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Review Article

Effect Of Nanofillers on the Mechanical Performances and Self-Healing of Composite Laminates: *Article Review*

Ali B. Jarallah[1], Batool M. Faisal [1], Hussein K. Dalfi[1], Thiago Santos [2]

[1] Department of Mechanical Engineering, University of Wasit, Wasit, Iraq

[2]Technology Centre, Federal University of Rio Grande do Norte, Brazil

Corresponding Author Email: Std2023203.A.B@uowasit.edu.iq

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ABSTRACT

Advanced composite materials are widely used in different applications because of their superior performances. However, damage failures (i.e. micro- and meso-cracks) occurred in these materials after subjecting to apply loading lead to reduce in their mechanical performances. In addition, repairing process of these damaged composites to enhance their reliability and endurance is not possible at remote locations. In this regards, self-healing composites are fabricated to heal cracks and damages, to restrict failure and enhance the longevity of structures. It is widely employed in numerous applications, particularly in newly developed vehicles and space applications. In this article review, the influence of adding nanomaterials on the mechanical properties and the healing of damaged composite materials is discussed. Furthermore, the mechanical performance of composite materials is influenced by the presence of nanoparticles. Additionally, the self-healing processes and their mechanisms in composite materials were reviewed when subjected to impact, flexural, and tensile forces.

Keywords: Composite Materials; Self-healing; Damage failure; Mechanical performances; Mechanisms of Self-healing

1. Introduction

Nowadays, the enhancement of the mechanical performances of fiber-reinforced materials has received more attention due to their applications in different sectors such as aerospace, automotive, and marine [1],[2]. In addition, their demand has grown in significant applications, particularly those where structural maintenance is costly and troublesome because of their attractive properties such as high specific strength and stiffness, high corrosion resistance and high fatigue resistance [3]. However, to get the composite with these characteristics, depending on the nature of the components, geometry and properties of the material, it can be used. For example, epoxy resins reinforced with fabric or polyester resin are the most prevalent.[4]. While, to improve the mechanical characteristics of composite materials, nanomaterials, which are further defined as solid particles or dispersion particles with sizes between 10 and 1000 nm are included [5]. that is one of the studies have been carried out in recent years that use nanomaterial reinforcement for enhancing the mechanical performances of composite laminates [6]. Composite materials consist of fibers or reinforcements and a matrix or host to make higher-quality materials than the constituents when they are used separately [2]. This review aims to provide summarized information on the recent developments in the field of composite material which have healed themself of external damage. In addition, the mechanism of self-healing when exposed to different types of applied loading, such as tensile, flexural and impact.

2. Polymeric Nano composite materials

A composite created with nanomaterials is called "Nanotechnology," while nano was used as a reinforcement in the compound. As well as, a nano composite material is mixed with two or more materials with differing

chemical and physical properties, to create a compound with unique features [7]. Whereas, for materials that have been successfully produced for aerospace applications and other fields, composites and nanocomposites have been studied, to enhance the mechanical properties of compounds, nanomaterials are added to improve the properties of the compound, based on their matrix components. Also, composites can be categorized into three groups: ceramic, metal, and polymer [8]. ***Jing et al.*** [9] produced the nanomaterials elastomeric copolymer and used as a reinforced part in the matrix of polymeric materials and this takes the shape of a composite. Therefore, using elastomeric copolymer particle-modified PA6 polyamide nanoparticles as result, the mechanical properties of elastomers in polymer matrices were significantly improved. The model was initially utilized to predict the general mechanical behavior of synthetic rubber particles derived from polyamide (PA6), enabling an evaluation of how different elastomer particle sizes influence the mechanical performance of polymeric systems. Furthermore, a second model, based on spherical particle geometry, was applied, and tensile test results confirmed the feasibility of employing spherical-shaped elastomer phases. Notably, the soft phase of the elastomer used in the experimental study exhibited a completely spherical morphology. These findings suggest that such spherical elastomer phases can be effectively employed to enhance the performance of various polymer composites utilizing PA6. In addition, the tensile strength of the PA6 polymer was also assessed and applied. ***X. Lin et al.*** [10] prepared copolymer block as a reinforcing polyamide PA6 to improve the mechanical properties and rheological behaviour, and thermal behaviour. Morphological observations showed that the addition of PU-G-mAh enhanced the dispersion of OBC particles in the PA6 matrix, which indicates a better compatibility between pure PA6 and OBC through some tests performed on the compound as tensile test, flexural, and achieved Charpy effect tests, respectively where an infrared scan was performed and where the compound was examined with infrared radiation to measure deformation. To further enhance performance, researchers attempted to reinforce it with fibers of a different kind to benefit from the OCB qualities. For instance, ***Sirui et al.*** [11] dispensed with PA6 and short Kevlar fiber as a supporting component in the matrix for olefin block polymers (OBC) to increase the tensile strength of OBC in the matrix. They added Kevlar fiber to the maleic anhydride-grafted polypropylene (MA-g-PP) to achieve the highest tensile strength in the compound. they also used traditional melting processing technology and the surface modification strategy to determine the fiber's strength and direction. Additionally, it was shown that while Virgin Kevlar fiber can be utilized to reinforce OBC, it can also result in noticeably higher tensile yield strength and modulus, only by applying a tiny quantity (3 wt.%) of MA-g-PP as a reaction compatibilizer to hydrolyzed or polydopamine-coated Kevlar fiber. It can also be employed to facilitate the peeling of Kevlar fibers, improve the interfacial strength, and guide fibers in the treatment of external cracks. Figure 1 presents a tomography image of the Kevlar fiber used in the study.

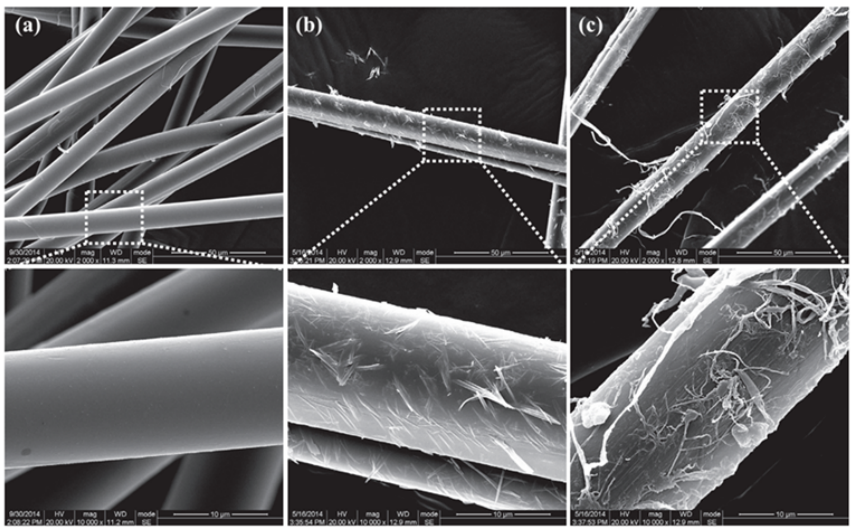

Figure 1. a)The shapes of Kevlar a virgin Kevlar fiber. b)hydrolyzed Kevlar
(c) polydopamine coated Kevlar fiber[11].

2.1. Preparation of Polymeric Nano composite materials

Nanomaterials are often prepared with composite materials to enhance their mechanical, chemical, and physical properties. In particular, nanomaterials have been incorporated into composite matrices to investigate their influence on these properties [12]. Thus, the strategy can be used in preparation of nano polymer compounds with a large variety of chemically different nanoparticles Commercial, such as, $BaTiO_3$, TiO_2, Ag and Al_2O_3 nanoparticles were incorporated and dispersed uniformly in polystyrene (PS) and polymethyl methacrylate (PMMA) matrices by designed cationic/anionic ligand [13]. ***Alaeddin Burak Irez*** [14] studied the effect of the incorporation of carbon nanotubes into polymer. These methods explained the direct mixing of fillers and matrix, modified either CNTs or polymer, and mixed them with the help of a third component. The same methods are unlikely to have been used in the case of the use of Graphene in a composite. The mechanical properties were improved by using graphene oxide, which was prepared from natural graphite and served as a nano filter in the polypropylene (PP) Matrix. Also, incorporation of carbon nanotubes nanofillers into polymer for example nanocomposites (carbon nanotubes) boost the mechanical properties of the compound by increasing its physical and chemical characteristics, carbon nanotubes with a density of 2.4 g/cm³ and a surface area of 65 m²/g are utilized in olefin block copolymers (OBC). Nanomaterials are the ones that do the self-healing process. ***Hossein et al.*** [15] studied the self-healing process in the composite materials that contains microcapsules of silica nanoparticles and diluted epoxy curing agent can be categorized using some of the required components. they were composed of Urea (Pardis Petrochemical Company, Iran), ammonium chloride, formaldehyde, and hydrochloric acid (Dr. Mojallali Industrial Chemical Complex Company, Iran) comprised the first group of raw ingredients used to create the microcapsules. Linear alkyl benzene sulfonic acid (LABSA-Behdash Chemical Company, Iran), carboxymethyl cellulose (NaCMC), and 1-octanol and resorcinol (Merck, Germany). Diglycidyl ether of bisphenol A (epoxy KER 828, Korea), ethyl acetate (Dr. Mojallali Industrial Chemical Complex Company) as a diluted agent, and silicon oxide nanoparticles with an average size of 20–30 nm (Platonic Nanotech, India) comprise the second group of ingredients that may be used as healing agents. The third group consisted of the components used to create the composites, which included glass fabric with a surface density of 400, epoxy resin (KER 828, Korea), and triethylenetetramine (TETA) hardener, The three groups represent capsules prepared for the self-healing process. as a result, preparation of the nanomaterials is very important to have significant barrier properties for corrosion protection and reduce the trend for the coating to blister or delaminate. ***Phuong et al.*** [16] presented an overview of nanocomposite preparation which shown in Figure 2. This method is called "Cold Spray Method".

