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## Chapter

# Composite Materials: A Review of Polymer and Metal Matrix Composites, Their Mechanical Characterization, and Mechanical Properties

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## Abstract

Unlike conventional materials, composites have become an optimal option for a range of modern, industrial, clinical, and sports applications. This is combined with their noteworthy physical, thermal, electrical, and mechanical properties, as well as low weight and cost investment funds in certain cases. This review article attempts to give an overall outline of composite materials, regularly polymer-matrix composites (PMCs) and metal-matrix composites (MMCs). Polypropylene (PP) polymer and aluminum alloy were selected as matrices for this concentrate in light of their appealing properties and their use in different applications. Various studies address the different build-up materials, material handling, and the various properties. Mechanical characterization is an important cycle process for the development and design of composite materials and their components. It includes the determination of mechanical properties, for example, stiffness and strength according to standard test techniques (i.e., tensile, compression, and shear test strategies) distributed by the ASTM and EN ISO associations. Comparable to the determination of fatigue strength and fatigue life for composite materials. With respect to mechanical properties of composite materials, this paper reports several variables and limitations that affect mechanical property estimates, including material constituents, manufacturing process, test parameters, and environmental conditions.

**Keywords:** composite material, reinforcement, matrix, polypropylene, aluminum alloy, mechanical characterization, standard test methods, static, fatigue, mechanical properties

## 1. Introduction

All materials can be divided into four classifications based on their tendency. The last classification consists of at least two separate materials from the other three

material classes combined into a single design unit [1]. Composite materials have been utilized as long as mankind has been gathering experience. Basically, every material in this world is a composite material, that is, a single piece of metal is actually a polycrystal (composite) of many individual crystals. Nevertheless, there are plenty of composite models in nature where the idea of composite material comes into play, for example, wood is really a sinewy material. Bone is another example of normal composite material. It is made of short and delicate collagen strands inserted in a mineral-matrix called apatite [2]. Animal bones were used by humans in the good old days as raw, regular composite material for fishing, hunting, and farming [3]. With the growth and development of societies in the last few years of the following 100 years, the world has had difficulty promoting advanced design materials to meet their needs. The 1930s can be considered as the start of the historical development of today's composites. In the 1960s, the concept of polymer-matrix composites (PMCs) advanced the economy in many areas, especially in the aerospace industry, to develop materials that are better protected against corrosion and fatigue damage. The energy emergency during the 1970s and the significant expense of fuel had expanded the interest for superior execution composites. Extraordinary efforts were made in the improvement of metal-matrix composites (MMCs) materials in the late 1970s. Toward the end of the twentieth 100 years, research focused on the use of low-cost carriers [3, 4]. Composite materials have supplanted steel parts, bringing about a weight saving of 60–80%. This makes them design materials and is utilized for assortment applications [5].

In the broadest sense, a composite is a material that consolidated at least two constituent materials or stages that have a distinctive point of connection between them [6, 7]. By choosing a suitable blend of composite and build-up material, it is possible to deliver a composite that precisely meets the needs of a specific application [8]. The matrix phase is soft and ductile, and serves to hold the reinforcing phase that is strong and stiffer and enhances the mechanical properties of the composite. The interface or the connection point between the two material phases transfers the loads applied by the external environment to the single reinforced material [9, 10]. In light of the matrix, composites are referred to as polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs). Polymer composites consist of a thermoplastic or thermosetting polymer as a matrix, while they give a wide assortment of properties [4]. PP [11, 12], polyamides (PA) [13, 14], polyetherimide (PEI) [14], polystyrene (PS) [12], polyether ether ketone (PEEK) [15], and poly(phenylene sulfide) (PPS) [14] are some examples of common thermoplastic resins. While polyesters (PE) [16], epoxides [16, 17], and vinyl esters [17, 18] are the best-known thermosetting materials. Thermoset composites are considered strong with high stiffness and strength and good fatigue and creep resistance, but have low ductility and poor impact resistance, also they cannot be recycled [19, 20]. While thermoplastic composites are harder, less brittle, and exceptionally impact resistance, but they exhibit unfortunate creep resistance compared to thermoset composites. The main benefit of thermoplastic is that they can be easily reused [20]. The ceramic matrix is usually supported by other reinforcing ceramic types. They offer exceptional corrosion resistance, excellent compressive properties, and strength at high temperatures with elevated melting points, but the main disadvantages of CMCs are the disappointing deformation. On the opposite side, metal matrix composites are considered advanced materials. The common metallic matrices used for composite applications are aluminum, copper, iron, magnesium, nickel, and titanium alloys. Metal composites offer better mechanical and thermal properties than conventional materials, particularly wear resistance and thermal conductivity [4].

