Applications of Nanocomposites and Polymeric Materials in the Aerospace Industry

Joe Silverman*, Daria Astaire†, Adel Siraeva‡, Liceth Barajas Moreno§
Florida Institute of Technology, Melbourne, Florida, 32901

The idea of polymer nanocomposites began in the early-1900s when the discovery of chain-like structures were being formed by chemical reactions, which will be known as polymers. The first reports of nanocomposites were posted during the mid-1900s, and ever since, scientists have been trying to find new ways to implement them into current designs to take advantage of their advanced characteristics. Nanoscience phenomena have gained public attention for a few decades, but several aerospace industry challenges prevent these new, improved materials from being widely used and implemented. Since nanoscience is a relatively new field, it takes time to standardize and integrate nanomaterials and polymers into current designs and manufacturing processes. Also, providing their standardization and compliance with the safety requirements is crucial, which also demands time and more research. Given that Nanocomposites are still in the experimental phase, numerous companies are still focusing on older materials and technologies more known for their reliability. The adaptation of nanocomposite materials in both aircraft and spacecraft construction presents the opportunity to significantly reduce weight, which has been a crucial goal in the aerospace sector. Reduced weight will facilitate improved fuel efficiency, which in turn will reduce overall carbon emissions. Combined with nanocomposites' increased durability to corrosion and extreme temperatures, this ensures aircraft systems' longevity while demonstrating environmentally sustainable air travel.

I. Nomenclature

$Nano - C$ = Nanocomposite
$PNCs$ = Polymer Nanocomposites
PMC = Polymer Matrix Composite
$CFRP$ = Carbon Fiber Reinforced Polymers
PC = Polycarbonate
$Thermo - s$ = Thermosets
$Thermo - p$ = Thermoplastics
PAI = Polyamide-Imides
UTS = Ultimate Tensile Strength
MPa = Megapascal

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*Undergraduate Student, Department of Aerospace, Physics, and Space Sciences, AIAA Student Member (1595367)
†Undergraduate Student, Department of Aerospace, Physics, and Space Sciences, AIAA Student Member (1603457)
‡Undergraduate Student, Department of Mechanical and Civil Engineering, AIAA Student Member (1602994)
§Undergraduate Student, Department of Aerospace, Physics, and Space Sciences, AIAA Student Member (1605224)

II. Background Information

In the pursuit of enhancing performance, reducing weight, and achieving sustainability in the aerospace industry, the integration of Nano-C and PNCs has emerged as a groundbreaking frontier. This research paper explores the potential of these advanced materials, assessing their cost-benefit dynamics, future applications like solar sails, and explains their superiority over conventional metals such as titanium, aluminum, or steel. In recent years, the aerospace industry has witnessed a shift towards lightweight, yet robust materials to meet the demands of modern aviation and space travel. At the forefront of this transition are Nano-C and polymer materials, revolutionizing the traditional style of construction.

Nano-C are engineered materials composed of two or more phases, where at least one phase has dimensions in the nanometer range. Conversely, polymeric materials refer to a diverse class of compounds characterized by long-chain molecules, offering flexibility, strength, and versatility in various applications. The appeal of Nano-C and polymer materials over conventional metals lies in their exceptional properties. Unlike common metals, these materials exhibit significantly reduced weight without compromising structural integrity. Their lightweight nature significantly reduces the overall weight of an aircraft, for instance, leading to enhanced fuel efficiency and reduced emissions. Moreover, Nano-C offer exceptional strength-to-weight ratios, making them ideal for withstanding the rigorous demands of flight operations. Their superior corrosion resistance, thermal stability, and electromagnetic properties make them ideal candidates for aerospace applications, ensuring prolonged operational lifespan and reduced maintenance costs.

From inception to completion, the construction of Nano-C and polymer materials involves detailed processes and specialized tools. It begins with the formulation of composite matrices, where nanomaterials are dispersed within polymer matrices to achieve desired properties. Advanced manufacturing techniques like injection molding, compression molding, and 3D printing are then employed to fabricate intricate components with precision and efficiency. Throughout the construction phase, tools such as spectroscopy, microscopy, and rheology analyzers play significant roles in characterizing material properties, ensuring quality control, and optimizing performance.

