Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 12, Issue 6, 2024
DOI (Journal): 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Research JoPC

Commercialization of Smart Polymers in Advanced Composite Structures for Industrial Applications

Bindiya Jain[1], Dev Kumar Mandal[2], Indrajit Ghosal[3,*], Krishnendu Ghosh[4]

Abstract

The commercialization of smart polymers in advanced composite structures represents a significant rise in material science, particularly for industrial applications. These smart polymers show unique properties such as self-healing, shape memory, & responsiveness to environmental disturbances, making them ideal for a wide range of applications. In this paper, the researcher explores the advancements in developing and applying smart polymers within composite structures, focusing on their potential. Revolutionize industries like atmosphere, civil infrastructure, biomedical engineering, & automotive manufacturing. Key challenges in the commercialization procedure with scalability, cost-effectiveness, & continuing durability. In this paper researcher examines current market movements, future forecasts, & the probable impact of these materials on sustainable development. Researchers do a complete analysis to provide insights into the practical integration of smart polymers into industrial applications, driving innovation & attractive performance in various sectors. A case study on the integration of smart polymers in aerospace composite structures involves a detailed analysis of specific aerospace where smart polymers were incorporated, examining the processes, challenges, outcomes, and the impact on performance, durability, & maintenance of the aerospace components.

Keywords: Smart polymers, shape memory polymers, sustainable and smart polymers, automotive manufacturing, performance enhancement

INTRODUCTION

The development of materials science has to the development of smart polymers, which are revolutionized advanced composite structures. Smart polymers can /respond to external helps like temperature, light, pH, and electrical or magnetic fields, and have a unique set of properties that can be finely tuned for specific applications. These materials have gathered significant attention due to their potential to enhance the performance, functionality, and durability of composite structures used in various industrial sectors. Industrial applications integrate of smart polymers into composite structures with new paths for innovation and efficiency [18]. These advanced materials are particularly beneficial in industries because adaptability and responsiveness are vital. The ability of smart polymers to alter their mechanical properties, shape, and other characteristics in response to environmental changes. Fiber-reinforced polymer (FRP) composites, introduced years ago, are widely used in many structural submissions. They are popular because they are lightweight, strong, chemically stable, multipurpose to process, and resistant to the destruction of materials and failure of a material [8]. The development of self-healing, shape memory, and sensor-embedded composites, significantly improves safety, durability, and overall performance. The commercialization of smart

***Author for Correspondence**
Indrajit Ghosal
E-mail: ghosal.m1981@gmail.com

[1]Associate Professor, Department Computer Science, Poornima University, Jaipur, Rajasthan, India
[2,4]Assistant Professor, Department Management, Brainware University, Kolkata, West Bengal, India
[3]Associate Professor, Department Management, Brainware University, Kolkata, West Bengal, India

Received Date: June 11, 2024
Accepted Date: July 29, 2024
Published Date: September 18, 2024

Citation: Bindiya Jain, Dev Kumar Mandal, Indrajit Ghosal, Krishnendu Ghosh. Commercialization of Smart Polymers in Advanced Composite Structures for Industrial Applications. Journal of Polymer & Composites. 2024; 12(6): 70–81p.

polymers in advanced composite structures presents both opportunities and challenges [15]. It is divided into two parts first, the potential market for these materials is vast, and the increasing demand because of high performance. Second, the transition from laboratory-scale research to large-scale industrial applications includes overcoming several hurdles, including material cost, processing techniques, scalability, & integration with existing manufacturing processes. An outline of the current state of smart polymers in advanced composite structures [6].

LITERATURE REVIEW

Our research paper is closely related to the following literature on Commercialization of Smart polymers in Advanced composite.

Smart Polymers

From the Stone Age to aluminum and finally, to our present-day polymers, many materials have become the subject of study by researchers who are looking for better ones to meet contemporary and diverse needs [28]. The polymer has become a material of the century and possibly, ever since then, there has been hardly any application it hasn't found its way into. The concept of using layer-by-layer fabrication in making three-dimensional (3D) structures traces back to the 1980s; it created complex architectures with defined features and functions [29, 30]. Polymer composites are crucial for various sectors such as transportation or aerospace due to their strength, lightness, cost-effectiveness, flexibility, and ecological friendliness [31]. Currently, these smart polymer composite materials show excellent characteristics that are being widely recognized. Smart polymer composites can change their mechanical properties electrical conductivity or optical absorption due to variations in temperature, humidity, or pressure [32]. Other potential advantages include better performance, enhanced efficiency, and self-healing capability upon external stimulation. Smart polymer composites include shape memory, conductive, and self-healing polymers. Shape-memory polymers recover their original shape when subjected to deformation, while conductive polymers can conduct electricity thereby making them suitable for devices like actuators and sensors. Self-healing polymers could rectify themselves from external sources of disturbances like cracks or fractures, thereby increasing the life of the material [33]. Generally, state-of-the-art smart polymer composite materials remain a rapidly evolving area with huge potential across numerous industries. Nevertheless, some challenges need to be overcome before this promise is realized including improved processing techniques, more research and development, and a better understanding of their properties and behaviours.

