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Nanomaterials in aerospace: Revolutionizing flight and exploration through nanoscale advancements

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Abstract. The rapid advancements in nanotechnology have paved the way for the exploration of innovative materials with unique properties that were once considered unattainable. As industries worldwide strive for more efficient and high-performance solutions, the aerospace sector, in particular, has recognized the immense potential of integrating nanomaterials to push the boundaries of what's achievable in aviation and space exploration. This paper delves into the history, characteristics, and advantages of nanomaterials, with a distinct focus on their application in aerospace. Nanomaterials, characterized by at least one dimension between 1 to 100 nanometers, exhibit unique properties, such as enhanced strength, lightweight attributes, wear resistance, high-temperature tolerance, and eco-friendliness. Notably, nanocomposites in aerospace structures can lead to weight reductions of up to 30%. The article also highlights specific nanomaterials like carbon nanotubes, nano-ceramics, and graphene, emphasizing their mechanical and structural properties. In aerospace applications, nanomaterials have been instrumental in strengthening aircraft structures, developing wear-resistant coatings, optimizing fuel additives, and thermal insulations, and enhancing sensor performances. Given the transformative impact of nanomaterials in the aerospace domain, they offer a promising avenue for future research and development, with the potential to revolutionize modern aerospace technologies.

Keywords: Nanomaterials, Aerospace applications, Composite materials

1. Introduction

The aerospace field has now become an indispensable and significant domain for every country, representing a crucial step for humanity into the unknown. This field is increasingly intertwined with emerging technologies, especially benefiting from the undeniable contributions of nanomaterials. Nanomaterials are a relatively recent class of materials, defined as substances where at least one dimension is within the nanoscale range, typically ranging from 1 to 100 nanometers in at least one dimension [1]. If a material does not meet this nanoscale criteria, it will not exhibit the unique properties associated with nanomaterials, making it essential to have at least one dimension in the 1-100nm range to manifest the fundamental characteristics of nanomaterials. The initial applications of nanotechnology can be traced back to ancient India around 1500 years ago, where the excavation of swords revealed the presence of Wootz steel containing carbon nanotubes to enhance the sword's hardness. The systematic study of nanoscale effects, however, emerged in 1960. Carbon black, a nanostructured material, was

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invented in 1900 and has since been used as a nanomaterial to improve tire longevity and impart black color [1]. This article primarily focuses on the applications of nanomaterials in the aerospace industry.

2. Advantages of Nanomaterials

2.1. High Strength and Abrasion Resistance

The high strength of nanomaterials is attributed to the presence of boundaries between nanoscale particles, which act as obstacles to dislocation motion, thereby increasing the material's strength. As the size of grains decreases, the surface area of contact between grains increases, leading to higher hardness and strength in the material. The increased strength of nanomaterials also imparts enhanced wear resistance. This is because mechanical behavior is typically determined by bonds. Metallic bonds tend to be ductile and, therefore, soft, while covalent bonds, due to their strong localized nature, are prone to brittle fracture. However, nanomaterials exhibit distinct properties. Their high strength reduces the occurrence of dislocations required for deformation, making them resistant to dislocation-based plasticity. Consequently, nanoscale dimensions contribute to increased material strength and wear resistance [1].

2.2. Lightweight and High-Temperature Resistance

While nanomaterials offer numerous advantages at the microscale, transitioning their micro-level functionalities to the macro level often requires the involvement of composite materials. Composite materials are capable of achieving this functionality. Nanocomposites containing nanocarbons can be used to create high-performance materials with reduced mass, increased stiffness, and high-temperature resistance [2]. By applying these nanocomposites to aerospace structures, weight reductions of up to 20% to 30% can be achieved, a level of efficiency that is challenging to attain with other advanced materials, unlike the ease of using nanomaterials. Additionally, nanocomposites can result in a weight reduction of 51% in subsonic transport aircraft. This serves as ample evidence of the impact of nanomaterials on mass reduction [3].

Furthermore, nanocomposites bring significant high-temperature resistance properties to the aerospace sector. For instance, many materials, including nanoporous insulation materials based on silica aerogels, offer higher thermal insulating performance than traditional insulating materials. These emerging materials open up new avenues for aerospace applications [2].