The classification of composites can also be based on the reinforcements and mainly consists of three main groups: particle reinforced composites, fiber reinforced composites, and structural composites. The particles can be of different sizes. To effectively support the composite, the particles must be small, have a certain size in all directions, and be uniformly introduced into the matrix. In fiber-reinforced composites, the reinforcements are in the form of fibers or strands. These can be continuous- or discontinuous-fibers depending on the orientation, three extremes are possible for discontinuous fibers: a parallel orientation and a completely or partially random orientation. The fibers, in particular, can be whiskers or wires, depending on their diameter and character. The first form has an extremely large length-to-diameter ratio and the wires have a relatively large diameter [21]. Discontinuous filaments are often not as effective as continuous fibers in enhancing some mechanical properties, such as strength, stiffness, and creep resistance, while they are particularly productive in advancing other properties, such as fracture toughness, wear resistance, and thermal and electrical conductivity [22]. Structural composites consist of a system of layers bonded together to form laminate or sandwich structures. Laminate composites typically consist of made of multiple layers (plies) of arranged or random fibers bonded together by the matrix, the lay-up of each layer depending on the planned loading of the structure in which the laminate is to be used [23, 24]. Consequently, sandwich structure results from the joining of two face sheets or skins on a lightweight foal core, which is utilized to isolate the skins [25].

The most commonly manufactured filaments in composites are carbon, glass, and aramid. Carbon fibers are classified by their modulus (UHM, HM, IM, and LM), strength (HT and SHT), precursor materials, and heat treatment temperature. Glass fiber can be adjusted for different applications, for example, E-glass, which is excellent as an electrical resistant, C-glass, which has better chemical resistance to acids, and type T-glass for thermal protection. S-glass is of high strength and is broadly utilized in composite materials [26, 27]. Aramid filaments are synthetic organic fibers formed by highly crystalline aromatic polyamides [9]. Nomex® and Kevlar® are two known aramid fibers, as claimed by Du Pont. They have high mechanical and thermal properties (tenacity, strength, strength, and melting point) although they display high resistance to most chemicals [27]. Ceramic fibers are made up of different metal oxides, nitrides, and carbides and combinations of them. They are accessible in various fiber lengths and fabrics. Ceramic reinforcements used to strengthen composites can be used in applications with temperature up to 1000°C due to the high melting point of about 2000°C for ceramic fibers [9]. Natural fibers are divided into three basic types, depending on their origins. Plant filaments so-called cellulosic or lignocellulosic fibers, such as bast strands, leaf, and wood strands. Animal fibers usually consist of proteins like collagen, keratin, and fibroin, such as wool and animal hair, and mineral fibers include the asbestos bunch, fibrous brucite, and wollastonite [28]. Natural filaments are characterized by their low density, high toughness, and acceptable strength properties, and also offer significant advantages, such as biodegradability, biodegradability, renewability, and environmental friendliness [9]. Both synthetic and natural fibers have advantages and limitations for such applications. Different classification of composites including other characterizations: material source, biodegradability.

Injection, extrusion, and compression molding are the predominant manufacturing processes for PMCs. Injection molding is the most recognized and cost-effective process for producing composites on a large scale. Both thermoplastics and thermosets are exposed to injection forming. Extrusion is probably one of the most common

processing methods for producing short FRPCs. Compression molding, on the other hand, is particularly suitable for the mass production of composite parts. Therefore, the sheet molding technique is another primary approach for composite manufacturing [9, 29]. Open molding, also called contact molding, including hand lay-up and spray-up, are additionally utilized to produce thermoset composites products [30]. The resin transfer molding (RTM) procedure is generally suitable for the medium-volume production of large parts [29]. It has a place in a category that is sometimes called liquid composite molding [31]. Thermoplastic sheet forming, thermoplastic pultrusion, and tape laying are used to produce thermoplastic advanced materials, such as continuous long fiber reinforced composites. Therefore, composite liquid forming, thermoset pultrusion, fiber winding, and autoclave are the best manufacturing processes for thermoset composites [32].

The processing strategies used for the production of MMCs are mainly divided into two classes. In the liquid-state process, the pressure causes the reinforcement to infiltrate through the liquid metal. Powder metallurgy is the most popular method in solid-state processes. This technique provides the most remarkable mechanical properties of metal composites reinforced with particles [8]. The friction stir process is also a strong solid-state process, which is characterized by the fact that it can improve the properties compared to the conventional processing technique [33]. Finally, the method of high-energy ball milling was usually used for the preparation of nanocomposites [34].

The reason for this review is to provide a compilation of information from the literature on polymer and metal matrix composites. PP and aluminum alloy composite were chosen as composites for this paper. Most of the research reviewed deals with these two materials, with a few exceptions where further results are needed.

## **2. Polymer and metal matrix composites: case of PP and aluminum alloys-based composites**

### **2.1 PP matrix composites**

PP is a thermoplastic polymer that comes in three explicit compositions: isotactic PP (iPP), syndiotactic polypropylene (sPP), and atactic polypropylene (aPP). There are also different types of PP: homo-polymer PP (HPP) in which the PP is composed entirely of propylene monomer in semi-crystalline solid form. Random copolymer (RCP) and impact copolymer, whose PP chains contain ethylene as a co-monomer in amounts (1–8% for RCP and 45–65% for ICP) [11].

