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The Future of ‘Self-Healing’ Technologies

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Abstract

Recent years have witnessed significant advancement in ‘self-healing’ technologies. This is unlike a decade back, when ‘self-healing’ materials which are capable of restoring functionalities such as electrical conductivity or even optical (e.g., display) property after mechanical damage were practically non-existent. This editorial provides a quick introduction on reported ‘self-healing’ technologies, particularly those with rapid healing time and impressive restoration of functionalities (e.g., up to 90%). There is also an emphasis on the utilities and benefits of ‘self-healing’ technologies, as well as some of the key challenges in their integration and translation. It is anticipated that, with continued development and seamless integration of ‘self-healing’ materials into modern-day settings, it is set to open up a new era of enhanced consumer experience, infrastructure maintenance, environmental management, as well as countless unprecedented and unique applications resembling those in science fictions.

Keywords: self-healing; functionalities; biotechnologies; applications; commercial opportunities

Introduction

Today, the concept of ‘self-healing’, i.e. the inbuilt ability of a material or a network to repair itself, has emerged to be a fairly hot topic transcending across diverse industries, including automotive, biomedical, construction, electronics, marine, telecommunication, wearable technology, aerospace and deep space exploration, etc. Getting a material to automatically ‘heal’ itself is very much nature-inspired, and this concept is now seen to be beneficially bridging some of previously unrelated industries (e.g., biotechnological and construction industries) with the potential to bring about immense commercial and social impacts. Undoubtedly, the concept of material ‘self-healing’ is leading a new wave of smart, fashionable, multi-functional, science fiction-inspired futuristic technologies [1-4], of which were previously driven mainly by the concept of material ‘stimulus-responsiveness’ (i.e. the ability of materials to respond to external stimulus) as the key to achieving smartness in materials or systems.

Rapid healing time

The field of materials science and engineering has since played an eminent role in the developments of ‘self-healing’ technologies, as presented in a recent review article which describes the working principles of self-healing polymeric materials in great details [1]. Among the more significant ‘self-healing’ technologies reported is the ‘self-healing’ conductive materials for electronics/bio-electronics (i.e. mainly achieved by integrating reversible bonds into conductive polymers, or incorporating conductive fillers into self-healing polymers) [1]. Another prominent example would be the ‘self-healing’ wiring systems for space shuttle orbiter as recently reported by the National Aeronautics and Space Administration (NASA) in 2017 (which is largely based on novel low-melting polyimide film matrix) [5]. Thus far, several ‘self-healing’ systems with rapid healing time below 20 s [5] or even 15 s [2] (at room temperature) have been reported, and brilliantly resulted in no visible scar in the healed

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films. Even more rapid rates of ‘self-healing’ (i.e. below 2 s, at elevated temperatures) exploiting the viscoelastic properties of materials have also been developed by NASA aiming for bulletproof, aircraft, rotorcraft and spacecraft applications [6-7].

Restoration of functionalities and advancement of TRL

While the notion of having objects or gadgets to instantly heal themselves seamlessly can appear to be overly idealistic (i.e. too good to be true in certain circumstances/applications), it is noteworthy that various pieces of scientific evidence have convincingly demonstrated the advanced ‘self-healing’ nature of designed materials, often with their proven abilities to regain partial, if not, close to full material functionality (e.g., up to ~90% of the original electrical conductivity, mechanical properties, etc) impressively within tens of seconds [1] and in some cases, fractions of seconds [7]. Today, ‘self-healing’ materials are being actively explored by NASA to raise the Technology Readiness Level (TRL) of thermal protection system applications targeted for use in space environments [8]. With these advances, it now seems that we are indeed not too far from witnessing the translation of many scientific fantasies into real-world scenarios.

A fantastic idea about ‘self-healing’ is that – it is not just about plugging the gaps and hardening cracks in material(s), but also about it offering to restore the mechanical, chemical, electrical and/or other functional properties of the material(s), such as the display properties of a touch screen sensor. As an example, a touch screen sensor capable of ‘self-healing’ was fabricated by laminating two composite films on an LED display (the composite films are made of silver nanowires (AgNWs) and a Furan / Maleimide Diels–Alder cycloaddition polymer) [9]. To heal the sensor which had been inflicted with a cut, high temperatures (i.e. conveniently applied by heating at 80°C using a hair dryer for 30 s) were used to restore the sensing and display functionality, and the touch screen sensor was able to withstand up to four cycles of cutting-healing events [9]. Increasingly, we are also witnessing growing efforts to promote material healing under benign conditions (i.e. avoiding the use of high temperatures and harsh chemicals to trigger self-healing) [1] so as to facilitate compatible use with human and in related biotechnological applications (e.g., wearable displays).

Targeted bio- and related applications of ‘Self-Healing’ technologies

Most notably, Tee *et al.* first reported an electronic sensor skin, i.e. e-skin, that was able to repeatedly self-heal at room temperature (through the combination of advanced electronics and polymeric science technologies), such that in the healed state the e-skin appeared aesthetically seamless, and was fully functional both electrically and mechanically to perform tactile (i.e. pressure) and flexion sensing [1-2]. Such advanced ‘self-healing’ sensor skin technology is currently being targeted for soft robotics and is widely perceived to offer high innovation potential to revolutionize a range of applications. In terms of biotechnological applications, the ‘self-healing’ sensor skin technology is highly targeted for bionic limbs (i.e. artificial limbs with the abilities to sense the environment and is controllable by user’s thoughts) which are subjected to wear and tear by daily activities. Just imagine imbuing ‘self-healing’ soft display (or even touch screen) technology within the sensor skin, one can already envision countless new and exciting functionalities/possibilities which will serve to immensely enhance the convenience/experience of the end users in their interactions with the environments.

