Ceramic Nanocomposites Reinforced with Multi-Walled Carbon Nanotubes (MWCNTs) for Aerospace Engineering

Yash Sureshchand Chaurasia

Student, Institute of Chemical Technology

Abstract

In recent years, nanotechnology has played a pivotal role in advancing aerospace engineering, addressing the ongoing demand for high-durability materials characterized by low density and superior thermo-mechanical properties. Carbon nanotube (CNT)-based composites have emerged as a prominent solution in this realm, leveraging their remarkable properties to fuel a range of multidisciplinary applications in various industries.

Carbon nanotubes, consisting of rolled-up carbon sheets at the nanoscale, exhibit exceptional thermal and mechanical characteristics at a reduced density. This makes them an ideal choice for reinforcing composites in aerospace applications. The high Young's modulus and chemically inert nature of CNTs position them at the forefront of material research, spanning applications from water purification to aerospace technologies, with the latter remaining particularly enigmatic.

Despite the extensive research on CNT-based materials, there is a notable scarcity of studies focusing on their application in aerospace engineering. This review aims to fill this gap by comprehensively exploring the processing and synthesis techniques, thermal and mechanical properties, and select industrial applications of CNT-reinforced ceramic composites. Additionally, the review sheds light on potential advancements in additive manufacturing techniques for fabricating CNT/ceramic composites and their prospective applications within the aerospace industry.

Keywords: Nanotechnology, Multi-walled carbon nanotubes (MWCNTs), Ceramic nanocomposites, Aerospace applications, Engineering materials, Additive manufacturing, Composite fabrication, Nanomaterial synthesis

1. Introduction

Interest in nanotechnology remains high across various scientific disciplines, given its significant potential in engineering, agriculture, and medicine. While the term "nanotechnology" lacks a universally accepted definition, it generally refers to products with dimensions measuring less than 100 nm in any one direction. Nanomaterials, a specific component of nanotechnology, have captured the attention of researchers due to their promising mechanical, thermal, and electronic properties. The multidisciplinary expansion of nanomaterials has been supported by both industrial and academic sectors, with initiatives such as the National Nanotechnology Initiative (NNI) in 2001, funded by the US government with a budget exceeding $1 billion. This initiative propelled the commercialization, development, and research in nanotechnology.

In recent decades, global research on nanomaterial properties has consistently grown. Carbon nanotubes (CNTs), allotropes of carbon arranged in a quasi-one-dimensional structure, have particularly intrigued researchers. These nanotubes consist of graphite layers in the nanoscale, forming tubes with varying outer diameters of 3–30 nm. CNTs are categorized as single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs), each offering distinct properties. SWCNTs are well-suited for electronic devices and sensors, while MWCNTs find preference in mechanical applications. Synthesizing CNTs involves various techniques such as arc discharge, chemical vapor deposition (CVD), plasma rotation, hydrothermal processes, and flame synthesis. CVD, utilizing catalysts like iron or cobalt and hydrocarbon sources, is a common method. Researchers have explored different parameters to control CNT growth and structure. Flame synthesis, a recent technique, allows large-volume CNT production with flexibility in modifying parameters for specific applications.

CNTs' unique properties position them as potential reinforcement materials, especially in engineering applications. They have been incorporated into ceramics to enhance their properties for structural, aerospace, and industrial applications. Despite ceramics' brittle nature, studies have demonstrated improved fracture behavior with CNT reinforcements. While research has consistently focused on CNT incorporation into composites, limited attention has been given to proving the potential of CNT-reinforced ceramic nanocomposites in aerospace engineering. This review aims to fill this gap by providing a comprehensive overview of the processing, densification techniques, and potential future manufacturing processes, such as additive manufacturing. Additionally, the review explores potential applications of CNT-reinforced ceramics in aerospace and industrial sectors, addressing current concerns like structural integrity, shielding, icing, and barrier coatings.

