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Classification and properties of composites based on matrix material

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Abstract

Composites are advanced materials engineered to combine the best properties of their constituent phases, resulting in superior mechanical, thermal, and chemical characteristics. They consist of a matrix material that acts as the binding phase and reinforcement materials that enhance the overall properties of the composite. The classification of composites based on the matrix material provides a systematic approach to understanding their behavior and applications. The primary classifications include polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs). Each type of matrix material contributes distinct properties: PMCs are lightweight and corrosion-resistant but have limited thermal stability; MMCs exhibit high strength, thermal conductivity, and toughness but are heavier and prone to corrosion; and CMCs offer exceptional thermal and wear resistance but are brittle and costly to produce. This paper provides an in-depth discussion of these classifications, focusing on their composition, properties, advantages, limitations, and applications in various industries. By highlighting the importance of matrix materials, this study aims to provide insights into the design, selection, and optimization of composites for specific engineering applications.

Keywords: Polymer matrix composites; Metal matrix composites; Ceramic matrix composites; Properties

1. Introduction

Composites are among the most significant advancements in material science, enabling engineers and scientists to develop materials with tailored properties that surpass the limitations of traditional materials. Unlike conventional metals, ceramics, or polymers, composites are formed by combining two or more distinct phases—commonly referred to as the matrix and reinforcement. This synergy between phases allows composites to achieve unique mechanical, thermal, and chemical properties, making them indispensable across a range of industries, including aerospace, automotive, construction, and biomedical engineering.

The matrix material is the continuous phase in a composite, encapsulating and supporting the reinforcement phase, which is typically in the form of fibers, particles, or whiskers. The matrix not only provides shape and structural integrity to the composite but also transfers stress to the reinforcement and protects it from environmental damage, such as oxidation, corrosion, or thermal degradation. On the other hand, the reinforcement phase significantly enhances specific properties, such as strength, stiffness, wear resistance, or thermal conductivity, depending on its nature.

The choice of matrix material plays a pivotal role in determining the properties and performance of a composite. Based on the type of matrix material, composites are broadly classified into polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs). Each class offers a distinct set of advantages and challenges, making them suitable for particular applications. For instance, PMCs are lightweight and flexible, making them ideal for aerospace and sports applications, while MMCs offer superior strength and thermal performance, which

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are essential in automotive and defense industries. CMCs, with their remarkable thermal resistance and durability, are predominantly used in high-temperature environments, such as turbine blades and heat shields.

As the demand for high-performance materials grows, understanding the classification and properties of composites based on their matrix materials has become critical for material selection and design in advanced engineering applications. This paper aims to provide a comprehensive overview of the classification of composites, focusing on the unique properties, benefits, and limitations of PMCs, MMCs, and CMCs. By doing so, it seeks to highlight how the matrix material dictates the overall behavior and potential applications of composites, as well as the ongoing challenges in their development and optimization.Composite materials are divided into five main groups according to the type of matrix material used: metal matrix composites, ceramic matrix composites and polymer matrix composites. The classification of composite materials according to matrix type can be seen in Figure 1.

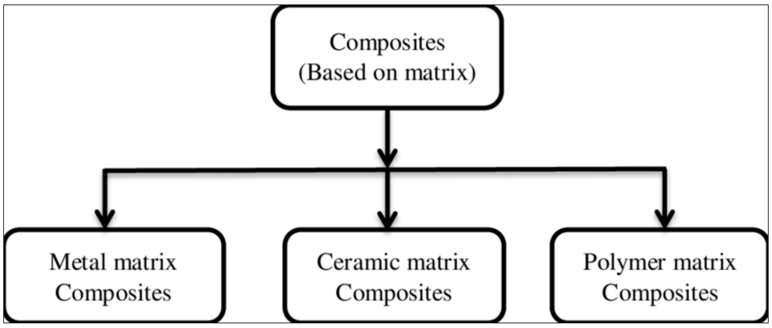

Figure 1 Composite materials by matrix type

1.1. Polymer Matrix Composites

The most commonly used matrix material for composites is polymers. There are two reasons for this. Polymers do not have superior mechanical properties. Their mechanical properties are insufficient for many structural applications. Their strength and rigidity are lower than metals and ceramics. Improving the properties of polymers by reinforcing them makes a significant contribution to the field of application. The second reason why polymers are widely used as matrix materials is that they do not require very high temperatures and very high pressures during composite production. For these two reasons, the use of polymers in composite materials has become very widespread [1].

Polymer matrix composite materials are divided into three groups as thermoset, thermoplastic and rubber. Polyester and epoxy resins are used more than other polymer matrices. The main reinforcement materials used are glass fiber, kevlar fiber, boron fiber and carbon fibers. The production methods commonly used in the production of polymer matrix composites are; hand spinning, wire winding, pultrusion, liquid flow technique, reinforced reaction, injection molding and extrusion methods. Polymer matrix composite materials are used in the marine sector due to their corrosion resistance and in the automotive, transportation and sports sectors due to their lightness. A polymer matrix composite material can be seen in Figure 2.