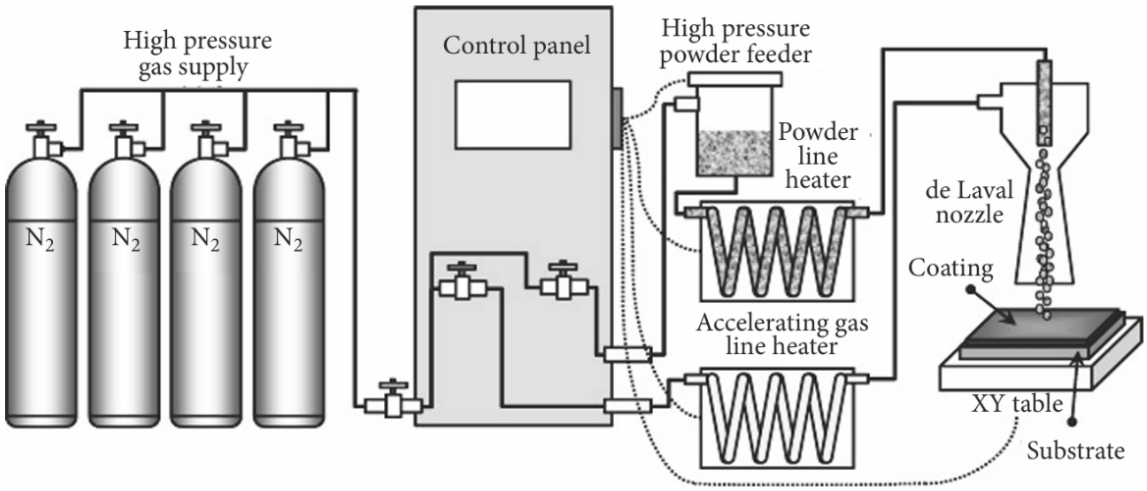

Figure 2. Preparation of nanocomposite by using cold spray method[16].

3. Effect of nano-particles on the mechanical properties of composite laminates

Many mechanical properties such as hardness, elastic modulus, and fracture toughness are improved by including nanmaterials into compoaite materials. For instance, ***Keun et al.*** [17] added 1.0% graphene oxide (GO) into a polypropylene (PP) matrix. Their results showed that improvement in stiffness with 286% rise a

127% improvement in modulus of elasticity, improvement 117% in fracture toughness, an increase in enhanced dispersion, inter-interactions, and mechanical entanglement. Figure 3 shows dispersion of GO in polypropylene (PP) matrix.

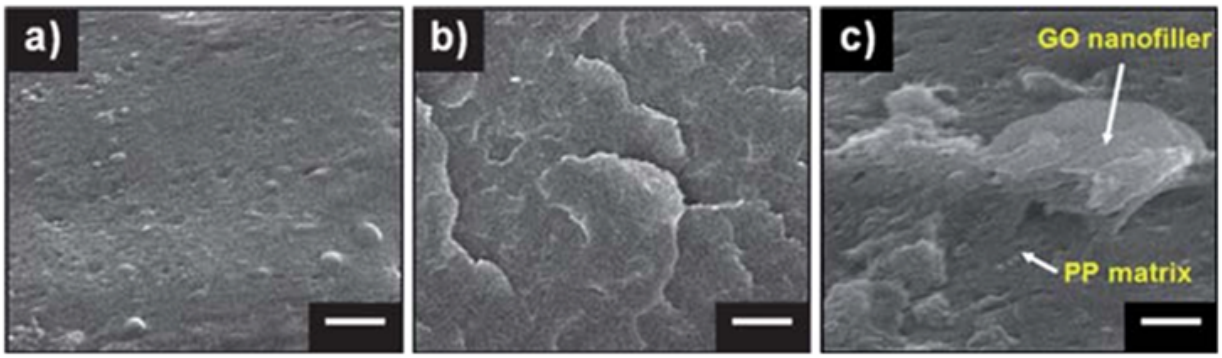

Figure 3. The cross sections of (a) pure PP, (b) GO/PP nanocomposites, and (c) GO nanofiller in GO/PP nanocomposites are displayed in the SEM pictures. 1.0 weight per cent of GO nanofiller was present in the PP matrix (scale bar: 500 nm)[17].

A. Devaraju et al. [18] studied the effect of adding nanomaterials (i.e. zinc nanoparticles) on the mechanical properties such as tensile, impact and flexural properties of composite materials have natural palm fibers. They found that the mechanical properties of the composite material and a compound prepared by chemical treatment sodium hydroxide found that 0.5% by weight gives better mechanical properties wed high mechanical resistance.

The effect of nanomaterials can also be observed on strengthening the properties of Kevlar to obtain the best mechanical properties of composite materials. The mechanical characteristics of epoxy composites reinforced with Kevlar fibers were improved by utilising a variable ratio of two or three nanomaterials and second nanoparticles with Kevlar fibers for activities that affected the impact, tensile, and shear mechanical behaviour. The fusing of Aluminium Oxide (Al_2O_3) and Silicon Carbide (SiC) nanoparticles with Kevlar fibers at varying compositions (1% to 4%), according to these test findings, influences the mechanical behaviour of the composite, including strength. According to the results, the material possesses an impressive ultimate tensile strength of 170.84 MPa and a flexural strength of 162.56 MPa. These features may be used in significant applications that utilise epoxy base material[19].

3.1. Tensile strength

Yong et al. [13] enhanced the mechanical properties of composite materials by adding nanomaterials of Titanium Dioxide (TiO_2) and Aluminium Oxide (Al_2O_3) in polystyrene (PS) matrices, as shown in Figure 4. The result of tensile strength increased by 77% with using TiO_2. Also, the Al_2O_3 improves the thermal decomposition temperature to twenty-four C^0. So, the properties of the compound have improved when exposed to tensile strength.

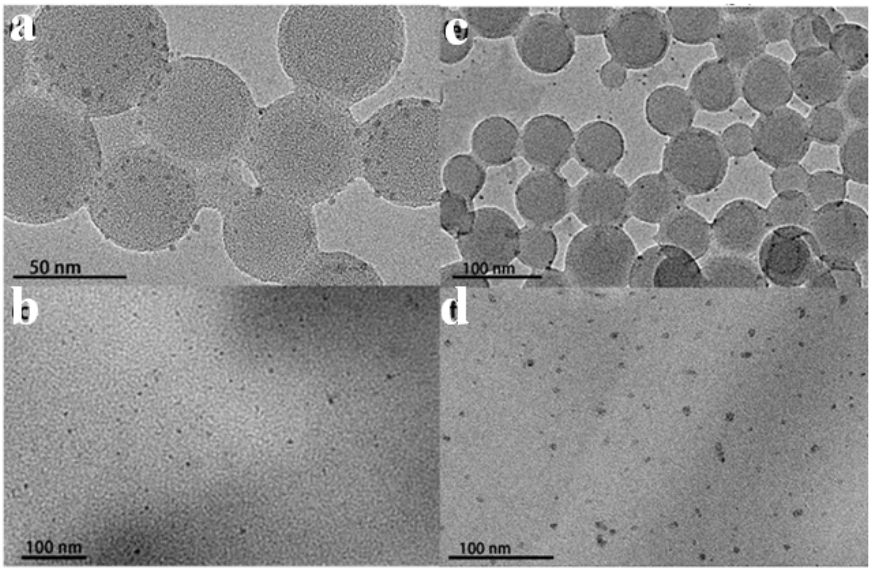

Figure 4. TEM image of Dispersion states of TiO_2 and Al_2O_3in PS matrix. a) $BaTiO_3$ latex. b) $BaTiO_3$ultrathin section. c) Al_2O_3latex. d) Al_2O_3ultrathin section [13].

