Mechanics of Advanced Composite Structures 11 (2024) 217 – 230

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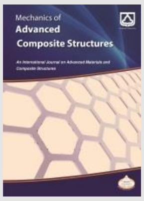
Mechanics of Advanced Composite Structures

journal homepage: http://MACS.journals.semnan.ac.ir



Multifunctional Properties of Metal Fibers Reinforced Polymer Composites – A Review

B. J. Fayzulla[a], M. Eroglu[b], I. N. Qader[c*]

[a] Department of Mechanical and Metallurgy, Erbil Technology College, Erbil Polytechnic University, Erbil, Iraq
[b] Departments of Metallurgical and Materials Engineering, Faculty of Engineering, Firat University, Elazig, Turkey
[c] Department of Physics, College of Science, University of Raparin, Sulaymaniyah, Iraq

KEYWORDS

Metal Fibers, steel fibers;
Hybrid composites;
Fine wires;
Mesh form.

ABSTRACT

The advent of metal fibers has led to the development of different fiber-reinforced composite systems via different manufacturing methodologies. Utilizing metal fibers as a single reinforcement can create completely new materials with unique physical structures and a synergistic effect on many properties. Steel, aluminum, titanium, and copper are examples of metal fibers used in industries such as aerospace, marine, automotive, and structural applications. Moreover, the possibility of combining various material systems (metal fibers - traditional fibers) to create hybrid composites allows for unlimited variation in cost and performance. In general, metals are available in the form of sheets as metal fiber metal laminate (FML), or as metal fibers in the form of fine wires, and mesh fibers. Investigation of fine wires and mesh fibers is still limited in the literature compared to the sheet metal form. Therefore, this work focuses on reviewing the processing techniques, properties, and applications of fine wires and mesh metals. In this paper, the application, methods of production, and several types and forms of metal fiber were described in detail. Moreover, the properties and applications of metal fibers reinforced polymer composite materials have been reviewed. The application of metalized fibers and the hybridization of metal fibers with synthetic and natural fibers reinforced polymer composites are also reviewed. To conclude, the potential of fine wires and mesh fiber forms, which are partially explored, seems to have excellent mechanical, thermal, and other material properties. Steel fiber is the most common metal fiber used due to its cost-effectiveness, availability in different forms, and high performance despite its heavy weight.

1. Introduction

The term “composite” indicates that two or more constituents are combined on a macroscopic level to form a unique structural material to use in different applications. One constituent is called the “reinforcement” materials whereas the other component is called the “matrix”. Fiber-reinforced polymer composite (FRP) is a class of composite materials consisting of reinforced materials such as glass, carbon, basalt, jute, and sisal-reinforced polymer matrix. FRPs are gaining more importance for specific applications in mechanical, construction, and many other manufacturing industries due to their high stiffness, high strength, and low density [1-4].

However, FRPs face a challenge in impact-loaded structures used in aerospace and automotive industries, challenges result from their relative lack of ductility, lack of ability to absorb energy before failure (brittle failure), and susceptibility to impact loading [5]. Some methods have been considered to address these shortcomings including the hybridization of metal fibers with brittle conventional fibers [6,7] or switching solely to metal fibers [8,9]. In comparison to other fiber kinds, metal fibers are denser. They do, however, have a property that cannot be found in other fiber types: they may

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* Corresponding author. Tel.: +964-750-4933789
E-mail address: inqader@gmail.com, ibrahimnazm@uor.edu.krd