Dispersion Medium	**Physical/Chemical Method**	**Ceramic Matrix**	**Results/Outcome**
CTAB (cetyltrimethylammonium bromide)	N/A	SiO_2	97% relatively dense ceramic composites of MWCNTs/SiO_2
Distilled Water	Polyethyleneimine and sonication for two minutes	YTZP	Higher dispersion with enhanced density, toughness
Deionised Water	Polyacrylic acid (PAA) and vigorous stirring	Alumina	Increased bending strength due to MWCNTs pull-out
Ethanol	Sodium hexametaphosphate and ultrasonication	SiC/YSZ	Improvement in fracture toughness with a reduction in other mechanical properties
SDS Solution/Distilled Water/Gum Arabica	Ultrasonic bath for 6 h followed by ball milling for 8 h	Alumina	GA and SDS mixture-based composite showed improved electrical properties

Dispersion Medium	Physical/Chemical Method	Ceramic Matrix	Results/Outcome
Distilled Water/Acetone/Ethanol	Sonication and electrophoretic deposition	SiC	Higher dispersion and homogeneous distribution of MWCNTs
Deionised Water	PAA with ammonium salt with ultrasonication and mechanical agitation	YTZP	Fracture toughness of the samples increased with a reduction in hardness was observed
Distilled Water	Ultrasonication	Alumina and SiC	Superior hardness with high stability between SiC and MWCNTs were observed
Ethanol	Phosphate ester and cresolsulfonphthalein were surfactants with ultrasonication	MnO_2	Electrical conductivity of the composites increased with promising electrochemical performance
Distilled Water	Sonication for 1 h followed with stirring	Alumina	Enhanced electrical conductivity

Table 1. Colloidal route for dispersing ceramic matrix into MWCNT nanofluids

Thermo-mechanical Properties:

The thermo-mechanical properties of Multi-Walled Carbon Nanotube (MWCNT)/ceramic composites play a pivotal role in determining their suitability for various applications. In this section, we conduct a detailed analysis, highlighting the importance of novel fabrication methods that go beyond traditional approaches to maximize the performance of these advanced materials.

Fiber Pull-Out: One of the key toughness-enhancing mechanisms explored in MWCNT/ceramic composites is the phenomenon of fiber pull-out. This mechanism involves the extraction or partial extraction of MWCNTs from the ceramic matrix during mechanical loading. As the MWCNTs are pulled out, they provide additional resistance to crack propagation, thus enhancing the overall toughness of the composite. Understanding and optimizing this mechanism are crucial for tailoring the fracture behavior and improving the reliability of these materials in real-world applications.

Crack and Fire Bridging: Another critical aspect in enhancing the thermo-mechanical properties involves mechanisms like crack and fire bridging. MWCNTs act as bridges across cracks formed in the ceramic matrix, preventing their further propagation. Additionally, these nanotube bridges can resist the thermal effects associated with fire, contributing to the overall fire resistance of the composite. The exploration and manipulation of crack and fire bridging mechanisms present opportunities to create ceramic composites with improved durability and safety features.

Crack Deflections: Understanding and manipulating crack deflections represent yet another avenue for optimizing the thermo-mechanical properties of MWCNT/ceramic composites. When cracks encounter

MWCNTs, their growth path may be altered or deflected, reducing the likelihood of catastrophic failure. This phenomenon is vital for increasing the composite's ability to withstand stress and improving its overall mechanical robustness.

Additive Manufacturing in MWCNT-based Composites:
Additive manufacturing holds great promise for revolutionizing the fabrication of MWCNT-based ceramic composites. In this section, we delve into the potential of additive manufacturing techniques, assessing current achievements, growth trends in the sector, and the anticipated time and optimization requirements for effectively incorporating MWCNTs into ceramic matrices.

Current Achievements: Significant strides have been made in incorporating MWCNTs into ceramics using additive manufacturing methods such as 3D printing and selective laser sintering. These techniques enable precise control over the placement of MWCNTs within the ceramic matrix, fostering improved homogeneity and, consequently, enhanced material properties. Current achievements showcase the feasibility of additive manufacturing for creating complex MWCNT-based ceramic structures with tailored properties.