Chun et al. [20] conducted tensile testing on nanostructured composite materials of polypropylene and nano silica. The tensile testing showed that the nanoparticles can simultaneously provide with tightening, strengthening, and toughening effects at a relatively low filler content (typically 0.5% by volume), and the loading rate is greatly emphasised while the intersection speed of tensile tests is increased. Also, he confirmed that the distribution of nanoparticles in the compound enhances the material's susceptibility to tensile resistance. So that, the composite made by ***Mustafa et al.*** [21] with cellulose nanocrystals and polyester resins, which are utilized with glass fibers for reinforcement, was subjected to mechanical tension testing. Since the addition of 4% cellulose nanocrystals results in excellent tensile qualities, the results validate that adding cellulose nanocrystals as a proportion of the weight does not negatively affect the mechanical properties of nanocomposites. By increasing the proportion of cellulose nanoparticles in the compound. When it was added silica nanoparticles were added to basalt fiber Reinforced Polymer, also creating the compound [22]. They found that a high specific surface area enhanced the tensile characteristics of the polymer composite reinforced with basalt fibers, demonstrating a notable increase in the tensile modulus of 6%, 14%, and 19% for weight percentages of 5 and 15 respectively. and 25% by mass% nano silicate concentration, respectively, in which the failure stress was not lessened. Additionally, a series of nanocomposites with 5 by weight per cent and 15 by weight were prepared in the second compound using a nano-silicate gel in epoxy. And 25% by mass of nano silica. They were performing static uniaxial tensile testing. This demonstrates that the tensile failure is unaffected by the nano silica gel and that the effect is the same even if its proportion in the combination is raised, and nano silica has an additional effect on the mechanical characteristics. Just like the increasing percentage of nano in the compound, tensile strength is also increasing. Also, the compound's capacity to withstand tensile stress is correlated with variations in the fraction of nanomaterials in the compound, while added carbon nanotubes and alumina nano powder in the % weight of nanomaterials in the epoxy matrix glue. It can improve the positive effects on the facades' anti-jamming and shear characteristics[23] as shown in Figure 5.

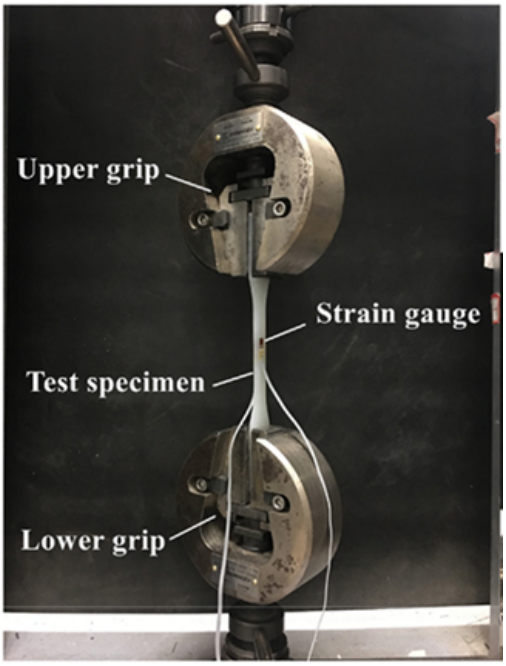

Figure 5. The specimen geometry on a device tension Tensile test[24].

3.2. Flexural strength

Flexural strength tests are used to investigate the mechanical properties of composite laminates after self-healing process by using smart shape memory alloy strips. In this test, it measures the maximum stress a material can withstand the bending or breaking. The specimens were damaged initially and then subjected to flexural tests after a certain period of healing time. The results showed that shape memory alloy (SMA) strip materials had a self-healing efficiency of 43.18% and 71.5% was achieved [25]. Figure 6 shows a device of flexural strength test.

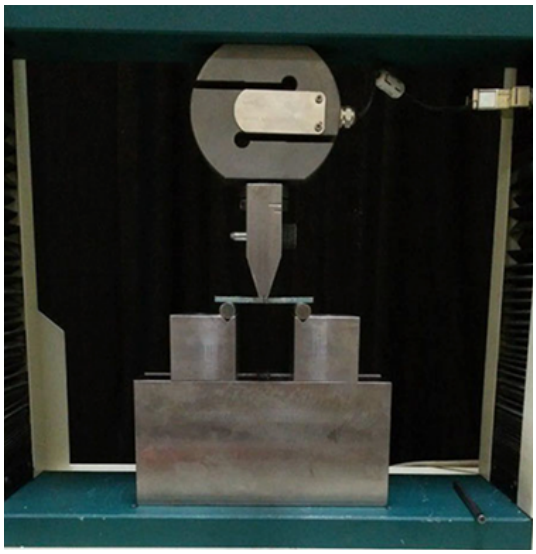

Figure 6**.** Three-point flexural test of composite[25].

Luiza et al. [26] used flexural testing and angle of conversion of a dimethacrylate resin containing different amounts of nanoparticulated clay. The first model, eight formulations with polymeric matrix-based BisGMA/TEGDMA (Bisphenol A Bis (2-hydroxy-3 methacryloxypropyl) Ether/ Triethyleneglycol Dimethacrylate), secondly four compositions with nanoparticulated clay Montomorillonite MTT, and compositions with barium glass at concentrations of volume 20, 30, 40, and 50 Vol%. However, at twenty per

cent, the elastic modulus and flexural strength were determined by the three-point bending test. Also, the addition of montmorillonite nanoparticles resulted in a similar degree of angle and higher elastic modulus values at all absorption tested, only at the twenty-percentage volume, the flexural strength was statistically higher. While ***Yasser et al.*** [27] made a nanocomposite from fiber and epoxy was combined with nano silica and nano clay to create a hybrid compound. This compound was then put through flexural testing, and a mathematical model was created to predict the compound's self-healing and mechanical behavior. Additionally, the Minitab program was fully utilized, and 20 experiments were made with six repeaters at the center points, and emotion tests were performed on twenty prepared materials. The best flexural test results (17.77 MPA) were found in 3.5 weight per cent nano silica, 4 weight per cent nano clay, and zero fiber direction. Five samples were acquired after preparation and testing. The software provided a percentage of prediction that was close to the results from the actual test, so the program can be relied upon at a reasonable rate in the upcoming real tests. The average flexural strength value was 17.2 MPa, where nano silica had a direct effect on the flexural properties and nano clay and fiber orientation had the opposite effect on maximizing flexural strength.

3.3. Impact resistance

The design of composite materials has had to be extremely sensitive to the effects of load shock on composite material segments in recent years due to the increased emphasis on space applications and other disciplines. A strategy for improvement has been evaluated by ***Hussein et al.*** [28] by using nanoparticles, rubber particles, and thermoplastic tightening agents. To avoid delamination is one of the most important problems that happen to compounds when exposed to a load effect between the layers of the compound itself, the compound is reinforced with nanomaterials to reduce this effect. For example, carbon nanotubes CNT to strengthen the resin matrix. Additionally, the impact behaviour and damage that are dependent on the impact energy level were examined. delamination increased the deflection and decreased the contact force by decreasing the plate's bending stiffness. When the fiber broke, the impact behaviour underwent a significant modification. The lower portion of the upper layers was also harmed by the tensile stress under impact loading, since the bending behaviour manifested independently in each separated layer as a result of the delamination. ***Kim et al.*** [29] used the ABAQUS/explicit program to concentrate on elucidating how low speeds affect the impact effect. While doing a shock impact test, specific criteria can be depended upon, such as measuring the impact's severity. Figure 7 shows the effect impact speed on self-healing. Also, Figure 8 shown a sample in the impact test.

