automotive where lightweight, structrally sound fabrics are preferred. In addition, we review legislation and norms related to the export of these textiles and propose measures to address their technical, logistical, and legal aspects.

KEYWORDS: Self-healing fabrics, adaptive fabrics,

I. INTRODUCTION

Self-healing is an innate feature of nature. Nowadays, researchers are concentrating on the development of nature-inspired materials with amazing properties. Self- healing materials are not part of science fiction anymore. They crossed the boundary between fiction and reality. Self- healing is such a property that is raising a storm in this field. Its property inspired by nature has been pursued in biomimetic designs and healing systems; the damaged structures are repaired by the strategic transportation of healed mate- rials and the polymerization healing process of the injured area. Healing means filling of discontinuity in materials with other materials that differ from the base materials. In general, the properties of healing materials are dissimilar from the matrix. Mostly, self-healing is aimed at getting again surface continuity of materials with concurrent repairing of significant physical and mechanical properties. Self- healing polymers are synthetically developed polymers with the aptitude to convert physical energy into chemical/physical or both responses to repair damage autonomously or no autonomously with external intervention without any human involvement to recover the initial properties, more particularly mechanical properties.

There is a range of potentials for SHPs. Various natural polymer composites and nanocomposites also show self-healing behavior. Cell walls of higher plant bio adhesives develop by using borate to crosslink neighboring protein chains, hyperbranched polyester, and soy polysaccharides; intrinsically, microporous poly(ether-ether-ketone) membranes with a structured surface of natural honeycomb result in improved performance; biologically soft tissue developing processes inspired nanocomposite hydrogel for wound and hemostatic healing; photosynthesis of plants inspired singlet oxygen generation and CO_2 fixation by a photo carboxylation process. The generations and classification of SHP. The polymers that pro- vide self-healing features are of two types: (a) intrinsic SHP and (b) extrinsic SHP. Intrinsic SHPs are innate reversibility- based compounds that can heal the damage by increasing the mobility of polymeric chains temporarily. On the other hand, extrinsic type self-healing is triggered by the incorporation of exogenous agents which then help for self-healing from embedded microcapsules on cracking.

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The thermal comfort of the human body is a widely dis- cussed topic as it significantly impacts our physiological and psychological health. Generally, humans strive to maintain a suitable temperature range in diverse environmental conditions to ensure regular physiological function. For example, during physical exercise, humans' muscles become highly active and generate a significant amount of heat, which necessitates effective heat dissipation to maintain body temperature within a normal range. Conversely, when inactive, especially in cold environments, reducing heat dissipation of the body is desirable to keep the body warm. To meet the above demands, it is crucial to properly regulate the heat transfer process between the human body and its surroundings.

Fabric plays a critical role in managing the thermal comfort of the human body since it acts as a medium for heat exchange between the human body and surroundings. More than 50 % of the human body's thermal energy is released into the environment through thermal radiation. Therefore, fabric with tailored spectrums can effectively affect the heat dissipation of the human body, thereby improving thermal comfort. In recent years, emissivity engineering techniques have been developed rapidly, and two kinds of advanced fabrics, radiative cooling fabric and thermal radiation insulation fabric, have garnered interest in personal thermal comfort regulation by enhancing and reducing the thermal emissivity of the fabric layers. For example, Cui et al. developed composite textiles with spectral selectivity for passive radiative cooling by adding zinc oxide nanoparticle to nanoporous polyethylene, which can achieve a fabric's temperature reduction of 8 ◦C compared to cotton.

Zhou et al. sprayed $Ti_3C_2T_x$ on the surface of the fabric to reduce the emissivity of the fabric surface to 0.195 at 7 μm–14 μm. The temperature of the human skin covered with the fabric is 2.68 ◦C higher than that covered with cotton fabric. Although the aforementioned fabrics con- tribute significantly to human thermal management by pro- viding mechanisms for enhanced and suppressed radiative heat dissipation, their spectral properties are static, which means these fabrics are monofunctional to keep humans cool and warm. However, the heat dissipation requirements of humans under resting and physical exercise are quietly different, which need dynamical thermal management for thermal comfort. Therefore, the concept of smart fabrics with switchable emissivity modulation for self-adjusting radiative heat dissipation enhancement and suppression has been proposed and developed. Cui et al. developed a smart fabric by sandwiching two nanoPE layers together, one is covered with a copper layer and the other is coated with carbon. This fabric exhibits an average emissivity of 0.894 on the carbon-coated side, while the side with the copper coating has an emissivity of 0.303. Similarly, Gao et al. introduced a dual-sided intelligent fabric using polyimide (PI) and Ag nanowires (AgNWs), which shows high reflectivity of 0.80 on the AgNWs coated side and strong infrared emissivity of 0.79 on the PI side. However, these fabrics often require active mechanical flipping to switch the different sides of the fabrics to achieve emissivity mod- ulation, which is not friendly for the end user. Aiming at this point, this work plans to propose a passive strategy to achieve dynamic emissivity modulation of the fabric, which is quite different from the above mentioned Janus fabric with active operation.

