Review Article

Recent progress of reinforcement materials: a comprehensive overview of composite materials

Dipen Kumar Rajak a, Durgesh D. Pagar b, Ravinder Kumar c, Catalin I. Pruncu d,e,*

a Department of Mechanical Engineering, Sandip Institute of Technology & Research Centre, Nashik, 422212, India
b Department of Mechanical Engineering, K. K. Wagh Institute of Engineering Education & Research, Nashik, 422003, India
c School of Mechanical Engineering, Lovely Professional University, Phagwara, 144411, India
d Mechanical Engineering, Imperial College London, Exhibition Rd., London SW7 2AZ, UK
e Mechanical Engineering, School of Engineering, University of Birmingham, Birmingham B15 2TT, UK

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A B S T R A C T

Emerged in the middle of 20th century, composite materials are now one of the hotspot research topics in the modern technology. Their promising characteristics make them suitable for enormous applications in industrial field such as aerospace, automotive, construction, sports, bio-medical and many others. These materials reveal remarkable structural and mechanical properties such as high strength to weight ratio, resistance to chemicals, fire, corrosion and wear; being economical to manufacture. Herein, an overview of composite materials, their characterization, classification and main advantages linked to physical and mechanical properties based on the recent studies are presented. There, were presented the conventional manufacturing techniques of composite and their applications. It was highlighted the tremendous need to discovery new generation of composites that should incorporate the synthetic or natural materials by implementing new efficient manufacturing processes. In the combination of matrix and reinforcement materials, the use of natural materials as constituent are compulsory in order to obtain a complete material degradable as environmentally friendly.

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Dr. Catalin Pruncu is a Charter and Member of the Institute of Mechanical Engineers (UK), since Nov, 2015. He has great experience in Microstructural characterization, Solid Mechanics, Fracture Mechanics, Tribology, Design Mechanics, Composite Materials & Finite Element Modelling determined both numerically and experimentally. Currently, his research is dedicated to further develop and validate hot form quench (HFQ®) Technology for use in the global automotive industry. As design engineer he was involved to design high integrity products for Spanish Navy. Developed a new design for metal seat ball valve assemblies for Nuclear and Marine industries & resolved some problems imposed by the surface engineering submitted to the tribological contacts (i.e. ball, seat, and ball/seat/ body of valves); predicted the wear produced in the ball valve mechanisms, conducted testing and failure analysis of existing valve products, investigated surface characteristics and tribological response for imposed contact combinations.

* Corresponding author at: Mechanical Engineering, Imperial College London, Exhibition Rd., London SW7 2AZ, UK.
E-mail: c.pruncu@imperial.ac.uk (C.I. Pruncu).
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Nomenclature

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>PMCs</td>
<td>Polymer matrix composites</td>
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<tr>
<td>CMCs</td>
<td>Ceramic matrix composites</td>
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<td>MMCs</td>
<td>Metal matrix composites</td>
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<tr>
<td>CNTs</td>
<td>Carbon nanotubes</td>
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<tr>
<td>PEEK</td>
<td>Polyether ether ketone</td>
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<tr>
<td>TFL</td>
<td>Transfer film layer</td>
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<tr>
<td>TGA</td>
<td>Thermal gravimetric analysis</td>
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<tr>
<td>DSC</td>
<td>Differential scanning calorimetry</td>
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<tr>
<td>RGO</td>
<td>Reduced graphene oxide</td>
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<tr>
<td>PVPBM</td>
<td>Poly 4-vinylpyridine-co-butyl methacrylate</td>
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<tr>
<td>PLA</td>
<td>Poly lactic acid</td>
</tr>
<tr>
<td>GO</td>
<td>Graphene oxide</td>
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<td>FRP</td>
<td>Riber reinforced polymer</td>
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<td>RTM</td>
<td>Resin transfer molding</td>
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<tr>
<td>Pip</td>
<td>Polymer infiltration &amp; pyrolysis</td>
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<tr>
<td>SMC</td>
<td>Sheet molding compound</td>
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<tr>
<td>BMC</td>
<td>Bulk molding compound</td>
</tr>
<tr>
<td>TMC</td>
<td>Thick molding compound</td>
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<tr>
<td>RFFM</td>
<td>Reinforced reaction injection molding</td>
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<tr>
<td>AM</td>
<td>Additive manufacturing</td>
</tr>
<tr>
<td>FFF</td>
<td>Fused filament fabrication</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra violet</td>
</tr>
<tr>
<td>LOM</td>
<td>Laminated object manufacturing</td>
</tr>
<tr>
<td>CBAM</td>
<td>Composite based additive manufacturing</td>
</tr>
<tr>
<td>CFP</td>
<td>Carbon fiber reinforced plastics</td>
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<tr>
<td>CMC</td>
<td>Ceramic matrix composites</td>
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<tr>
<td>CA</td>
<td>Cellulose acetate</td>
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<tr>
<td>BFRP</td>
<td>Basalt fiber reinforced polymers</td>
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<td>BLP</td>
<td>Basalt lines pipes</td>
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</table>