In essence, the integration of nano composites and polymer materials signifies a transformative leap in aerospace engineering, promising efficiency, sustainability, and innovation. As we navigate towards a future marked by space exploration and renewable energy solutions, these materials are an effective solution in propelling humanity towards new horizons of discovery and advancement.

III. Nanocomposites in the Aerospace Industry

A. Chemical Composition

Nano-C are heterogeneous multiphase solid materials that consist of two parts: polymers, also called matrix, and inorganic solids. Two distinct materials can be combined to obtain a Nano-C with enhanced characteristics. Due to their small size, Nano-C exhibit unique properties of the original materials with improved characteristics. The addition of nanoscale reinforcement materials creates a minimal distance between the fillers, enhancing the properties of the resultant materials. Nanotechnology has gained popularity and is undergoing intensive research. Varieties of Nano-C have evolved depending upon the type of matrix used for which they are widely classified into three categories (as in the case of micro composites): polymer matrix nanocomposites (PMNCs), ceramic matrix nanocomposites (CMNCs) and metal matrix nanocomposites [1].

B. Types of Nanocomposites in Aerospace Applications

Polymer-matrix nanocomposites (PMNCs) are the most commonly used nanocomposites in the aerospace industry. Polymers are relatively inexpensive and have shown promising results in engineering industry applications. This material is obtained by combining polymer matrices, often epoxy resin, and additives, usually nanofillers. Those nanofillers can be clay nanoparticles, carbon nanotubes (CNTs), or nanoclays. Clay nanoparticles offer exceptional strength, barrier characteristics, and elasticity. CNTs provide excellent electrical conductivity, stiffness, and thermal stability, which results in lightweight structures. Nanoclays have enhanced fire resistance characteristics and flame retardancy.

Ceramic-matrix nanocomposites (CMNCs) have a ceramic matrix, usually silicon nitride or alumina, enhanced with nanofillers. Silicone carbide (SiC) and Silicon nitride (Si3N4) are nanoparticles included in Non-oxide CMCs that can serve as nanoparticles that provide superior strengthening [2]. Fillers provide advanced thermal stability, strength oxidation, and wear resistance. These properties are crucial for aerospace elements in extreme conditions.

Metal-matrix nanocomposites (MMNCs) are promising materials that require more research for future aerospace applications. One example of nanofillers is Alumina (Al203), which improves strength and stiffness and shows thermal stability. Alumina as a filler shows a great combination with the components that experience stress and friction during their operation. Metal-matrix nanomaterials offer better properties than previously used, commonly known materials in aerospace, ensuring lightweight and maximum possible performance.

C. Key Properties of Nanomaterials

Nowadays, the best materials for the aerospace industry are expected to have exceptional resistance to corrosion, strength, toughness, impact resistance, fatigue life, and scratch resistance. Similarly, the aero vehicles flying at high altitudes or in space should have excellent solar absorption, radiation resistance, and high thermal emissivity. (direct quote, PNCs in aerospace industry). Nano-C demonstrated remarkable results compared to the traditional materials. Mechanical, chemical, electrical, and other properties make Nano-C of great interest to the aerospace industry.

Increased surface area, resulting from the smaller size of Nano-C, ensures adequate interfacial bonding and distinguishes them from bulk counterparts. The surface area is significantly enlarged compared to their volume. It reduces the weight and improves fuel efficiency and overall structural integrity.

By replacing traditional materials, the weight of components can significantly drop. This factor leads to fuel efficiency and increased payload capabilities. Weight reduction can also give the industry a cost-efficient and more environmentally beneficial solution.

Despite the small size of nanoparticles, their mechanical properties, such as strength, stiffness, break stress, wear resistance, and homogeneous dispersion, are significantly improved compared to traditional materials. This reinforcement is obtained because of the nanofillers, which ensure resistance to deformation and maintain the structure's best performance.