In this work, we introduce a spectrally self-adaptive
smart fabric (SSSF) by covering a highly breathable polyester fabric with a network of AgNWs for the thermal management of the human body. The emissivity of the SSSF can be passively controlled in response to the body's movement status from dry to wet states, dynamically achieving radiative heat dissipation enhancement and suppression for humans at different activity levels. During resting status, the SSSF maintains a low-emissivity state ($\varepsilon = 0.39$) to suppress radiative heat loss from the body to surroundings, while it changes to a high-emissivity state ($\varepsilon = 0.83$) when the sweat penetrates the SSSF to enhance radiative heat dissipation during exercise. Experimental demonstration indicates that the SSSF at the low-emissivity state can save heat loss power of 19.5 % compared to the traditional commercial fabric. Besides, the heat dissipation power of the simulated skin is enhanced by 67.6 % when the SSSF switches from low-emissivity mode to high-emissivity mode coupled with evaporation cooling. These results underscore the significant potential of the SSSF for passive thermal management of the human body.

II. SELF HEALING FABRIC

Application of SHPs in Different Sectors

Investigation on self-healing started in 1970 due to the healing of polymer cracks. Polymer with self-healing features is newly developed advanced materials with extended lifetimes which can mend themselves when they got damaged without the requirement of detection or repair by manual interference of any kind. The SHP is used to decrease the

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damage and further chance of material failure along with the long life cycle of polymers and polymer composites. The growth of polymer with self-healing ability is nothing but the advanced modification of the common polymers by incorporating the self-healing features. Application of SHPs covers the field like coatings or paints, sensors, soft robotics, 3D printing, biomaterials, textile, and automobile. Similarly, their potentiality of real-world applications is also analyzed.

Now, SHPs are coming out of the lab to real-world applications. It can be used to reduce the cost of maintenance, prolong durability, assure safety, and fabricate advanced materials. In recent years, great emphasis has been given to self-healing materials for real-life engineering approaches. The presence of a material is determined by its functionality in any system. Functionality is a combination of instance properties like electrical and thermal conductivity, color, brightness, adhesion, reflectivity, and hydrophobicity, Varieties of SHPs are devel- oping with desired properties to improve functionality for the application in different fields. The enormous versatility of SHPs offers possibilities to apply them in different sectors. The real-world demands, as well as the related implementations, will determine the success of SHPs. Here, we will discuss the application of SHP in different fields with numerous functions.

Construction Materials. Multiple cycles of self-healing are a matter of concern in the case of the performance of structures made of concrete. Researchers used a mixture of polyvinyl alcohol fibers, steel, superabsorbent polymer, and biochar containing immobilized bacteria to investigate crack healing, recovery of mechanical property, and permeability after multiple cycles of damage. Precipitation of microbial calcite by immobilized bacteria containing bio-char combined with a superabsorbent polymer and fiber found superior healing capability for a wider crack surface (>600 μm) and microlevel internal cracks comparing autogenous mechanism and concrete mixed with superabsorbent polymer and fiber.

In an alternative investigation, the speedy self-sealing can be improved by mixing composites of sulfur polymer combining superabsorbent polymer with Portland cement and calcium sulfoaluminate composed binary cement. The healing capabilities of the superabsorbent polymer as an SHP are very fast, which can heal the damage within 30 mins. The superabsorbent polymer particles taped up and connected the two crack surfaces quickly by swellingup the absorbing water. This self-healing is promoted by nucleation and growing of hydrated yields around the nucleus. A better rapid self-healing increased proportionallywith an increasing calcium sulfoaluminate ratio.