Shape Memory Polymers

Commonly referred to as "shape memory polymers", intelligent polymer composites revert to their original shape despite undergoing deformations. These materials are activated by changes in pressure, humidity or temperature. This ability of these materials to return back into their initial states has been attributed to transition temperatures/pressures where the material changes from a flexible/malleable state to a rigid/shape-maintaining condition. Shape-memory polymers are made by typically mixing a polymer with a shape-memory substance such as an alloy [34]. The mechanical strength needed has been provided by the polymer while allowing the material to return to its original shape was made possible by the shape memory agent. By giving them this feature, SMPs have become truly exceptional, as they can take up particular shapes, remain in those shapes when subjected to high pressures or temperatures and revert back again when these temperatures reduce or these pressures cease [24, 49]. In addition, SMPs like catheters and stents that can be flexible upon implanting into the body but straighten back after being used are commonly employed in the medical field [35, 48]. Similarly, SMPs played a vital role in the transportation sector in making lightweight cars that do not consume too much fuel and aerospace ones whereby strong yet light structural components were designed. There are several ways of controlling the transition temperature or pressure of SMPs including adding plasticizers, using crosslinking agents as well as substituting polymers with alternate ones or changing the shape memory agents. In conclusion, shape-memory polymers represent an exciting class of materials with unique properties and potential uses in various industries. Returning to its original form after being altered offers many advantages. The room to grow and get better makes SMPs a hot area for future study and new ideas [36].

Sustainable and Smart Polymers

Polymers have made our lives easier and brought many benefits to humanity. However, they've also had some unexpected negative influence on the environment and climate change. We can divide sustainable polymers into two main groups: biobased synthetic polymers and natural polymers. People have used natural polymers like cellulose, lignin, hemicellulose, starch, protein, and modified biopolymers to make bioplastics and composites, among other things [27, 37]. We can create synthetic biobased polymers from various types of molecular biomass, including amino acids, terpenes, furan, plant oils, and rosin acids [38-40]. Scientists have made big strides in turning biomass into polymers in the area of sustainable chemistry. Molecular biomass can boost bio-based polymers more like how we've engineered petrochemicals through molecular engineering. However, creating materials with the same or even better sustainable and economic qualities is a big challenge. Scientists often don't pay much attention to processing, but it can play a key role in improving material properties.

Performance Enhancement

Smart polymer composites are a type of sensible made up of a polymer matrix and smart fillers or elements that can counter external stimuli, such as temperature, light, and PH [38]. These materials might transform the edifice industry by presenting enhanced characteristics. Smart polymer composites can be engineered to adjust to Fluctuating loads and conditions, contributing to amended performance in the go-ahead and extreme settings, making them suitable for custom in high-performance and disaster-resistant buildings [30, 39]. Smart polymer composites can be engineered to self-repair in the event of damage, thereby reducing conservation and reparation costs and extending the life of the structure [25].

METHODOLOGY

In this approach commercialization of smart polymers in advanced composite structures researchers use the case study of the aerospace company Boeing [40, 19]. Boeing is the principal global aerospace manufacturer. It is the fourth largest defence independent in the world. Revenue on 2022 is the major exporter in the United States by dollar value. Boeing was started by William Boeing, Seattle, Washington, on July 15, 1916. The case study based on Boeing those methods is selected to provide an in-depth, contextual analysis of a specific instance for smart polymer commercialization [12].

Define Smart Polymer Unique Properties, Potential Advantages, and Current Status in The Research with Industrial Use

Smart polymers are stimuli-responsive polymers [4, 46]. These polymers can change their physical, & chemical properties according to environmental like temperature, pH, light, magnetic fields, or electric fields, etc. Adaptive Response by light is when exposed to specific wavelengths of light, transitions at specific temperatures, and change their solubility or swelling behaviour with pH changes, Polymers respond to electric & magnetic fields [13]. Case Study on Smart Polymer Integration in aerospace composite structures offers the potential for self-healing composites, which can enhance the safety and durability of aerospace components. Shape memory polymers (SMPs) have properties of smart materials that can return to their original shape after deformation when showing to a specific incentive such as heat. In aerospace applications, SMPs can be used to create self-healing composites, which can repair minor damages autonomously [42, 16].

The aerospace industry was selected due to its strict safety requirements and the high potential impact of self-healing composites [29, 5]. The XYZ aerospace company is an inventor in adopting advanced materials for aircraft structures. XYZ Aerospace Company is an innovation and commitment to safety. Shape Memory Polymers (SMPs) were added to carbon fiber reinforced polymer (CFRP) materials used in aircraft main body and wings [24,9]. These SMPs can fix small cracks(break) that form during flights, which helps the aircraft last longer and be safer. For research and development, aerospace collaborated with foremost universities and research institutes to develop the SMP composite. The project received funding from government aerospace innovation grants and commercialization. Models are exposed to difficult testing, flight conditions, and weakness tests. The self-healing ability is validated by repeated damage and repair cycles. The company operated closely with flight regulatory bodies to meet safety standards & obtain necessary certifications. Scaling up manufacturing meant improving how SMPs were added to the process of making CFRP. They worked with suppliers to ensure there was always enough high-quality SMP material. The main competitors were traditional CFRP composites and other emerging self-healing materials [44-10-1]. XYZ Aerospace's SMP composite offered a unique combination of lightweight, high-strength, and self-repair capabilities. The marketing strategy emphasized the safety and maintenance cost benefits of the SMP composite. Demonstrations and pilot projects were conducted with key customers [3,20]. Educating potential customers about the benefits and reliability of SMP composites was crucial. XYZ Aerospace conducted workshops and provided detailed technical documentation. The company secured additional funding through strategic partnerships and government grants [11-23-47]. Educating potential customers about the benefits and reliability of SMP composites was crucial conducted workshops and provided details. Financial constraints Initial development and certification costs were high. The company secured additional funding through strategic partnerships and government grants.

Company Overview

Imagine XYZ Aerospace, a leader in implementing advanced materials for aircraft structures. It has focused on innovation & safety. The company combined SMPs into carbon fiber reinforced polymer (CFRP) materials have aircraft bodies and wings. These SMPs can repair minor cracks during flights, increasing the longevity & safety of the aircraft.