Several other biotechnological applications of self-healing technologies include their uses as bio-textiles (i.e. e-sutures, parts of e-hearts, etc) and biomimicry artificial parts/tissues with inbuilt ability to heal themselves. Besides their main applications as electronics (or with electronics) and exciting opportunities in the field of biotechnology, ‘self-healing’ is also applicable to modern day textiles [10] – as chemically protective suits (i.e. made of fabric coated in ‘self-healing’ thin films) targeted for farmers, factory or chemical industry workers, etc, with substantial commercial interest from textile producers [11]. Other bio-related applications (i.e. some with actively ongoing research investigations) include ‘self-healing’ electrical insulation/conductive biomaterials for implantable devices, tissue engineered scaffolds, cosmetics, hair/nail cuticle coatings, etc. which will eventually lead to exciting advancements and commercial opportunities in various bio- and related fields.

Biotechnological ‘Self-Healing’ materials

Recent advances also suggest that biotechnology is actively driving many of the innovations of ‘self-healing’ materials. For example, a ceramic material’s ‘self-healing’ ability is extensively advanced through biotechnology (e.g., ceramic materials were reportedly imbued and self-healed by bacteria, fungus, sunflower oil, etc) [12-14]. Before it was announced that bacteria/fungus could repair cracks on roads and buildings, few would have imagined that biotechnology could be usefully and profitably applied in the seemingly unrelated construction industry. Even as of today, it is undeniable that biotechnology holds the advanced solutions to many of the problems the world is facing, or will face in the near future. Its contribution to the innovation of ‘self-healing’ ceramic materials (e.g., concrete) could provide high-end technological solution(s), for instance, to resolve the multi-trillion problems such as that of infrastructure underinvestment (e.g., in the United States), or save the massive reparative costs of buildings in many developed or developing countries.

The application of a natural protein (i.e. SRT protein) obtained from squid to produce ‘self-healing’ textiles is another example demonstrating the concept of a biotechnology-driven ‘self-healing’ material [15]. The SRT protein (extracted from within the teeth ringing the suction cups of squid) has been applied to repair damaged textiles to restore its full mechanical properties. While remarkable and intriguing, it requires further research/advancement mainly because the textiles did not fully recover aesthetically to regain the original seamless appearance despite the restoration in mechanical properties. Besides, there remains a concern on how to viably produce the squid protein in huge, commercially viable quantities. It seems that one would need to turn to white biotechnology (i.e. industrial biotechnology) [16] to answer some of the scaling challenges faced by existing ‘self-healing’ biotechnologies. Alongside, the fact that many reported ‘self-healing’ electronics/textiles technologies are still commercially unavailable in the consumer market today suggests the real challenges to scale up the production (i.e. thereby emphasizing the need to select cost-effective materials, which are also available in commercially viable quantities, etc). In other words, further investigations are still very much needed to bring ‘self-healing’ technologies into commercialization.

Key benefits of ‘Self-Healing’ technologies

Even so, the commercial and environmental importance of ‘self-healing’ technologies is not to be overlooked. Besides serving functional, sensory, aesthetic, and cost-saving purposes, 'self-healing' technologies are paving the path towards sustainable development by generating less material waste resulting from replacement of faulty/defective materials [1]. Overall, the benefits of 'self-healing' technologies are immense despite the scaling challenges. When successfully applied, not only can they be used to treat visible or open cracks in various materials, they are also highly beneficial for healing internal, hard-to-detect, and/or tedious-to-repair cracks (i.e. ones which usually escape detection by visual examination, often require ultrasonic or radiographic examination techniques to detect, or are simply too costly and/or time-consuming to repair) [5]. The above-mentioned reasons explained why 'self-healing' technologies are being actively pursued across various industries, and are being particularly highly valued by NASA for advancing space exploration technologies to enhance system safety and reliability while lessening maintenance burden.

Integration/Translation of 'Self-Healing' technologies

Finally, in the context of biotechnology (i.e. biomedical or bio-related applications), it is unavoidable that one also pays close attention to the bio- or skin- compatibility of 'self-healing' gadgets/devices intended for human use (i.e. direct skin contact or implanted). Dermatology or skin allergy tests will come in useful in screening suitable 'self-healing' materials (or their components) for safe contact with human skin, for example. Besides, with digital disruption, i.e. the onset of artificial intelligence (AI) (– "machine programmed to think, work, and react just like humans" as described by Dell Technologies) [17] or machine learning technologies [18-19], one also starts to contemplate on how to handily apply these in the developed 'self-healing' materials or systems for boosting their performance, sustainability, and relevance in the new age. Finally, there is also a quest to promote seamless integration of 'self-healing' materials into existing systems and procedures so that these futuristic technologies can be easily and readily adopted for real world applications. Inevitably, these often also require mechanical property enhancement [20-21] of existing self-healing materials to match the demands or requirements of the respective applications, and this is even more so when intended for use in extreme environments with harsh and challenging conditions (e.g., strong winds, heavy snowfall, extreme cold/heat or pressure).

Conclusion

With continued development and seamless integration of 'self-healing' materials into modern-day applications, it is set to open up a new era of enhanced consumer experience, infrastructure maintenance, environmental management, as well as countless unprecedented and unique applications resembling those in science fictions. To achieve these futuristic technological outcomes, one should allow much room for visualizing new opportunities/possibilities by 'self-healing' technologies, in order to bring about many more useful and innovative applications to benefit the society as a whole. In this regard, it is anticipated that biotechnology and AI will play increasingly prominent roles in driving further advancements and adoptions of 'self-healing' technologies, mainly through introducing novel/enhanced bio-features, data-driven customized healing strategies, as well as through bestowing performance or production advantages such as mechanical robustness, ease of scaling up, cost-effectiveness, enhanced biocompatibility, eco-friendliness, etc.

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