Polymer-cement composites were formulated by mixing poly(ethylene-co-acrylic acid) zinc salt powder, bisphenol A diglycidyl ether (BPA), two base cement H, and thermal shock-resistant cement (TSRC). Polymer-cement composites maintained their self-healing property for thirty days at 300°C. These cement composite materials showed a com- pressive strength of more than 1000 psi after a day, just as the requirement of wellbore applications. These advanced polymer-cement composites are mechanically stable, ductile,and self-healable. It is expected that conventional wellbore cement could be replaced by polymer cement which can be applied for the extraction of geothermal and fossil energy.

Paint and Coat. The addition of epoxy resins to a painting enhances the colors and gives the piece a glossy, clean finish. The development of epoxy resin systems which are mechanically tough yet easily healable and recyclable is highly desirable but remains considerably difficult. These innovative epoxy resins based on plant oils were successfully produced using dithiol modified boronic ester and completely epoxidized plant oils by a "thiol-epoxy" click reaction that is thermally triggered. The maximum tensile strength of the plant oil-based epoxy resins was 43.2 MPa, and the maximum was 25% elongation at break. At normal temperature, the self-healing effectiveness of vegetable oil- based epoxy resins might be 90% in a day. Furthermore, even after 9 rounds of reprocessing, the mechanical qualities of resins that have been recycled remained at 80% of those of the original resins. These recent developments of epoxy resin-based SHPs with desired toughness added a new height to the potential of using SHPs even for critical engineering construction material.

By combining an epidermis-like hierarchical multiple- layered structure with mechanically stable graphene oxide, the fundamental dilemma of achieving stiffness with self- healing can be overcome. This type of smartly ordered system of coating can provide long-term stability with an effective healing ability. Among all self-healing polymeric films, it has the greatest stiffness (31:4± 1:8 GPa) and hard- ness (2:27 ± 0:09 GPa), which is similar to the enamel of the tooth. This hybrid layer-by-layer assemble technique was demonstrated by depositing a thin quasilinear layer-by-layer (l-LBL) film

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with graphene oxide (GO) nanosheets as 2D fillers on top of a thick exponential layer-by-layer (e-LBL) counterpart to imitate the hierarchical stratified structure of the epidermis. The exponential layer-by-layer part is generally made of poly(vinyl alcohol)/tannic acid.

Epoxy monomer as a self-healing agent and dodecyl amine as a corrosion inhibiting agent is enclosed in a single coated layer providing self-directed corrosion inhibition which helps to develop a smart coating around the metal. Titania (TiO_2) nanotubes with an average size of 0.02 μm were impregnated with dodecylamine and epoxy monomer where titania nano- tubes interspersed into the epoxy matrix that can be applied on steel. The damaged area was nearly healed within 96 hrs, and the reduction in the corrosion rate is observed for epoxy and healing additives-coated steel even after emerging in saline water after 5 days. Microcapsules responsive to UV dispersed coating are formulated for repairing damage in space. UV-responsive microcapsules are made by UV- triggered polymerization of Pickering emulsions and then embedded in silicon resin matrices. The inner polymeric shell of microcapsules is quickly degraded by the outer pure TiO_2 shell under UV radiation. Due to the dual release method, UV-responsive microcapsules can discharge more agents even more effectively than commonly employed damage healing systems. Furthermore, the harmful effects of UV radiation in space can be transformed into beneficial ones using this UV- responsive microcapsule. This property makes the material suitable for use in aerospace coatings. Additionally, in a very recent study, researchers described a strategy for creating a strong and low-temperature mendable supramolecular system of polypropylene glycol- (PPG-) polydimethylsiloxane- (PDMS-) Zn by integrating both high dynamic crosslink bonds and low crosslink density into polyurea networks. The resulting PPG-PDMS-Zn-0.5 polymer showed 0.98 MPa tensile strength and showed 97% self-healing efficiency at -20°C. This type of supramolecular polymers with unique features can also be applied in Antarctic pole exploration anti- frosting and anti-icing paints.

III. ADAPTIVE FABRICS

Fabrication and characterizationof the SSSF

In a resting status, the human body produces a heat output of approximately 70 W/m^2. In cold environments, employing low-emissivity fabrics is essential to minimize the radiation heat loss from the body and maintain thermal comfort. Conversely, during physical activity, the heat output of the human body can exceed 150 W/m^2, making fabrics with high emissivity beneficial for the dis- sipation of excess heat. Therefore, fabrics with adjustable emissivity provide benefits in maintaining thermal comfort for the human body before and after physical activity. Based on this consideration, we propose a strategy for passive emissivity modulation. The fabric needs to have low emissivity at resting status (i.e., low-emissivity state) and this can be achieved by covering a reflecting coating on top of the fabric, while the fabric needs to transmit the sweatand change it to be high emissivity at physical activity status (i.e., high emissivity state).