Fillers to the main matrix in PMNCs, CMNCs, and MMNCs enhance the temperature resistance and ensure greater thermal conductance. The addition of trivial amounts of SWCNTs (1%) can enhance the thermal characteristics of industrial epoxy (up to 120%) and hence does not require any chemical functionalization process [3].

Electrical properties are also tailored to face the most demanding needs of the aerospace industry. CNTs as nanocomposite fillers can help disperse the electrical current to improve lightning stroke protection. Electronic interference (EMI) shielding helps protect the electronics on the board.

The integration of the Nano-C in the industry can create plenty of advantages. Key characteristics of Nano-C can improve existing designs and make them more efficient in their functionality concerning cost, structure, safety, and environmental benefits. Future research is crucial for the improvement of existing characteristics.

D. Techniques Suitable for Aerospace Manufacturing

Manufacturing of nanocomposites is a multistep, challenging process. Nanoparticle production includes chemical vapor deposition (CVD), ball milling, and sol-gel processing. The next step is nanoparticle dispersion. A few methods are available: Ultrasonication and shear mixing. Composition formation is the next essential step. It can be done by Solution and Melt processing. The last step is shaping, which includes additive manufacturing and machining.

E. Applications of Nanocomposites in Various Components

Lightweight and robust materials with high-performance characteristics are needed in the aerospace industry. Composites account for an average of 25 percent of an aircraft's weight once launched [4]. Compared to designs with aluminum and steel, nanocomposites can be implemented in aircraft design to attain lighter and more potent products. The lighter structure can contribute to the better overall performance of the aircraft. Reinforcement of structural integrity offers increased strength and stiffness of components.

Implementation of Nano-C in industry can significantly reduce drag components. A Smoother structure design can improve the aerodynamics of the aircraft. Fire resistance is essential for aircraft safety; Nano-C can be engineered to offer improved fire resistance. Nano-C can serve as a barrier for the potential fire.

Nano-C can be used in coatings for aircraft to prevent icing in extreme temperatures. This can ensure safety and eliminate deicing procedures. Besides that, implementing new materials can enhance corrosion resistance and durability.

Improved radar performance in spacecraft is another promising application. Protective covers, also called radomes, can serve as covers for radar antennas, which can prevent signal damage and loss.

Manufacturing of Nano-C into aerospace applications undergoes an active development phase. Transforming lab-scale production to industrial scale is a long and challenging process. The cost of nanomaterials and their manufacturing can be higher than traditional materials. Using these materials requires implementing safety protocols to prevent potential health hazards.

Recent developments in aircraft design, as seen in the Bombardier C series, Airbus A380, and Boeing B787 aircraft, have led to a dramatic increase in the use of composites and a corresponding increase in the bonding of the leading aircraft structure [4].

IV. Polymeric Materials in the Aerospace Industry

A. Current Applications

Although Polymers have existed for over a century, their usage only began to gain popularity in the 1970s. [5] Certain characteristics of the various forms of polymers sparked interest in the eyes of engineers. While materials such as steel or iron have valuable mechanical properties, specifically ultimate tensile strength, they are not ideal in regards to the reduction of overall weight. Polymers also tend to have insulating properties that become useful when dealing with heat or electricity and elasticity, which is crucial when dealing with excessive force.

In today’s innovations, polymers are used in a vast selection of items, especially in the aerospace industry. Commercial airlines, constantly look for more ways to implement polymers and take advantage of their light-weight functionality. From smaller items, such as food trays and overhead storage panels, to larger, more significant items, like wings, there are endless opportunities to incorporate polymers and improve any design.

B. Limitations

Polymers can be an incredible addition to the aerospace industry; however, they have their weaknesses, just like everything else. UTS is the maximum force an object can withstand before breaking, measured in MPa. [6] While metals have a high UTS, polymers, in most cases, are the opposite. Forms of polymers, in particular, crystalline structures, tend to become weak and fragile under pressure. [7] For this reason, using CFRPs often decreases the risk of an object’s failure under force.