1. Introduction

The reason for rapid growth in usage and popularity for composite material in the field of engineering and material sciences is that they provide highly attractive combination of stiffness, toughness with light weight and corrosion resistance properties [1-4]. A composite material, the name itself elaborates the definition that it’s a composition of materials. It is formation of two or more constituent materials having significantly different physical or chemical properties when combined together produces a material which possesses unique characteristics different from the constituent elements [5,6]. This enhancement makes composite material stands superior when compared to properties possessed by individual material. The concept of composite material is well illustrated by naturally occurring composite materials such as wood which is made up of fibrous chains of cellulose molecules in a matrix of organic polymer lignin [7,8]. Another example of natural composite is bones, composed of inorganic crystals called hydroxyapatite in a matrix of an organic material called collagen [9,10]. Further classification and type of composite materials based on their constituents are discussed in subsequent chapters. Unlike mixtures and solid solutions, the component of composite material do not blend or dissolve or lose their individual identities, instead they combine and synergistically contribute their traits to improve the properties of final product [11,12]. We can identify the characteristics of distinct components within the finished structure of composite when examined through a microscope [13]. Composite material is an amalgamation of a base material and a filler material. Base material is also called as matrix or a binder material as it surrounds and binds reinforcement of other material. Filler material or reinforcement is in the form of fragments, particles, and fibers, whiskers of natural or synthetic material [14-16]. Matrix is generally seen as relatively soft phase with specific physical and mechanical properties like ductility, formability and thermal conductivity [17]. In the matrix reinforcement of materials with high strength, high stiffness, and low thermal expansions are embedded. Reinforcement phase in composites are therefore usually stronger and stiffer than the matrix as it carries the applied load to the material.

As the components of a composite material influences its properties, there is need of studying their classification and distinct properties thoroughly [18-20]. Since composite materials being employed for wide variety of applications in major fields, plenty of researchers have commenced developing various types of advance manufacturing techniques to increase productivity and efficiency [2,21,22]. This study proposes a better understanding towards how composites are categorized, their dominating properties, manufacturing techniques and potential applications to replace monolithic material.

2. Classifications

Composite materials are classified according to the type of constituents used as shown in Fig. 1.

2.1. Based on matrix phase

2.1.1. Polymer matrix composites (PMCs)

PMCs are composed of thermosetting plastics or thermoplastics matrix with dispersed reinforcement of carbon, glass, Kevlar, metal fibers [26-29]. Thermosets are more popular in use than thermoplastics due to their higher strength and resistance to high temperatures [30]. Thermosets are prepared by mixing resin with hardener. Laminar structure is most widely used made by stacking and bonding thin layers of fiber and polymer until the desired thickness is obtained. PMCs are low cost composites due to easy handling techniques and simple fabrication methods [31,32].

2.1.2. Ceramic matrix composites (CMCs)

CMCs are type of ceramics generally composed carbon, silicon carbide (SiC), aluminum oxide (Al₂O₃), silicon nitride (Si₃N₄) fibers embedded in ceramic matrix structure [33]. They are designed to overcome the drawback of monolithic ceramics, brittleness. Due to failure strain of the matrix is lower than the failure strain of the fibers; CMCs are referred as inverse composites. While in most of the polymer or metal matrix composites the phenomenon is exactly reverse. Hence, under loading conditions it is the matrix which fails first, in order to prevent an early failure of the brittle fibers [34,35]. The fabri-
cation of CMCs is done under specific processing techniques named as Gas- or liquid-phase routes. In this process with the inner phase and the matrix are formed around the fibers from gaseous or liquid precursors [36,37].

2.1.3. Metal matrix composites (MMCs)
The matrix material of MMCs are compulsorily metallic (mostly aluminum (Al), magnesium (Mg), copper (Cu) & titanium (Ti)) and reinforcement could be either dispersed ceramics like oxides & carbides or it could be metallic (i.e. tungsten, molybdenum, lead). Reinforcement contributes a few percentages to around 50% of the total volume of the composite material [38]. Al based MMCs are most widely used in automobile and aerospace industries as reinforcement compounds such as SiC and Al2O3 are mixed easily and effectively in molten Al to achieve desired properties like superior strength, improved stiffness, reduced density, controlled thermal expansion and improved wear resistance [39–41]. Due to high stiffness and abrasive structures there is high tool wear rate during machining process of MMCs therefore, usually unconventional machining techniques are used for MMC whereas no contact between tool and the material [42].

2.2. Based on reinforcements

2.2.1. Fiber
In fiber reinforced composite materials, dispersed phase of synthetic fibers such as glass, carbon, basalt and Kevlar in a composite structure revealed enhanced material properties such as high strength, stiffness and resistance to chemical, temperature and wear [43–47]. Currently, use of natural fiber reinforcement has gain tremendous popularity among researchers. Chemically treated natural fibers showing improved impact toughness and fatigue strength, moreover they are abundantly available at cheap rates, biodegradable hence eco-friendly and they have low density compared to synthetic fibers [48,49].

2.2.2. Particle
When compared to fiber based composites, particle based composites is a less effective means of strengthening. Particle reinforced composites find applications where high levels of wear resistance are required such as road surfaces. The hardness of cement is increased significantly by adding gravel as a reinforcing filler material. The advantage of particle reinforced composites is their low cost and ease of production and forming [50,51]. Concrete being a very good example, the aggregate of coarse rock or gravel is embedded in a matrix of cement. Here aggregate provides stiffness and strength while cement acts as binder to hold the structure together [52]. When high volume fraction of iron based glassy particles as reinforcement used for MMCs it led to significant hardening of the Al matrix which results in a remarkable combination of high strength and plasticity [53].

2.2.3. Sheet
Sheet based composites generally termed as sheet molding composite (SMC) is a glass reinforced thermostet molding material with glass reinforcement which is usually compression molded [2,54,55]. It combines long glass fiber and unsaturated resins to produce a high strength molding composite. SMCs are applicable for large structural components as it shows high strength-to-weight ratio. It also offers additional benefits in part design such as fastening attachments and sub-assemblies. When compared to cylindrical shell panel, the buckling temperature is higher for spherical panel [56].