Research and Development

To develop the SMP composite, XYZ Aerospace work together in leading universities and research institutes. The project received funding from government aerospace innovation grants. The SMP composite was tested under tough flight conditions to prove its self-healing abilities with repeated damage & repair cycles. The company worked closely with inflight regulatory bodies to meet safety standards & obtain necessary certifications.

Competition and Market Strategy

The main competitors were traditional CFRP composites & other emerging self-healing materials. XYZ Aerospace's SMP composite offered a unique combination of lightweight, high-strength, and self-repair capabilities. The marketing strategy highlighted the safety and maintenance cost benefits of the SMP composite [21, 22]. The company conducted demos and pilot projects with key customers and organized workshops to educate potential customers about the benefits and reliability of SMP composites. Detailed technical certification was provided to support these efforts [14].

Financial Considerations

Initial development and certification costs were high, but XYZ Aerospace secured additional funding through strategic partnerships and government grants [26]. These financial strategies helped overcome initial constraints and supported the project's success.

The Integration of Smart Polymers in Aerospace Composite Structures, Boeing

Integrating smart polymers into aerospace composite structures using reinforcement learning can be approached to solve this case study [24]. The algorithm demonstrates that reinforcement learning will be used to integration and performance of SMP composites in aerospace applications.

The Figure 1 presents a structured framework for the integration of smart polymers into aerospace composite structures that align with reinforcement learning. This framework is the objective to enhance the performance of materials by embedding smart polymers within them. The process defining the objective integrating SMPs and evaluating their performance under varying conditions. The State Space is defined by environmental factors like temperature and composite structures are exposed to these states Action Space encompasses the potential adjustments or actions that can be made to optimize the material's performance [7,2]. This critical component that measures the success of these actions, guiding

Journal of Polymer & Composites
Volume 12, Issue 6
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

the optimization process to ensure that the desired outcomes are achieved. The decision-making is initialized, evaluated, and optimized, ensuring continuous improvement. The framework emphasizes the importance of Implementation and Testing to validate the effectiveness of the strategies in real-world scenarios. This comprehensive approach ensures that the integration of SMPs into aerospace structures is both efficient and effective [17,43].

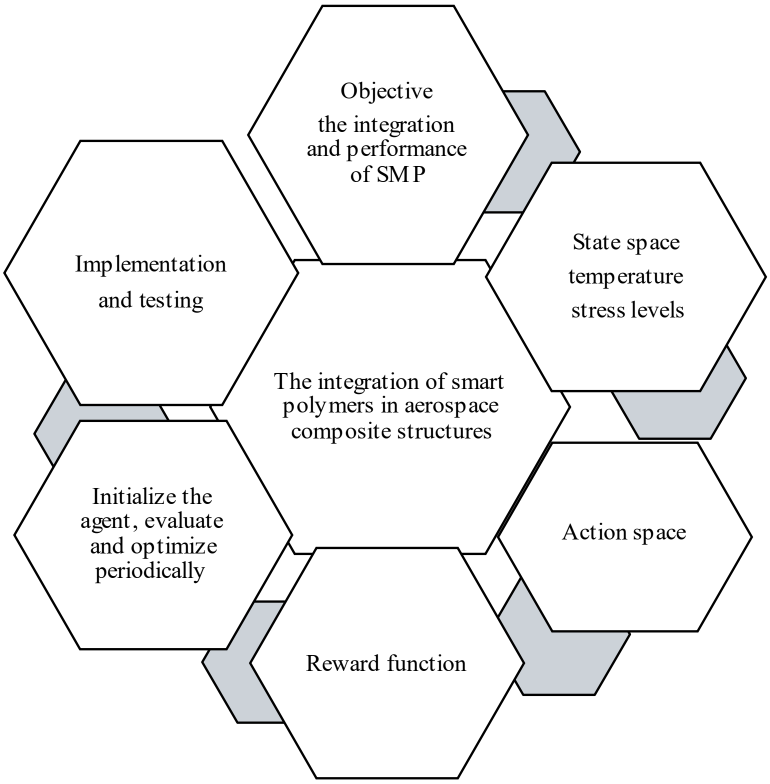

Figure1. The integration of smart polymers in aerospace. composite structures. created by author.

JOIN IN SMART POLYMERS IN AEROSPACE COMPOSITE STRUCTURES

1. Define state (S), action (A), and reward (R) spaces.
2. Training Loop (For each)
3. Reset values to get the initial state

While not done

- Select action using policy derived
- Execute action
- Observe reward
- Next state
- Update

4. Evaluate and Optimize
5 Implementation and Testing
6. Continuous Improvement

In the above algorithm smart polymers into aerospace composite structures based on reinforcement learning, start by defining the state (S), action (A), and reward (R) spaces. The state space has various conditions and configurations of the aerospace structures, such as temperature, stress levels, & material properties. The action space involves probable adjustments like modifying SMP attention and repair techniques. The reward function evaluates performance based on structural integrity, self-healing efficiency, and compliance with safety standards. The reinforcement learning agent trained a series of initial states. The agent will select an action using a policy derived from its learning algorithm, execute the action, observe the reward, and transition to the next state. The agent then updates its knowledge based on this experience. After training, evaluate & optimize the agent's performance refining the reward function and adjusting hyperparameters. Implement the optimized policies in real-world manufacturing & testing of SMP composites, ensuring they meet aerospace industry standards. Finally, continuously improve the system by retraining the agent with new data to adapt to changing conditions and requirements.