CFRPs fall under two categories: Thermo-p and Thermo-s. Each type has its own uses based on its characteristics. Aside from the lower tensile strength, polymers also tend to release toxic fumes when altered. Whether cutting or melting an object, polymers can release dangerous vapors, and chemically hazardous particles in the air through the ‘dust’ or excess material being removed. [8]

C. Thermoplastics

In the world of polymers, Thermo-p are among the most commonly used forms. Given that Thermo-p can be manipulated using high temperatures, they become a versatile material, that can be recycled to perform multiple tasks. [9] For example, from the 3D printing aspect, materials known as ‘filaments’ are melted inside a Fused Deposition Modeling printer, otherwise known as FDM. Through extrusion, these filaments allow the user to turn their ideas into reality. [10] Besides the fact that everyone is able to create anything, there are some differences between various types of these filaments. Materials such as PC, polylactic acid (PLA), and thermoplastic polyurethane (TPU), all have different qualities that help determine whether or not a material is optimal for a given function.

PC, for example, is often referred to as the ‘strongest’ among various types of filaments, which, in turn, makes it a favorable option when dealing with objects in a ‘high-stress environment.’ [11] In regards to PLA, it tends to have a lower strength yield and poor heat resistance; because of this, PLA is best for objects that perform as prototypes, rather than the final product. TPU, however, is possibly the least common of them all. Due to its ‘flexible’ characteristics, it can be used as a shock absorber, or a gasket to seal an item to be ‘airtight’. Unfortunately, due to its unique environmental requirements, producing an item consisting of TPU becomes more complicated for the average person.

D. Thermosets

While Thermo-s can be altered and repurposed, Thermo-s are quite the opposite. Once solidified, Thermo-s remain in a permanently fixed form, meaning they cannot be changed without creating the risk of compromising their functional abilities. [12] When compared to items such as metal or wood, Thermo-s rank highly among their alternatives. Aside from being lightweight, Thermo-s have every quality that thermoplastics contain and more.

Due to the structure of Thermo-s being chemically bonded, factors such as the impact of large amounts of force, strength, and durability, are all significantly enhanced. Given that Thermo-s are exceptional in impact resistance and durability, they become a desired material when dealing with moving or continuously used parts.

E. Polyimides-Imides

A common form of Thermo-s is referred to as PAIs.[13] A PAI material is often a Thermo-s; however, it is possible to incorporate additional cyclic groups to its chemical structures which, in turn, would make a PAI as a Thermo-p. [14] PAI in the form of a Thermo-s, have properties that are critical when dealing with the aerospace industry. PAI materials, unlike their metal substitutes, are dielectric, which means that if there is an electrical charge present, it would not pass through the object. [15] This can be extremely useful when dealing with sensitive electronics, where even the slightest amounts of electrical disharges, could compromise the technology, and put everyone, or everything, at risk of failure or harm. PAIs also have fantastic performance under extreme conditions, such as high temperatures, or chemical exposures. [16]

V. Future Applications of Nanocomposites and Polymers

A. Development of self-healing polymers

A polymer is a substance composed of giant molecules formed by the union of multiple monomers. These materials are now used because of their numerous advantages: resistance to corrosivity, lightweight, flexible design and fabrication processes, thermal isolation, and electric isolation, among others. These newly developed self-healing polymer technologies have also caught the industry's attention thanks to the properties that prolong the material's durability, maintenance, and cost, but mainly because it can self-heal after mechanical and chemical damages.

Furthermore, the polymers use mechanisms to self-heal and work on their structural components: Extrinsic mechanisms where capsules containing activation agents work like the vascular and capsule methods and intrinsic mechanisms based on chemical bonds within the polymer matrix like the dynamic covalent bonds and the non-covalent bonds [17]. The vascular method contains a network of microscopic vessels distributed within their matrix so that when the damage occurs, a healing agent, like a precursor monomer, will be free to flow on the structure so that when it arrives on the damaged side, it can polymerize the damage [18]. Usually, damages are cracks or breaks. Similarly, the capsules method is based on healing agents encapsulated in microcapsules and placed dispersedly in the matrix so that when damage occurs, it will make the capsule break; releasing the agent will need a mechanism of activation like a change on the pH, heat, or a capsule rupture so it will polymerize the damage.