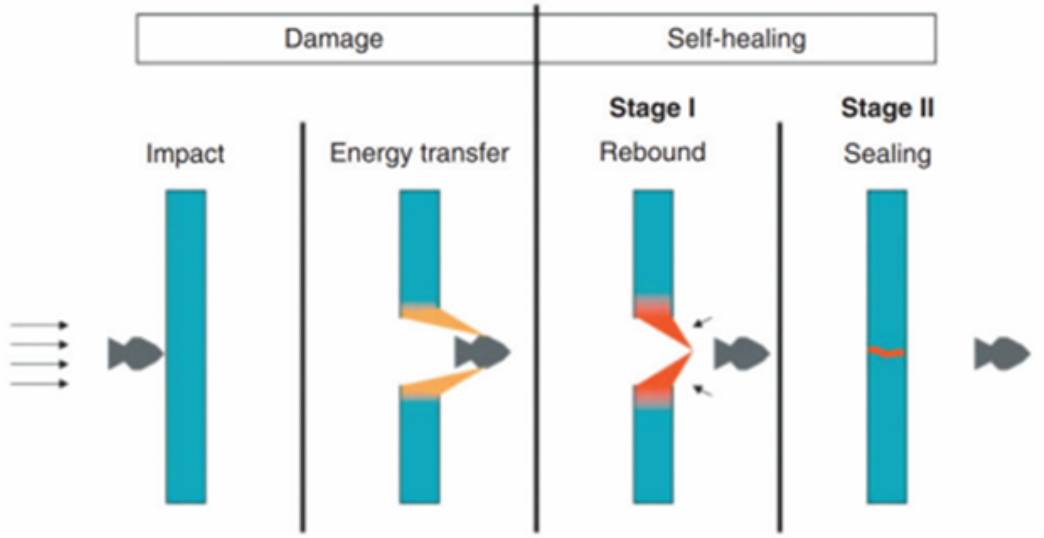

Figure 7. The process of self-healing of the compound after exposure to the intensity of the impact at a certain speed [30].

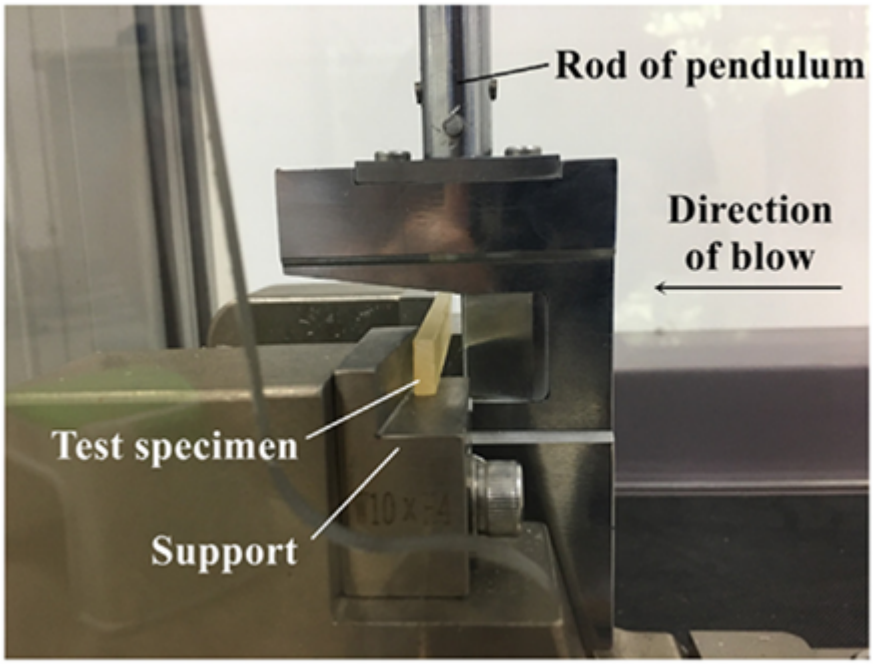

Figure 8. The specimen geometry on a device impact test [24].

Kevin et al. [31]studied the behaviour of fibre-reinforced composite beam under a bending test to confirm the application of the impact treatment. They used of a novel air-assisted detector connecting method. Since the shock-damaged beam samples were treated with two-part epoxy and amine healing agents, the addition of microchannels to the composite samples did not affect the composites' bending stiffness or strength. However, there was an average 25.7% decrease in after-effect emotion power. When the healed samples were compared to control samples that did not receive any factors, the flexion test revealed an 83% recovery of units and a 47% restoration of strength. The damage in the vessels, which were reinforced with carbon fiber to enhance the self-healing process through the low-speed of impact intensity. ***Norris et al.*** [32]adopted ultrasound scanning and post-impact pressure (Tsai) analysis, it was demonstrated that the vascular segments matched the residual compressive strength relationship established for conventional segments, where what harm was meticulously determined by the host platelets. This is a crucial factor in determining the best vascular spacing for a dependable self-healing system. By repairing matrix cracking and discharge damage, the healing mechanism fully restores the post-impact compression force to the range of evaluated impact energies (2.5–20 J). This technology success greatly increases greatly improves composite structures' durability, safety, and dependability. Thus, the composite reinforced with self-healing woven glass fabric corrected small fractures and mild damage in the matrix of the created epoxy laminates by inserting microcapsules loaded with epoxy and mercaptan, subjected to low impact velocity. Hence, when the healing mechanism allowed the slides to heal entirely at room temperature without the need for manual assistance, as shown in Figure 9, such as applying external pressure, the healing-induced decrease in the afflicted areas was seen via an acoustic scanning microscope. In the context of capsules, microcapsules with a greater concentration and/or bigger volume are thought to be advantageous for providing more healing factor to fractured areas. The influence of mechanical recovery and crack rehabilitation, as well as the damage reduction rate, is directly correlated with the impact energy[33].

Moreover, an impact test has been performed on composite metals using epoxy composite strips reinforced with woven glass fabric. Then, a pressure test has been performed (Compression after impact CAI) to evaluate the mechanical performance of the slices both before and after crack healing. To produce healing, the chemicals need to be heated to 140 degrees Celsius for half an hour. This indicates that the impact test conducted on composite materials strengthened with nanoparticles indicates that the self-healing mechanism is sufficiently robust to be depended upon in any application using composite materials[34].

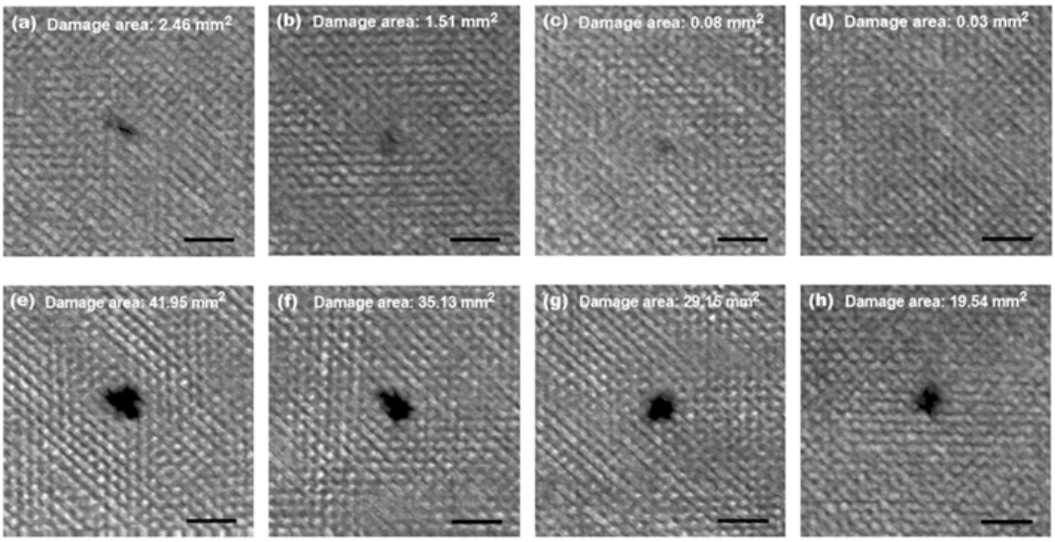

Figure 9. Images show the self-healing process of the impacted composites at different times of healing. Impact energy is 1.5 J and healing times as (a) 0 hr, (b) 1 hr, (c) 12 hr, and (d) 24 hr. Impact energy is 3.5 J and healing times as (e) 0 hr, (f) 1 hr, (g) 2 hr, (h) 24 hr. [33].

4. Self-healing of damaged composites

Self-healing properties are one of the reforming properties, especially in various industrial fields, including the automotive industry, electronics, optics, especially rockets and Space Applications. So, guidelines are provided for striking a balance between the track repair's mechanical properties while, during the composites' self-healing procedure. Self-healing possesses the ability to autonomously restore itself. In polymer compounds containing a self-healing agent, these materials can reversibly heal their damage[35]. Also, there are many ways that can be used to get self-healing from composites when the space rocket is exposed to a shock from a meteorite at different speeds, whether the speed of the meteorite is high or low. Figure 10 shows how it can do self-healing [36].