Many engineering plastics have been replaced by PP due to this they have good mechanical performance and are easy to process and recyclable, lightweight, and economically viable. For example, PP accounts for more than 40% of the total plastics in automobiles and is strengthened with various types of fibers [35]. For this reason, since its discovery, PP has been attractive to numerous researchers and modern companies to improve and enhance its properties and make it useful for additional engineering applications. K. Okuno and R. T. Woodhams [36] investigated the viscosity of the mica flake-filled PP melts and their mechanical properties. As a result, the properties of the molded composite exhibit modulus values that are higher than unfilled PP. George C. Richardson and Jhon A. Sauer [37] examined the possible reinforcing effects of six different types of filler particles on composites made of thermoplastic isotactic PP. They used as reinforcements the chopped strand glass fibers,

ceramic whiskers (alumina  $\text{Al}_2\text{O}_3$  and silicon carbide  $\text{SiC}$ ), two different glass spheres (type E with a small diameter of 10 to 40 microns and types P with a larger diameter of 75 to 110 microns), and finally carbon spheres. Their results showed that adding a higher modulus filler to a lower modulus PP matrix increases the stiffness of the composite, as well as when the fillers are glass spheres. The addition of carbon spheres to the PP matrix leads to a reduction in tensile strength and ductility. D.M. BIGG [38] investigated the electrical, thermal, and mechanical properties of PP matrix composites loaded with randomly scattered short aluminum fibers (three types with three different aspect ratios). The results showed an increase in the electrical conductivity of the composites and in the thermal conductivity, without sacrificing the advantage of low density. Shigeo Miyata et al. [39] estimated some properties of PP matrix composites enhanced by four types of  $\text{Mg}(\text{OH})_2$  magnesium hydroxide particles. By incorporating more than 57% by weight of  $\text{Mg}(\text{OH})_2$  particles, the composite becomes nonflammable, and their stiffness also improves when the crystallite size of  $\text{Mg}(\text{OH})_2$  becomes larger in the range of up to about 2  $\mu\text{m}$ . Conversely, the strengths have considerably reduced.

Since glass and carbon fibers are the most widely used reinforcing materials, they possess all the advantageous properties that made the rapid development of PP matrix composites and their use in many applications possible in recent decades. J. Karger-Krocis et al. [40] studied the fatigue crack propagation (FCP) of short- (SGF) and long-glass (LGF) fibers reinforced molded PP composites on notched compact tensile specimens (CT). The FCP response of long-glass fiber reinforced PP exhibited less sensitivity to notching and fiber arrangement than that of the short fiber reinforced versions. For further, J.A.M. Ferreira et al. [41] focused on the static and fatigue behavior of PP/glass-fiber thermoplastic composites produced from a bidirectional woven cloth mixture of E-glass fibers and PP fibers, this composite was made with a fiber volume fraction of 0.338. S.-Y. Fu et al. [42] investigated the tensile properties of short-glass (SGF) and short-carbon (SCF) fibers reinforced injection molded PP composites. The addition of both glass and carbon fibers significantly enhanced the modulus and strength of the composites, with SCF/PP composites exhibiting the most remarkable strength, the modulus values of SGF/PP were the highest, and that attributed to the high strength of carbon fibers and the high stiffness of the glass fibers on the opposite side. K. Senthil Kumar et al. [43] described the development of long-glass fiber reinforced polypropylene (LFRP) composites. LFRP pallets of different sizes were produced by extrusion with a specially developed impregnation die and then injection molded into LFRP composites. Optimum content of 5 wt.% of MA-g-PP compatibilizer was added to PP-matrix in order to get better adhesion between fiber and resin. F. Rezaei et al. [44] characterized a short-carbon fiber reinforced PP (10% SCF/PP) composite as a substitute of a steel bonnet. The effects of the length and composition of fibers on mechanical properties of SCF/PP composites fabricated by compression molding technique were additionally explored. The experimental results revealed that the carbon-fiber-reinforced PP composite is a good option for replacing steel in car bonnet, with much lower weight and higher mechanical properties. P. Russo et al. [45] observed that the use of PP in combination with maleic anhydride (PP-g-MA) as a compatibilizer improved the mechanical performance of a woven glass fabric reinforced PP composites laminates. Therefore, the addition of the compatibilizer to the PP matrix improved the adhesion between glass fibers and PP matrix, which increased the ability to transfer the load from the polymer matrix to the reinforcement phase glass and carbon fibers are used as reinforcement for PP homopolymer used in structural applications. The two types of

fibers showed advantages and drawbacks in terms of their stiffness, adhesion with the matrix, and compositions. Carbon fibers are more costly and their composites are stiff but have only moderate strengths due to poor interfacial adhesion [46].