2.3. Eco-friendly and Energy-Saving

Nanomaterials also offer significant advantages in terms of environmental protection. For example, TiO_2 can efficiently convert most organic compounds and some inorganic substances into harmless CO_2 and H_2O through photocatalysis. Compared to macroscopic TiO_2, nanoscale TiO_2 exhibits higher performance. Nanosized TiO2 shows significantly enhanced photocatalytic activity, making it a more efficient catalyst and greatly improving its prospects for environmental applications. This is because nanoscale TiO_2 has a larger surface area, allowing it to decompose more organic substances simultaneously. In recent years, this nanomaterial has found widespread use in wastewater treatment, construction materials, coatings, and other areas, holding great promise [4].

Meanwhile, nanocomposite materials have made remarkable contributions to energy conservation, particularly in the field of automotive fuel efficiency. Some gasoline micro emulsifiers contain nanoscale metal particles, which can enhance gasoline quality and significantly improve combustion. According to tests, such gasoline can increase power by 20% to 28% and reduce fuel consumption by 10% to 20%, offering a promising avenue for energy-efficient automotive research [5].

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3. Characteristics of Nanomaterials

3.1. Carbon nanotube (CNT)

Carbon nanotubes (CNTs) are derived from graphene, which is a two-dimensional form of carbon. CNTs produced from graphene can be categorized into two main types: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) (Figure 1). The production process for SWCNTs involves rolling up a flat sheet of graphene into a cylindrical shape, resulting in a single-walled carbon nanotube. Typically, SWCNTs have a diameter range of 0.7 to 1.4 nanometers and can reach up to micrometer lengths. MWCNTs, on the other hand, consist of multiple layers of SWCNTs arranged concentrically, resembling a coaxial assembly of single-walled carbon nanotubes.

Carbon nanotubes possess unique nanostructures due to their composition from graphene, which itself is a one-dimensional material. What sets graphene apart is its exceptional electrical conductivity. Simultaneously, carbon nanotubes exhibit remarkable mechanical properties because they are among the materials with the highest known Young's modulus. SWCNTs have a Young's modulus of approximately 1210 gigapascals (GPa), while MWCNTs have a Young's modulus of around 1260 GPa. This can be compared to common materials like copper (110 GPa) and steel (200 GPa), highlighting the exceptional strength properties of carbon nanotubes [1].

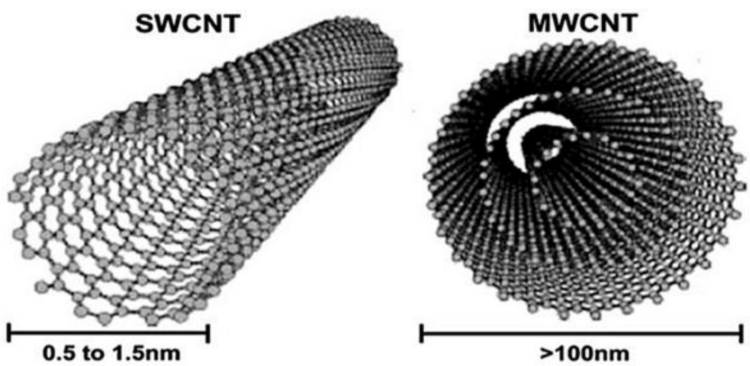

Figure 1. Diagram of typical CNT structures [1]

3.2. Nano-ceramics

Nanoceramics can be prepared using two different approaches, depending on the properties of the materials and the desired outcomes. One approach involves the preparation of nanocomposite ceramic materials, while the other involves incorporating nanomaterials into glazes to enhance strength.

Nanoceramic composite materials refer to ceramics that incorporate nanoscale second-phase particles to increase their strength. These materials have relatively large interfaces due to the presence of nanoscale particles, and the particles at the interface are not arranged regularly. This makes it easier for atoms to move under the influence of external forces. As a result, nanoceramic composites exhibit different mechanical properties compared to traditional ceramics, including enhanced toughness and some level of ductility, without sacrificing strength. Nanoceramic composite materials have the potential to significantly alter the mechanical properties of materials and offer promising avenues for research [6].

Incorporating nanomaterials into glazes is another approach, and it involves strengthening the structural integrity of ceramics without compromising their original mechanical properties. This method is characterized by its ability to reinforce ceramics by adding nanomaterials to the glaze [6].

3.3. Other nanomaterials

Graphene is a two-dimensional material composed of carbon atoms arranged in a flat, single-layer lattice structure. It is the thinnest and hardest known nanomaterial in the world, with a strength reaching up to 130 gigapascals (GPa) [7]. Its shape consists of a hexagonal flat sheet. This material finds extensive

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applications across various fields, both in the military and civilian sectors. Graphene exhibits remarkable mobility, with a carrier mobility of up to 15,000 $cm^2/V \cdot s$, which is twice that of indium antimonide [8].