DOI: 10.22075/macs.2023.29308.1461
Received 2022-12-15; Received in revised form 2023-08-18; Accepted 2023-09-08

have their strength and failure strain greatly changed without modifying their stiffness [10]. The most frequently studied metal fiber is steel fiber. Stainless steel fiber has characteristics such as resistance to corrosion, reduced elongation at high tension, and excellent flexibility. Stainless steel wire mesh is frequently used in a variety of products, including industrial sieves, chemical filters, architectural ornamentation, dryer belts, and conveyor belts for both the food and non-food industries. Stainless steel wire mesh is frequently utilized due to its advantageous traits for industrial applications and architecture. The exceptional corrosion resistance of woven stainless steel is unquestionably its main advantage. While high-alloy steels can withstand extreme conditions like low/high temperatures, high pressures, acids, alkaline solutions, and so forth, low-alloy steels can resist corrosion under normal atmospheric conditions. While some alloys retain toughness at very high temperatures, some steels are exceptionally strong at very low temperatures. Because of its hygienic qualities and ease of cleaning, stainless steel is frequently used in the food and pharmaceutical industries. Strong and long-lasting, stainless steel wire mesh can tolerate challenging conditions. Thus, stainless steel can be regarded as a low-maintenance material, making it typically a cost-effective option when comparing costs across the life cycle of the item [11]. Because they differ from other fiber types in terms of their physical characteristics, metal fibers also offer a lot of potential. To guard against lightning strikes, some metal fibers, such as copper or aluminum, have a high electrical conductivity that is frequently used in aircraft [12].

The open scientific literature [13-15] states that many functional properties can be imparted to laminated polymer composites consisting of a single reinforcement of metal fibers or metal fiber-hybrid composites. By incorporating metal fiber into the polymer matrix, for instance, the toughness can be significantly enhanced. In general, ductile inclusions can toughen brittle substances [16]. With their ability to pull out and deform plastically, ductile reinforcements can add fracture toughness to a polymer matrix. There may be more toughening to be obtained when the fibers stay in the matrix and plastically deform rather than pulling out in the case of metal reinforcements that are not already toughened. The force that is attempting to pull the fiber out of the crack increases when these fibers bridge the crack due to their plastic deformation [17].

In addition to steel fiber-reinforced polymer, steel fiber-reinforced concrete is the subject of extensive research [18-21]. In this area of study, Zhang et al. [22] studied the effects of the interaction between steel fiber and basalt fiber on the mechanical characteristics and workability of made sand reactive powder concrete using the steel fiber and basalt fiber as the influencing factors through the central composite design.

This review includes an overview of metal fibers and metal-reinforced polymer composite materials. The uses, production methods, and types of metal fibers have been explored in detail. The properties of metal fibers reinforced composites were evaluated. Finally, this study discusses the application of metal fibers reinforced polymer composites. The more general studies are also considered in this work; the applications of metal fibers reinforced composites and the applications of metal fibers reinforced hybrid polymer composites.

2. Applications, Manufacturing Methods, and Types of Metal Fibers

2.1. Applications

Metal fibers are manufactured fibers produced from metals, which may be composed only of metal or in conjunction with other materials. A metal fiber differentiates from a metal filament by its diameter. For instance, for Bekaert, filaments lower than 100 μm diameters are defined as fibers. Metal fibers exist in many forms such as fine wires, bundles, and mesh fibers. They are the most preferred basic materials for different applications such as filtration, conductive plastics, and heat-resistant textiles. Historically, metal yarns and filaments have been known and used for about 3,000 years ago. Gold and silver were formed into very thin sheets, cut into strips then converted to fabrics, examples including Persian carpets and Indian sari. In the twentieth century, when Dobeckmum Company manufactured its first metal fiber in 1946, the use of metal fibers extended to different applications. During 1964, metal fibers in the fine form of 1μm of 304-type stainless steel were produced by Brunswick. Nowadays, metal fiber is a mature sector with an extended range of technology [23]. Metal fibers possess high porosity and thermal, mechanical, and electrical properties. Based on these properties, metal fibers can be used in a wide range of applications; these applications can be summarized as:

1. Highly porous structures make them suitable for filtration applications.
2. The low electrical resistance is beneficial in electro-conductive textiles, where electrical conductivity is required.
3. They resist extreme temperatures due to their excellent thermal resistance;

therefore they can be used for heat-resistant textiles.