Aramid fibers are other synthetic fibers that are generally used to reinforce PP polymer. They provide very good properties for a polymeric material. They are particularly popular because of their increasing use in industrial applications and advanced technologies [47]. N.K. Cuong & Z. Maekawa [48] investigated the effects of manufacturing conditions on the mechanical properties of thermoplastic PP composites with aramid fibers. The composite laminates were prepared by varying the impregnation time and compression pressures. Tensile properties were found to enhance with increasing the impregnation time, or the compression molding pressure led to lower void content in the composites. In any case, SEM micrographs surfaces indicated weak adhesion of the aramid fibers and the PP matrix. J. Maity et al. [49] studied the incorporation of chopped Twaron filaments into PP polymer. Also, the surface modification of Twaron fibers by direct fluorination technique, and its influence on the mechanical and thermal properties of PP/Twaron fiber composites. The surface modification leads to better adhesion with the PP matrix and, thus to an enhancement in the properties of PP/Twaron fiber composites. Xiaousi Chen et al. [50] reported in detail the mechanical and thermal properties of chopped aramid fibers (Kevlar 1414) reinforced PP polymer composites. Crystallization and flammability behavior were also investigated. Tensile strength of the composites improved with the addition of aramid fibers, with maximum strength achieved at 20 wt.% aramid fibers, which present 11.8% higher than unreinforced PP. Impact strength also improved, with PP/AF composites able to withstand 40.1 KJ/m<sup>2</sup> at 40 wt.% AF loading, 3.7 times that of PP matrix. Moreover, the PP/AF composites had superior thermal stability and char residue relative to pure PP. In addition, the AF had an effective impact on promoting the flame retardancy of the PP/AF composites. Rajat Kapoor et al. [51] investigated the dynamic compressive behavior of PP fabric composites reinforced with Kevlar fibers under compressive loading with a high strain rate. The PP/K composites laminates were manufactured by using vacuum assisted compression molding technique, and maleic anhydride grafted-PP (Mag-PP) was added to PP for enhancing the interfacial property between Kevlar fiber and PP matrix. The influence of increasing strain rate from 1370 s<sup>-1</sup> and 4264 s<sup>-1</sup> on the dynamic compressive response of PP/Kevlar laminates was evaluated in terms of peak stress, strain at peak stress, toughness, and compressive stiffness. All of these properties had increased with increasing strain rate. As result, the peak stress multiplied threefold, toughness improved tenfold, and elongation at peak stress nearly doubled. Calvin Ralph et al. [52] investigated the potential of 10, 20, and 30 wt.% short-basalt fibers (SBF) as reinforcement for the PP matrix. Mechanical testing of short-basalt-PP composites indicated that the addition of basalt fiber significantly improved the tensile and flexural properties, but in the opposite case, the impact properties decreased. In addition, these mechanical properties were strongly influenced by fiber sizing, as adhesion increased greatly, which provided the greatest improvement in tensile and flexural strength, but led to lower impact strength.

PP can be modified with mineral fillers, in order to produce a composite material with a reduced cost and enhanced thermomechanical properties study by Trotignon et al. [53] focused on the effect of the low concentration of mineral fillers on the mechanical properties of PP homopolymer. Findings showed that all fillers, regardless of their concentration, lead to an increase in the maximum stress at around 50%. elastic and yield properties of all specimens are partially not affected by the stresses.

In this work [54], nano-sized SiO<sub>2</sub> and ZnO nanoparticles were obtained by the sol-gel process, they have distinguished-mechanical properties. UV and heat ray shielding effect, also EFKA commercial dispersant and silane coupling agent were used to improve particle dispersion and particle-polymer adhesion, respectively. Haydar U. Zaman et al. [55] studied the effects of nano- and micro-ZnO concentration on the morphology, mechanical, and crystallization behavior of iPP polymer. Three compositions of iPP/mZnO and iPP/nZnO composites were made with ZnO content ranging from 2, 5, and 8 wt.%. The nanoparticles (5 wt.% nZnO) displayed good dispersion in the matrix, whereas the microparticles (5 wt.% mZnO) showed a broad size distribution, which significantly impact the mechanical properties of the composites. Similarly, the DSC measurement showed that the crystallization temperature of iPP/nZnO was much higher than that of iPP/mZnO. F. Mirjalili et al. [56] prepared a nanocomposite containing PP and alumina nanoparticles ( $\alpha$ -Al<sub>2</sub>O<sub>3</sub>) by using a Haake internal mixer and adding a dispersant agent (titanium dioxide powder TiO<sub>2</sub>) to the PP polymer. The alumina nanoparticles with the contribution of dispersant agent enhanced the tensile and the flexural properties of the composites with the amount of 4 wt.% and 5 wt.%, respectively.

Polymer nanocomposites reinforced with carbon fillers, for example, graphene, graphite, and carbon nanotubes (CNTs), have been investigated for use as strengthening materials for various applications due to their attractive properties, including low mass density, outstanding mechanical properties, and superior electrical and thermal conductivity [57–59]. In these studies, Kyriaki Kalaitzidou et al. [60, 61] examined the possibility of using exfoliated graphite nanoplatelets xGnP, as reinforcement in PP and fabricated by melt mixing followed by injection molding. The nanocomposites xGnP-PP exhibited outstanding mechanical and thermal properties compared to the polymer matrix, with the highest value of thermal conductivity observed for 25 vol% xGnP/PP being six times that of PP. In addition, the xGnP-PP composites exhibited better performance compared to commercial carbon fiber-reinforced PP composites due to the morphological differences between exfoliated graphite nanoplatelets and carbon fibers, as xGnP reduces the CTE in two dimensions, while carbon fibers only in the direction parallel to its axis [61]. Sok Won Kim [62] proved that the addition of low concentrations of multi-walled carbon nanotubes to the PP matrix improved the thermal conductivity and the thermal diffusivity of the polymer. The addition of 2 wt.% MWCNTs resulted in a doubling of the thermal conductivity. In addition, the thermal conductivity can be raised threefold by surface treatment of the nanotubes. Rumiana Kotsilkova et al. [63] have prepared by an extrusion process nanocomposites containing reinforcement of some weight fractions of 0.1 to 3 wt.% MWCNTs and isotactic PP (iPP) matrix. Thermogravimetric analyses (TGA) performed on the nanocomposites showed better thermal stability compared to the matrix polymer. The contribution of MWCNTs to the overall modules of the nanocomposites was highlighted. Dynamic mechanical tests demonstrated the improvement of the storage modulus with increasing MWCNTs content was demonstrated, as well as during tensile tests, the young modulus showed a maximum improvement of about 23% compared to the iPP-matrix. Young Soo Yun et al. [64] found that the morphological differences between the alkylated graphene oxides (AGOs) and the one-dimension alkylated carbon nanotubes (ACNTs) produced a different reinforcement effect in the composites. AGO fillers have been conducted to better thermal conductivity, and high performance in thermal degradation temperatures compared to ACNT fillers. Furthermore, AGO was beneficial for Young's modulus, only 0.1 wt.% AGO was required to increase it by more than 70%. However, the tensile strength and