2.3. Based on scale

2.3.1. Nano-composites
Desired material properties can be achieved by combining two or more distinct materials at nano scale which result in the formation of a novel material called nano-composite. Generally, nano-composites are classified as unintercalated, intercalated, and exfoliated composites and these are prepared by using template synthesis, intercalation of polymer, in situ polymerization, and melt compounding [57,58]. Biomedical nano-composites are nano composites designed for biomedical applications such as dental treatments [59], bone tissue engineering [60], drug delivery in cancer treatments [61] and wound dressings [62,63].

Exceptional optical properties of composite materials are utilized efficiently by embedding transparent matrix material [64]. CNTs graphene and its oxides, MoS2/graphene nano-composites showed enhanced optoelectronic properties advantageous for photonic applications [65–69] while black phosphorus nano-structure is used for treating cancer in biomedical applications [70].

2.3.2. Bio-composites
Demand of biodegradable, environmental friendly materials compels researchers to seek new opportunities developing
bio-composites. Bio-composite made of sugar palm fibers reinforced in the sago starch matrix reveals enhancement in thermal stability, reduced water absorption tendency, increased tensile and tearing strength, and durability of a material [71–75]. Bio-nano-composites fabricated at nanoscale have showed potentiality in variety of applications such as tissue engineering scaffolds, bio-packaging etc. [76–82]. Antibacterial property of ginger fiber has been effectively utilized to sustain food packaging quality [83].

3. Distinct properties

3.1. Impact resistance

An enhanced impact resistance has observed in mechanical meta-materials with magnetic inclusions when compared to their non-magnetic counterparts. When magnitude of magnetic moment that associated with magnetic inclusions increased within the system, there is an improvement in impact resistance of the entire structure. The magnetic inclusions within the system have the capability to minimize the negative effects of the collision from an external body. Therefore, it is concluded that the use of composite materials minimizes the damage caused by the automobile collision, also improves the efficiency of existing protective devices and thus these are expected to be useful in the case of a variety of applications ranging from military-related protective devices to automobile exterior body parts [84–87]. Recently developed fique fiber reinforced epoxy matrix composite is replacing conventional aramid fabric plates which were used as armor for personal protections. When a ballistic test with high velocity 7.62 × 51 mm ammunition is carried out fique fiber shows outstanding results. Also, being a natural fiber, it is environment friendly [88,89]. Carbon nanotubes (CNTs) and graphene materials possess very high strength and stiffness value makes them demanding for energy absorber applications. Such a tough and being lightweight composites, these are used for the fabrication of the upcoming body armors. High-performance natural fibers, such as curaua fibers are new promising composite fiber available in ballistic systems [90].

3.1.1. Temperature resistance

The experimental results showed that thermal insulation properties are improved by using wool fibers as reinforcement in the cementitious matrix to obtain mortars and plasters for construction industry. A wool fiber shows noticeable improvements in the thermal insulation of the resulting composites, regardless of their length. Thermal resistivity of the samples filled with wool increases by increasing the fiber content [91,92]. Even at elevated temperatures, Polyether ether ketone (PEEK) composites showed more effectiveness to develop resilient Transfer Film Layer (TFL), while on steel counterpart it is not uniform and it is temperature dependent as well. Nature of TFL decides the coefficient of friction which is an important parameter while considering mechanical properties of a material. In case of composites mechanical properties like wear resistance, rigidity, hardness, deformation, breakage of polymeric chains retained even at high temperatures [93]. Thermal gravimetric analysis (TGA) was done to study the thermal stability of treated sisal fibril/kenaf fiber reinforced hybrid composite. Thermal stability of hybrid composites was higher about (3–4%) than the K40F60 and S40F60 composites [94]. The differential scanning calorimetry (DSC) results showed that Cb-PCM being very convenient melting and freezing temperatures for keeping thermal comfort of building envelopes and relatively high amount of latent heat storage/release capacity. Also, TGA results demonstrated that composite had high thermal degradation stability [95].

3.1.2. Wear resistance

When compared to pure casted copper addition of SiC-graphite reinforcement in copper (Cu) increases the wear resistance of the copper. It was observed that the wear rate is 50% less than pure casted copper when 10 wt% vol. of graphite-SiC reinforcement is added to Cu. It also provides a lubrication film on the surface. A fine SiC particle prevents the material from abrasion and plastic deformation [96]. Boron carbide (B₄C) reinforced aluminium silicon composites when investigated experimentally, it had showed that there is increase in wear resistance by 40% with increased in porosity of composite material when 0.5%vol. graphene supplementation contributed [97].

3.1.3. Corrosion resistance

Multilayer Reduced Graphene Oxide (RGO) and Poly 4-Vinlypyridine-co-butyl methacrylate (PVPM) composite coating prepared by ecofriendly Electrophoretic Deposition (EPD) technique serve as a protective coating for copper. RGO-PVPM composite coating shows uniform, pore free and enhanced corrosion inhibition efficiency of up to 95.4% [98]. Initially in organic coatings, silicon nitride was used as anti-corrosive pigment. But to protect Q235 carbon steel an effective strategy by combining inorganic fillers and organosilanes proposed to enhance the dispersibility of silicon nitride in epoxy resin. The results showed that modified silicon nitride coating exhibits good anticorrosion performance [99].

