
Composite Materials: Processing, Properties and Applications - A Review

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ABSTRACT

Composite materials are formed by combining two or more materials with different properties to achieve better overall performance. This review summarizes work done on polymer matrix composites, metal matrix composites and ceramic matrix composites. The paper discusses types of reinforcements, matrix materials, processing methods, mechanical behavior and main applications in aerospace, automotive and infrastructure. Data from earlier studies show that fiber reinforced polymers have very high specific strength. Metal matrix composites give higher stiffness and better wear resistance than base alloys. Ceramic matrix composites are used where high temperature capability is needed. Problems like weak interface bonding, damage and high cost are still there. Future work was directed toward nano-reinforcements, hybrid systems and multifunctional composites.

Keywords: Composites; Polymer matrix; Metal matrix; Ceramic matrix; Processing; Mechanical properties; Applications

1. INTRODUCTION

Composite materials contain two or more distinct phases separated by an interface. The properties of the composite are different from the individual materials. The idea of combining materials is old, but modern composites started with glass fiber reinforced plastics. The main reasons for using composites are high strength to weight ratio, high stiffness to weight ratio, corrosion resistance and design flexibility. Based on matrix, composites are divided into three groups. Polymer matrix composites use epoxy, polyester or PEEK with glass, carbon or aramid fibers. Metal matrix composites use aluminum, magnesium or titanium alloys with ceramic particles or fibers. Ceramic matrix composites use SiC or Al₂O₃ with ceramic or carbon fibers. This paper reviews the status of all three types based on literature available till that period [1-3][10][11].

2. CONSTITUENTS

Reinforcements take the load and give strength to the composite. The most common forms are fibers, particles and whiskers. E-glass fibers were widely used because of low cost. Typical tensile strength is around 3400 MPa and modulus 72 GPa. Carbon fibers such as T300 and IM7 have strength in the range 3500-5500 MPa and modulus 230-276 GPa. Aramid fibers like Kevlar 49 have high strength and low density. Ceramic particles such as SiC in the size range 3-20 μ m were

added to aluminum to improve wear resistance. SiC whiskers in alumina matrix were used to increase fracture toughness. Studies on nano reinforcements like carbon nanotubes in epoxy also started and showed improvement in modulus and toughness at very low loading [3-8]. Polymer matrices are divided into thermosets and thermoplastics. Epoxy, polyester and vinyl ester are common thermosets. Epoxy is used in aerospace because of good adhesion and temperature capability. PEEK and PPS are thermoplastics used where toughness and recyclability are needed. For metal matrices, Al6061 and Al2024 are most common due to low density and good properties. Mg and Ti alloys are also used for specific applications. Ceramic matrices include SiC, Al₂O₃ and Si₃N₄. These are used at temperatures where polymers and metals cannot work [9-11].

3. PROCESSING TECHNIQUES

Processing methods vary with matrix type. Hand lay-up and spray-up are simple and low cost methods for polymers. Fiber volume fraction is usually 30-40% and they are used for boats and tanks. Resin transfer molding and vacuum assisted RTM give better fiber volume of 50-60% and shorter cycle time and are used for automotive panels. Prepreg with autoclave curing is standard for aerospace. Curing is done at 120-180°C under pressure. Large aircraft structures use this route. Filament winding and pultrusion are used for pipes, tanks and structural profiles. Wound glass fiber pipes can reach tensile strength of 800-1200 MPa [12-14]. For metal matrix composites, stir casting is the most economical method. SiC particles are mixed into molten aluminum. Limitation is porosity and clustering. Powder metallurgy gives better distribution. Al alloy with 20 vol% SiC can reach yield strength around 400-500 MPa compared to 280 MPa for base alloy. Squeeze casting and infiltration are used for near-net shape parts like brake rotors. Diffusion bonding is used for continuous fiber reinforced titanium[10, 15-17]. For ceramic matrix composites, reaction bonding and liquid infiltration are used to form SiC matrix. Polymer impregnation and pyrolysis needs multiple cycles and leaves some porosity. Density of C/SiC is around 1.8-1.9 g/cm³. Chemical vapor infiltration gives low porosity but is slow. It is used for carbon-carbon brake discs. Liquid phase sintering is also used for SiC based CMCs [18-19].