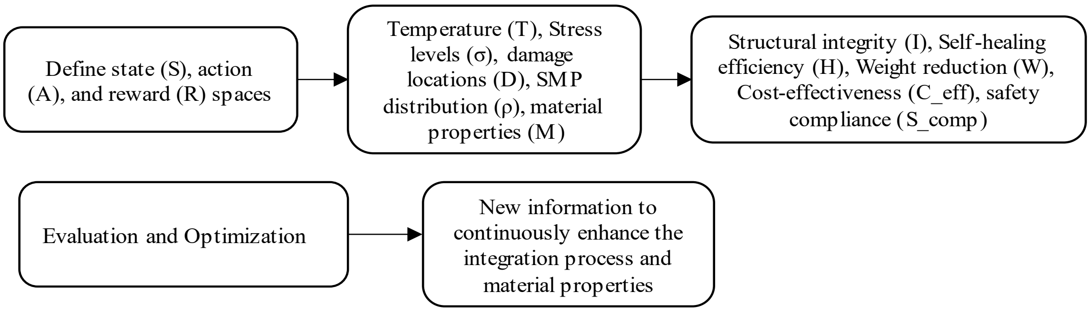

Figure 2. Reinforcement learning for smart polymer integration in aerospace composite structures. created by author.

Explain Figure 2 a basic application of reinforcement learning to enhance the performance of an adaptive small, vertical or angled delay at the tips of an aircraft's wings using a simplified environment. The state space (S) contains variables such as airspeed, angle of attack, aircraft's wing deflection, strain on the winglet, & temperature. The action space (A) consists of control signals for smart polymer actuators, represented as two continuous values. The reward (R) is a simplified lift-to-drag ratio calculated based on the state.

Table 1. Smart Polymers in Advanced Composite Structures for Industrial Applications Different Industries. Source https://www.avient.com/products/advanced-composites/explained.

Aspect	Aerospace	Automotive	Construction	Medical Devices	Consumer Electronics
Primary Applications	Adaptive winglets, morphing structures, vibration damping	Adaptive body panels, suspension components, sensors	Self-healing materials, adaptive facades, load sensors	Biocompatible implants, drug delivery systems	Flexible displays, wearable sensors
Key Benefits	Fuel efficiency, improved performance, reduced maintenance	Weight reduction, improved safety, enhanced performance	Increased durability, energy efficiency, reduced maintenance	Improved patient outcomes, personalized treatments	Enhanced user experience, device durability
Market Drivers	Fuel cost savings, regulatory compliance, performance demands	Fuel efficiency, emissions regulations, safety standards	Sustainability, longevity, energy efficiency	Aging population, advanced diagnostics, personalized medicine	Consumer demand for innovation, miniaturization
Challenges	High cost, long certification processes	Cost, integration with existing manufacturing processes	Cost, standardization, regulatory approval	Regulatory hurdles, biocompatibility, long-term stability	Rapid obsolescence, integration with existing technology
Future Prospects	Increased adoption in next-gen aircraft, smart materials	Integration into mass-market vehicles, smart materials	Expansion in green building projects, smart infrastructure	Growth in personalized medicine, advanced medical devices	Expansion in IoT devices, next-gen consumer products

Table 1 comparison table highpoints the commercialization parts of smart polymers popular advanced composite structures for work applications across different industries. Industry news portals & technical blogs, offer insights into the latest advancements and commercialization efforts in this rapidly growing market. By exploring these sources, gather comprehensive and up-to-date information on the use of smart polymers across different industrial applications.

THE IMPACT OF SMART POLYMERS IN AEROSPACE COMPOSITE STRUCTURES

```
import matplotlib.pyplot as plt
import numpy as np
components = ['Traditional Composite', 'Smart Polymer Composite']
lifespan = [10, 20]
mcosts = [50000, 20000]
conditions = np.arange(0, 10, 1)
tresponse = np.sin(conditions) * 50 + 50
spresponse = np.cos(conditions) * 50 + 100
plt.figure(figsize=(12, 8))
plt.subplot(2, 2, 1)
plt.bar(components, lifespan, color=['orange', 'green'])
plt.title("Lifespan of Components")
plt.ylabel("Years")
plt.ylim(0, 25)
plt.subplot(2, 2, 2)
plt.bar(components, mcosts, color=['orange', 'green'])
plt.title("Maintenance Costs Over 10 Years")
plt.ylabel("Cost ($)")
plt.ylim(0, 60000)
plt.subplot(2, 1, 2)
plt.plot(conditions, tresponse, label='Traditional Composite', marker='o')
plt.plot(conditions, spresponse, label='Smart Polymer Composite', marker='x')
plt.title("Adaptive Response Efficiency Under Varying Conditions")
plt.xlabel("Operational Conditions Index")
plt.ylabel("Response Efficiency (%)")
plt.legend()
plt.tight_layout()
plt.show()
```

Figure 3 shows the impact of smart polymers in aerospace composite structures towards Traditional and Smart Polymer Composite. The Python code generates a set of visualizations to compare two types of composites, traditional composite and smart polymer composite. A bar chart displays the lifespan of each composite, showing that the smart polymer composite lasts twice as long as the conventional composite. The second subplot is a bar chart of the maintenance costs over 10 years with the traditional composite being more expensive to maintain compared to the smart polymer composite.

WHICH OF THESE SOPHISTICATED COMPOSITES IS UTILIZED THE MOST FREQUENTLY?

The frequency of use for sophisticated composites often depends on the specific industry and application. Fiber-reinforced polymers (FRPs) include carbon fiber-reinforced polymers (CFRPs) and glass fiber-reinforced polymers (GFRPs) are widely used in high strength-to-weight ratios and are found in applications ranging from aerospace and automotive to civil engineering and sports equipment. Metal Matrix Composites (MMCs) are used in high-temperature and high-stress applications, such as aerospace components and high-performance automotive parts. Ceramic Matrix Composites (CMCs) are used in high-temperature environments, like turbine engines and heat shields. These FRPs are most frequently utilized due to their versatility and broad range of applications.