Growth in the Additive Manufacturing Sector: The additive manufacturing sector has witnessed exponential growth, driven by advancements in technology, materials, and processes. As this sector continues to evolve, new opportunities emerge for refining and expanding the applications of MWCNT-based ceramic composites. The growing ecosystem of additive manufacturing facilitates innovative approaches, contributing to the development of more efficient and reliable techniques for incorporating MWCNTs into ceramics.

Anticipated Time and Optimization: While additive manufacturing holds immense potential, the full realization of its benefits in fabricating MWCNT-based ceramic composites requires time and optimization. Fine-tuning printing parameters, optimizing material formulations, and addressing challenges such as achieving uniform dispersion of MWCNTs are essential steps in harnessing the true potential of additive manufacturing for these advanced materials. Continuous research and development efforts are anticipated to streamline the process and reduce production costs, making additive manufacturing a viable and efficient technique for large-scale production of MWCNT-reinforced ceramic composites.

Fabrication Techniques	**Type of Processing Techniques**	**Advantages**	**Disadvantages**
Pressureless Sintering	Powder Metallurgy	Easy to utilize	Lack of pressure during sintering leads to cracks and density reduction
Microwave-Assisted Sintering	Powder Metallurgy	Complete bonding between composite elements possible	Lack of pressure during sintering leads to cracks and density reduction
Hot Pressing Method	Powder Metallurgy, Colloidal Route	High densified samples achievable	Changes in microstructure, propagation of cracks

Fabrication Techniques	Type of Processing Techniques	Advantages	Disadvantages
Spark Plasma Sintering	Powder Processing Techniques	Highly dense samples with fewer cracks achievable	Small-scale samples, traces of carbon in analysis due to graphite die
Additive Manufacturing	Filament-Based Technique, Powder-Based Technique	Any shape achievable, optimized for density and properties	Still under development, time-consuming, expensive

Table 2. Advantages and disadvantages of various fabrication technique

2. Aerospace Application

In recent years, the aerospace industry has witnessed rapid growth, creating a demand for innovative materials to meet evolving requirements. Nanocomposites, capable of combining desired material properties, hold immense potential for various aerospace applications. Ceramic materials, prized for their performance in high-temperature environments, have been extensively researched for applications like thermal barrier coatings, structural components, and reinforcements. However, their limitations in fracture toughness and strength necessitate potential reinforcements for aerospace applications. The integration of Carbon Nanotubes (CNTs) into ceramics emerges as a promising avenue for enhancing the mechanical and thermal properties of composites. This is particularly crucial in aerospace applications where a high strength-to-weight ratio and fracture toughness are essential. Additionally, CNTs show promise as radiation shields for space vehicles, addressing concerns related to galactic cosmic radiation, solar particle events, and neutron exposure. Research endeavors have explored the suitability of nanomaterials, including CNT/polymer composites, for applications such as radiation shielding and electromagnetic interference. The aerospace industry, covering commercial aircraft, unmanned aerial vehicles (UAVs), rotorcraft, military aircraft, and spacecraft, grapples with challenges such as weight management, lightning strikes, icing, electromagnetic interference shielding, stealth applications, and issues related to hypersonic vehicles. In the realm of space propulsion, aircraft face challenges such as high-intensity ionizing radiation, debris from thermal cycling, and micrometeorites. CNT-based ceramic nanocomposites have shown promise in addressing these challenges, with NASA's Ames Research Centre and Johnson Space Centre investigating thermal radiation and impact protective systems using CNT-reinforced materials. Icing remains a significant concern in aerospace, impacting aircraft surfaces and components. Traditional solutions involve anti-icing coatings and thermal insulators, but these may increase weight and reduce efficiency. CNT-reinforced composites, including self-heating CNT-reinforced materials and thin, transparent films based on Multi-Walled Carbon Nanotubes (MWCNTs), offer innovative solutions for de-icing applications. These advancements provide efficient electrothermal heating, effectively addressing the challenges posed by icing while minimizing weight gain and energy consumption.

