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Review Study on Mechanical Properties of Self-Healing materials for Aerospace Applications

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Abstract. Self-healing materials as the name suggest these materials can self-heal themselves. Self-healing materials is the need of the future. It has a most prominent and effective application in the field of aerospace, but it is not limited to the aerospace industry. Concrete cement being the cheapest also has the application of self-healing agents that leads to the replenishment of cracks easily so that the life span of the concrete increases furthermore. Another prominent field where self-healing materials have a wide application is ESDs electronic storage devices because of the sensitivity of ESDs. Not only restricted to ESDs it is also planned to be used in robots as the chances of wear and tear are more and is skin sensitive. Further in this review, mechanical properties such as strength, toughness, hardness, and fatigue are discussed.

Keywords: Aerospace, Mechanical, Review, Self-Healing.

1. Introduction

At first, hearing self-healing materials, we get the idea that it will be for the aerospace sector because the term only signifies aerospace because it requires high safety and performance. Self-healing is inspired by the curing of a wound in human or animal skin. Concrete cement undergoes small crack formation which is difficult to identify and further leads to big cracks resulting in moisture entering the concrete and corrosion of steel rods. Therefore, if the concrete is manufactured by self-healing agents embedded inside then the life span and performance of concrete will increase. Electronic storage devices are another category in which the material should self-heal itself because the production of heat may lead to the explosion or expansion of devices. So, they are also a sensitive area. Self-healing materials will lead to great advantages in this sector. As the world continues to enter into the industrial revolution 5 the human workforce will be overtaken by robots. Robots' skin will be made like the skin of humans, sensible to temperatures and they will work in industries the wear and tear of robot skin will become the main problem. If the coating is made up of self-healing material, then the longevity of the industries will increase as well as greater production will be there. In self-healing materials, the mechanical properties of the material get even better than the original material and are capable of repairing the cracks. The mechanical properties include strength, the toughness of the material, at what load does the material fractures, and many more but strength, toughness, and fracture matters the most among all properties.