elongation were reduced relative to the PP polymer. On the other hand, 0.5 wt.% of ACNTs was sufficient to increase the elastic modulus and tensile strength by 37% and 20%, respectively. The interfacial interaction between the fillers and the matrix also contributed to these different reinforcing effects, with AGO and PP having a greater interaction than ACNT and the PP matrix. Chien-Lin Huang et al. [65] also noted a decrease in tensile strength and maximum elongation with an improved elastic modulus of the carbon filler reinforced conductive composite. In terms of mechanical properties of the PP matrix, 20 wt.% graphene nanosheets (GNs) and carbon fibers (CFs) reinforced conductive composites showed a decrease in tensile strength by 34% and 8%, respectively, while they increased tensile strength by 150% and 158%, respectively. Moreover, GNs proved a significant influence on the crystallinity temperatures and electrical conductivity of the PP matrix as CF. Moustafa Mahmoud Yousry Zaghoul et al. [66] found a significant increase in the flexural strength and modulus of PP matrix reinforced with two different carbon fillers, namely multiwalled carbon nanotubes (PP-MWCNT) and synthetic graphite (PP-G), with more significant improvement was noticed for CNTs. In particular, the flexural modulus was 49% and 74% better at 2 wt.% and 10 wt.% loading than that of PP-G composites, respectively. A similar trend was observed in the fracture toughness tests, the inclusion of carbon fillers resulted in an impressive enhancement in fracture toughness, with the maximum load supported by MWCNT-reinforced composites being 38% higher than that of synthetic graphite-reinforced composites. Bartolomeo Coppola et al. [67] Illustrated the potential use of carbon nanotube reinforced PP nanocomposites (PP/CNTs) as strain-gauge sensors for structural monitoring. PP/CNTs nanocomposites with 5 and 7 wt.% of CNTs have shown attractive sensing properties in terms of gauge factor (GF). Moreover, their excellent mechanical and electrical properties are made from the appropriate substitutes for sensing materials. Since their ease of preparation and flexibility, they can be easily used in several application areas.

In recent years, with the demand for the utilization of renewable sources and sustainable materials, natural reinforcements have gained the attention of many researchers and scientists thanks to their biodegradability characteristics. P. Bataille et al. [68] studied the effects of surface pretreatment of alpha-cellulosic hardwood pulp fibers with a weighted-average fiber length of about 240 micrometers, as well as processing time and temperature, on the mechanical properties of the cellulose-containing PP. In order to modify the interfacial interaction between the PP matrix and cellulose fiber the silane-coupling agents and maleic anhydride modified PP were used. X. L. Xie et al. [69] investigated the structural properties, as well as the mechanical behavior of injection molded composites of isotactic polypropylene (iPP) and 0, 10, 20, and 30 wt.% of chopped sisal fiber (SF) with an average length of 10 mm. The thermal stability of PP/SF composites has shown that they could be processed by injection molded in the same way as for PP homopolymers. Moreover, the stiffness of the PP/SF composites was improved by the fibers, but their tensile strength decreased due to the poor interfacial bonding between PP and sisal fibers. Byoung-Ho Lee et al. [70] fabricated bio-composites from long and discontinuous of two kinds of natural fibers (kenaf and jute fibers) and PP matrix. It was found that an optimum nominal fiber fraction of 30% by weight of kenaf fiber reinforced composites, gives the highest tensile and flexural modulus, while for the jute fiber reinforced PP composites, fiber content of 40% by weight seemed to be the optimum value. This limitation of fiber content was attributed to the void content in the bio-composites, which may be caused by nonuniform packing or lack of PP fibers-matrix. The shortness of both natural and PP fibers may help the incorporation of more natural fibers