4. Using high-quality alloys provides the metal fibers with outstanding corrosion resistance when used in corrosive environments [24].

2.2. Manufacturing

There are several methods to manufacture metal fibers including bundle drawing, foil shaving, melt spinning, and machining. The produced fiber can then be converted into knitted, braided, woven, or non-woven products. The new fiber products in each of these methods are differing in length and cross-sections. Figure 1 shows four types of metal production; bundle drawing, foil shaving, melt spinning, and finally machining. Bundle drawing is the most common technology to produce metal fibers. It allows the production of continuous bundles of desired diameters and several kilometers in length. The resulting cross-sections of the fibers are; octagonal, rectangular, kidney-shaped, and staple fibers tuning of the geometry, respectively as seen in (Figure 1 A-D) [23].

2.3. Types of Metal Fibers

There are several types of metal fibers including, stainless steel, titanium, aluminum, and copper fibers. Stainless steel is the most common, potential type in terms of properties, performance, cost, and availability. It is currently available in three forms (fine wires, mesh fibers, and bundle). High corrosion resistance can be improved by adding chromium which produces a self-healing oxide film on them. Moreover, the presence of noble metals such as nickel and molybdenum leads to more improvement in their mechanical properties. Figure 2 shows images of stainless-steel fibers. Titanium, compared to other metals has excellent properties such as high corrosion resistance, high melting point, high strength, and low density. It is lighter than steel, however as strong as steel, thus it can be used in many structural applications like chemical plants, chemical plants, etc. One of its limitations, it reacts chemically with other materials at high temperatures. Hence, a special production process is required, so the cost of metal will be higher. Presently, titanium is available only as fine wires form. Aluminum is one of the most widely used in lightweight structures like aircraft due to its attractive properties like low density; high electrical conductivity, high chemical corrosion resistance, and good thermal conductivity. Moreover, aluminum is recyclable without losing its properties. Apart from high toughness, malleability, and ductility, copper fibers also have high thermal and electrical conductivity. Thus it has been employed in some applications [10,25-28].