On the other hand, the dynamic covalent bonds method, just as its name indicates, is based on some covalent bonds that can be formed as a reaction to external stimulation like temperature, pH, or light changes. When it activates, it will allow the polymer to chain and repair the material [19][20]. Likewise, the polymers that use non-covalent bonds act like the covalent bonds' reaction, but their internal structure will vary; some examples of this mechanism are the hydrogen bonds, dipole-type, and ionic interactions, making these materials have various healing feasible activities. Moreover, recent research informed of creating a new polymer with form memory [21]. This technique will be activated thermally, resulting in polymers exhibiting partial macroscopic healing and double- and triple-repeatable shape memory with almost 100% stiffness recovery.

The scientific community believes that this material will be used more frequently in various aerospace projects since it allows obtaining critical characteristics in the optimization of resources in space missions; for example, thanks to the fact that the polymers are lighter than usual, the rocket or plane They will be lighter, thus allowing fuel efficiency to be optimized as well as reducing emissions without affecting the strength of the material since structures with self-haling polymers will be more robust.

B. Nanoporous polymers

Nanoporous polymers are materials created from elements such as B, C, N, and O and have promising applications, specifically in gas storage, separations, and catalysis. There are four specific types of nanoporous polymer networks: covalent organic structures, conjugated microporous, intrinsic microporosity polymers, and hyper cross-linked polymers [22].

Nanoporous contain two types of porous materials according to IUPAC: first, mesoporous materials are materials with pore widths between 2 and 50 nm, and second, microporous are materials that have mineral widths less than 2 nm, which means that The focal point is materials where the porosity acts as a function of the molecular structure that will be accessible to the guest molecules [22]. To maintain the stability of the pores, solid construction components must be used to prevent the collapse of the structures and allow the space to be used more effectively. This robustness requirement has been fundamental in the chemistry used until now to create nanoporous polymers. Typically, this chemistry is based on aromatic monomers, such as alkynes or alkenes. To create three-dimensional networks, at least one of the monomers (called a node) must have a connection. This facilitates network formation when monomers link these nodes with at least degree 2 functionality (the struts). The network will only maintain its porosity permanently after removing the solvent if the structure does not collapse and close the pores.

Porous polymer networks have two types: amorphous and crystalline. Amorphous networks can have a larger pore and have a disordered statistical structure. Likewise, they require high-performance reactions to achieve as close a condensation as possible. On the other hand, crystal networks have ordered structures, generating pore sizes that are as similar as possible. They are uniform and correlate with the size of the monomer struts [23]. They are typically formed through chemical reactions that generate reversible bonds, allowing for more stable internal thermodynamics. The best example of this type of structure is covalent organic frameworks.

Due to the chemical properties of these materials, they have a wide range of applications. They can offer large surfaces, maintaining constant stability in their physical and chemical properties. Additionally, they have a high level of modularity, meaning they can be broken down into smaller parts (modules), and each can function independently. This makes these materials versatile and adaptable to various needs and uses, as well as sustainable and suitable for separations that are energy efficient [23].

C. Bio-derived polymers

Due to concerns about global warming and the fervent need to find solutions to slow this phenomenon, bio-based polymers are getting more attention because they are based on renewable resources. Firstly, it should be clarified that biodegradable polymer and biologically based polymers are two different terms since the first refers to the deterioration of the physical and chemical properties of the material, leading to its complete degradation. In contrast, the second refers to the chemical base. With which these are created and are not always biodegradable.