into the biocomposites. N.A.M. Aridi et al. [71] proved that the addition of rice husk fillers to a PP polymer improved the mechanical strength and stiffness of rice husk/PP composites. In addition, a struktol coupling agent was added to the composites to facilitate the PP fiber interaction. The 50 wt.% filler-loaded composites exhibited the maximum tensile strength, flexural strength, and flexural modulus, on the other hand, 35 wt.% of filler loading was found to be the highest elastic modulus, flexural strength, flexural modulus, and impact strength. Ngo Dinh Vu et al. [72] investigated the thermal, mechanical, and biodegradability properties of cellulose fiber (CF) reinforced PP green composites. Cellulose fibers were extracted from rice straw and prepared by the melting method. The poor thermal properties of cellulose fibers result in reduced thermal stability of PP/CFs composites with different loading levels of CFs. The strength of PP/CFs composites was also decreased, whereas their stiffness modulus was increased with the increasing CFs content. The maximum strain of pure PP showed 57.5%, but it significantly decreased with CFs loading, probably related to the weak interactions between PP-matrix and CFs, which generates stress concentration points and agglomerations. Nitish Kumar et al. [73] used animal fiber (hair) as reinforcing material and PP as the resin. The percentage of horsehair (HH) varied from 0, 10%, 20%, and 30%, where the fiber length was fixed, and the composite specimens were prepared using the film stacking method. The specimens of 20% horsehair and 80% PP (by weight) showed the best composition in mechanical characterization. Numerous other natural fiber-reinforced PP composites have been investigated, notably: Abaca fiber [74, 75], flax fiber [76], hemp fiber [77], oil palm fiber [78], banana fiber [79], kenaf fiber [80], ramie fiber [81], sisal fiber [82], cotton stalk fibers [83], coconut coir fiber [84], kapok husk [85], wood fiber [86], jute fiber [87], rice husk [71], wheat straw fiber [88], bagasse fiber [89], and pineapple leaf fiber [90].

Hybridization is an important direction for future research, which is obtained by combining two or more different types of fibers in a single matrix, hybrid composites have a balance between inherent advantages and drawbacks. Several studies have already been carried out in this regard, Himani Joshi and J. Purnima [91] developed chopped E-glass fibers and wollastonite mineral fiber reinforced PP hybrid composites (PP/GF/W), prepared by extrusion compounding and injection molding techniques. A positive hybrid effect was found for ultimate strength, while a negative hybrid effect was noticed for tensile modulus. Meanwhile, with an increase in the volume fraction of wollastonite fibers, the failure strain of the hybrid composites increased slightly. Hybridization with small amounts of mineral fibers allows these glass fiber composites to be employed in more engineering applications. R.V. Sheril et al. [92] improved the properties of homopolymer PP, by reinforcing it with two different combinations of mineral fillers, namely talc with silica (T/SI), and talc with  $\text{CaCO}_3$  (T/CC). As a result, the hybrid composite CC/T showed a superior Young's modulus, whereas tensile strength was nearly the same compared to SI/T. In addition, the thermal stability of SI/T was better compared to CC/T. In terms of flammability rate, the SI/T composite showed a lower burning rate than CC/T, which indicates that the SI/T composite was less flammable. N. Gamze Karsli et al. [93] investigated the hybrid reinforcement effects of surface treated or untreated carbon nanotubes (CNTs) (0, 1, and 4 wt.%)/glass fiber (GF) (0, 30 wt.%) on the morphology, mechanical and electrical properties of PP-matrix composites prepared by means of extrusion and injection molding techniques. The hybrid-reinforced composites exhibited higher stiffness and strength values when compared with only CNTs or GF reinforced composites. In addition, the electrical resistivity measurements of the

hybrid composites decreased as the amount of nanotubes varied from 1 wt.% to 4 wt.%. The combination of glass fibers and carbon nanotubes enhances the reinforcing ability of nanotubes in polymer composites, because of the improved polarity of the system. Alok Agrawal and Alok Satapathy [94] developed hybrid composites of homopolymer PP as a matrix reinforced with aluminum nitride (AlN) microfillers and solid glass microspheres (SGMs) with an average size of 90–100  $\mu\text{m}$ , for microelectronics applications. The thermal conductivity of the combination PP/20 wt.% AlN/10 wt.% SGM showed the highest values and maximum value of the dielectric constant. These results highlight the potential application of this new class of polymer composites in future electronic packaging materials. Maliha Rahman et al. [95] evaluated the change in mechanical properties of PP by reinforcing it with two natural fibers, such as chopped pineapple leaf and banana fiber. The hybrid composites reinforced with discontinuous and random fibers were prepared using the compression molding technique, and the ratios of pineapple leaf and banana fiber varied of 3:1, 1:1, and 1:3. In addition, a chemical treatment with 5% sodium hydroxide was performed for both pineapple leaf and banana fiber. The combination of 5 wt.% hybrid fibers with a banana ratio of 3:1 gave the best mechanical properties of the PP-based composites. Rupam Gogoi et al. [96] developed high specific strength PP composites using short-carbon fibers (SCF) and hollow glass microspheres (HGM). The hybrid composite with 10 wt.% HGM and 8 wt.% SCF showed an improvement in mechanical strength (up by ~110 and ~112% over pure PP). However, the addition of just 5 wt.% of SCF and HGM reduced the impact strength by ~78%–80% of the samples compared to unfilled PP, which could be described as the poor fiber-matrix and filler-matrix interfacial adhesion that may have caused an ineffective load transfer. Mariana Desiree Reale Batista et al. [97] developed hybrid composites combining two types of cellulose fibers, long- and short-glass fibers (LGD and SGF) or talc in a homopolymeric PP matrix. All the composites were prepared by injection molding under the same processing conditions, with the total fiber mass content fixed at 30 wt.%, with the cellulose concentration varying gradually from 0 wt.% up to 30 wt.%. Significant improvements in the mechanical, thermal, and morphological properties of the hybrid composites were observed, which the LGF/cellulose A composites exhibited the best mechanical properties, while (SCF/Mica)/cellulose B, talc/cellulose B exhibited superior thermal properties. At the same time, these properties decreased with increasing cellulose content. However, an optimal amount of cellulose fiber has sufficient properties that could reduce or replace some of the inorganic reinforcements in various applications, such as automotive applications, contributing to weight and cost savings, and contributing to the sustainability of the composites. Various hybrid reinforcements have been investigated and studied, such as glass and carbon [98], boron nitride – nano-hydroxyapatite [99], MgO - lignin fillers [100], kevlar - basalt [101, 102], clay - graphite [103], zirconia - MWCNTs [104], kenaf - carbon nanotubes [105], banana - coir [106], sisal - carbon/glass [107], bagasse -  $\text{CaCO}_3$  [108], glass - bamboo [109], coir - betel nut fiber [110], basalt - wood [111], glass - stainless steel [112], graphene - graphite [113].