There are also nanomaterials composed of metals and nanometal oxides, which are materials formed by combining polymers, metals, and non-metals through various processes to obtain properties that the original constituent materials do not possess. These materials cover a wide range of applications, and their presence can be observed from the microscale to the macroscale in various fields [3].

4. Application of Nanomaterials in Aerospace

4.1. Aircraft Structural Strengthen

Nanomaterials are widely utilized in various parts of aircraft as composite materials. For example, in the Airbus A380, a significant portion of the primary load-bearing structures, such as the central wing box, rear fuselage, and wing ribs, employ these composite materials. Additionally, the Boeing 787 (B787) uses even more composite materials, making it the largest commercial jetliner in the world to extensively utilize composite materials. The primary objective of employing these composite materials in these aircraft is weight reduction. Nanomaterials can simultaneously achieve weight reduction and increased strength, making them increasingly prominent in the construction of various components in aircraft [9]. As a result, advanced composite materials have become one of the four major structural materials in the aerospace industry [3]. Composite materials not only enhance aircraft structures but also significantly improve aircraft performance. For instance, aerodynamic load alleviation techniques using composite materials can enhance structural efficiency, reduce costs, and take advantage of the corrosion resistance and fatigue resistance properties of composite materials to lower expenses [3].

4.2. Coating Materials

Gradient coatings are excellent for wear resistance, and when nanoscale materials are used as raw materials for gradient coatings, they can further enhance wear resistance. For example, the application of nanoscale Fe_3Al/Al_2O_3 in laser cladding on a 45 steel plate is a notable example. The wear resistance of this coating is over 14 times that of the 45 steel, and the wear rate is not influenced by material wear. This is because this material lacks abrupt changes in composition and structure at the microscale, improving the bond strength of the coating and ensuring the reliability and durability of functionally graded materials as engineering materials [10]. Such materials can also be applied in automotive coatings [5].

Additionally, nanocoatings can offer corrosion resistance. For instance, nanoscale SiO_2 composite steel plate coatings are one such material. When subjected to external forces, these coating materials with absorbed nanoscale SiO_2 particles in molecular chains can evenly disperse load stress, thereby enhancing the corrosion resistance of the coating [11].

4.3. Fuel Additives and Thermal Insulations

Nanomaterials can be applied as fuel additives as well. For example, nanoscale palladium prepared by processes like hydrogen arc plasma can serve as a combustion promoter for carbon monoxide (CO). This material can achieve excellent results, consistently maintaining a zero CO content in the exhaust gas [12]. When the level of carbon monoxide is kept very low, it can have environmental benefits.

Nanomaterials are also well-suited for thermal insulation applications due to their properties. For instance, in processes like High-Velocity Oxy-Fuel (HVOF) spraying, which offers high particle velocity compared to other thermal spray techniques, nanomaterials can be effectively used. This reduces the exposure time of nanoscale structures to heat, resulting in nanocoatings with advantages such as dense microstructure, high bonding strength, high hardness, and low surface roughness. This nanotechnology has applications in various areas, such as the HVOF-nano 316 stainless steel coating, which exhibits significantly improved hardness compared to conventional 316 stainless steel powder [13].

4.4. *Sensors*

Nanomaterials can significantly enhance the performance of sensors. For instance, in an H_2O_2 biosensor, the use of metal-inorganic composite nanoparticles and polyvinyl alcohol-butanal as a composite immobilized enzyme membrane matrix has been employed to create a glucose biosensor. This sensor improves the interference resistance, resulting in a 32-fold increase in signal-to-noise ratio compared to the previous sensor [14]. Nanotechnology has the potential to bring about breakthroughs in optical technology, although it may take some time to fully develop. As optical disc technology continues to advance, traditional optical storage has approached its limits due to optical diffraction effects. Further advancements at the nanoscale are needed to achieve significant breakthroughs in this field [15].

5. Conclusion

In summary, nanotechnology holds significant potential in many fields and can serve as a foundational material in various aspects, offering a highly promising direction for long-stagnant cutting-edge technologies. This is particularly evident in the aerospace industry. In this sector, the nanoscale dimension can undoubtedly provide substantial assistance, such as the ability of nanomaterials to simultaneously enhance strength while reducing weight, which is an indispensable trait in the early stages of aerospace exploration. This has the potential to reduce substantial costs and redirect resources toward research and development. Of course, nanotechnology offers not only this particular attribute but also many other promising characteristics concealed within the realm of nanoscale dimensions, awaiting exploration by researchers.

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