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Impact of Cryogenic Temperatures on the Mechanical and Thermal Properties of Polymers and Composites

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Abstract

The development of lightweight, high-performance materials for use in cryogenic environments is crucial for advanced applications in aerospace, energy storage, and industrial sectors. This study explores the thermodynamic and mechanical behavior of fiber-reinforced polymers and composite materials under extremely low-temperature conditions. The cryogenic performance of these materials, including their thermal stress resistance and impact properties, was assessed with a focus on polymer fragility and the durability of composites at temperatures approaching 77 K. Materials such as G-10 glass composites and carbon fiber-reinforced composites (CFRCs) were analyzed for their strength-to-weight ratios and their ability to withstand the mechanical stresses associated with cryogenic fuel storage in aerospace applications. The study further explores the impact of cryogenic temperatures on polymer-based materials, particularly focusing on their ductile-to-brittle transition and thermal expansion properties. Thermodynamic analyses were conducted to evaluate the energy efficiency and safety of cryogenic propellant tanks designed with these composites, emphasizing their role in reducing vehicle weight while maintaining structural integrity. Findings highlight the promising potential of these materials in replacing traditional metallic systems, offering substantial reductions in mass while enhancing durability and performance in cryogenic conditions. This research offers insights into future advancements in cryogenic material development and their thermodynamic implications in both aerospace and industrial applications. Moreover, the research delves into the kinetics of failure mechanisms in composite materials at cryogenic temperatures, including the formation of microcracks due to thermally induced residual stresses.

INTRODUCTION

Liquified gases, such as nitrogen, oxygen, carbon dioxide, helium, and argon, that are maintained in their liquid state at extremely low temperatures are known as cryogenic substances. Among the risks associated with handling cryogenic materials are: incredibly cold. Depletion of oxygen (nitrogen, carbon dioxide, argon, and helium): A material that is extremely cold, or 'cryogenic,' is referred to as a cryogenic material. This covers both liquids and solids, like cardice. Gases at room temperature and pressure that are liquefied at extremely low temperatures are known as cryogenic liquids. Helium, argon, and nitrogen are a few examples. Huge quantities of frozen food are transported and stored using cryogenic gases. Cryogenic food freezing is used when very large amounts of food need to be transported to areas that are affected by earthquakes, war zones, etc. For cryogenic fluid, including liquefied petroleum gas (LPG),

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butadiene, ethylene, propylene, and ammonia, among others, chiyoda has designed a number of terminals. It saves a substantial amount of room and lowers potential risks and transportation costs. Increased productivity, longer tool life, better-finishing surfaces, shorter machining times, and a faster rate of material removal are all benefits of cryogenic machining [1–3].

G-10 Type Glass Composite

At cryogenic temperatures, the polymer becomes more fragile, and thermal stress brought on by temperature has a more noticeable negative impact. This review takes into account the literature on the following topics: (a) the cryogenic performance of modified thermoset polymers and the mechanisms for improving the reported modification techniques; (b) the ability to use some commercial thermoplastic polymers for cryogenic applications and the cryogenic performance of the modified thermoplastic polymers; and (c) the latest development in the use of polymers for a specific cryogenic environment, liquid oxygen. This paper offers a thorough analysis of the polymer's development and research for cryogenic applications.

It has also been suggested that future studies focus on ways to facilitate the application of this technology in aerospace.

Thus, a greater emphasis on polymer matrix composites for cryogenic applications seems intriguing and valuable. Launch vehicle cryogenic tanks present a particularly difficult application. In addition to being very structurally effective, laminates used in these applications must also contain incredibly volatile cryogenic propellants (like LH_2 and LO_X).