2. Literature Review

Oluwafemi Sedoten Kuponu et. al (2022) have addressed two main drawbacks of self-healing materials of now and have found a solution to them. The solution comprises self-healing material based on electrolysis and piezoelectricity which has two systems i.e. Fault diagnosis which is used to measure the damage rate and adaptive feedback system used to ensure that the damage rate and healing response matches. Stefano Paolillo et.al (2021) has reviewed self-healing epoxy material mainly focusing on giving high-performance composites, several tests are carried out to measure the healing efficiency and how to bring it into practical implementation in industries. The possibility of a circular economy which will change the landscape in composite manufacturing along with disadvantages and measures to overcome are discussed. The future application in aviation and space fields are discussed. Nik Nur Farisha Nik Md Noordin Kahar et.al (2021) has studied about self-healing polymeric materials and its different mechanisms. The applications of this material in different field along with the behavior to prevent structural failure by restoring mechanical properties are discussed. Shankar Kadam et.al (2021) have studied the different manufacturing and properties-based processes for self-healing carbon reinforced for composites, microcapsules, and supra molecular elastomers, and also investigated various advanced self-healing materials and mechanisms for healing composites with the application for future. Merryn Haines-Gadd et.al (2021) has analyzed the importance of self-healing material in the field of circular economy, and their co-relatability which will not only lead to getting advanced self-healing material but this will increase product longevity and gives immortality a hope. M. Harikrishna Kumar et.al (2021) has discussed different types of intrinsic self-healing materials as it is more preferred and potential material in aerospace as well as engineering material rather than fiber-reinforced composites due to the formation of cracks at impact load which reduces the life of material and increases the risk of lives in the aerospace sector. Panpan Li et.al (2021) has focused on regulating the ability to heal synthetic materials; the traditional method finds the regulation of the system chemistry a bit clumsy but it is as similar to the self-healing process and has various complex biochemical reaction associated with it. Munmun Priyadarsini et.al (2021) have discussed two types of self-healing i.e automatic and non-automatic, the importance of self-healing in the field of medicines, commercial, and industries is also studied. Josefine Meurer et.al (2021) have studies on self-healing biobased ionomers which are manufactured from itaconic acid derivatives which can be found in rice, corn, and others. The thermal and mechanical properties are studied with thermos-gravimetric analysis, differential scanning calorimetry, FT-Raman, and FT-IR measurements. Bo Liang et.al (2021) has studied the self-healing of asphalt and asphalt mixture materials with their mechanisms, influencing factors, evaluation method, and improvement aspects. Paul Christopher JE et.al (2020) review and compares the preparation of healing carriers in a vascular self-healing system, which is one type of method for making a self-healing material, with the intrinsic self-healing system and conclude that it is difficult to make healing carriers rather than healing materials. Also, the healing material is tested under fatigue, impact, and ballistic characteristics for aerospace applications. Giovanni Fortunato et.al(2020) have developed a self-healing coating of self-healing nanocomposite which has an application in optics and it is based on the DA(Diels-alder) system chemistry. The structure was studied by UV-vis spectroscopy, the thermal properties were studied by calorimetric analysis and the surface hardness of the coating was enhanced by silica nanoparticles in a DA-based matrix retaining the healing ability. Siheng Li et.al (2020) has studied complexing PAAm with PAA with chelate Fe+3 ions for increasing the mechanical properties and for further betterment it is also soaked in aqueous NaCl solution which is a self-healing polymeric hydrogel. Yuhan Li et.al (2020) have suggested a method for the preparation of elastomers by a mechano-responsive strategy. By this, the elastomer will possess high mechanical strength, toughness, and fracture energy at all room temperatures for self-healing materials. Van Phu Vu et.al (2020) have given up the ideas about the use of self-healing materials in sensors and conductors in recent days, and also highlighted the strength and weaknesses of self-healing materials in context or relation to the sensors. Further, in this research how can self-healing materials be made by soft electronic mechanisms with further development is discussed. Ajmir Khan et.al (2020) has stated the recent research on CANs of polyamides, polycarbonates, polyurethanes, polyesters, and polyurea; CAN's will help us reduce pollution as they are recyclable and reusable, unlike plastics. Furthermore, CAN's which can self-heal, mechanical properties, market value, challenges as well as outlook is also studied.

Weicong Mai et.al (2020) has studied in detail the self-healing materials to be used for ESDs-Electronic storage devices. Due to the uncertainty of renewable resources of energy the use of electronic storage devices with self-healing material so they can be prevented deformations and volumetric changes are suggested. This paper provides the future pathway for self-healing materials used in EDMs. Wei Zhang et.al (2020) have discussed autogenous and autonomous self-healing concrete. In detail, the fabrication, performance, characterization, mechanism, mechanical properties, and durability of both types of self-healing concrete are examined. Sydney D. Menikheim et.al(2020) have addressed the concern of self-healing polymers used in knee and hip replacements so that the revisit to the hospital for the above concern will reduce. This paper also analyzes the gap between the development of this material and the clinic for application with biomaterials. The parameters such as the adaptability with the human body, toxicity, reproducibility, and robustness are also addressed. R. Duarah et.al(2020) investigated the fabrication of hyperbranched polyurethane nanocomposites with nano-reinforcing material as silica nanoparticles with different weight percentages and by in-situ fabrication method. Mechanical properties that are strength, toughness, and hardness are also discussed. Nand Jee Kanu et.al (2019) have studied the fabrication, characterization, techniques, functionality recoveries, and improvement of smart materials that are self-healing carbon fiber laminates, supramolecular elastomer and microcapsules consisting of rejuvenator along with graphene/HMMM hybrid shells which will be the necessity of future materials. Composite with CNTs i.e. carbon nanotubes are studied as sustainable self-healing materials. Yuye Zhu et.al (2019) has suggested a material in which self-healing agents get activated by the help of UV radiation as a result it can be implemented in in-orbit damage repairing. It is used in the form of UV-responsive microcapsule-based coating which has a dual-release mode and follows the traditional method of crack repairing. Panpan li et.al (2019) has reviewed the importance, the methodologies, and the future applications of system chemistry of synthetic materials for the purpose of self-healing. Traditionally, self-healing was studied by complex-system chemistries which coincides mostly with that of biological repairing of the system.