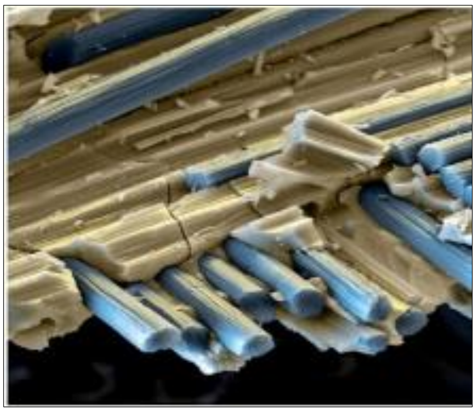

Figure 2 Polymer matrix composites

Polymer Matrix Composites (PMCs) are a type of composite material where a polymer resin acts as the matrix phase, and the material is reinforced with fibers, particles, or other fillers to improve its mechanical, thermal, and electrical properties. These composites combine the advantageous characteristics of polymers, such as flexibility, ease of processing, and low cost, with the superior strength, stiffness, and durability provided by the reinforcing phase. This makes PMCs highly versatile and widely used in a broad range of applications, including aerospace, automotive, construction, sporting goods, and electronics.

The matrix of a PMC is typically a polymer resin, which serves as the continuous phase, holding the reinforcement materials in place and providing shape and structural integrity to the composite. Common matrix materials include thermosetting resins such as epoxy, polyester, and vinyl ester, and thermoplastic resins such as polypropylene, polyethylene, and polyamide. Thermosetting polymers are commonly used when higher mechanical properties, better thermal stability, and chemical resistance are required, while thermoplastics are preferred for faster processing, recyclability, and ease of molding. The matrix material provides flexibility to the composite and influences its environmental resistance and ease of manufacturing.

Despite these advantages, PMCs also face challenges, such as limited high-temperature resistance compared to metal matrix or ceramic matrix composites and potential thermal expansion mismatch between the polymer matrix and the reinforcement phase. Additionally, some PMCs may have lower impact resistance and reduced long-term performance when exposed to UV radiation or extreme environmental conditions.

Nevertheless, ongoing research and advancements in polymer chemistry and processing technologies continue to improve the performance, cost-effectiveness, and sustainability of PMCs. As manufacturing techniques evolve, PMCs are expected to become even more integral in high-performance, lightweight applications across multiple industries, offering a balance of strength, flexibility, and affordability.

1.2. Metal Matrix Composites

The production of boron and silicon carbide fibers in the early 1970s has led to the detailed study of the use of light metals as reinforcement. Although the degradation of metal matrix and fibers at high temperatures was previously an obstacle to the process, the fiber surface coating processes that have been found have enabled the production of metal matrix composites. Thus, metal matrix composites, in which the main structure is the matrix metal and a ceramic reinforcement phase is generally used as the reinforcement element, have been produced. The metal matrix composite material can be seen in Figure 3.

Metal matrix composites have superior mechanical properties, superior rigidity, high shear and compression strength, and high temperature resistance compared to polymer matrix composites. They have almost no moisture absorption properties, are flame retardant, have high electrical and thermal conductivity coefficients, and are resistant to radiation. Despite all these advantages, their costs are very high and they are currently in the development phase [2, 3].

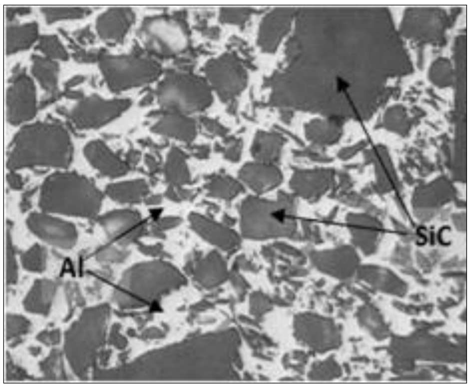

Figure 3 Metal matrix composites

Metal matrix composite materials offer very good alternatives to traditional materials. Ceramics with high elasticity modulus are combined with metals with plastic deformation properties to develop materials with fracture toughness, high wear resistance, and high compression strength. They have begun to be used in very special parts and components in the automotive, aerospace, and defense industries [4].

Metal Matrix Composites (MMCs) are advanced materials that consist of a metal or metal alloy matrix reinforced with fibers, particles, or whiskers of ceramic or other high-strength materials. By combining the desirable properties of metals, such as toughness, ductility, and thermal conductivity, with the exceptional stiffness, strength, and wear resistance of reinforcements, MMCs exhibit superior performance compared to traditional metals and alloys. These unique properties make MMCs essential in high-performance applications, particularly in aerospace, automotive, defense, and electronic industries.

The matrix material in MMCs serves as the continuous phase, providing structural integrity and the ability to withstand environmental conditions. Common matrix materials include lightweight metals such as aluminum, magnesium, and titanium, as well as high-strength alloys. These metals are chosen for their desirable mechanical properties and low density, particularly in applications where weight reduction is critical.

The reinforcement phase enhances specific properties, such as strength, stiffness, wear resistance, and thermal stability. Ceramic materials such as silicon carbide (SiC), aluminum oxide (Al_2O_3), boron carbide (B_4C), or carbon fibers are commonly used as reinforcements.