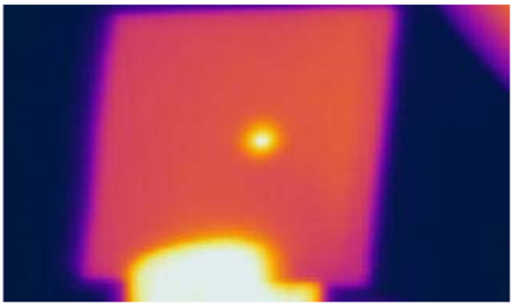

Figure 10. The Thermal photo of self-healing after penetration of the projectile[36].

Chang et al. [24] enhanced the mechanical properties of composite materials they have been using two distinct agents, vinyl and epoxy resin, with silica nanoparticles added to them. The results were measured by measuring the strength of the impact and tension, as shown in Figures 5,8, respectively. The highest recovery rate with epoxy was 49% in impact and tension with nanoparticles, and for Ester, it was 93% when the weight of the composite material increased by 3%. Basalt and saturated carbon fibers will have greater tensile strength and impact resistance than those without epoxy resins containing silica nanoparticles.

Weihong et al. [37] used a shape memory alloys (SMA) and engineered composite cement fibers (ECC), whose capacity was shown in the composite's self-healing properties. When compared to samples made of concrete, the SMA-ECC samples showed a notable improvement in strength and ductility. By successfully lowering the number and breadth of cracks, samples using SMA-ECC showed encouraging crack healing capabilities. As the degree of target movement increases, the self-healing capability diminishes. According to the findings of

mechanical testing, a novel method called ultrasonic has been applied to minimize damage and repair cracks, improve the structure's longevity, and save maintenance costs, as shown in Figure 11 processes of self-healing.

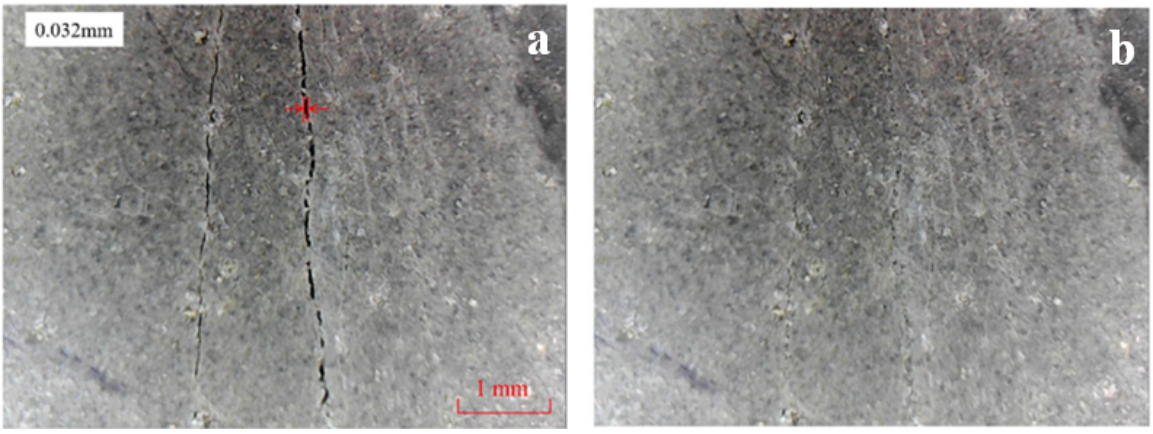

Figure 11. Self-healing of a crack of Specimen: (a) before healing, (b) after healing[37].

Moreover, ***Lee et al.*** [38] used epoxy (diglyceryl ether of bisphenol A) and a hardener (mercaptan/triple amine) that were encapsulated within an alginate biopolymer to create multi-core self-healing microcapsules using the electrospray method. These dry microcapsules had diameters between 300mm and 400 mm and were associated with basic contents of 74% and 59% for epoxy and hardener, respectively. The surface of these nuclei has a rough surface, and the multi-core internal structures are roughly 3-6 mm thick. By using scandium (III) triflate as a catalyst, these microcapsules formed a two-way healing system with a double capsule and a capsule catalyst, demonstrating their ability to tolerate temperatures as high as 200 degrees Celsius. The impact of Sharpie healing, which began at a capsule load, was tested in order to assess both self-healing regimens. The effectiveness of both self-healing regimens was assessed by evaluating the Sharpie healing effect, which began at a 20% by weight capsule load for both healing regimens. As a result, the healing effectiveness of 68–85%, the two-capsule self-healing mechanism exhibits up to four healing cycles. Also, the capsule stimulator's self-healing mechanism heals in two to three cycles with a healing effectiveness of 66 to 89%. Multiple healing is facilitated by the capsules' multinucleated interior structure, which regulates the release of healing elements. For the first time, it was demonstrated that multi-core capsule self-healing genes may give capsule-based self-healing chemicals several healing cycles.

Dongli et al. [39] used a series of UV-curable polyurethane acrylic resins (DSPUAs) with varying disulfide bond contents by the reaction of polytetrahydrofuran diol and 2,2'-Dithiopecyethanol (DTBO) mixtures with isofuran disocyanate (IPDI). This new nanomaterial was utilized to prepare a composite material treated with ultraviolet radiation in order to treat external cracks that the materials develop when exposed to UV radiation. due to the dynamic disulfide exchange reaction, DSPUA polymers with disulfide bonds exhibit good self-healing behaviour. Additionally, the self-healing speed of UV coating can be considerably enhanced by increasing the amount of disulfide groups present in the prepolymers. Given that the materials utilized to make the coin are regarded as commercially available, to elucidates DSPUA's photo-induced self-healing characteristics and how the disulfide group composition affects DSPUA's capacity for self-healing**.** Figure 12 shows how the material self-fixes due to UV radiation.

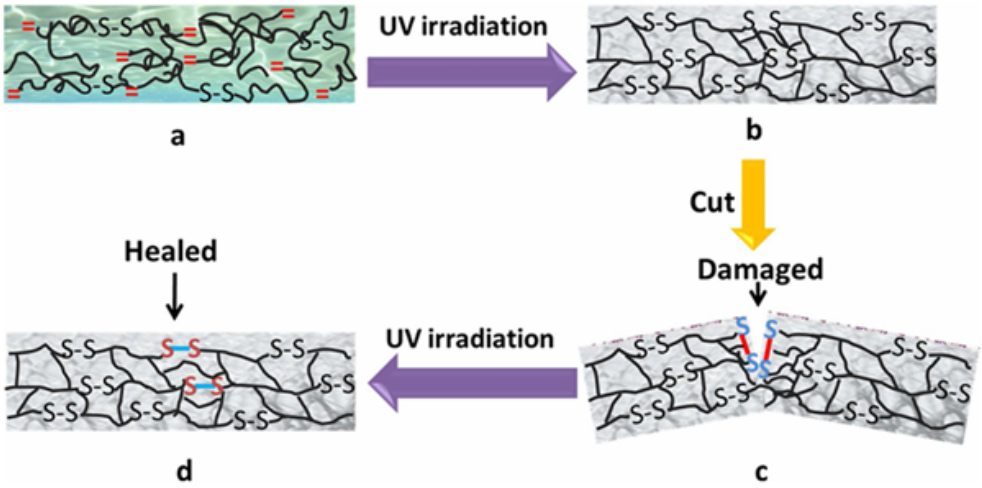

Figure 12. Explanation of ultraviolet while to radiation exposure: a) previously self-healing mechanism. (b) following radiation exposure (c), the material damage (d), and self-healing materials[39].

4.1. Self-healing materials

Self-healing process allows for the reuse of the same material repeatedly. Thus, it is save for energy harvesting and storage. This trait is crucial for extending the material's service life[40]. Therefore, materials are used in many military applications, particularly space applications, which have a unique potential to undergo change physically or chemically in response to self-healing when exposed to high temperatures, electromagnetic waves, or electric waves. Where, self-healing? This crucial property leads to an enhancement in its utility as a material. As a result, the chemical response of materials to healing their micro-crack [41]. Figures 13 and 14 present the chemical response to self-healing as a different operation of chemical interactions resulting in cross-linked network formation and the main differences between these figures have been shown in Table 1.