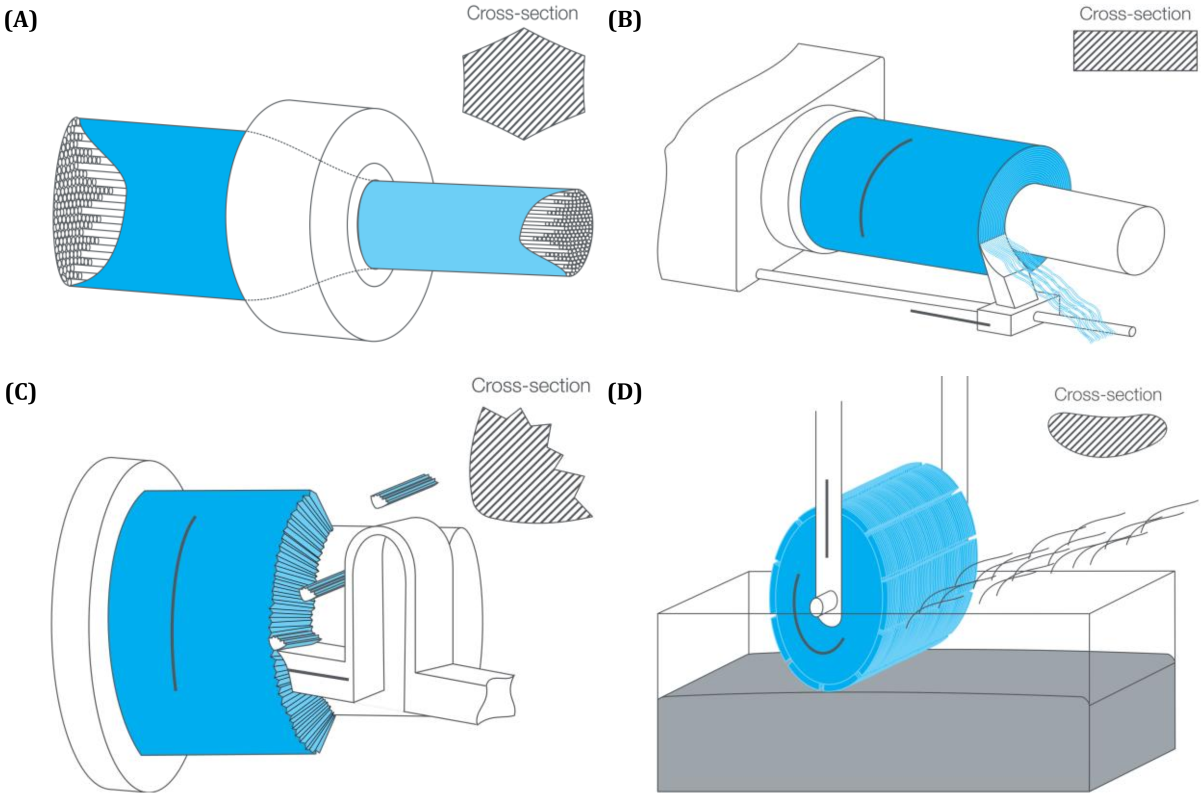

Fig. 1. Metal fibers production processes (A) Bundle drawing, (B) Foil shaving, (C) Melt spinning, (D) Machining [23]

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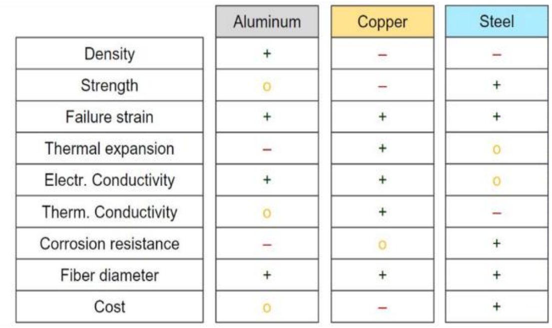
Figure 3 compares aluminum, copper, and steel fibers' properties. The three metals in the figure seem to have different values of thermal expansion, thermal conductivity, and strength. At the same time, the three metal fibers are normally having good failure strain. Steel fibers have a higher density than copper and aluminum fibers. It, however, possesses a valid compromise between cost and properties [30]. Table 1 lists the tensile, electrical, and thermal expansion properties of different fiber-forming metals. They show good tensile properties with reasonable ductility (except tantalum, titanium, and tungsten) and exceptionally high electrical conductivity.



	Aluminum	Copper	Steel
Density	+	–	–
Strength	o	–	+
Failure strain	+	+	+
Thermal expansion	–	+	o
Electr. Conductivity	+	+	o
Therm. Conductivity	o	+	–
Corrosion resistance	–	o	+
Fiber diameter	+	+	+
Cost	o	–	+

Fig. 3. Comparison between aluminum, copper, and steel fibers [30]

Fig. 2. Stainless steel fibers [29]

Table 1. A summary of various fiber-forming metal properties [28]

Metal	Density (g/cm³)	Tensile strength (MPa)	Elongation at break (%)	Resistivity (×10-6 Ω cm)	Coefficient of thermal expansion (μm/[m °C])
Aluminium (7000)	2.8	76	50	2.7	25.5
Copper	9.0	221–455	55	1.7	17.7
Nickel	8.9	317	30	6.4	13
Stainless steel (304)	8.0	505–840	>40	72	17.8
Stainless steel (316)	8.0	460–860	>60	70–78	17.8
Tantalum	16.7	310	–	13	7
Titanium	4.5	241–552	15–25	60	9.2
Tungsten	19.3	530–1920	8	5.4	4.5