Biopolymers reduce dependence on fossil fuels and are produced by synthesizing renewable components in bacterial fermentation. Still, there are three ways to make these polymers: Producing bio-based monomers through conventional chemistry and then polymerizing to create biopolymers, such as polylactic acid or polyethylene. Second, biologically based polymers, such as starch, can be used with some partial modification to make them more complete. Third, through bacteria, they produce biopolymers such as polyhydroxyalkanoates. [24]

Although this environmentally friendly solution is a great option, fossil fuels continue to represent great competition thanks to their low price, and several challenges must be faced, such as the management of raw materials and the performance of the original materials—biological and production costs. The current industry is mainly focused on manufacturing versions of already existing monomers and polymers since it is a more straightforward strategy to replace something already used with a biological version of it.

On the other hand, some biopolymers such as PLA (Polylactic Acid) and bio-based polyethylene have already found applications in the aerospace industry since they have the high standard of specific performance and safety properties that this industry seeks. Conversely, PLA is a biopolymer produced from corn starch or sugar cane, so its result can be implemented using light. Still, resistant materials are necessary, such as in manufacturing aircraft interiors, where the aim is to reduce the environmental impact. Similarly, bio-based polyethylene is produced from ethanol derived from biological sources. It is implemented in applications where corrosion resistance, low weight, and durability are sought, like some structural components.

VI. Conclusion

The utilization of Nano-C in the aerospace industry promises a transformative era of innovation and advancement. Looking to the future, the integration of Nano-C and polymer materials holds immense potential across various aerospace applications, offering unparalleled benefits and opportunities for exploration. By harnessing the unique properties of nanomaterials within polymer matrices, engineers can envision lighter, stronger, and more efficient aircraft structures, propulsion systems, and thermal protection mechanisms. The versatility of Nano-C allows for tailored solutions to meet the evolving demands of modern aviation and space travel, from reducing fuel consumption and emissions to enhancing durability and reliability in extreme operating conditions. Furthermore, the emergence of manufacturing techniques and material formulations paves the way for advancements in space systems, satellite technology, and renewable energy applications. As we continue to push the boundaries of material science and engineering, Nano-C emerge as indispensable enablers of progress, driving us towards an unbounded future in aerospace engineering. Through strategic investment and collaborative research, the industry stands in a position to unlock the full potential of Nano-C, shaping a future of unlimited possibilities.

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References

[1] Bhat, A., Budholiya, S., Aravind Raj, S., Sultan, M. T. H., Hui, D., Md Shah, A. U., and Safri, S. N. A., "Review on nanocomposites based on aerospace applications," Nanotechnology Reviews, Vol. 10, No.1, 2021, pp. 237-253.https://www.degruyter.com/document/doi/10.1515/ntrev-2021-0018/html

[2] Karadimas, G., and Salonitis, K., "Ceramic Matrix Composites for Aero Engine Applications—A Review," Applied Sciences, Vol. 13, No. 5, 2023, p.3017 https://www.mdpi.com/2076-3417/13/5/3017

[3] Biercuk, M.J., Llaguno M.C., Radosavljevic M., Hyun J.K., Johnson A.T., and Fischer J.E., "Carbon Nanotube Composites for Thermal Management," Applied Physics Letters Vol. 80, no. 15, 2002, pp. 2767–2769. https://pubs.aip.org/aip/apl/article/80/15/2767/1059761/Carbon-nanotube-composites-for-thermal-management

[4] Milne S., "Nanocomposites in Aerospace," AZoNano, 23 Sep. 2014. https://www.azonano.com/article.aspx?ArticleID=3258

[5] "5 Types of Plastic Used in the Aerospace Industry," Plastivision, 16 Apr. 2019. https://www.plastivision.org/blog/5-types-of-plastic-used-in-the-aerospace-industry/

[6] "What is Ultimate Tensile Strength?" Metal Supermarkets, 27 Jul. 2023. https://www.metalsupermarkets.com/what-is-ultimate-tensile-strength/

[7] "Polymer: Definition, Properties, Types, and Applications," Xometry, 30 Mar. 2023. https://www.xometry.com /resources/materials/what-is-polymer/