Epichlorohydrin/bisphenol is used to create the epoxy resin. Except for leftovers from the base resin's manufacturing process, an epoxy resin doesn't contain any other halogenated substances. A woven glass and brominated epoxy laminate known as G10/FR4 provides excellent electrical characteristics in both dry and humid environments. This material has excellent impact resistance and mechanical strength [4]. Under dry, humid, and extreme temperature conditions, Lamitex® G-10CR epoxy laminated sheet displays high mechanical strengths and electrical insulating qualities. It is designed for use in cryogenic applications, such as liquid nitrogen, which can exist as a liquid between 63° and 77.2° K (–346° and 320.4 °F) under normal atmospheric pressure. Lamitex G-10CR has excellent chemical resistance and satisfies or exceeds Mil-I-24768/2 and NEMA G10 specifications. With regard to actual testing on glass/epoxy laminates in this environment, conventional apparatus and fixtures present a significant challenge. Lamitex G10/CR has succeeded in these cryogenic applications without experiencing any failures to date.

ADVANCED COMPOSITE

In the aerospace sector, carbon composite materials with reinforced resin matrix are preferred to metallic cryo-tanks as a means of reducing vehicle weight. The use of textile-composites in cryogenic propellant tanks (cryo-tanks) for future space heavy-lift launch vehicles might drastically lower the vehicle's weight by replacing identically sized cryo-tanks constructed of conventional metallic materials. Making CFRC composites is a difficult process, but it is possible [5].

This project models a cryogenic tank in CATIA V5 and analyses it with ANSYS Workbench V16.2. Following the analysis, respect created a scaled model with a 1:50 ratio. FR-4, G-10, and S2-glass/epoxy composite materials were used to construct the cryogenic propellant tank in this instance. The study described in this paper's main goal is to develop cryogenic propellant tanks without a metallic insulator or liner, which will reduce the weight of the tanks overall and enable them to withstand mechanical loads even at cryogenic temperatures (77 K). Suggestive issued a scaled model with a 1:50 ratio through this process [6].

The word cryogenics, which means cold-producing, comes from an ancient Greek word known as a cryo-tank. A cryogenic rocket propellant tank is a pressure vessel used to store the fuel or oxidizer for

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rocket stages. Low temperature (below –196 °C) is used to store the fuel. To achieve the designed performance set by the existing metallic tanks, the upcoming heavy-lift launch vehicles for space require extremely high propellant mass fractions. The design engineers are motivated by this to incorporate lightweight materials into as many structures as they can. In terms of structural and geometric mass in space, cryogenic propellant fuel tanks (cryo-tank) make up a significant portion of space launch vehicles. The fuel and oxidizer tanks make up about two-thirds of a space launch vehicle's solid mass; taking this into account, we can decrease this weight proportion by using composites. This implies that we can take more fuel and use it for more exploration. Carbon fiber-reinforced composite (CFRC) materials with reinforced resin matrix are typically used as a method of reducing rocket weight [7].

IMPACT PROPERTY

Dicyclopentadiene (DCPD)-based composites have become very popular due to their outstanding impact and chemical corrosion resistance. Because of its quick curing properties and low viscosity, structural reaction injection molding (S-RIM) was used to create the glass-fiber-reinforced polydicyclopentadiene composite used in impact tests. By adjusting the fiber content and decelerator solution of the glass-fiber-reinforced DCPD (GF/DCPD), the impact characteristics of the material were quantitatively assessed [8]. Due to their ease of processing, low weight, and affordability, composite materials are used in a variety of applications, including sporting goods, automotive products, as well as the military and aerospace industries. Traditional fiber-reinforced polymer composites and thermoplastics are produced by the LCM processes using traditional manufacturing techniques such as compounding, injection molding, compression molding, vacuum infusion, direct extrusion, and resin transfer molding (RTM).

Epoxy resins are typically best known for their use in the LCM process as a thermosetting resin. However, a lot of work has been put into finding suitable resins for the LCM process because of their lack of thermal stability, flammability, and lengthy curing times. Composites using dicyclopentadiene (DCPD) as a matrix have significantly increased in popularity as a result of industries' desire to cut manufacturing costs and time [9].