3. Properties and Application of Metal Fibers Reinforced Polymer Composites

Despite their high density, metals have been prevailing materials in numerous applications throughout history because of their certain properties like ductility, availability, and ease of manufacturing. Closed metal reinforcements, such as thin sheets or foil forms have been used in many applications [31-33]. The combination of thin metal sheets and polymer composite laminates has created a group of hybrid materials called Fiber Metal Laminate (FML). Although FMLs typically have metal sheets made of aluminum alloy [34-37], magnesium, and titanium-based FMLs have also been created [38-42]

The FML offers significant improvements over the properties of both metals and polymer composite individually. Due to their excellent mechanical properties, considerable density reduction, and damage tolerance behavior, FML has been used in many applications like aircraft structures [37,43-47]. However, the manufacturing of FML is the most challenging problem due to the lack of bonding capability at the fiber/metal interface [48,49]. The use of open metal in the form of wire, mesh fibers reinforced polymer composites can create completely new materials with a unique physical structure and a synergistic effect on many properties. The utilization of current production methods for fiber-reinforced composites can now be applied since metal fibers are utilized instead of a sheet. Thus, more complex and detailed structures might be produced. By incorporating metal mesh, the composite gains the ability to naturally shield electromagnetic energy, enhancing its functionality. More specifically for this study, the metal mesh's capacity for plastic deformation may be advantageous in the event of an impact since it serves as an additional mechanism for absorbing energy and for delaying the perforated threshold energy [50].

While being superior to FMLs, open metal fiber reinforced composites have manufacturing challenges due to the low ability to bond at the fiber-metal interface. One of the main concerns regarding new developments in metal fibers to address these problems is surface treatment [51,52]. In certain studies, the steel fiber was cleansed in an alkaline soap bath for 30 minutes before surface treatment, followed by a rise in deionized water [50,53]. Stainless steel fiber-filled polymer composites' mechanical characteristics can be improved by applying surface treatment [54]. Karunagaran and Rajadurai [55] found that the tensile strength, flexural strength, and inter-laminar shear strength of the hybrid composites after surface treatment were significantly higher than those of the untreated hybrid composites. The surface treatment applied to the glass fiber and steel wire mesh was said to have improved the interfacial bonding. Callens et al. [56] conducted an experimental evaluation of the tensile performance of cross-ply and unidirectional UD composites reinforced with ductile stainless-steel fibers. By utilizing various silane coupling agents, silane treatments were employed to modify adhesion. The tensile strength and strain-to-failure of both UD and cross-ply laminates were shown to increase with a 50% increase in adhesion. Improved adhesion additionally slowed down and prevented the expansion of the crack matrix. On metal wire mesh, Prakash et al. [51] used acid treatment to perform surface leaching. They found that silane surface-treated E-glass fibers, 304 stainless steel and Al-6061 wire mesh give improved mechanical results. Also, Karunagaran et al. [57] discovered that glass fiber/stainless steel wire that has been treated with acid demonstrated superior properties with respect to absorbed energy, impact resistance, and stiffness.

In terms of properties, much research has been carried out on the mechanical, thermal, tribological, and electrical properties of metal fibers reinforced polymer composites. Relevant research about these properties is presented in the below paragraphs.

The mechanical properties of the metal fiber-reinforced polymer composites are characterized by many tests like tensile, flexural, interdelamination, and impact tests. In this context, de Ferran and Harris (1970) reported that the compression strength of steel-wire/polyester composites increased with increasing fiber volume fraction of steel wires (Figure 4) [58].

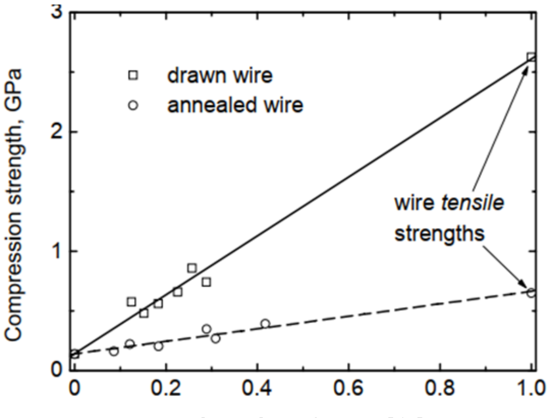


Fig. 4. Fiber volume fraction [58].