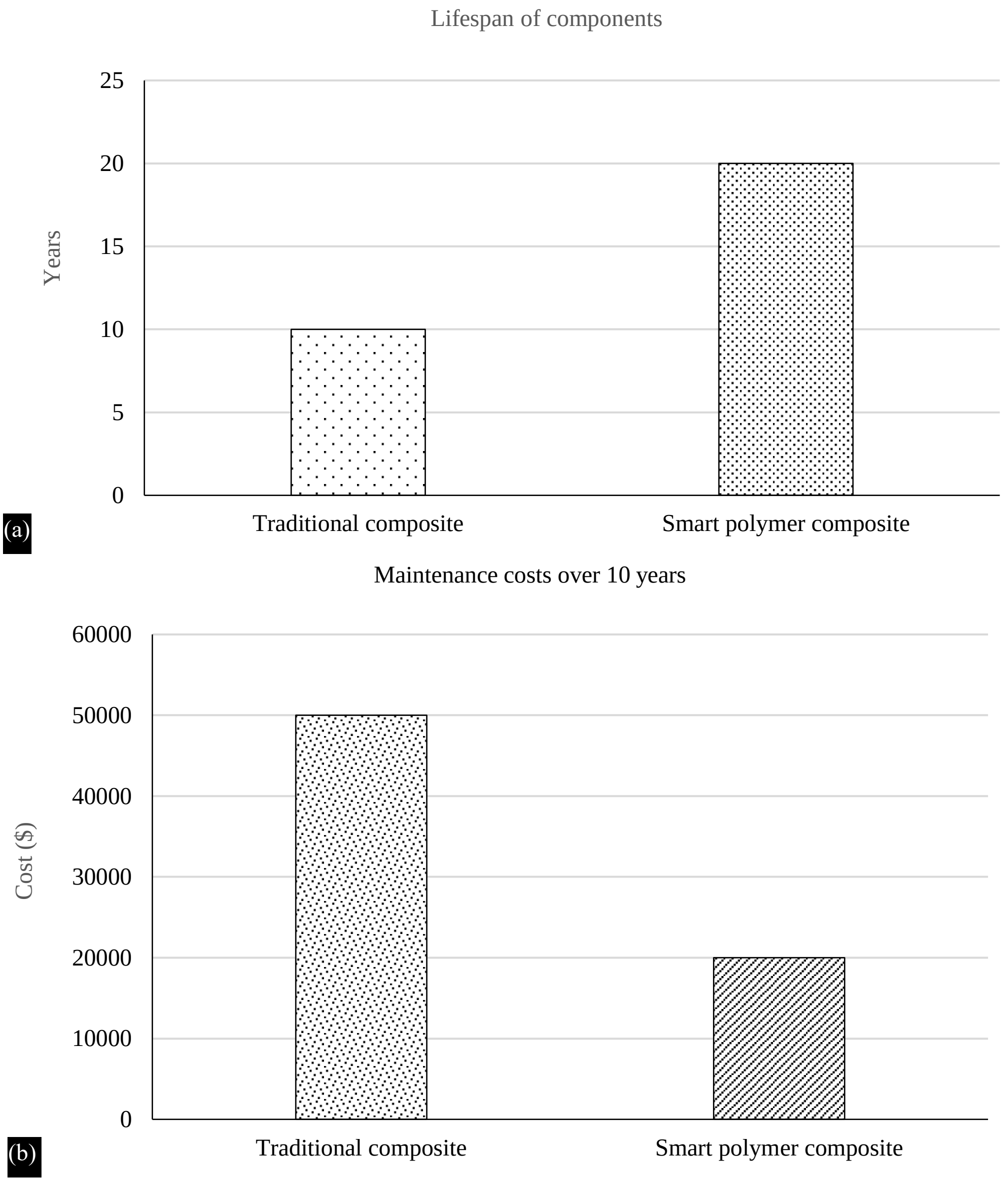

Figure 3. The impact of smart polymers in aerospace composite structures. created by author.

WHAT KINDS OF APPLICATIONS NEED COMPOSITES THAT ARE BASED ON POLYMERS?

Various kinds of applications need composites that are based on polymers like aerospace aircraft structures and components that require a combination of light weight and high strength. Automotive parts like body panels, bumpers, and internal components where weight reduction and impact resistance are important. Construction in concrete structures and for making durable and weather-resistant panels. Sports and restoration are high-performance equipment like bicycles, tennis rackets, and golf clubs. Marine as boat hulls and other components exposed to harsh marine environments. Medical devices, equipment that requires biocompatibility and strength.
These composites are based on polymers.

WHAT EXTENTS DO COMPOSITE MATERIALS FALL INTO THE THREE PRIMARY CATEGORIES?

Primary categories are Metal Matrix Composites (MMCs) consist of a metal matrix aluminium or titanium, ceramic and metallic fibres. These are high strength and thermal stability. Polymer Matrix Composites (PMCs) use a polymer such as epoxy or polyester as the matrix and are reinforced with fibres like glass or carbon. They are valued for their lightweight and high strength-to-weight ratio. Ceramic Matrix Composites (CMCs) involve a ceramic matrix reinforced with ceramic fibres or particles. They are used for their high-temperature fighting and thermal stability. This category has its specific properties and applications, making composites highly versatile and useful across various industries.