During the fabrication process, AgNWs are utilized as a porous low-emissivity coating on fabrics. These AgNWs self-assemble into a network on the surface of the fabric, achieving a high reflectivity (low emissivity) due to the small distances between wires, which are significantly less than the wavelength of mid-infrared light. Moreover, the polyester fabric with small interstitial spaces is selected as the substrate to enhance the surface area available for AgNW attachment and to reduce the loss of AgNWs from the fiber gaps during the coating process. Additionally, thegaps between fibers of the polyester fabric facilitate sweatpenetration from the skin to the exterior surface of the AgNWs, thereby enabling a high emissivity state. Of course, the permeability characteristic is one of the characteristicsof most polyester fabrics.

The fabrication process of the SSSF is depicted. First, the AgNWs solution is diluted and sprayedonto the surface of the commercial polyester fabric. Subsequently, the fabric is dried in an oven. This spraying and dry- ing process is repeated until all the AgNWs are fully coatedonto the fabric surface. The AgNWssprayed onto the fabric adhere to the polyester fibers and AgNWs exhibit a mesh-like distribution. Besides, it can be found that the AgNWs encase the polyester fibers. To prove the AgNWs have successfully coated onto the polyester fabric surface, EDS characterization is further conducted.

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The infrared reflectivity of the fabric is improved when AgNWs are applied and this reflection is further enhancedby enlarging the mass concentration of AgNWs. This improvement is attributed to the denser coverage of AgNWs on the fabric surface as the concentration of AgNWs increases, which results in a corresponding increase in reflectance. Notably, although the infrared reflectivity is enhanced by high-concentrated AgNWs, the excessive den- sity of AgNWs compromises both their adhesion to the fabricand leads to an escalation in costs. Hence, a mass density of 3 mg/cm^2 for AgNWs is applied for the SSSF, achieving a reflectivity of 0.61, which corresponds to an emissivity of 0.39 based on the fact that the SSSF is infrared opaque.

To describe the infrared characteristics of the SSSF under the low emissivity state, an optical simulation is performed based on a simplified silver metal grid model that is used to simulate an equivalent AgNWs grid. It can be observed from the SEM image that the AgNWs net- work is dispersed on the surface of the fabric. However, due to the coarse fibers of the fabric, the AgNWs net- work is not continuous and is segmented by the fibers of the fabric. Therefore, the AgNWs network on the fabric surface is composed of numerous tiny AgNWs networks. The equivalent silver metal net- work model, where L represents the distance between adjacent silver metal wires and D represents the distance between adjacent silver metal tiny networks. As L increases from 100 nm to 300 nm, the reflectivity (at the wavelength of 10 μm) of continuous silver metal networks (D = 0 mm) decreases from 0.95 to 0.8. Evidently, the simulated results of the continuous metal network significantly exceed the actual reflectivity. This is because the fabric surface is high roughness and the physical segmentation of silver nanowire networks by the polyester fibers in the fabric. To further describe the spectral characteristics of the fabric surface, the reflectivity of adjacent tiny metal networks at different D is simulated. When L = 200 nm, as the D increases from 0 μm to 2 μm, the infrared reflectivity(at the wavelength of 10 μm) decreases from 0.9 to 0.55.

During resting status, the fabric can preserve a state of dryness, which exhibits a low emissivity surface dueto the metallic characteristics of AgNWs. This feature sup-presses radiative heat loss from humans. However, during physical activity with sweat, the sweat penetrates the fabric and adheres to the exterior surface of the SSSF. Due to thehigh emissivity characteristic of water, the SSSF exhibits enhanced radiative properties. Simultaneously,as the sweat evaporates from the fabric surface, it also carries away a portion of the generated heat. The combined effect of radiative and evaporative heat dissipation contributes to the strong heat release of the human during intense physical activities. Consequently, the SSSF exhibits an emissivity of 0.39 under a dry state, while the emissivity rises to 0.83 under a wet state, achieving an emissivity mod- ulation of 0.44. The sweat penetrative capability of the SSSF is crucial in modulating the emissivity. To demonstrate the sweat-penetrative property of the SSSF, we place the SSSF on a color-changing paperthat turns blue upon contact with water. When water drips on the fabric, the water passes through the SSSF, and the paper underneath turns blue. The interstices between the polyester fibers in the fabric, as well as the gaps between the AgNWs networks, are far larger than the diameter of water molecule, thereby facilitating the permeation of water through these gaps. The permeability of fabric towater depends on the characteristics of polyester fabric, and AgNWs has little effect on the permeability of fabric. Therefore, the evaporative cooling performance of SSSF is minimally affected compared to ordinary polyester. Furthermore, to assess the wear resistance and waterresistance, the SSSF is placed in water and continuously stirred for 24 h. Measured spectral emissivity shows that the emissivity is only attenuated by 0.1.