3.1.4. Damping

When compared to 14 FRP footbridges with the non-FRP foot bridges, the dynamic property shows that they are found to have 2.5 times higher damping ratio than that of steel, concrete, and steel-concrete composite footbridges. However, they seem to have a lower damping ratio than timber footbridges [100]. In p-GNPs/epoxy and f-GNPs/epoxy composites, the damped natural frequencies decrease with addition of GNPs nano-fillers due to decrease in toughness of nano-composite. When experimental vibration results are investigated it was confirmed the effect of graphene nanoplatelets was beneficial on the damping ratio of high content epoxy nano-composites [101].

3.1.5. Electrical

Hybrid composite with sisal and kenaf fiber showed improvement in mechanical strength with increase in tensile strength, flexural strength and impact strength. Sisal and kenaf fiber hybrid polyester composites showed its suitability for various electrical insulation applications. The dielectric constant (ε₀), dissipation factor (tan δ), and dielectric loss factor (ε’’0) of hybrid composites were observed 3.59, 0.0095, and 0.0106
at 20 kHz [94]. Lithium Iron Phosphate (LiFePO4) batteries are currently replacing conventional lead acid batteries which shows application in the batteries of electric vehicles. Due to high cost of raw materials and tedious preparation process, the re-synthesis of LiFePO4 from spent batteries becoming more economical and convenient process. LiFePO4/ Reduced Graphene Oxide composite obtained from the process shows better electrochemical performance, including smooth CV curves, low electrochemical impedance, high capacity, flat voltage plateau, and high columbic efficiency, stable cycle performances at 0.2C and 1C and excellent rate capacity [102]. When compared to each individual component, the use of ternary composites for super capacitor materials like manganese dioxide (MnO2) carbon based material could be highly beneficial in electrochemical performance providing cycling stability. Recent studies in carbon materials such as carbon nanotubes, graphene, porous carbon, and carbon spheres helps to improve conductivity, capacitance of active MnO2 as composite electrode material. Carbon support stores electrical charge in it reflecting its applications such as inkjet and screen printing, where manufacturing cost is reduced [103].

3.1.6. Chemical Monitoring, receiving and transducing the information in the various form of energy is the function of a sensor. Use of composite nano-materials as a sensing device has boosted since past decade and the advancements in their performance is achieved [104,105].

CNTs are used as chemical sensors to sense chemical vapors nano-materials such as graphene and CNTs shows outstanding electrochemical and optical characteristics that make them ideal candidates for chemical sensors used in biotechnological, pharmaceutical, and environmental applications [106–108]. An electronic tongue made of composite material used as a biosensor [109,110].

For a noval chemical sensor, surveillance and monitoring electrochemical devices with high precision, cost-effectiveness and the ability of interacting with variety of biological and chemical components are the influencing factors. Bio-polymers such as, cellulose, starch, lignin, chitin, chitosan, alginate, polyhydroxalkanoates, poly lactic acid (PLA), pullulan, collagen and gelatin are used for the fabrication of bio-composites which offers biocompatibility, biodegradability and are easily available in abundance. Chemical sensors made of bio-composite serves material properties including high Young’s modulus, dimensional stability, and low coefficient of thermal expansion [111–113].

3.1.7. Flexural strength Jute fiber reinforced composites are found to be a better alternative to synthetic fiber composites due to their properties being light in weight, easily available in abundance, low cost, biodegradable and high flexural strength [114]. Manufacturing techniques with variation in size, orientation and weight segment of reinforced material highly influences the mechanical behavior of composite. Also the moisture content and immersion time influences the flexural strength and other mechanical properties of composite material [115]. A composite made of poly lactic acid resin reinforced with bamboo fibers shows increase in the flexural strength with increase in fiber content up to 70%. When tested, flexural strength possesses by composites possess flexural strength of 273 MPa, in the case of molding temperature of 160 °C [116].

3.1.8. Lightweight Particle shape and size in particle based composite decides the density of material. In copper matrix reinforced with copper-graphite hybrid metal matrix composite the addition of graphite in the matrix decreases the density of composite material which is beneficial in light weight applications [96,117,118].

3.1.9. Acoustic Luffa fibers have superior sound absorption properties. By using perforated linen, sound absorption coefficient of 10mm thick luffa fiber reinforced bio-composite is increase to 0.3 for frequency of 0.5–6 kHz [119]. The elastic and high damping properties of luffa fiber composites allows them to be used in many sound and vibration isolation applications like airplanes, automobiles, yachts and architecture fields. Also, being an environmentally friendly biodegradable material it will rapidly gain popularity in the field of composite manufacturing [120–122].

3.1.10. Radiopacity PEEK-OPTIMA polymer introduced by barium sulfate fillers in the form of fine powder when added increases the radiodensity (or radiopacity) of the polymer, making it more visible under X-ray inspection [123,124]. Complex 3-D shapes like screws, pins or contoured bone plates are manufactured with pultrusion process using continuous fiber-reinforced PEEK-OPTIMA as it possess high strength and stiffness competing with metallic implantable materials. Also it is pultruded into rods, tubes or hot pressed by various means into flat plates [125].

3.1.11. Puncture resistance Glass fiber polyester shows no perforation at higher temperature and loading condition while, specimens without reinforcement gets damaged with perforation even at lower temperature [126]. Sandwich structured composite made of recycled polyester and kevlar fibers with inner layer of glass fibers revealed improvement in mechanical properties with increased puncture resistance making it a potential candidate for insoles [127].