Abdon Pena-Francesch et.al (2019) has researched a synthetic protein that is capable of self-healing itself for micro and macro mechanical damage in a time less than a second, resulting in high strength of the material by local heating. These are mainly used for soft actuators and robots which are capable of resisting impact load but fail in case of small mechanical damage like tear, cutting, etc. due to their soft nature. Maria Kosarli et.al (2019) have performed experiments on a scanning electron microscope, differential scanning calorimetry, Thermogravimetric analysis, and solid-state nuclear magnetic resonance and also studied epoxy self-healing mechanisms by in-situ emulsification polymerization. The material is urea- formaldehyde microcapsules containing an epoxy healing agent. Amir Sidiq et.al (2019) has reviewed different types of self-healing materials added to concrete. Experimentation and evaluation of factors, which are Performance, application, efficiency based on polymeric, biotechnological, chemical components for crack healing, and improvement of strength are studied in detail. X.F. Wang et.al (2019) has studied the autogenic, bacteria self-healing process by assessment by several suitable methods like microscopy, thermos-analysis, spectroscopy, imagining of the healing process, microstructure, and review based on mechanical properties. Self-healing by the process of encapsulation is discussed with the future application of cementitious self-healing material. Yue Cao et.al (2019) has researched a self-healing material made up of fluorocarbon elastomer and ionic liquid of fluorine which is like skin and can heal itself in both dry and wet conditions. Future applications such as human-machine interference and soft aquatic motors can be manufactured from this material. Huy Hoàng Nguyễn et.al (2019) have experimentally investigated alkali-activated slag(AAS) based composites which are eco-friendly, fiber reinforced, ultra-high ductile by the help of microscopy and measurement of stiffness recovery by resonant frequency, SEM/EDS analysis was also carried out. Tangjie Long et.al (2018) have investigated the polymerization of imidazolium-based ionic liquid monomers which is +vely charged and contain urea group, with 3-sulfopropyl methacrylate potassium salt monomers which are then dialyzed in water. The dissipation of energy is taken care of by the H-bonding of the urea group and the dialysis strengthens the mechanical property of hydrogels. Niels van Dijk et.al (2018) have discussed and presented various scientific ways that are also industrially suitable for the self-healing of metal. The approach consists of two types of gateways one which is an intrinsic mechanism and the other which needs an external intervention for the healing process. Jiheong Kang et.al (2018) have found a solution to the previously used elastomers and self-healing polymers that lacked mechanical toughness and viscoelastic. A new polymeric material with crosslinked multi-strength hydrogen bonding interaction is made by which the mechanical properties increased. Yuting Zou et. al(2018) have addressed and found a solution for bringing intrinsic self-healing material to market. The solution is a self-healing material MXene an epoxy coating with is light sensitive and also enhancement of the properties of this coating is studied. Min Wook Lee et.al(2018) have discussed the fabrication of vascular systems like self-healing mechanisms that are solution-blowing and electrospinning. Currently used healing agents, some other methods of fabrication consisting of hollow fibers, mechanical properties by spectroscopy, visualization, and thermal analysis are carried out. Sathiskumar A. Ponnusami et.al (2017) have proposed a cohesive zone-based model, which is primarily used for fractures, and it also includes a self-healing material for the purpose of repairing cracks. This model can be used for both intrinsic and extrinsic self-healing materials, and also it can be used as a model for analyzing, optimizing, and developing new self-healing materials.

3. Mechanical Properties

Strength: In the case of cementitious material, they can purely bear the compressive load but the main chance of crack formation is the tensile load. Which makes self-healing an important thing. The strength of cementitious self-healing materials can be tested by two methods such as the destructive or non -destructive method. The destructive method consists of again two methods that are three-point and four-point bending stress. The three-point test produces a crack at a certain position with a notch as shown in fig 1 and 2.[26] Self-healing polymeric hydrogel is prepared by complexing PAAm (polyacrylamide) with PAA (polyacrylic acid), further to increase the mechanical properties Fe^{+3} ions are chelated into it and soaked in NaCl. The addition of Fe ion increases the crosslinking density as a result it leads to high tensile strength and low strain at break as shown below [13] Self-healing polyampholyte hydrogels are prepared by one-step polymerization of imidazolium-based ionic +vely charged liquid monomer comprising urea groups, with 3-sulfopropyl methacrylate potassium salt monomers i.e. -vely charged followed by dialysis with deionized water. The dialysis of monomer ratio of 1:1 is done for 1,3,7,10,15d times. It was observed that the tensile strength increases and the strain decrease after this many times on dialysis.[30]