IV. CURRENT STATE OF TEXTILE INDUSTRY

Integration of self-healing and adaptive fabrics is making strides within the textile industry, although it is still in the process of emergence. Advances in nanotechnology and special coatings that enable automatic repair and adaptive responses to external stimuli are the focus of the current enhancements. Microcapsules performing the repair are highly likely in such fabrics, which autonomously release healing agents in response to damage incurred. For instance, polyurethane coatings of embedded microcapsules could seal small cuts when in contact with air or water, increasing durability and sustainability. This technology is presently being piloted for workwear usage, such as waterproof garments for professional purposes, though commercial application remains limited, given the challenges associated with industrial scale-up and resistance to larger damages.

© 2024 IJMRSET | Volume 7, Issue 12, December 2024| DOI: 10.15680/IJMRSET.2024.0712057

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Of similar interest in self-healing fabrics lies the functional enhancement, especially in protective wear. An example of research into textiles embedded with enzymes has shown potential in neutralizing hazardous chemicals and has beneficial prospects in medical or industrial settings. This technology shall offer potential with polyelectrolyte layers for garments that will autonomously mend themselves after chemical exposure and protect against effects of toxins that could basically change the entire scope for the safety helmet along with secure wear in a high-risk environment.

V. CONCLUSION

Considering the long-term stability, self-heal ability, and flexible nature, SHPs are the best composite material among the next-generation materials. This material can be used in many diverse environments with higher stability comparing conventional material. Therefore, using this composite material would be economic in industrial sectors. The progress of SHPs day by day makes this type of material worth using in every sector. The special features of newly developed SHPs reveal a new way to produce and apply advanced materials. Now, these new types of material enable us to pro- duce various products with a longer lifetime and stability. The experiments to develop new SHPs and experiments on SHP composites incorporating different elements or com- pounds should be continued to get the best to apply in every sector and obtain more versatility of SHPs. Ensuring the availability of SHPs is a must to apply on large scale. This will not be possible through critical and expensive synthesis methods. Developing synthesis methods that are less critical, greener, and cost-friendly needs more attention from the researchers. The green synthesis route is important because we should not mess with nature, stay with it, and observe the pathways of nature more closely to get inspiration for developing amazing SHPs. At present, products are success- fully being used in different sectors containing SHP. Although the development of SHPs has done much through advanced research, there is a lot of progressive research still to be done to take the SHPs in practical and industrial applications. Approaches to the industrial application of SHPs just have started, and it is time to fasten the seat belt and start the journey to the era of SHPs.

In this work, we have designed a spectrally self-adaptive smart fabric (SSSF) based on polyester fabric and AgNWs, which can dynamically regulate its surface emissivity in response to sweat, benefiting the smart thermal manage ment of the human body across varying levels of physical activity. During the resting period, the SSSF remains dry with an infrared emissivity of 0.39, effectively suppressing radiative heat loss and keeping warm. Conversely, during intense physical activity, sweat penetrates to the exterior surface of the SSSF, resulting in a high emissivity of 0.83, facilitating enhanced radiative heat dissipation and keep- ing cool. Indoor experiments have demonstrated that the heat dissipation power of the SSSF is 19.5 % lower than that of commercial textiles in resting status under a fixed skin temperature. However, when changing to physical activity, the heat dissipation power of the SSSF is increased by 67.6 % based on enhanced radiative and evaporative heat dissipation. Overall, this study introduces a straightforward and cost-effective approach to improving the thermal com- fort of the human body during both active and resting status based on self-adaptive emissivity modulation engineering, showing potential in the fields of personal thermal management.

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