1.3. Ceramic Matrix Composites

Ceramics have relatively high strength and stiffness, but they are brittle. Accordingly, the main purpose of developing and producing ceramic matrix composites is to increase their toughness. In this way, it is aimed to minimize brittleness by taking advantage of the high strength and stiffness of ceramics. Ceramic matrix composites are mostly used in high-temperature systems such as gas turbine blades and automotive engine parts. An example of a ceramic matrix composite is shown in Figure 4.

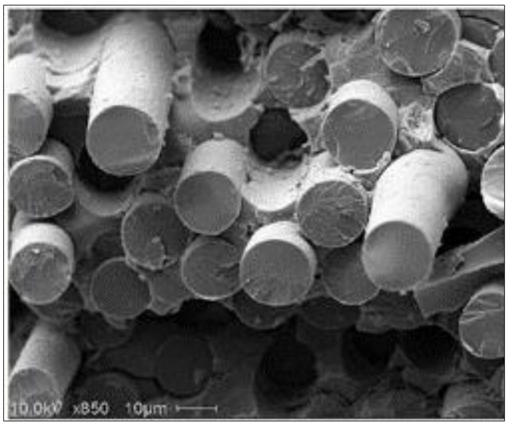

Figure 4 Ceramic matrix composites

The compounds used in ceramic matrix composites are; Al_2O_3, SiC, Si_3N_4, B_4C, CBN, TiC, TiB, TiN and AIN. Ceramic matrix composites are obtained by using one or more of these compounds with different structures [5]. Other areas of use of ceramic matrix composites are military equipment, space vehicles and armor. Reinforcements added to the ceramic matrix are; carbon, glass and ceramic. In materials where the ceramic matrix is reinforced with ceramic fiber, brittleness decreases, and a high strength and tough material emerges. Ceramic matrix composites produced using alumina and zirconia have also begun to be used as biomaterials in recent years [1, 6].

Ceramic Matrix Composites (CMCs) are advanced materials that consist of a ceramic matrix reinforced with ceramic fibers, whiskers, or particles to improve their mechanical properties and overcome the inherent brittleness of monolithic ceramics. While ceramics are well-known for their high-temperature resistance, wear resistance, and chemical inertness, they are also prone to fracture under stress due to their lack of ductility. CMCs address this limitation by improving fracture toughness, damage tolerance, and thermal shock resistance, making them ideal for demanding applications where traditional ceramics would fail.

The matrix of a CMC is typically composed of ceramic materials such as silicon carbide (SiC), alumina (Al_2O_3), zirconia (ZrO_2), or silicon nitride (Si_3N_4). These materials are selected for their ability to withstand high temperatures, resist oxidation, and maintain structural integrity under harsh environmental conditions. The matrix provides the overall structure of the composite and protects the reinforcement materials from damage. The reinforcement phase usually consists of ceramic fibers (such as SiC fibers), carbon fibers, or whiskers, which are embedded into the matrix. These reinforcements significantly enhance the toughness and strength of the material, allowing it to resist crack propagation and improve its overall damage tolerance.

CMCs offer several key properties that make them suitable for high-performance applications. Their high-temperature resistance allows them to maintain strength and stability even in extreme heat, which is why they are used in aerospace components like turbine blades and heat shields, where high thermal stability is required. Additionally, CMCs are lightweight, which makes them ideal for weight-sensitive applications like aircraft and spacecraft. Their wear and corrosion resistance also make them ideal for components exposed to harsh environments, such as chemical reactors or cutting tools. The low thermal expansion of many ceramic matrices ensures that CMCs can endure rapid temperature changes without cracking. Furthermore, thermal shock resistance allows them to survive extreme variations in temperature, which is critical for applications in engines and reactors.

However, CMCs do have certain limitations, including their high production costs and complex fabrication processes. Manufacturing methods such as chemical vapor infiltration (CVI) or liquid silicon infiltration (LSI) are required to incorporate the fibers into the matrix, which can be expensive and time-consuming. Additionally, machining CMCs can be challenging due to their hardness and brittleness, requiring specialized tools and techniques. Despite these challenges, ongoing research is focused on improving the manufacturing processes and exploring new reinforcement materials to reduce costs and improve the performance of CMCs.

Due to their superior mechanical and thermal properties, CMCs are increasingly used in high-performance applications, particularly in aerospace, defense, energy, and industrial sectors. In aerospace, they are used in turbine blades, re-entry heat shields, and brake systems. In defense, CMCs are found in armor materials and high-temperature components. In the energy sector, CMCs are used in gas turbines and nuclear reactors, where their ability to withstand extreme temperatures and radiation is essential. The ongoing advancements in the development and manufacturing of CMCs continue to expand their potential applications, making them critical materials for future technologies in extreme environments.

2. Conclusion

The matrix material is the main element of composites. It protects the fibers from external factors. It determines the properties and usage areas of the composite. The most commonly produced composite material in the industry is polymer matrix composites. Among the metal matrix composites, the composite type with high temperature resistance is ceramic matrix composites.

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