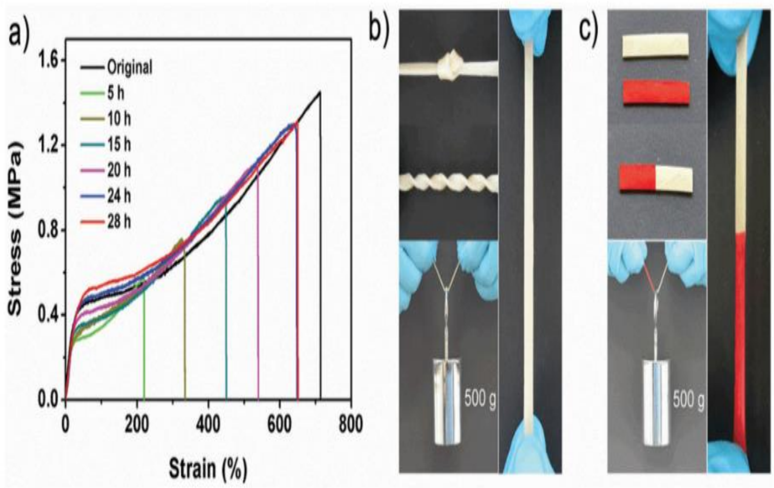

FIGURE 1. Stress vs strain [13]

Toughness: At room temperature, self-healing elastomers possess high toughness and most importantly have plastic-like strength used as puncture-resistant tire sealant for military-grade automobiles. Keeping in mind the strain-induced crystallization of rubber to make it stronger and tougher, in the same way, a reversible self-healing strategy is used to develop self-repairable polyurethane thermosetting elastomer is developed which is high in all mechanical properties.[14]when f-SNP materials are uniformly dispersed in HPU, the polar functionality of f-SNP interact with HPU matrix resulting in stiffness and successful load transfer from HPU matrix to the nanomaterials in the composite leading to high toughness of the material.[20]

By incorporation of sacrificial bond through polymerization with triple network of molecules in elastomers, elastomers are toughened and have high stretch ability.[32]

Hardness: Surface hardness in the coatings is sought to provide a protective layer against mechanical damage. Nano-reinforced coatings are usually made by introducing Nano fillers into an organic matrix subject to the condition it should be homogeneously distributed without forming aggregates while coating. By using unchanged silica nanoparticles in the hybrid DA-based coating the surface hardness i.e. the scratch resistance of the coating is highly improved as shown in fig3 which is measured by the pencil hardness test. Usually, the silica content is 1wt% or 3wt% [12]. Intrinsic self-healing materials are not much in the market because of their two drawbacks mainly i.e remote activation and satisfying practical properties. By using the material MXene which is an epoxy coating, light sensitive, and works on the DA system chemistry the hardness, healing efficiency, and polarization resistance were improved. As measured by the pencil hardness test the hardness was increased from HB to 5H as shown in fig4[33]. The hardness of self-healing ionomers is measured by the Vickers hardness test. The hardness of ionomers was found low than the polymers [10]