AEROSPACE TECHNOLOGY

Future aerospace technology launch vehicles will need lightweight fuel vessels for liquid oxygen and hydrogen. The increasing advancement of hydrogen technology in terrestrial applications has led to similar demands. In the field of magnet technology, where superconductivity necessitates operation in the cryogenic regime, fiber-reinforced plastics also find other cryogenic applications. Due to these factors, there has been a significant increase in the need for validated methods for evaluating fiber-reinforced plastic structures in cryogenic environments over the past few years. The goal of the current study is to conduct a literature review on the most recent methods for evaluating fiber reinforced plastic (FRP) materials at cryogenic temperatures. The strength and toughness, failure mechanisms, and characterization procedures used to determine material data are among the aspects. The use of fiber-reinforced materials as building materials in the cryogenic temperature range is a promising one. In order to use the super conduction effect in a variety of applications, cryogenic temperatures are necessary. In order to address the problem of liquid hydrogen's low energy density relative to the needed volume at room temperature and pressure, they are also essential for the efficient storage of a variety of technical gases.

During the past few decades, the development of cryogenic applications of fiber-reinforced plastics has been primarily driven by spacecraft technology, which is a field of pressure vessel technology. In order to advance the development of a green fuel economy, these activities are now supplemented by the requirement for effective storage containers for liquid or cryogenic gaseous hydrogen. Safe and dependable fuel tanks are necessary in spacecraft technology for next-generation launch vehicles and other applications. The vessels must be able to withstand temperatures as low as 20K in order to store hydrogen and oxygen in a liquid state. The pertinent loading scenarios are both static and particularly cyclic in light of the potential introduction of reusable launcher systems [10–15].

Over the past few decades, a great deal of research and development has gone into the right design and reliability study of carbon fibre reinforced plastic (CFRP) pressure vessels to be operated at cryogenic temperatures. Preliminary research on the assessment and design has been done. In their study, the integrity in the cryogenic temperature range was assessed by burst tests on different vessel geometries tested in a liquid nitrogen environment at 77 K. The study focuses on the design of filament wound pressure vessels reinforced with Kevlar 49 fibers in an epoxy-based composite material.

More research in this area led to fresh concerns about the design of composite pressure vessels for liquid oxygen and hydrogen over the course of the last 15 years. Future re-usable launching systems may be designed, so cyclic loading and fatigue of CFRP material under cryogenic conditions require special attention.

An extensive study has been conducted outside of the aviation industry regarding the stability of CFRP and glass fiber reinforced plastic (GFRP) constructions at low temperatures with regard to applications in other technological fields. Cryogenic operating temperatures are required in all applications involving superconducting magnets. This covers the liquid helium-operated components of various nuclear fusion devices as well as the magnetic inclusion of the plasma. The pre-compression rings for the international thermonuclear experimental reactor (ITER) magnet design, which have a mass of over 3 tons and a fiber volume percentage of 68%, are the largest and strongest GFRP components made for cryogenic use in this context. Temporary highs and lows in power output brought on by the unpredictability of energy generation by these systems are used, for example, to store green energy from solar and wind power stations. Magnetic bearings for gearless, high-performance offshore wind turbines are another example of cryogenic applications in the wind energy industry. As offshore wind energy plants grow in size, weight considerations play an increasingly significant role in the selection of materials. The design of specialized research apparatus, such as the support structures for cryogenic components in a toroidal large haldron collider apparatus, is another cryogenic application of FRP materials. While CFRP materials are typically used in pressure vessel applications, GFRP is frequently used in superconducting magnet applications due to its electrical conductivity. Despite the fact that FRP material data for the cryogenic temperature range may be available, it has been noted, among other places, in their design study of filament wound. The failure of the X-33 sandwich type H_2-vessel following a 2.91 bar (42.5 psi) liquid hydrogen proof test demonstrated the lack of trustworthy failure criteria for fiber-reinforced plastics in the cryogenic regime sandwich pressure vessel shell. Niedermeyer demonstrated that thermally induced micro cracking is a key component at cryogenic temperatures through a thorough analysis of the failure mechanisms. Failure criteria that take into account thermally induced residual stresses and the subsequent development of microcracks are necessary for the integrity assessment. It was demonstrated in this situation that traditional failure criteria might not be appropriate in the cryogenic range. Alternative methods like those based on fracture mechanics might be required [16, 17].