Callens et al. [56] evaluated experimentally tensile behavior of unidirectional UD and cross-ply composites reinforced with ductile stainless-steel fibers, where the authors have highlighted that annealed stainless steel fibers are a good choice for structural applications due to its potential to create tough polymeric composites materials. Amanda et al. investigated the effect of the volume fraction of glass-to-steel fibers on the mechanical properties of glass /steel hybrid epoxy composites. They tested coupons with and without holes under monolithic and half-cyclic tensile loading to obtain stress-strain relationships, hysteresis behavior, and failure mechanisms. To understand the failure mechanisms, photographs around the broken section have been taken. On the other hand, Callens et al. [59] combined steel fibers with brittle and ductile matrix to prepare composite laminates, The results indicated the strain-to-failure was 7.3% in the case of the use of a brittle matrix and 12.7% with a ductile matrix.

Satish et al. [60] studied the behavior of steel/nylon bi-directional mesh-reinforced polyester composite subjected to in-plane tensile and compressive loading. In general, the results showed that the laminate with higher steel fiber content sustains more load irrespective of fiber orientations. However, the specimens with 0/90° orientations sustain more loads than others, thus it can be established that fiber orientation is an important factor. Faes et al. [14] studied the influence of the matrix toughness and the fiber/matrix adhesion of the steel fiber-reinforced textile composite through the static tensile test. The microscopic analysis was performed to identify the relation between the mechanical behavior and the damage morphology. It was found that distributed damage increases the toughness of a textile composite due to its effect to soften the transversal structure which interlocked the ductile load-bearing of yarns. Samanci [61] prepared a bidirectional plane woven steel fibers composite with the use of different weight fractions and particle-filled polymers. The critical stress intensity factors of these specimens were determined by using three methods including J-integral, initial notch depth, and compliance methods. The mechanical properties were studied in terms of flexural strength and modulus, where the results showed an improvement with respect to reinforcement materials content. Karakuzaet et al. [62] studied the elastic-plastic stress of symmetric and non-symmetric woven steel fiber composites with the use of the nine-node finite element method. It was found that separate loading steps can remain within small deformation when the orientation angles of the laminated plate were changed. Vinayagamoorthy et al. [63] produced different polyester composites combining jute fibers with glass, bronze, and steel fibers. The produced laminates were subjected to tensile, compressive, flexural, and impact tests. They found that jute/bronze fibers reinforced polyester composites showed improvement in terms of compressive and impact strengths while jute/glass fibers reinforced polyester composites recorded an increase in flexural and tensile strengths. Schmeer et al. [64] manufactured steel fiber reinforced glass fibers reinforced hybrid composites. Although the SEM images showed a non-perfect interface and bonding, the mechanical properties showed an improvement in terms of stiffness and strength. Mosleh and colleagues [5] compared the effect of the use of two different steel fiber diameters on the penetration impact resistance of steel fiber-reinforced composites. The results revealed that penetration impact and toughness in the case of the use of 30 mm is pronouncedly higher than for the 14 mm.

Steel fiber-reinforced polymer composites were introduced in the work by Durai Prabhakaran et al. [8], which is thought to be novel for the creation of composite products. These composites are made of 0.21 mm steel fibers or filaments that are encapsulated in polyester resin. Micro-mechanical models were used to estimate the mechanical properties of unidirectional steel fiber-reinforced polyester composites, which were then experimentally assessed and compared with the actual results. Steel fabric with unidirectional fibers and steel fibers wound on a metal frame with 0 orientations are two different types of steel fiber-reinforced polymer composites that were researched. During tensile, compressive, and shear testing, the effect of the fiber volume fraction and the role of polymer yarns (weft) on mechanical properties were examined. The following findings were drawn: Unidirectional steel fiber/polyester composites have a lower strain-to-failure than typical unidirectional glass/polyester and glass/epoxy composites, combined with high stiffness. The compressive failure of unidirectional steel fiber/polyester laminates occurred as a result of fiber micro-buckling, and the shear failure shown on fracture surfaces shows that the interface link between the polyester resin and the steel fibers is weak.