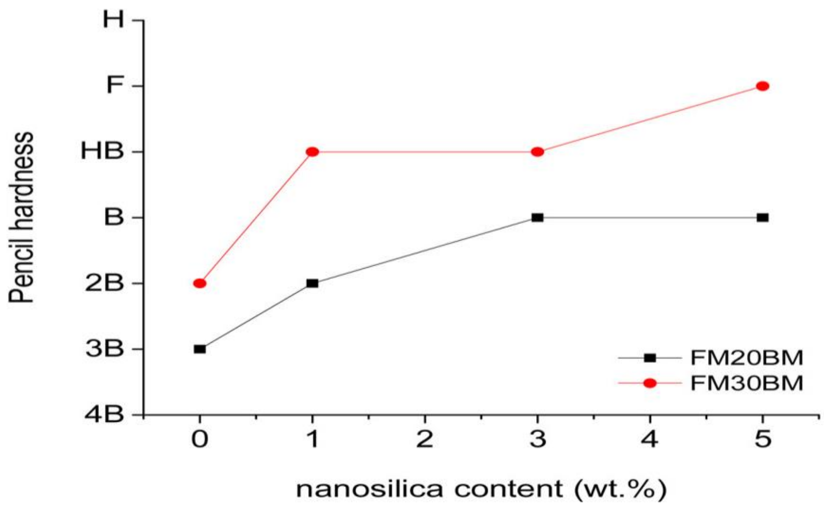

FIGURE 2. Hardness measurement for nanosilica contents [12].

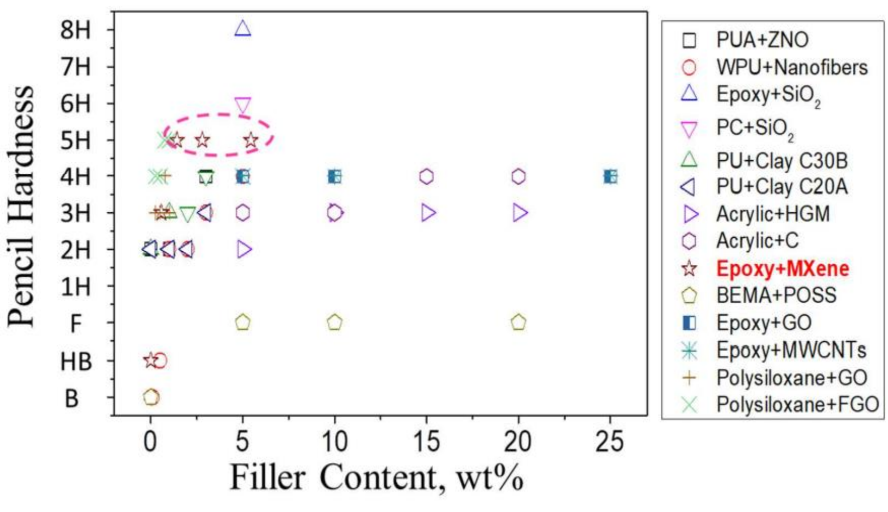

FIGURE 3. Hardness variation vs filler content [33]

Fatigue: The fatigue is mainly done using the taper double cantilever geometry, in which the material is exposed to different kinds of variable stress and strain till the time it doesn't crack. It is done in 3steps i.e injection of pre-catalysed self-healing agent at no load, constant load, and cyclic load[12].On electrospun and solution-blown nanofiber to get the relation between stress and strain the tensile tests are carried on in which for a long span static fatigue test is performed keeping strain constant. It was observed that the cohesive energy of the sample1 while it was fatigued for 3 hrs had similar to sample2 which was measured after being fatigued for 3hrs but in the case of sample 3 which was fatigued for 3 hrs and rested for 24 hrs had 8 times more this suggests that the epoxy precursors released while damage due to fatigue have enough time efficiency to repair [34]. For asphalt pavements, fatigue cracks are produced because of continuous loading which is primary distress. The cracks lead to the wastage of material because of unnecessary transportation of additional material therefore self-healing is the best solution for asphalt pavements [11].

4. Conclusion

The importance of bringing self-healing materials is not only just for reducing cost or increasing the life span of the material, rather the most important thing is the amount of non-reusability of the existing materials. As the no of materials increases the waste is increased doubled. As it is not only the final material, the production has also wastage and all factors included produce double the existing wastage. If it increases like this then the pollution due to the materials will be at its peak and leading to human life threat. Therefore, the coming of self-healing material would be more beneficial to the environment and off-course to human society in terms of business and safety. Even for now there are many self-healing materials proposed but their application is very less, we have to give more focus on the manufacturing of self-healing material.

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