## **2.2 Aluminum alloy matrix composites**

Aluminum alloys have been the most popular and attractive choice for the automotive and aerospace industries because they possess excellent characteristics, such as lightweight, high-strength, flame retardant properties, good corrosion resistance, easy mass production, and low cost. However, they have poor high-temperature

performance and wear resistance. Al alloys of 2000 series, 5000 series, 6000 series, and 7000 series are heavily utilizable [114]. For this purpose, aluminum metal matrix composites (AMMCs) are usually developed by adding a ceramic reinforcing phase to the alloy matrix. The required properties are achieved by the high-strength ceramic particles, whiskers, or fibers uniformly distributed in the aluminum alloy-matrix. Aluminum alloys have become the most employed matrix by companies for the fabrication of metal-matrix composites [115]. The use of ceramic whiskers enables us to take advantage of the mechanical performance of ceramics, as they provided the largest increases in strength and stiffness available, as well as creep resistance. However, the difficulty in obtaining a uniform dispersion in the matrix, processing costs, and high whisker prices, make them less recommended at the current time [116]. Aluminum matrix composites (AMCs) reinforced with ceramic particles have quickly emerged as a promising material, in particular, due to their superior tribological properties and corrosion resistance behavior. Moreover, the low price and ease of manufacture of particulate reinforcement composites should be noted, while they can manufacture by the traditional methods of mechanical mixing of the particles with the matrix material [117, 118]. Carbides in the form of whiskers and particulates, such as silicon carbide (SiC) and boron carbide (B<sub>4</sub>C), have been widely used to strengthen aluminum metal matrix, which are important structural ceramics due to their high hardness and thermal stability [119]. T. G. Nieh et al. [120] investigated the mechanical behavior of discontinuous, whiskers, and particulate SiC reinforced aluminum composites were manufactured by powder metallurgy techniques. At elevated temperature, all composites showed creep behavior that was significantly different from that of the neat matrix. They exhibited more creep resistance, with some improvement at 20 vol.% SiCw-6061Al, due to the higher creep resistance property of the whiskers. D. P. H. Hasselman et al. [121] pointed out that the thermal conductivity of a 40 vol.% SiC particulate reinforced aluminum matrix is highly dependent on the mean size of the SiC particulates ranging from 0.7 to 28 μm. They have found a decrease in thermal conductivity with decreasing SiC particle size since as the particle size decreases and the total interfacial area increases, the relative contribution of the SiC to the total conductivity of the composite decreases. N. Chawla et al. [122] characterized the mechanical behavior and microstructure of 20 vol.% SiC particulate reinforced 2080 aluminum matrix composites processed by a novel, low-cost sinter-forging technique. The microstructure of the sinter-forged composites showed relatively uniform dispersion of the SiC particles. Moreover, the sintered composites showed higher elastic modulus and tensile strength of 103 GPa and 434 MPa, respectively. The fatigue behavior of sinter-forged composites was also determined. A.A. El-Daly et al. [34] studied the mechanical properties and hardness of SiC nanoparticle reinforced aluminum matrix composites by employing the pulse-echo overlap (PEO) method as a nondestructive technique. 99.7% pure Al powder was reinforced with 2.5, 7.5, and 12.5 % by volume of nano-SiC particulates with an average size of 70 nm and fabricated by employing high-energy ball milling with cold-pressing and sintering technology at 550°C for 1 hour. As a result, a great improvement was shown with 12.5 vol.% nano-SiC particulates, elastic modulus increased by about 38%, and shear modulus by about 25% compared to the matrix material. Also, the hardness improved from 3.8 to 7.1 GPa, while Poisson's ratio was retained from 0.296 to 0.237. These improvements were essentially due to the stronger interfacial bonding. Qiyao Hu et al. [123] fabricated A356-SiC and 6061-SiC composites using the vacuum-assisted high pressure die casting (HPDC) process. A356 and 6061 aluminum alloys were reinforced with 10 vol.% SiC particles with angular

morphology. A uniform distribution of SiC particles was achieved in the composites with decreases in porosities to very low values of 1.4% for A356-SiC and 1.8% for 6061-SiC composites and good interfacial bonding. As a result, the HDPC composites exhibited significant mechanical properties, such as hardness, tensile strength, and elongation. Yuming Xie et al. [124] found that the aluminum matrix composites containing 5 wt.% of silicon carbides (SiC) and fabricated by deformation-driven metallurgy (DDM) were not only cost-effective but also process high mechanical performance, with the elastic modulus and hardness of the composites improved by 202% and 251% of the performance of pure aluminum, respectively. Jinkwan Jung and Shinhoo Kang [125] prepared a boron carbide-aluminum (B<sub>4</sub>C-Al) composite by an infiltration method. An improvement in the properties of B<sub>4</sub>C-Al composites was indicated after the addition of titanium metal and titanium-based compounds to B<sub>4</sub>C to enhance the wettability of the molten-matrix on the boron carbide skeletons. Heat treatment of the boron carbide skeleton prior to infiltration in the temperature range of 1000–1400°C was also considered.