3.1.12. Flame retardant Use of fire retardant filler materials in the matrix of polymer composites being practiced since past many years, moreover some elements possess self-extinguishing property and using these materials as constituent of a composite makes it a fire resistant material [128–130]. Recently developed graphene foam (GOTP) is manufactured by mixing graphene oxide (GO) solution with Hexachlorocyclotriphosphazene. GOTP foams are environment friendly and possesses flame retardant feature and are light in weight. They also have compressible structure and microwave absorption capacity which offers many potential applications in aerospace industry [131].
Table 1 – Different types of reinforcements and matrix material used for composite materials with their applications and manufacturing techniques.

<table>
<thead>
<tr>
<th>Ref No.</th>
<th>Composite material</th>
<th>Enhanced properties</th>
<th>Applications</th>
<th>Manufacturing techniques</th>
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</thead>
<tbody>
<tr>
<td>[89]</td>
<td>Fique fiber</td>
<td>Impact resistance</td>
<td>Body armor</td>
<td>Cold pressing</td>
</tr>
<tr>
<td>[92]</td>
<td>Sheep wool fibers</td>
<td>Temperature resistance</td>
<td>Mortars or plasters in construction industry</td>
<td>Mixing</td>
</tr>
<tr>
<td>[93]</td>
<td>Titanium dioxide</td>
<td>Wear resistance</td>
<td>Tribological application</td>
<td>Mechanical extrusion and injection molding</td>
</tr>
<tr>
<td>[TiO₂]</td>
<td>particles</td>
<td></td>
<td></td>
<td>Compression molding</td>
</tr>
<tr>
<td>[94]</td>
<td>Sisal/knaf fibers</td>
<td>Tensile, flexural, impact strength</td>
<td>Press board used in transformer assembly, high strength electrical insulation</td>
<td></td>
</tr>
<tr>
<td>[96]</td>
<td>SiC/graphite</td>
<td>Wear resistance</td>
<td>Heat exchanger</td>
<td>Liquid state stir casting</td>
</tr>
<tr>
<td>[powder</td>
<td>Cu</td>
<td></td>
<td></td>
<td>Solvent casting</td>
</tr>
<tr>
<td>[116]</td>
<td>Jute fibers</td>
<td>Abrasive wear resistance</td>
<td>Tribological application</td>
<td></td>
</tr>
<tr>
<td>[130]</td>
<td>Basalt fibers</td>
<td>Fire resistance</td>
<td>Hot gas filtration systems</td>
<td>Vacuum bag resin infusion</td>
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<tr>
<td>[Vinyl ester resin]</td>
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</table>

Table 1 presents a summary of different types of reinforcements and matrix material used for composite materials with their applications and manufacturing techniques.

4. Manufacturing techniques

Composites are manufactured through variety of different techniques, sometimes there could be a combination of two or more processes [132]. Manufacturing techniques are chosen based on the type matrix or fiber material used; some of the composite manufacturing techniques are categorized through Fig. 2 [133,134].

4.1. Open molding

In this process materials are exposed to air to cure and to get hardened.

4.1.1. Hand lay-up

It is the most common and widely used composite manufacturing process as it requires least amount of equipment’s. In this process, a gel coat is applied to an open mold and then successive layers of resin (matrix/binder material) and fiber reinforcement which are in the form of woven, knitted, stitched or bonded fabrics are manually applied to make a fiber reinforced polymer (FRP) composite structure [137,138]. Brushes and rotating rollers are used to force resin into the fabrics for the purpose of removing air bubbles as displayed in Fig. 3. There is no requirement of heat for the curing process as laminates are left until it gets cured naturally to the room temperature [136]. For the experimentation to study mechanical properties of alkali treated plain woven banana fabric reinforced biodegradable composites, 60:40 wt fractions of banana fabric and polyvinyl alcohol were used to fabricate composite laminates by hand lay-up technique [139].

4.1.2. Spray up

In spray-up process, chopped fibers of reinforcement material are held in a hand gun and resins are sprayed simultaneously into the mold simultaneously a roller is used to fuse resin and reinforcement together as illustrated in Fig. 4 [141,142]. Then deposited material is left under atmospheric conditions to cure to the room temperature. A chopped laminate provides good conformability and the process is quite faster than hand lay-up process when it is subjected to mold complex shapes. In spray up process operator manipulates the thickness and consistency of coat therefore, this process is automated as it uses portable equipment and also it allows on site fabrication [143].

4.1.3. Filament winding

It is an automated open molding process which uses a rotating mandrel as mold. Reinforcement fibers drawn from continuous roving are passes through hot resin bath shown in Fig. 5, resin infused continuous fibers are wrapped around the rotating mandrel that has the internal desired shape of product [145]. After applying sufficient layers, laminate is set for curing and mandrel is removed. It provides high tensile strength, strength to weight ratio and uniformity to the products. It is an automated computer controlled process, usually allows manufacturing hollow cylindrical shapes [146,147].

4.2. Closed molding

Resin and fibers are cured inside the mold, mostly automated process therefore used for large volume production.

4.2.1. Vacuum bag molding

First a flexible thin film of nylon, PVA or polyethylene is placed over wet lay-up, the reinforcement is saturated, then edges are sealed and vacuum bag is mounted on a mold as displayed in Fig. 6. It uses atmospheric pressure to reduce air pressure from vacuum bag. Then external atmospheric pressure exerts force on vacuum bag to consolidate the laminate by removing entrapped air, excess resin which results in higher percentage of fiber reinforcement [149,150]. The fabrication of 3-ply carbon fiber and multi walled carbon nano-tubes laminate composites were performed by hand lay-up assisted vacuum bagging technique, where laminate was fabricated by hand
The layup process and consolidated for 45 min using vacuum bagging technique [151].