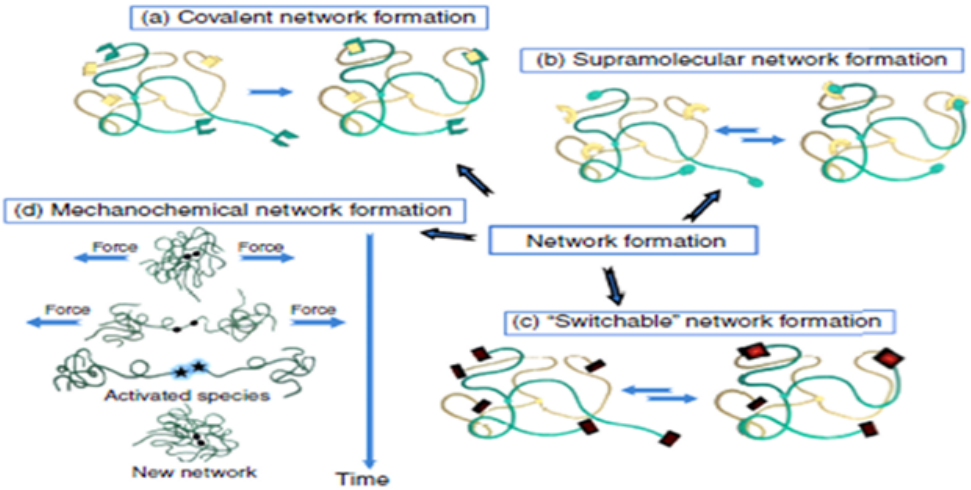

Figure 13. A similar network was formed by different patterns of chemical reactions. (a) Covalent network formation,(b) supra-molecular network formation,(c) "switchable" network formation and (d) mechano-chemical network formation [41].

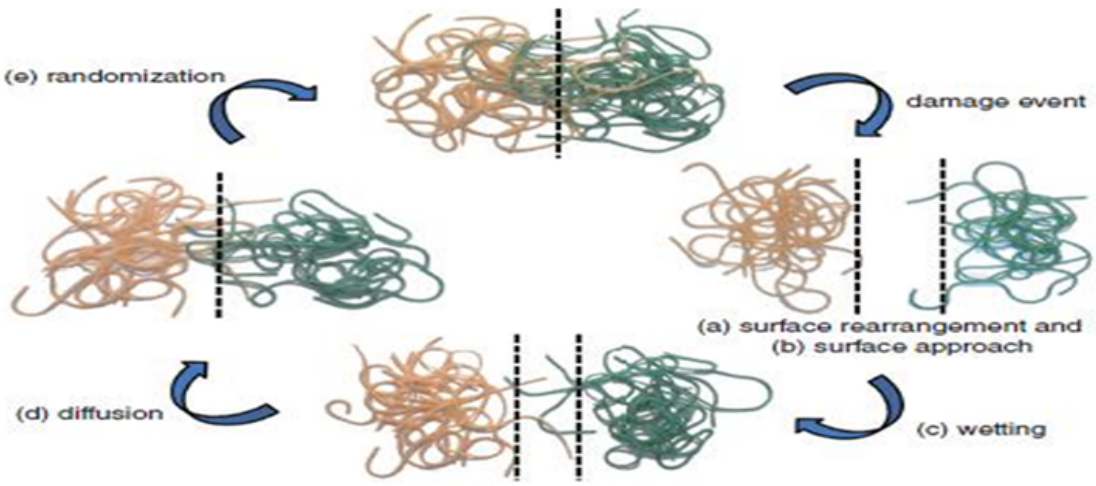

Figure 14. Self-healing stages of the mechanism. (a) Surface rearrangement, (b) surface approach, (c) wetting, (d) diffusion and (e) randomisation [41].

Table 1. Main differences between various patterns of chemical reactions in Figure 13 and the mechanism stages of self-healing in Figure 14.

	Chemical Reaction Patterns	**Self-Healing Stages**
Purpose	Describes how networks are formed via chemical reactions.	Describes the physical/chemical steps that occur during healing after damage.
a	Covalent Network Formation: Stable bonds are formed via chemical covalent bonding.	Surface Rearrangement: Polymer chains rearrange to expose fresh surfaces.
b	Supramolecular Network Formation: Non-covalent, reversible interactions (e.g., hydrogen bonding, van der Waals)	Surface Approach: Separated surfaces move closer for a healing interaction.
c	Switchable" Network Formation: Networks that can be turned "on/off" via external stimuli (e.g., heat, light)	Wetting: Chains at both surfaces interact and wet each other to enable bonding.
d	Mechanochemical Network Formation: Networks formed by applying mechanical force that activates chemical bonds.	Diffusion: Polymer chains diffuse across the interface, allowing entanglement
e	Not applicable	Randomization: Molecular chains mix and homogenize, completing the healing process.

Ha Young and Sang-Ho [42] enhanced the self-healing property based on materials self-healing by used strengthening the compound's chemical chain. The high efficiency of the self-healing property, was demonstrated by using an ethylene glycol group in functional polymethacrylates and bismaleimide, respectively, was prepared, while these used chemicals in the thermally reversible Diels-Alder reaction as shown in Figure (15) chemical action have high self-healing property efficiency.

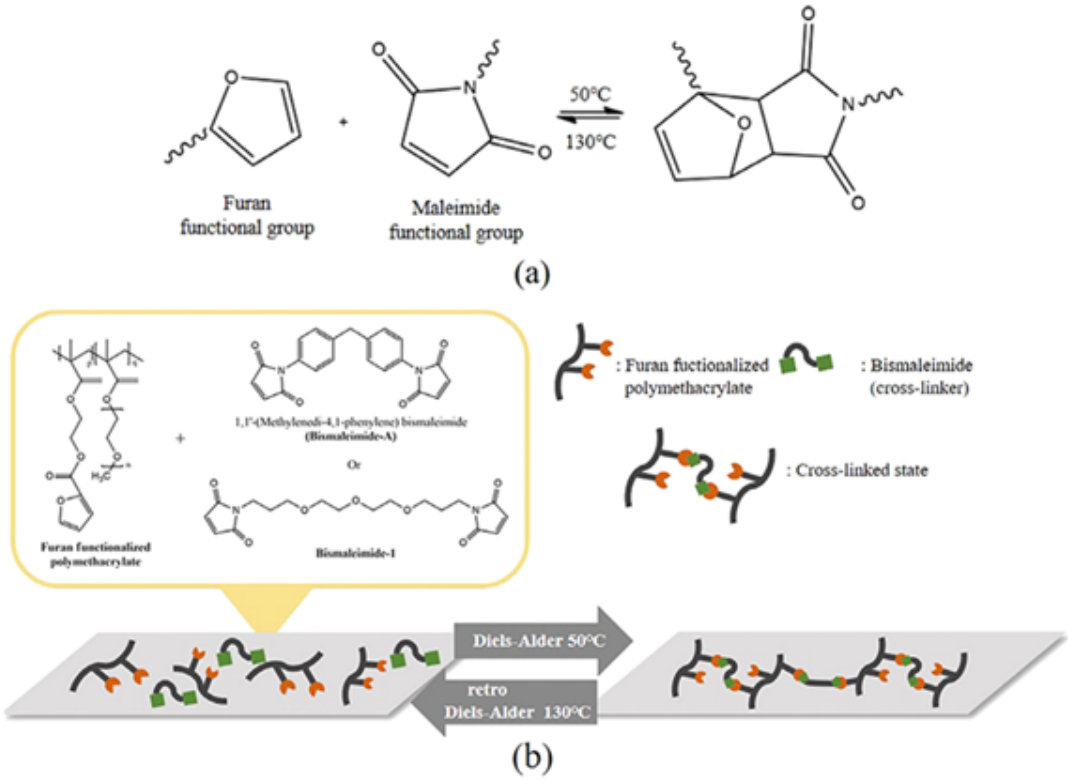

Figure 15. (a) The Diels-Alder reaction and Diels-Alder reaction occurs between the furan and maleimide functional groups (b furan functionalized polymethacrylate and bismaleimide), healing process got[42].

Revathi et al. [43] clarified that while minerals can mend damage from mechanical use, their self-healing mechanism is modelled after nature. The economy and society can benefit greatly from self-healing materials, especially in higher-tech industries like chemistry, energy, and high-tech. They encourage sustainable building and manufacturing practices in addition to lowering maintenance. Repairing flaws in metal surfaces can increase their lifespan and lower maintenance costs as shown in Figure 16 damaged material was healed.