[8] "Polymers," Hesperian Health Guides. https://en.hesperian.org/hhg/Workers%27$Guide_{t}o_{H}ealth_{a}nd_{S}afety:$ $Polymers$

[9] "What is a Thermoplastic? (Definition and Examples)," TWI. https://www.twi-global.com/technical-knowledge/faqs /what-is-a-thermoplastic: :text=A%20thermoplastic%20is%20a %20class, moulding%2C%20thermoforming%20and %20blow%20moulding

[10] "Thermoplastics," Plasticseurope. https://plasticseurope.org/plastics-explained/a-large-family/thermoplastics/

[11] "What is Carbon Fiber Reinforcement Polymer?" CRP Technology. https://www.crptechnology.com/insights/carbon-fiber-reinforced-polymer/

[12] "Thermoset Vs. Thermoplastic (What is the Difference?)," TWI. https://www.twi-global.com/technical-knowledge/faqs/thermoset-vs-thermoplastic

[13] "Thermosets Vs. Thermoplastics," Romeo RIM. https://romeorim.com/thermoset-vs-thermoplastics/

[14] "Polyimide: Properties, Processing, and Applications," Matmatch. https://matmatch.com/learn/material/polyimide

[15] “Comprehensive Guide on Polyimide (PI),” Omnexus https://omnexus.specialchem.com/selection-guide/polyimide-pi-plastic: :text=Known%20for%20excellent%20thermal %20stability,electronics%2C%20aerospace%2C%20and %20automobiles

[16] “PAI (Polyamide-imide),” Polymersghapes. https://www.polymershapes.com/product/pai/

[17] Idumah C. “Recent advancements in self-healing polymers, polymer blends, and nanocomposites” Sage journals, published online 20 Mar 2020. https://journals.sagepub.com/doi/full/10.1177/0967391120910882

[18] Yang, D., Meure, S., and Solomon, D. “Self-healing polymeric materials: A review of recent developments” Progress in Polymer Science, 18 Feb 2008. https://citeseerx.ist.psu.edu/document?repid=rep1type=pdfdoi=6593212b619e 37283ad526bb8a3fca9535f95c33

[19] Song, T., Jiang, B., Li, Y., Hongling, Z., Jiang, D., Seok, I., Murugadoss, V., Wen, N., and Colorado, H. “Self-healing Materials: A review of concept developments” Es Materials and manufacturing, 6 May 2021, ch.14, pp.1-19. https://www.espublisher.com/uploads/article$_{p}df/esmm5f465.pdf$

[20] Leng-Duei, K. “The future of ´self-Healing´ technologies” Annals of Biotechnology, 27 Aug 2018. https://meddocsonline.org/annals-of-biotechnology/the-future-of-self-Healing-technologies.html

[21] Islam, S. and Bhat, G. “Progress and challenges in self-healing composite materials” Royal society of chemistry, published online 2 Feb 2021. https://pubs.rsc.org/en/content/articlehtml/2021/ma/d0ma00873g

[22] Dawson, R., Cooper, A., and Adams, D. “Nanoporous organic polymer networks” Progress in Polymer Science, Vol. 37, Apr 2021, pp. 530 – 563. https://www.sciencedirect.com/science/article/abs/pii/S0079670011001080

[23] Ananghan, S., and Bandyopadhyay, S. “Polymer Nanocomposites: from synthesis to applications” Nanocomposites and polymers with Analytical methods, 2011, pp. 1-29. https://books.google.com/books?hl=eslr=id=enCPD wAAQBAJoi=fndpg=PA3dq=price+efficiency+of+nanocomposites+and+polymersots=2emd-E3OKgsig=zuZ5JRFi6BHA ziJV8N3goNtuGEMv=onepageq=price%20efficiency%20of%20nanocomposites %20and%20polymersf=false

[24] Atria Innovation “Biopolymers” , published online 7 Feb 2022. https://www.atriainnovation.com/en/biopolymers/