RESULT AND FINDINGS

The Figure 4 indicates the efficiency of the composite with the operational conditions index. The final line plot depicts the response efficiency of each composite under varying operational conditions. The traditional composites response efficiency pattern, the smart polymer composite pattern with higher response efficiency. This set of visualizations effectively highlights the comparative advantages of smart polymer composite in terms of lifespan, maintenance costs, and adaptive response efficiency. The visualizations are based on the impact of smart polymers in aerospace composite structures. The lifespan of components bar graph shows that components made with smart polymer composites have a longer lifespan compared to traditional composites. Maintenance costs, the second bar graph illustrates that over 10 years, maintenance costs are lower for smart polymer composites, indicating long-term cost savings. The adaptive response efficiency graph compares the adaptive response efficiency of traditional composites and smart polymer composites under varying operational conditions. Smart polymers demonstrate a more stable and efficient adaptive response which is crucial for aerospace applications. These graphs highlight the advantages of smart polymers in extending component lifespan, reducing maintenance costs, and enhancing adaptability in aerospace composite structures [41].

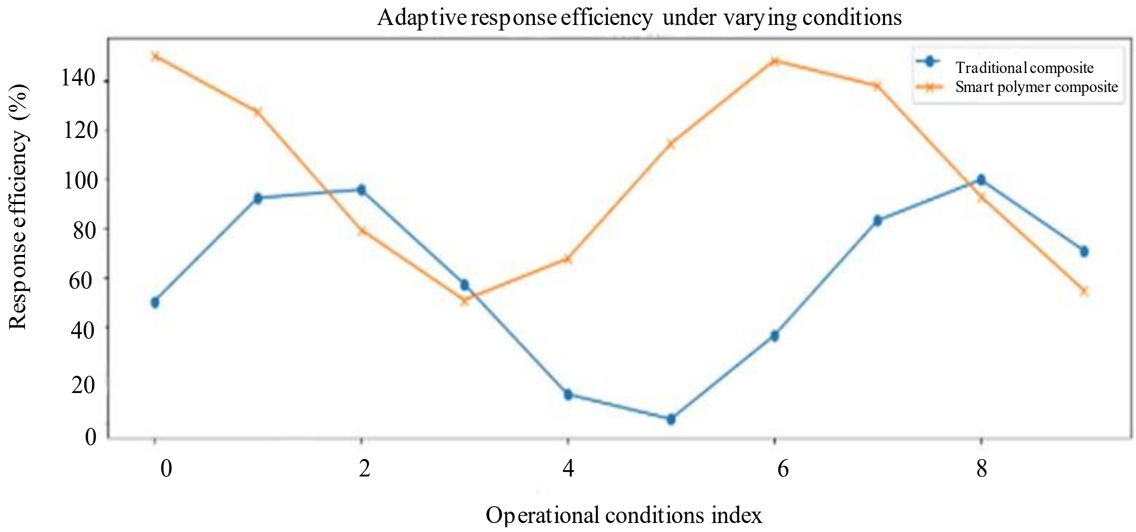

Figure 4. The efficiency of composite with operational conditions. created by author.

Self-healing properties allow for the autonomous repair of microscopic cracks, which extends the lifespan of components and reduces maintenance costs. Despite challenges in scalability and long-term reliability, ongoing research aims to advance multifunctional smart polymers that could revolutionize aerospace engineering. Smart polymers & aerospace composite structures are showing significant promise with their enhanced mechanical properties, adaptive capabilities, & self-healing functionalities. These materials improve the flexibility, strength, toughness, and damage resistance of composites, resulting in lighter and stronger aerospace components. Smart polymers enable adaptive structures that can dynamically alter their aerodynamic profiles, boosting efficiency. The results of incorporating smart polymers in aerospace structures can be illustrated through a comparison of traditional composites and smart polymer-enhanced composites across several key metrics. Component Lifespan graph showing the lifespan of components using traditional composites versus smart polymer composites. Maintenance Costs bar graph comparing the average maintenance costs over time for components made with traditional composites versus those enhanced with smart polymers. Adaptive Response Efficiency line graph representing the adaptive response efficiency of smart polymers in comparison to traditional composites under varying operational conditions [45,28].

CONCLUSION

The commercialization of smart polymers in advanced composite structures and the sustainable optimization of 3D printing processes can be achieved, leading to transformative advancements in both aerospace and additive manufacturing industries. The integration of reinforcement learning with resin-based 3D printing and the incorporation of smart polymers into aerospace composite structures both highlight the potential for significant advancements in their respective fields. For additive manufacturing, this combination not only enhances printing efficiency and quality but also promotes environmental sustainability by focusing on energy efficiency, waste reduction, and sustainable material selection. In aerospace engineering, smart polymers promise to revolutionize the industry with their superior performance, adaptability, and self-healing properties, despite the challenges in scalability and integration. Future research should continue to address these challenges, with a strong emphasis on sustainability and reliability.

Limitations and Future Scope

Aerospace composite structures smart polymers have several limitations. Scalability is a key encounter, with a need for developing cost-effective & scalable manufacturing processes. Long-term reliability is vital to ensure the stability & consistent performance of these materials. Integrating smart polymers into existing composite systems can be technically complex. Future research is focused on addressing these challenges to fully unlock the potential of smart polymers for advancing aerospace structures. Limitations in current research include restricted experimental conditions, insufficient data, & simplifications in modelling the resin-based 3D printing process and composite structures smart polymers. These limitations delay the ability to assess the robustness and significance of the findings presented. Future work should focus on addressing the scalability and long-term reliability of smart polymers, integrating them seamlessly into existing composite systems, and developing robust, data-rich models for resin 3D printing processes. By overcoming these challenges, the commercialization of smart polymers in advanced composite structures for industrial applications can be achieved, paving the way for significant advancements in aerospace & other high-tech industries.