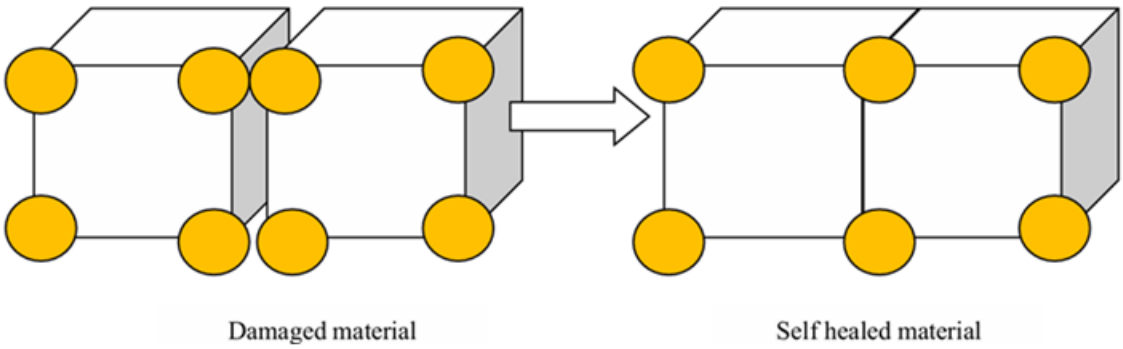

Figure 16. Mechanism of self-healing on damaged material [30].

Panhua et al. [44] enhanced UV-shielding silicon dioxide zinc oxide SiO_2/ZnO hybrid shell for potential application in space coatings. Materials with nano-capsules in their compounds, particularly those that self-heal when exposed to UV light, have a faster rate of self-healing, where UV light is prevalent. Using a layer-by-layer deposition technique, a proposed self-healing system that uses a single microcapsule that reacts to UV light and a basic epoxy resin, zinc oxide hybrid shell for polymer coating. This new scientific approach disrupts the healing process and provides timely access.

4.2. Mechanism of Self-healing

Self-healing is referred to autonomic, healing, and spontaneous repairing process, which denotes their capacity to mend themselves without outside intervention. Figures 17 and 18 present the effect of the explosion of nano capsules that are mixed with an epoxy healing agent to heal the damage [45].

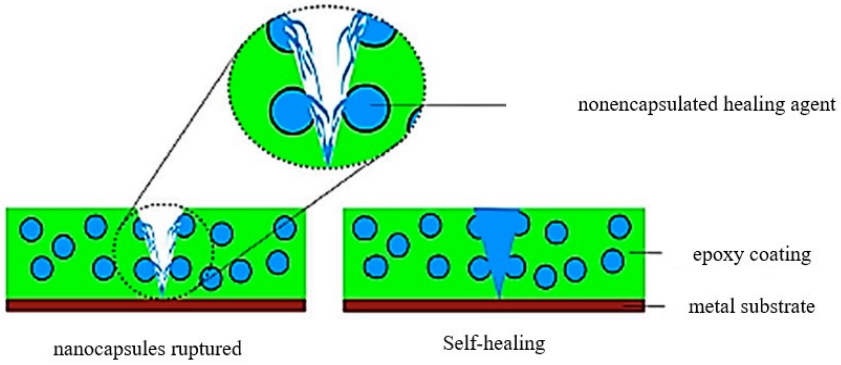

Figure 17.The figure shows the mechanism of self-healing using nano capsules in a nano polymer compound [35].

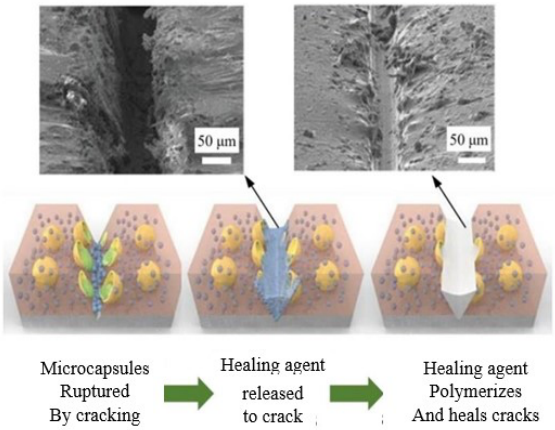

Figure 18. Microcapsules showed the mechanism of self-healing by microcapsules[45].

Kang et al. [46] developed an elastomer through water synthesis, combining conventional and zwitterionic polyol. They found that the elastomer has high permeability (~92%) and a low yellow index value (1.9). It also maintained its mechanical and optical properties thanks to zwitterionic assemblies. The self-healing science demonstrated a healing rate of up to 94–100% in both dry and wet environments, in contrast to ionic plastics with randomly dispersed ions (80–87%) and traditional non-ionic plastics (~69%). Additionally, the polymers contributed to its mechanical qualities. Controlling the degree of zwitterion localization within the self-healing zwitterionic material optimised its self-healing capabilities, as shown in Figure 19, which illustrates the mechanism of self-healing under different weather conditions. The fabricated material with localized zwitterionic clusters exhibits superior self-healing efficiency. Furthermore, the zwitterionic self-healable elastomer aims to maximize its self-healing capabilities and overcome the limitations of conventional self-healing materials by controlling the concentration of zwitterions within a local domain.

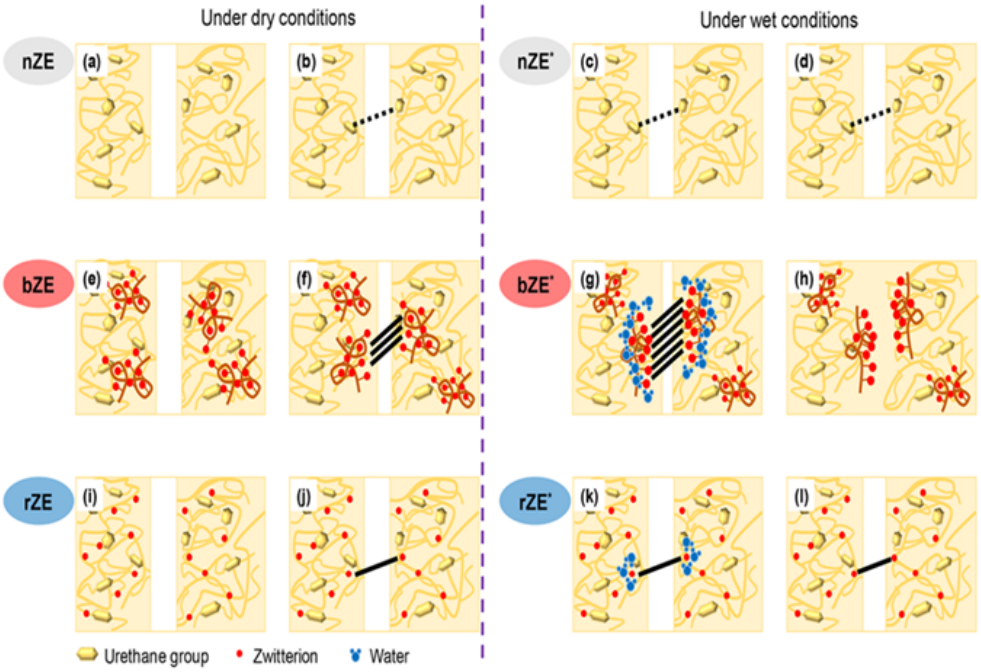

Figure 19. The process of self-healing is illustrated for the interpretation of the references to color in this figure, where under dry conditions and wet conditions [46].

Mahamudul et al. [47] developed a self-healing process in polymer hydrogels, with significance and distinctive mechanical and chemical characteristics, and adopted for self-healing of wounds and tissues. Furthermore, their reactions can be regulated by external stimuli (such as pH, temperature, pressure, or radiation), and their real-time applications are further limited by the trade-off between mechanical durability and healing performance. Figure 20 shows the mechanics of self-healing of graphene oxide and the other forms. as in Figures 21 The diagram shows the reaction mechanism that leads to the self-healing process that occurs between the guest and the host based on active oxidation and reduction. the CD undergoes the interaction between the host and the guest with iron ions through redox phenomena. Finally, figures 22 and 23 show the effect of Fe^{+2} ions coordinated on self-healing and pH-dependent Schiff base bond of the hydrogel, respectively.