4.2.2. Vacuum infusion
It is also termed as resin film infusion process; it is slightly different from the vacuum bag molding as vacuum is applied before resin is introduced. The vacuum bag is positioned and sealed at mold perimeter and a perforated tube is placed between the vacuum bag and resin container. Then it uses a vacuum pressure to resin to suck in and consolidate the laminates as a perforated film is placed over dry reinforcement. Laminated gets compacted when resin is pulled into the mold, leaving no room for excess resin [153–155].

4.2.3. Resin transfer molding
It injects resin under pressure using injection equipment into the mold cavity where dry reinforcement materials are already placed. The resin transfer molding (RTM) is illustrated in Fig. 7. It provides flexibility to the combination of fiber orientation. RTM is done at room temperature with fast cycle time [156–158]. It renders flexibility over combination of material and its orientation, including 3-D reinforcement.

4.2.4. Compression molding
Compression molding is mainly useful for complex fiberglass-reinforced polymer parts as it is a high-volume, high-pressure method which works on a rapid cycle time. It uses metal molds pre heated from 250° to 400°F mounted on large hydraulic or mechanical molding presses. The compression molding process is shown in Fig. 8. First, resin charge is kept in a mold where one of the mold is fixing and other movable mold part is hot pressed the material to form the structure [145,146]. On the basis of type of material to be molded, there are several types of compression molding, sheet molding compound (SMC), bulk molding compound (BMC), thick molding compound (TMC), and wet lay-up compression molding [160]. To overcome the difficulty of adding high content of bamboo fibers into the epoxy resin, hand lay-up technique followed by compression molding is used [161].

4.2.5. Pultrusion
Pultrusion is scalable manufacturing process (Fig. 9) desired to produce constant cross section of FRP elements [145,163,164]. It is a continuous process having very high structural properties and is adaptable for both simple and complex cross-sectional shapes. Using tractor mechanism, continuous strands of glass, carbon or basalt fiber infused in a resin bath are pulled through a steel die. The steel die heated rapidly so that the saturated reinforcement gets consolidated in it and sets the shape of the stock [165,166].

4.2.6. Reinforced reaction injection molding (RRIM)
In this process two or more resins are mixed together in the mixing chamber to form a thermosetting polymer under high pressure. Reinforcement agents like glass fibers or mica are added to the mixture. Then the resin mixture is metered into a mold with the help of high pressure pumps or injection cylin-
4.2.7. **Centrifugal casting**

This process, resin and reinforcement are deposited inside the surface of cylindrical rotating mold. Centrifugal force holds the mixture against the inner wall of cylindrical mold until it gets cured. Process can be understood from Fig. 11 where molten resin is poured in the basin which sets into the mold cavity. To overcome the limitation of low particulate volume percentage material while producing nano size TiB₂ particles within an aluminium matrix, centrifugal casting process is employed [171–173].

The resultant liquid is low viscous liquid though mixing occurs at high pressure. The mixed resin with low viscosity is easily injected into the mold cavity (Fig. 10) at relatively low pressure about 50 psi. Without acquiring any additional heat Polymerization takes place very quickly within the mold cavity [168,169].
Fig. 9 – Pultrusion process [167].

Fig. 10 – Reinforced reaction injection molding process [170].

4.2.8. Continuous lamination
Products having opaque, translucent flat, panel like structures are manufactured using continuous lamination process. The machine combines reinforcement and resin on plastic film. With the help of compacting rollers pressure is applied and trapped air is removed. After completion of curing in an oven, panels are rolled on a huge roller forming a laminate sheet which then trimmed to width and cut to length as demonstrated in Fig. 12. When there is a requirement of special surface effects they are created by using embossed carrier films [175,176].

4.3. Cast polymer molding
Cast polymers do not have fiber reinforcement in it; they are designed to meet specific requirements according to application [177].

4.3.1. Gel coated cultures stone molding
A gel coat is specialized polyester resin material and coat provides an outer coating to composites to protect the material by external means; it is sprayed on a mold surface and then left for curing. Then it is blended with variety of fillers which are going to be used as reinforcement for fabrication of certain composite [178].

4.3.2. Solid surface molding
To make material surface look aesthetically alluring solid surface molding is chosen as it uses blend of polyester resin or acrylic resin with vacuum mix technique to make matrix material void free. Simulation of natural granite stone is one of the examples.

4.3.3. Engineered stone molding
In this type of molding process small amount of resin is combined with stone particles and then poured in to the mold cavity. Vacuum assisted press technique is used to extract air from the matrix and then formation is compressed to achieve low porosity casting. Presence of real stones in the matrix of material provides high durability, high heat resistance, low thermal expansion, strain and scratch resistance.

4.4. Advanced manufacturing techniques
The above described conventional composite manufacturing processes require molds which limit the formability and make the process costly and a bit tedious when it comes to complex structures. While additive manufacturing (AM) uses a fabrication technique where composite structures are made lay by layer with the use of computer aided designing process [179–181].