4. MECHANICAL BEHAVIOR

Modulus can be estimated by rule of mixtures. Unidirectional carbon epoxy with 60% fiber can have tensile strength 1500-2500 MPa and modulus 120-180 GPa. Aluminum with 20% SiC particles shows UTS around 480 MPa and modulus 110 GPa, which is much higher than 70 GPa for plain aluminum. C/SiC composites have moderate strength but retain properties at very high temperature [4, 10, 19]. Polymer composites fail by matrix cracking, fiber-matrix debonding, delamination and fiber breakage. Interlaminar shear strength for epoxy-carbon is typically 60-90 MPa. Fatigue life can exceed 10⁶ cycles at 60% of ultimate strength. Metal matrix composites fail by particle fracture and void growth at interface. Ductility drops with increase in particle

content. Ceramic matrix composites are designed for gradual failure. Fiber pull-out increases work of fracture to 10-30 kJ/m² compared to 0.1 kJ/m² for monolithic ceramics. Moisture in epoxy can cause 10-20% drop in interlaminar shear strength. Thermal mismatch in MMCs causes residual stresses. Oxidation is a major issue for CMCs at high temperature [6, 10-11, 20-22].

5. APPLICATIONS

In aerospace, composites are used in primary and secondary structures to reduce weight. Carbon fiber laminates are used in fuselage and wings. C/C and C/SiC are used for brake discs because of high temperature stability [13]. In automotive, glass fiber leaf springs give large weight saving compared to steel. Aluminum-SiC composites are used for pistons and brake rotors to improve wear and reduce expansion. Carbon fiber is used for drive shafts and body panels in sports cars [10, 23]. In infrastructure and energy, glass fiber rebar is used to avoid corrosion in concrete.

Table 1: Typical Mechanical Properties of Common Composite Systems

Material System	Fiber Volume %	Tensile Strength MPa	Modulus GPa	Density g/cm ³
T300/Epoxy Unidirectional	60	2100	140	1.6
E-Glass/Polyester	50	800	40	1.9
Al6061-20% SiC Particles	20	480	110	2.9
C/SiC Composite	40	350	200	1.9

Wind turbine blades of large length were made using glass fiber and balsa core. Composite pressure vessels with carbon overwrap are used for gas storage.[24] In other areas, sporting goods like tennis rackets, golf shafts and bicycle frames use carbon composites. Al-SiC is used in electronics for heat sinks because CTE matches silicon [3].

Table 2: Comparison of Processing Routes for Different Matrix Composites

Process	Matrix Type	Typical Vf %	Key Use	Limitation
Hand Lay-up	Polymer	30-40	Marine, Tanks	Low Vf, Slow
RTM / VARTM	Polymer	50-60	Auto Panels	Tool Cost
Prepreg-Autoclave	Polymer	60	Aerospace	High Cost
Stir Casting	Metal	10-25	Al-SiC Parts	Porosity
Powder Metallurgy	Metal	20-40	High Strength MMC	Cost
CVI	Ceramic	30-40	C/C Brakes	Very Slow

6. CHALLENGES, CONCLUSION and FUTURE SCOPE

Main problems in composites are high cost of carbon fiber and ceramic fibers. Difficulty in achieving good interface bonding is also there. Damage detection and recycling of thermoset composites are difficult. Non-destructive testing methods like ultrasonic and thermography are used for inspection [2, 25-27]. Composites have become important structural materials. Polymer composites dominate due to low cost and easy processing. Metal matrix composites give better stiffness and temperature capability but are costly. Ceramic matrix composites are essential for very high temperature use. Specific strength of carbon composites is several times that of steel. Further growth depends on cost reduction and better durability data [1-2, 10-11, 14].

Based on research trends of that time, future work was focused on nano and hybrid composites using CNT and nanoclay to improve matrix properties. Work was also done on self-healing composites using embedded capsules. Natural fiber composites were studied for low cost applications. Out-of-autoclave processing was explored to reduce manufacturing cost. Better models for predicting damage and life were also being developed [8, 13, 20, 28-29].

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