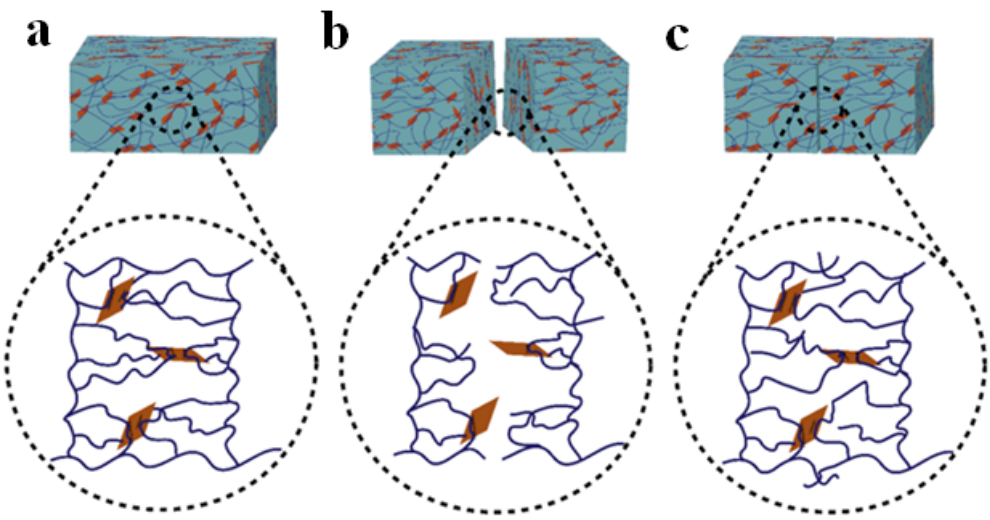

Figure 20. The self-healing mechanism of graphene oxide Synapse polyacrylamide hydrogel is shown by drawing (a) a new hydrogel sample, (b) a cut sample, and (c) a healed sample. Polymer chains(line) where hydrodynamics is reversible undergo Oh-polar groups of return surfaces (rectangular shape) [47].

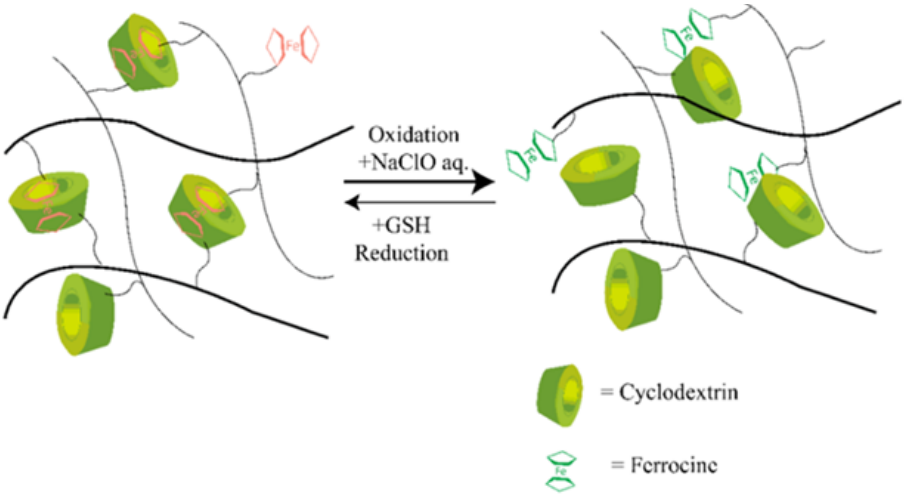

Figure 21. Self-healing hydrolysis SHH the process of cyclodextrin: S.D, where on the right side the bonds are broken by the presence of an oxidizing agent and the CDS undergo the required bonding with the virocin molecules marked in red [47].

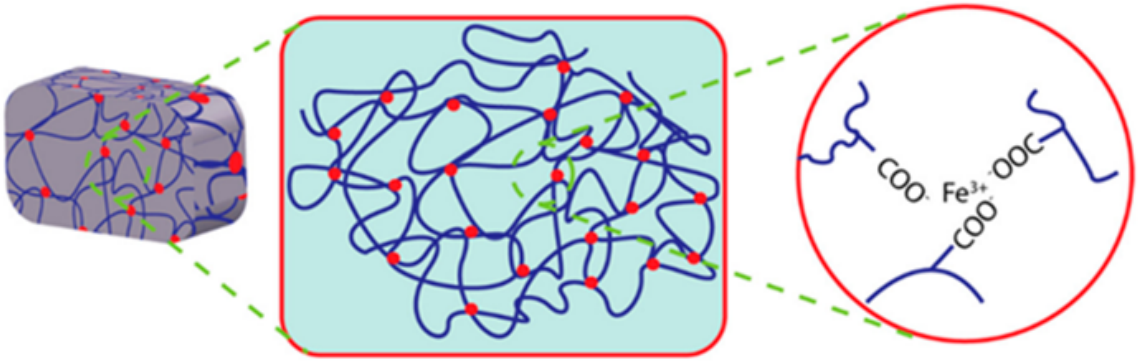

Figure 22. Fe^{3+} ion organized self-healing hydrogel [47].

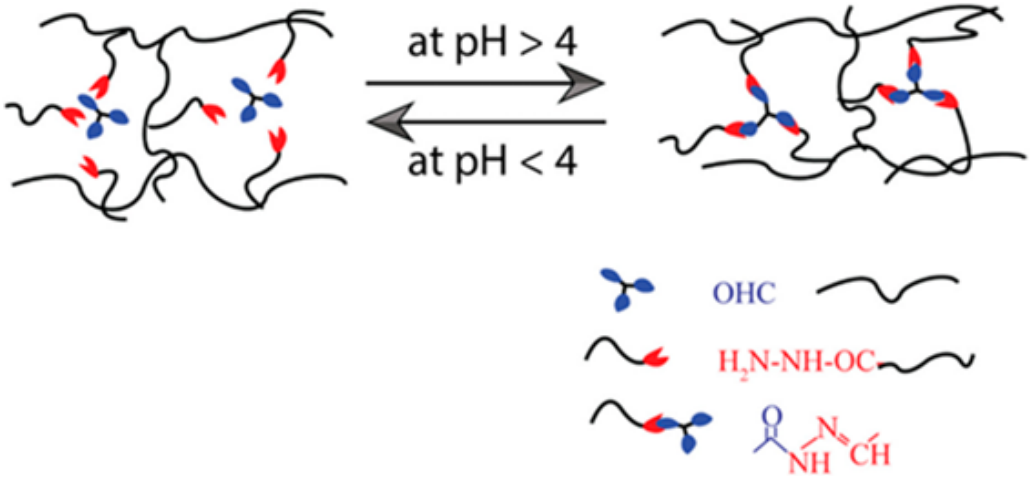

Figure 23. The self-healing mechanism dependent on the pH-dependent Schiff base bond of the hydrogel [47].

5. Conclusions

Composite laminates have been established as suitable materials for the diffident applications such as automotive and aerospace industries because of their unique and unparalleled structural properties. However, there is a significant reduction in their mechanical performances when the subjected to the external loads because of different damage failures occurred inside their structures. In this regards, self-healing process has a gained interest because of the materials have the capability to reversibly heal their damage.

This brief review highlighted one of the key characteristics of these materials: the ability of the composite to self-heal when supported by nanomaterials. It also reviewed the healing process that takes place in composite materials and how nanomaterials can intervene to treat mechanical damage. For example, Graphene oxide grafted with magnetite nanoparticles (RGU/Fe3O4) and the inclusion of multi-walled carbon nanotubes, for instance, exhibit the self-healing mechanism of nanomaterials when exposed to UV light. When other kinds of nanoparticles are subjected to heat, electromagnetic radiation, or other mechanisms that promote self-healing, they react or undergo self-healing processes. However, this research concentrated on the presence of nanoparticles during mechanical testing as well as the impact of their incorporation and associated variables on composite materials. The mechanism of composite material mechanics, the manufacturing process, the inherent self-healing processes of the material, and the ability of composite materials to self-heal or self-repair when subjected to impact, flexion, and tensile forces were all taken into consideration in order to identify the impact that determines the properties of composite mechanics.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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Author Contributions

All authors proposed the research problem and Ali B. Jarallah collected recent articles and organized them in simple shapes. Dr. Batool M. Faisal and Dr. Hussein K. Dalfi verified the recommendation in the proposed work. All authors discussed the results and contributed in writing the final version of this paper.

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Notation list

Abbreviations	Meaning
TiO_2	Titanium Dioxide
Al_2O_3	Aluminum Oxide
$BaTiO_3$	Barium Titanate
SiO_2	Silicon Dioxide
$DGEBA$	Diglycidyl Ether of Bisphenol A Epoxy Resin (DGEBA base)
$DSPUA$,	Disulfide Polyurethane Acrylic Resin
$GECC$	Engineered Cementitious Composite
MMT	ontmorillonite (Nano Clay)
$BisGMA$	Bisphenol A-glycidyl Methacrylate
GO	Graphene Oxide

PS	Polystyrene
PP	Polypropylene
$IPDI$	Isophorone Diisocyanate
$PTHF\ diol$	Polytetrahydrofuran diol
BMI	Bismaleimide
SMA	Shape Memory Alloy
$SMA - ECC$	Shape Memory Alloy – Engineered Cementitious Composite
ZNo	Zinc Oxide

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