4.4.1. AM techniques are classified into 4-processes
- Material extrusion: Material is deposited in the solid filament or in paste form through a nozzle. The technique used to melt and extrude the filament is called fused filament fabrication (FFF) [182].
- Vat photo polymerization: It uses ultra violet (UV) light to cure photopolymer. Though it prints in high resolution, the choice of materials is very limited.
5. Applications

5.1. Automotive

5.1.1. Braking system

Fig. 13 shows automotive carbon ceramic brake and braking system in automobile where temperature reaches up to thousands degree Celsius, braking material need to withstand poorly. FFF and LOM stands short with conventional manufacturing techniques when it comes to tensile strength [183,184]. Improvement in combustion thermal efficiency with the enhancement of volatile hydrocarbon cracking is observed. This facilitates reduction in nitrogen oxide (NOx) emissions and improved thermal efficiency of coal combustion for fired burners [185].
and functionally perform well, carbon fiber reinforced silicon carbide (C-Si) brake materials are being competitive brake materials for high speed train, heavy vehicles, emergency brakes cranes [186,187].

5.1.2. Electric vehicles
An asymmetric super capacitor device of nickel cobalt oxide reduced graphite oxide (NiCO$_2$O$_4$–rGO) composite material exhibits better stability towards multistage charge discharge cycling. This replicates that NiCO$_2$O$_4$–rGO is promising candidate for high energy storage application such as energy storing device (batteries) of electric vehicles [189]. Fig. 14 battery placement of an electric vehicle is displayed. Efforts has been made since past several years understanding the characteristics of black phosphorus concerning application in the field of nano-electronics, nano-photronics, and optoelectronics as electrochemical energy storage devices, such as lithium, sodium ion batteries and super capacitors. Black phosphorus revealed remarkable electronic, photonic, and mechanical properties such as large specific surface area, anisotropy, tunability and direct band gaps [190–192].

5.1.3. Trunk lid and body stiffener
Lightweight structures are essential to achieve the efficiency standards in energy and transportation industry. Carbon fiber reinforced plastics (CFRP) stand replacement for electrical instruments considering its electrical properties. Creating more free space in the under hood area CFRP acts as a super capacitor for energy storage functions of electrical body parts such as, trunk lid, body stiffener [194–196]. Carbon fiber trunk lid of BMW E46 M3 CSL model is shown in Fig. 15.

5.1.4. Wireless signal transmission
In a car, there are number of wires used to gather information from sensors or to operate several devices. While obtaining a reserve network cable cords are replaced completely when carbon reinforced fibers are used to transmit electrical signals. A fiber composite structure comprised of layers of conductive fiber composites insulated in between used as a communication device when devices like transceivers are connected. Requirement of separate wires are eliminated when voltage applied to either layer of composite which conducts electric power to electrical devices [198].

5.2. Aerospace

5.2.1. Aircraft brakes
High temperature sections such as exhaust nozzle ceramic matrix composites are used. Also with properties like high coefficient of friction, longer life and resistance to environmental conditions such as oxidation, carbon fiber reinforced silicon carbide is used for aircraft brakes where temperature reaches up to 1200 °C [187,199].

5.2.2. Aircraft structure
Aircraft structural material should withstand under acute temperature variation preserving its desired mechanical properties with uttermost damage tolerance. Polymer matrix composites carries higher strength and stiffness replacing conventional aluminium based alloys in the field of aerospace sciences [200–204].

5.2.3. Gas turbine
Increase in combustor inlet temperature while minimizing the coolant gas requirement for combustor liner cooling is achieved by using integrally woven ceramic matrix composites (CMC). This multi-hole cooled CMC offers substantial combustion gain which finds application in development of gas turbine [205,206]. Gas turbine manufacturing is presented in Fig. 16.

5.2.4. Telescope antenna
Hubble space telescope used high gain antenna made of 6061 aluminium matrix diffused in bonded sheets of P100 graphite fibers. A 3.6m long antenna offers the desired stiffness and low coefficient of thermal expansion to maintain the position during space maneuvers [208].

5.2.5. Aircraft’s seat and carpet fabric
Multilayer polymeric/TiO$_2$ composites possesses double self-cleaning property which provides photo-oxidation and anti-sticking. Based on these properties, the material is used for fabric of seats and carpets in aircrafts [209].

Fig. 15 – Carbon fiber trunk lid of BMW E46 M3 CSL [197].
5.3. Mechanical

5.3.1. Heat exchanger
In the tropic or sub-tropical region where temperature and humidity is high, liquid-to-gas heat exchangers find application for cooling. It utilizes porosity of ceramic composite to transfer heat and mass in the return air stream. Water in the porous ceramic tubes lowers the temperature. It is also used in winters to humidify the supply air [210,211].

5.3.2. Sliding bearing
Fig. 18 shows bearing shells and for the application in a motor sliding bearing is invented which uses low to moderate content of tin and extremely low content of nickel. Remarkable results show improvement in the adaptability and particle compatibility. These properties play vital role when it used at high sliding speeds as a main bearing shell or a connecting rod bearing shell [212].

5.4. Bio-medical

5.4.1. Skin grafting
Chitosan composite as bio-resorbable material due to its porous structure employed for wound healing applications as it promotes adherence, proliferation and migration of cells. Its porosity provides gas permeation, enhanced water absorbing capacity, cell interaction with drugs. The chitosan-based matrix biomaterial composite is applicable for large dressing areas particularly in severe skin damages or when urgent recovery during skin grafting is required [214,215].

5.4.2. Orthopedic
Titanium with its biocompatibility, mechanical properties, and ability to integrate into native bone were widely being used as implants, pins, screws, wires and plates in orthopedic, plastic/reconstructive and general surgery. However, the potential of graphene and CNT materials is replacing to titanium as their ability to absorb biomolecules and proteins induce spontaneous osteoblastic differentiation and gained the popularity to improve the osseointegration of titanium. These materials also support tissue growth which allows them to be used in tissue engineering in vivo [216,217].