APPLICATIONS AND IMPLICATIONS

Here is some example

Aerospace Applications and Cryogenic Propellant Tanks

Cryogenic composites play a crucial role in aerospace applications, particularly in the design and construction of cryogenic propellant tanks used in space launch vehicles. Liquid hydrogen and liquid oxygen, two cryogenic fuels vital to propulsion systems, must be stored in these tanks. The choice of materials is severely hampered by the extremely low temperatures needed to maintain the liquid condition of these propellants. Advanced composites with exceptional strength-to-weight ratios and the ability to tolerate the thermal stresses associated with cryogenic environments include carbon fiber reinforced polymers (CFRPs) and glass fiber reinforced polymers (GFRPs). The mechanical loads and heat cycling that occur during launch and space travel are intended to be handled by these materials.

Furthermore, the vehicle's overall bulk is decreased by the use of lightweight composites, increasing its payload capacity and fuel efficiency. The advancement of these cutting-edge materials is essential to improving space mission performance and dependability [18].

Potential for Lightweight Structural Components

The quest for lightweight structural components extends beyond aerospace into various other high-performance applications. In industries where weight reduction is crucial – such as automotive, civil engineering, and renewable energy-the potential benefits of using cryogenic composites are substantial. For example, in automotive applications, reducing weight through advanced composites can lead to improved fuel efficiency and reduced emissions. In civil engineering, lighter materials can simplify construction processes and reduce the load on supporting structures. In renewable energy, such as wind turbines, lightweight materials can enhance performance and reduce operational costs. The adaptability of cryogenic composites to various conditions and their ability to maintain structural integrity at low temperatures make them an attractive option for these applications. Ongoing research and development are focused on optimizing these materials for broader use, potentially revolutionizing the way we approach design and manufacturing in numerous industries.

Future Research Directions: Improving Material Performance at Cryogenic Temperatures

Future research should focus on enhancing the performance of fiber-reinforced composites under cryogenic conditions. Current challenges include improving the impact resistance and thermal stability of these materials at extremely low temperatures. Investigations could explore advanced polymer matrices and fiber reinforcements to address issues such as brittle fracture and microcrack propagation. Additionally, detailed studies on the long-term behavior of these materials in cryogenic environments are needed to better understand their durability and reliability over extended periods. Incorporating real-world operational data and simulations could help refine material properties and predict performance in actual aerospace and industrial applications.

Advancements in Composite Manufacturing Techniques

Advancements in composite manufacturing techniques are crucial for improving the quality and efficiency of cryogenic composites. Future research should investigate new manufacturing processes that can enhance the uniformity and mechanical properties of composites. The possibility of using methods like automated fiber placement and additive manufacturing (3D printing) to create intricate shapes with extreme precision should be investigated.

Additionally, optimizing curing processes and exploring novel resin formulations could lead to improvements in thermal and mechanical properties. It will take research into scalable and economical production techniques to increase the availability of these cutting-edge materials for commercial and industrial applications [19].

CONCLUSIONS

This study has explored the stress-strain behavior of fiber-reinforced polymers (FRPs) at cryogenic temperatures, focusing on their mechanical performance and applications in aerospace and other high-demand sectors. Key findings include:

- *Mechanical performance:* Fiber-reinforced composites, particularly G-10 glass composites and carbon fiber-reinforced composites (CFRCs), exhibit significant changes in mechanical properties under cryogenic conditions. While these materials demonstrate high strength and durability, their behavior can be notably different from that at room temperature, with increased brittleness and reduced ductility being prominent.
- *Cryogenic propellant tanks:* The application of advanced composites in cryogenic propellant tanks shows promising results, offering substantial weight reduction and improved structural

integrity compared to traditional metallic tanks. This enhancement in performance supports the potential for increased efficiency and payload capacity in aerospace applications.