R.M. Mohanty et al. [126] indicated that increasing the percentage until 25 wt.% of B<sub>4</sub>C particulate addition to the Al 1100 metal matrix resulted in a decrease in interfacial strength due to the weakening of the grain boundary of the composites when sintered at 837 K below the melting point of Al in a vacuum. In turn, the modulus and hardness improved with the increase of reinforcement from 0 wt.% to 25 wt.%, from 22 GPa to 183 GPa, and from 50 to 550 Hv5, respectively, indicating the high dependence of the modulus on the weight percentage of boron carbide particulates. E. Mohammad Sharifi et al. [127] enhanced the hardness, compressive, and wear properties of high purity aluminum by adding different amounts (5, 10, and 15 wt.%) of B<sub>4</sub>C nanoparticles with an average size between 10 and 60 nm. With increasing content of B<sub>4</sub>C nanoparticulates, the sample containing 15 wt.% showed the highest compressive strength of 485 MPa compared to pure Al (130 MPa), the same improvement in hardness, which increased from 33 HV for pure Al to 164 HV for the composite. The wear resistance is well known for a significant increase. K. Shirvanimoghaddam et al. [128] investigated the manufacturing of aluminum-boron carbide composites using the stir casting method. They found that changing the processing parameters (e.g., temperature, surface treatment of particles, stirring speed, and stirring time) and the volume fraction of reinforcements affected the microstructure and mechanical properties of the composites. Increasing the volume fraction of B<sub>4</sub>C from 0 to 20 vol.%, increasing processing temperature from 800°C to 1000°C, and increasing stirring times to 12 min enhanced the mechanical properties and wettability potential of aluminum and B<sub>4</sub>C particulates.

Titanium carbide (TiC) reinforced aluminum alloy composites are furthermore being more researched, [129, 130].

### **3. Conclusion**

Composite materials are advanced designing materials. Thanks to the proper selection of matrix reinforcement, easy access to these constituents, their lightweight, and their exceptional physical, thermal, electrical, and mechanical properties, composite materials are becoming an alternative to conventional materials and are used in various applications. This review article provided a general overview of composite materials, explicitly PP polymer matrix composites and aluminum alloy metal matrix composites. A number of studies have been discussed in order to illustrate

the different reinforcing materials, material processing, and the different properties, such as physical, mechanical, electrical, thermal, and tribological. Various types of reinforcements were discussed in detail, along with their reinforcing effect on PP and aluminum alloy matrices. Carbon, glass, and aramid were the most commonly used synthetic reinforcing materials as they impart excellent modulus, strength, and fatigue resistance to the PP polymer. Mineral fillers and ceramic whiskers, such as mica and carbides, have been shown to improve the thermomechanical properties of the resulting polymer composites, with cost saving. Oxide fillers, including alumina, zirconium, and magnesium oxide, were investigated for their improved tribological properties and impact resistance. Graphite, graphene, and carbon nanotubes were reported to provide exceptional mechanical properties and higher electrical and thermal conductivity for the conductive composites. Natural reinforcing materials and industrial waste particles have in turn been studied by numerous researchers to benefit from their biodegradability and environmental friendliness. Some hybrid composite materials are a reviewer for both PP and aluminum alloys, weighing the benefits and drawbacks of the various hybrid reinforcement. These standards provide researchers and users of such materials with a structural guide for proper material preparation and testing to ensure their quality and accuracy. These mechanical properties are highly dependent on a variety of factors and parameters, including material constituents, manufacturing processes, testing parameters, and environmental conditions. As follows:

- In most studies, increasing the reinforcement content was found to improve the mechanical properties, as well as the fatigue strength of both PP- and aluminum alloy-based composites. However, mechanical properties tend to decrease above a certain particle content, due to the agglomeration of these particles.
- A study has found that long-fiber reinforced PP composites have better mechanical properties compared to short-fiber reinforced PP composites. On the other hand, nanoparticles were found to strengthen aluminum alloys more compared to microparticles, resulting in more cycles to failure.
- Since most composites are anisotropic, they exhibit differences in their mechanical properties depending on their orientation with respect to the direction of loading. The mechanical properties of fiber-reinforced composites are highly influenced by the number of fibers aligned with the loading direction.
- Many reinforcing materials are not compatible with the matrix, resulting in poor interfacial adhesion. Modifications, such as treating the fibers or adding a coupling agent, to the polymer can help improve adhesion between the reinforcement and matrix phases of a composite material. In the case of an alloy matrix reinforced composite, preheating or coating of ceramic particles can help.
- Moisture and temperature are the two major environmental factors affecting the fatigue behavior of composites. High moisture or high environmental conditions have been indicated to reduce fatigue life.

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