5.4.3. Haemodialysis
Protein retention is observed to be highest for cellulose acetate- carbon nanotubes- graphene oxide (CA/CNT/GO) composite membranes. These materials found their application in tissue regeneration, water-oil purification, heavy metal ions removal, gas separation, haemodialysis or oxygenating apparatus [218] (Fig. 17).

5.5. Marine

5.5.1. Podded propeller
Marine screw propellers are subjected to high loading and vibration; also being a roto-dynamic machines which are subjected to pulsating forces, bending, axial thrust, centrifugal forces. Alloys of aluminium and stainless cast steel, aluminium bronze, manganese bronze were used to be conventional propeller materials carrying drawbacks of corrosion, cavitation, formation of galvanic cell, resulting high maintenance cost. Therefore, carbon fiber reinforced plastic having high strength to weight ratio, improved fatigue properties, non-corrosion in marine environment, high thermal resistance and low maintenance cost is used as a propeller material [219–221]. Fig. 18 displayed azipod propeller used for submarines.

5.5.2. Anti-biofouling
Biofouling is accumulation, colonization and attack of organisms on micro and macro levels which causes severe problems such as corrosion, distortion, alteration of surfaces submerged in a water, increased weight and drag leading to reduction in speed and costs up to 40% additional fuel consumption. Use of nano-composite coating with electrolytic deposition method seems to be proficient solution. Nanomaterials possesses effective antimicrobial properties which creates a biofilm acting as a barrier between structural material surface and marine environment [223,224]. Fig. 19 an example of biofouling, zebra mussels attacked a marine instrument resulting failure of its function.

5.5.3. Hull
For the development of hulls and marine craft structures, a polymeric core with sandwich composite panels of glass or carbon skins are implied. Light structures, fast produc-
tion rate, high strength and durability these properties of composite materials finds numerous applications in marine environment. Epoxy based composites with CNT are the most favored type of composite using in marine industry [226–228]. Fig. 20 is representing a hull part of ship.

5.5.4. Marine structures
When treated to sea water aging mechanical properties of all types of metals, alloys or composites deteriorated. Compared to plain glass and carbon fiber reinforced polymer composites, water absorption tendency of hybrid composites (GCG2C9) was lowest. Compared to plain GFRP, the retention in mechanical properties of the hybrid composites was more. Hybrid composites (GCG2C9) shows lowest water absorption with highest flexural strength of 462 MPa. This property helps to fabricate frames and outer body of ships and other marine structures. [230,231].

5.6. Chemical
5.6.1. Radiation proof material
Basalt fibers do not absorb nuclear radiation; therefore they are used in transportation and storage of radioactive nuclear materials. Also basalt based geo composites find application at nuclear waste disposal sites as radiation proof protective caps which provides protection against release of nuclear underground wastes for several centuries [231–233].

5.6.2. Piping
When compared to steel basalt fiber reinforced polymers (BFRP) based pipes withstand higher pressures up to 1000 atm. Therefore used for transportation of corrosive chemicals and in shaft linings. Basalt lining within the boilers prevents the abrasion of material at higher temperature when compared to low sulfur coal. Similarly, basalt lines pipes (BLP) are used for the transportation of mining chemicals like chlorides of sodium and potassium which are known for their high abrasive and corrosive property in the slurry form [185,234].

5.6.3. Fuel cells
Graphene-CNT-Copper nano-composites offers high hardness, wear resistance, good electrical and thermal conductivity which is ideal for heat sink materials and some microelectronic devices. Moreover, metal nano-composites find potential applications in electrode materials of fuel cells and hydrogen storage materials [235,236].

5.7. Miscellaneous
5.7.1. Mortar
Mortar made of chopped Basalt fiber reinforcement with cement as a matrix material reveals enhanced properties like high strength, higher strain to failure, resistance to repeated impact, better stability, reduced drying shrinkage, improved toughness and thermo-chemical resistance. With these properties mortar with basalt fiber reinforcement is generating dominating applications in construction industry [237].

5.7.2. Bicycle frame
To overcome the shortcoming of high cost and low impact toughness carbon fiber is now replacing with hybridize carbon fiber with natural fibers such as flax. When compared to Al, carbon fiber, Ti, and steel; flax has superior damping characteristic. A prototype bicycle frame fabricated which weighs around 2.1kg made of 70% flax fiber and 30% carbon fiber (approx.) [238].
6. Conclusion

Composites materials gained enormous popularity in the research and manufacturing industries due to their desirable properties that cannot be achieved by any of the constituent materials acting alone. Till now researchers have taken efforts to fuse different variety of constituent elements to fabricate composites and several tests were carried out to study their properties and phase change. Further, researchers have optimized the content percentage and other several parameters that blend the formation of a superior composite in order to achieve highest material efficiency. Towards achieving maximum material efficiency, researchers have developed many advanced manufacturing techniques to overcome the time delay and complexity of conventional processes. The majority of them succeeded to improve material properties to employ them for potential applications in major fields such as aerospace, automotive, chemical, sports. However, these days’ bio-composites with the use of the natural bio-degradable materials are dominating the market as they are revealing unforeseen properties being environment friendly.

6.1. Future scope

Despite of major research efforts made in the field of composite manufacturing, there is enormous scope to develop advance manufacturing techniques in conjunction to automation that allows increasing the productivity of material. It is worth to further investigate the hybridization of natural biodegradable materials with synthetic materials as constituents of the composite structure which helps to boost strength and stiffness of material being environment friendly.

Conflicts of interest

The authors can confirm that this work has not been published elsewhere and also it has not been submitted simultaneously for publication elsewhere.

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