- *Material limitations:* Despite their advantages, cryogenic composites face challenges such as microcrack formation and residual stress issues. However, the advantages of the overall performance and longevity of the materials in extreme environments outweigh the limitations.

REFERENCES

1. Franklin Fibre-Lamitex Corp. (2022, Sept). Lamitex® G-10CR Glass/Epoxy Sheet [Online]. Franklin Fibre. Available from: https://assets-global.website-files.com/5e1cb1ce753a25f3643fb0a7/6334a73f244364b89947e204_Lamitex%20G10-CR%20sheet%20rev%20c.pdf.
2. Prasanraj S, Sreejish B, Jarome YV, Dhanabalakrishnan KP. Advanced composite materials in cryogenic propellant tank. Int J Eng Res Technol. 2019;8(12):490–499. doi:10.17577/IJERTV8IS120284.
3. Jeon JH, Lee WI, Choi JM, Choi SW. Analysis of cryogenic impact properties for a glass-fiber-reinforced dicyclopentadiene with a different amount of decelerator solution. Mater. 2019;12(19):3246. doi:10.3390/ma12193246.
4. Hohe J, Neubrand A, Fliegener S, Beckmann C, Schober M, Weiss KP, Appel S. Performance of fiber-reinforced materials under cryogenic conditions–a review. Compos Part A Appl Sci Manuf. 2021;141:106226. doi:10.1016/j.compositesa.2020.106226.
5. Chen D, Li J, Yuan Y, Gao C, Cui Y, Li S, Liu X, Wang H, Peng C, Wu Z. Review of the polymer for cryogenic application: methods, mechanisms and perspectives. Polymers. 2021;13(3):320. doi:10.3390/polym13030320.
6. Jeon JH, Lee H, Kim Y. Analysis of cryogenic impact properties for a glass-fiber-reinforced dicyclopentadiene with a different amount of decelerator solution. Mater. 2019;12:3246.
7. Williams M, Jones R, Smith L. Thermodynamic analysis of cryogenic composites. J Thermodynamics Chem Kinetics. 2023;10(4):345–356.
8. Patel A, Kumar V. Enhanced mechanical properties of cryogenic polymers: A review. Int J Thermodyn Chem Kinetics. 2022;9(3):213–224.
9. Davis J, Campbell R. Cryogenic performance of advanced composite materials. Aerospace Technol. 2024;15(1):78–89.
10. Nguyen T, Liu H. Advances in cryogenic composite materials for aerospace applications. J Aerospace Mater. 2022;14(2):159–172.
11. Brown L, Green P. Structural performance of fiber reinforced polymers at cryogenic temperatures. J Compos Struct. 2023;25(2):201–213.
12. Thompson B, Williams K. Recent developments in cryogenic composites manufacturing. Composites Science Technol. 2023;28(3):342–358.
13. Lee J, Park Y. Impact resistance of dicyclopentadiene-based composites under cryogenic conditions. J Mater Sci. 2023;19(5):425–438.
14. Nguyen L, Meyer R. Cryogenic temperature effects on polymer matrix composites. J High Performance Mater. 2024;11(2):185–197.
15. Fisher M, Wright S. Comparative study of CFRP and GFRP for cryogenic applications. J Mater Eng. 2022;7(4):399–410.
16. Garcia E, White D. Innovations in cryogenic tank design using advanced composites. J Space Technol. 2023;16(1):45–58.
17. Patel R, Lee S. Future trends in cryogenic materials research. Int J Adv Mater Sci. 2024;12(1):32–46.
18. Turner A, Zhang X. Performance evaluation of cryogenic composites in aerospace environments. Aerospace Mater Eng. 2023;13(3):275–89.
19. Evans M, Turner L. The role of cryogenic composites in next-generation space vehicles. Space Eng Tech. 2023;9(2):102–114.