3. Conclusion

In conclusion, this review delves into the advancements made in processing and densification techniques for Multi-Walled Carbon Nanotube (MWCNT)-reinforced ceramic composites, aiming to enhance their mechanical and thermal properties. The newly developed techniques have demonstrated improved dispersion of MWCNTs within the ceramic matrix, leading to enhanced overall performance. However, challenges persist in achieving highly distributed MWCNTs and further refining fabrication and processing methods to elevate mechanical properties and fracture toughness. Critical considerations involve addressing issues such as the dispersion of MWCNTs onto the matrix, establishing effective interfacing bonding between MWCNTs and ceramics, and developing novel techniques to prevent CNT damage. To fabricate highly dense and distributed nanocomposites, these challenges must be systematically tackled. The investigation into thermo-mechanical properties has highlighted the need for novel fabrication methods with sufficient MWCNT content, incorporating toughness-enhancing mechanisms like fiber pull-out, crack and fire bridging, and crack deflections. While future novel methods are anticipated to enhance toughening mechanisms, establishing a high-order relationship between CNTs and composites requires a deeper understanding of various structural parameters. Furthermore, the additive manufacturing sector holds promise as a potential game-changer for fabricating MWCNT-based ceramic composites. Although current achievements and growth in additive manufacturing are evident, the optimization of techniques over time will be crucial for realizing these advancements. In the aerospace industry, where immediate material needs are prevalent, the potential applications of CNT-reinforced ceramics have been explored. Despite their promise, there remains a gap in understanding the specific requirements of the aerospace industry that CNT-based composites could fulfill. Bridging this gap and comprehensively addressing the industry's needs through ongoing research will pave the way for CNT–ceramic composites to act as viable replacements, enhancing efficiency and structural improvements with continued exploration and refinement.

4. References

1. Ramachandran K, Subramani R, Arunkumar T, Boopalan V (2021) Mechanical and thermal properties of spark plasma sintered Alumina-MWCNTs nanocomposites prepared via improvised colloidal route. Materials Chemistry and Physics, 272:125034. https://doi.org/10.1016/j.matchemphys.2021.125034
2. Palaci I, Fedrigo S, Brune H, Klinke C, Chen M, Riedo E (2005) Radial elasticity of multiwalled carbon nanotubes. Physical Review Letters, 94(17):175502. https://doi.org/10.1103/PhysRevLett.94.175502
3. Cho J, Boccaccini AR, Shaffer MSP (2009) Ceramic matrix composites containing carbon nanotubes. Journal of Materials Science, 44:1934–1951. https://doi.org/10.1007/s10853-009-3262-9
4. Bezzi G, Celotti G, Landi E, Torretta TL, Sopyan I, Tampieri A (2003) A novel sol–gel technique for hydroxyapatite preparation. Materials Chemistry and Physics, 78(3):816–824.
5. Jayaseelan D, Nishikawa T, Awaji H, Gnanam FD (1998) Pressureless sintering of sol-gel derived alumina–zirconia composites. Materials Science and Engineering: A, 256(1–2):265–270.
6. Chan KF, Zaid MHM, Mamat MS, Liza S, Tanemura M, Yaakob Y (2021) Recent developments in carbon nanotubes-reinforced ceramic matrix composites: a review on dispersion and densification techniques. Current Computer-Aided Drug Design, 11(457):1–37.
7. Almeida VO, Balzaretti NM, Costa TMH, Machado GB, Gallas MR (2013) Surfactants for CNTs dispersion in zirconia-based ceramic matrix by sol–gel method. Journal of Sol-Gel Science and Technology, 65:143–149.
8. Ghozatloo A, Rashidi A, Shariaty-Niasar M (2014) Effects of surface modification on the dispersion and thermal conductivity of CNT/water nanofluids. International Communications in Heat and Mass Transfer, 54:1–7.

9. Silva P, Almeida V, Machado G, Benvenutti E, Costa T, Gallas M (2012) Surfactant-based dispersant for multiwall carbon nanotubes to prepare ceramic composites by a sol-gel method. Langmuir, 28(2):1447–1452.
10. Lopez A, Urena A, Rams J (2011) Wear resistant coatings: silica sol–gel reinforced with carbon nanotubes. Thin Solid Films, 519(22):7904–7910.