REFERENCES

1. Kapoor, Radhika, and Indrajit Ghosal. "Will Artificial Intelligence Compliment or Supplement Human Workforce in Organizations? A Shift to a Collaborative Human–Machine Environment." International Journal on Recent Trends in Business and Tourism (IJRTBT) 6.4 (2022): 19-28.
2. Prasad, Bikram, and Indrajit Ghosal. "Perception of cancer patients towards the service quality of the healthcare industry: A paradigmatic research on serviceability." International Journal of Innovative Technology and Exploring Engineering 8.11 (2019): 676-681.
3. Ikram H, Al Rashid A, Koç M. Additive manufacturing of smart polymeric composites: Literature review and future perspectives. Polymer Composites. 2022 Sep;43(9):6355-80.
4. Nasar A, editor. “Smart Polymers and Composites”. Materials Research Forum LLC, 2018.
5. Ye L, Lu Y, Su Z, Meng G. Functionalized composite structures for new generation airframes: a review. Composites science and technology. 2005 Jul 1;65(9):1436-46.
6. Nadgorny M, Ameli A. Functional polymers and nanocomposites for 3D printing of smart structures and devices. ACS applied materials & interfaces. 2018 May 9;10(21):17489-507.
7. Mendes-Felipe C, Oliveira J, Etxebarria I, Vilas-Vilela JL, Lanceros-Mendez S. State-of-the-art and future challenges of UV curable polymer-based smart materials for printing technologies. Advanced Materials Technologies. 2019 Mar;4(3):1800618.
8. Guo Z, Poot AA, Grijpma DW. Advanced polymer-based composites and structures for biomedical applications. European Polymer Journal. 2021 Apr 15;149:110388.
9. Gibson RF. A review of recent research on mechanics of multifunctional composite materials and structures. Composite structures. 2010 Nov 1;92(12):2793-810.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

10. Oladele IO, Onuh LN, Siengchin S, Sanjay MR, Adelani SO. Modern applications of polymer composites in structural industries: a review of philosophies, product development, and graphical applications. Applied Science and Engineering Progress. 2023;17(1):6884.
11. Cardoso VF, Correia DM, Ribeiro C, Fernandes MM, Lanceros-Méndez S. Fluorinated polymers as smart materials for advanced biomedical applications. Polymers. 2018 Feb 8;10(2):161.
12. Collins MN, Nechifor M, Tanasă F, Zănoagă M, McLoughlin A, Stróżyk MA, Culebras M, Teacă CA. Valorization of lignin in polymer and composite systems for advanced engineering applications–a review. International journal of biological macromolecules. 2019 Jun 15;131:828-49.
13. Chen Y, Zhang J, Li Z, Zhang H, Chen J, Yang W, Yu T, Liu W, Li Y. Manufacturing Technology of Lightweight Fiber-Reinforced Composite Structures in aerospace: current situation and toward intellectualization. Aerospace. 2023 Feb 22;10(3):206.
14. Scheiner M, Dickens TJ, Okoli O. Progress towards self-healing polymers for composite structural applications. Polymer. 2016 Jan 28;83:260-82.
15. Oladele IO, Omotosho TF, Adediran AA. Polymer-based composites: an indispensable material for present and future applications. International Journal of Polymer Science. 2020;2020(1):8834518.
16. Koumoulos EP, Trompeta AF, Santos RM, Martins M, Santos CM, Iglesias V, Böhm R, Gong G, Chiminelli A, Verpoest I, Kiekens P. Research and development in carbon fibers and advanced high-performance composites supply chain in Europe: a roadmap for challenges and the industrial uptake. Journal of Composites Science. 2019 Aug 22;3(3):86.
17. Chopra, I., & Sirohi, J. (2009). Smart structures theory. *Advancement of Science*. https://doi.org/10.1017/CBO9781139025164
18. Baykara T. From the classical scheme to Asmart/functional materials system: a generic transformation of advanced materials technologies. Procedia-Social and Behavioral Sciences. 2015 May 11;181:79-88.
19. Ghosh AK, Dwivedi M, Ghosh AK, Dwivedi M. Advantages and applications of polymeric composites. Processability of polymeric composites. 2020:29-57.
20. Chauhan, P. S., & Bajpai, A. (2022). Polymer composites for tribological applications. *Advancement of Science*.
21. Mrazova M. Advanced composite materials of the future in aerospace industry. Incas bulletin. 2013 Jul 1;5(3):139.
22. Saleh Alghamdi S, John S, Roy Choudhury N, Dutta NK. Additive manufacturing of polymer materials: Progress, promise and challenges. Polymers. 2021 Feb 28;13(5):753.
23. Rajak DK, Pagar DD, Menezes PL, Linul E. Fiber-reinforced polymer composites: Manufacturing, properties, and applications. Polymers. 2019 Oct 12;11(10):1667.
24. Liu YD, Choi HJ. Recent progress in smart polymer composite particles in electric and magnetic fields. Polymer international. 2013 Feb;62(2):147-51.
25. Tian X, Todoroki A, Liu T, Wu L, Hou Z, Ueda M, Hirano Y, Matsuzaki R, Mizukami K, Iizuka K, Malakhov AV. 3D printing of continuous fiber reinforced polymer composites: development, application, and prospective. Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers. 2022 Mar 1;1(1):100016.
26. Mohd Nurazzi N, Asyraf MM, Khalina A, Abdullah N, Sabaruddin FA, Kamarudin SH, Ahmad SB, Mahat AM, Lee CL, Aisyah HA, Norrrahim MN. Fabrication, functionalization, and application of carbon nanotube-reinforced polymer composite: An overview. Polymers. 2021 Mar 26;13(7):1047.
27. Hollaway LC. The evolution of and the way forward for advanced polymer composites in the civil infrastructure. Construction and Building Materials. 2003 Sep 1;17(6-7):365-78.
28. Parmar H, Khan T, Tucci F, Umer R, Carlone P. Advanced robotics and additive manufacturing of composites: towards a new era in Industry 4.0. Materials and manufacturing processes. 2022 Apr 4;37(5):483-517.
29. Sharma A, Singholi AK. Effect of nanosilica on shape memory and mechanical characterization of polylactic acid wood composite. Polymer Composites. 2021 May;42(5):2502-10.
30. Al Rashid A, Khan SA, Al-Ghamdi SG, Koç M. Additive manufacturing: Technology, applications, markets, and opportunities for the built environment. Automation in Construction. 2020 Oct 1;118:103268.

31. Jagadeesh P, Puttegowda M, Rangappa SM, Siengchin S. Role of polymer composites in railway sector: an overview. Applied Science and Engineering Progress. 2022 May 27;15(2):5745-.
32. Bi X, Huang R. 3D printing of natural fiber and composites: A state-of-the-art review. Materials & Design. 2022 Oct 1;222:111065.
33. de Souza MC, Moroz I, Cesarino I, Leão AL, Jawaid M, Dias OA. A review of natural fibers reinforced composites for railroad applications. Applied Science and Engineering Progress. 2022 May 27;15(2):5800-.
34. Zheng N, Xu Y, Zhao Q, Xie T. Dynamic covalent polymer networks: a molecular platform for designing functions beyond chemical recycling and self-healing. Chemical Reviews. 2021 an 4;121(3):1716-45.
35. Yao K, Tang C. Controlled polymerization of next-generation renewable monomers and beyond. Macromolecules. 2013 Mar 12;46(5):1689-712.
36. Jain B, Sharma S. Green AI: Carbon-Footprint Decoupling System. Deep Learning Techniques for Automation and Industrial Applications. 2024 Jul 8:179-97.
37. Wilbon PA, Chu F, Tang C. Progress in renewable polymers from natural terpenes, terpenoids, and rosin. Macromolecular rapid communications. 2013 Jan 11;34(1):8-37.
38. Gandini A, Lacerda TM, Carvalho AJ, Trovatti E. Progress of polymers from renewable resources: furans, vegetable oils, and polysaccharides. Chemical reviews. 2016 Feb 10;116(3):1637-69.
39. Delidovich I, Hausoul PJ, Deng L, Pfützenreuter R, Rose M, Palkovits R. Alternative monomers based on lignocellulose and their use for polymer production. Chemical reviews. 2016 Feb 10;116(3):1540-99.
40. Ghosal I, Prasad B, Gupta B. Restructuring the green consumerism through e-commerce portals: a behavioural congruence during post-covid-19. InFuture of Work and Business in Covid-19 Era: Proceedings of IMC-2021 2022 Apr 12 (pp. 89-99). Singapore: Springer Nature Singapore.
41. Jain B, Ghosal I, Chotia A, Jayarathne PA. Blockchain and IOT Devices: A Futuristic Approach for Digital and Smart Supply Chain. In Applications of Block Chain technology and Artificial Intelligence: Lead-ins in Banking, Finance, and Capital Market 2024 May 25 (pp. 73-88). Cham: Springer International Publishing.
42. Dandotiya M, Ghosal I. An Impact of Cyber Security and Blockchain in Healthcare Industry: An Implementation Through AI. InNext-Generation Cybersecurity: AI, ML, and Blockchain 2024 May 19 (pp. 117-133). Singapore: Springer Nature Singapore.
43. Oladele IO, Omotosho TF, Adediran AA. Polymer-based composites: an indispensable material for present and future applications. International Journal of Polymer Science. 2020;2020(1):8834518.
44. Khalid MY, Arif ZU, Noroozi R, Zolfagharian A, Bodaghi M. 4D printing of shape memory polymer composites: A review on fabrication techniques, applications, and future perspectives. Journal of Manufacturing Processes. 2022 Sep 1;81:759-97.
45. Mirabedini A, Ang A, Nikzad M, Fox B, Lau KT, Hameed N. Evolving strategies for producing multiscale graphene-enhanced fiber-reinforced polymer composites for smart structural applications. Advanced Science. 2020 Jun;7(11):1903501.
46. Palaniappan M, Palanisamy S, Murugesan TM, Alrasheedi NH, Ataya S, Tadepalli S, Elfar AA. Novel Ficus retusa L. aerial root fiber: a sustainable alternative for synthetic fibres in polymer composites reinforcement. Biomass Conversion and Biorefinery. 2024 Mar 19:1-7.
47. Palaniappan M, Palanisamy S, Khan R, H. Alrasheedi N, Tadepalli S, Murugesan TM, Santulli C. Synthesis and suitability characterization of microcrystalline cellulose from Citrus x sinensis sweet orange peel fruit waste-based biomass for polymer composite applications. Journal of Polymer Research. 2024 Apr;31(4):105.
48. Ayrilmis N, Kanat G, Yildiz Avsar E, Palanisamy S, Ashori A. Utilizing waste manhole covers and fibreboard as reinforcing fillers for thermoplastic composites. Journal of Reinforced Plastics and Composites. 2024 Mar 7:07316844241238507.
49. Palanisamy S, Vijayananth K, Murugesan TM, Palaniappan M, Santulli C. The prospects of natural fiber composites: a brief review. International Journal of Lightweight Materials and Manufacture. 2024 Jan 19.