Michaël Guy Callens [65] created two different composite types: completely unidirectional and quasi-unidirectional woven fiber architecture. The distribution of fibers is the primary distinction between the two microstructures. The findings demonstrated that composites reinforced with steel fibers combine high stiffness and low strain-to-failure. An important distinction was found between the failure of the 0° layers with highly packed fiber bundles separated by resin-rich zones and the layers with a more homogenous fiber distribution using acoustic emission registration to better understand how the microstructures of these materials affect their fracture behavior. It was believed that because of how tightly the fibers are packed together, cracks tend to form around the threads rather than allowing them to begin to separate from one another inside the bundles. As a result, the fiber necking process, which is the last stage of composite failure, is postponed. A fiber's stress state changes when it starts necking due to the proximity of other steel fibers. As a result, it is discovered that the composite failure strain is increased by the presence of tightly packed bundles. Also, Pazhanivel et al. [66] examined the glass fiber/stainless steel wire-reinforced polymer composite's flexural and tensile properties. The laminates were reinforced with stainless steel wires at varied depths and pitches. Stainless steel wire reinforcement has been found to greatly increase the mechanical properties of laminates, and depending on the application, the pitch distance can be changed to further the desired laminate property. In conclusion, mechanical properties such as tensile strength, flexural, toughness, and failure strain of polymer composites can be improved with the use of metal fibers.

Bigg D. M. [26] investigated the mechanical, thermal, and electrical properties of aluminum fibers reinforced polymer composite. The results showed that the tensile strength at low fiber content was close to the unfilled polymer. The thermal properties recorded an improvement, and the resistivity below 20 ohm-cm was recorded when less than 8% volume of aluminum fibers was used. The critical concentration in which aluminum fibers filled composite becomes electrically conductive can be highly reduced with the addition of metal randomly dispersed aluminum fibers. Shyr and Shie [67] investigated the effects of magnetic loss, complex permittivity, and conductivity on electromagnetic wave shielding mechanisms in the case of the use of blended textiles of polyester fibers with stainless steel fibers. The results indicated that the electromagnetic interference shielding of the blended textiles of polyester fibers with stainless steel fibers exhibits an absorption dominant mechanism, which ascribes to the dielectric loss and the magnetic loss at a lower frequency and ascribes to the magnetic loss at a higher frequency, respectively. Kim et al. [68] suggested that the use of stainless steel filters as the collector electrodes can be an interesting alternative design of an electrostatic precipitator.

The tribological properties of fiber-reinforced polymers have been searched by many researchers [69-71]. The effect of steel fiber loading on friction, wear, and mechanical properties was studied in composite brake pad materials. It was observed that the coefficient of friction increased until 5wt. % steel fiber content. Although the fade resistance was improved when the steel fibers were added to the composite matrix, the mechanical properties deteriorated. And, the effect of the addition of steel fibers on the wear was observed above 15wt.% [72]. Stephen Bernard and Jayakumari [73] used rockwool and steel fiber to produce composite samples. They investigated friction-wear properties in terms of wear resistance, coefficient of friction, and oscillation amplitude of coefficient of friction. The result indicated that the use of 12% steel fibers and 8% rockwool fibers is the best choice for the best tribological performance in brake lining applications. Manoharan et al. [74] compared the tribological, chemical, thermal, physical, corrosion resistance, and mechanical properties of oxide-coated steel and mild steel fiber-based brake friction composites. Results showed that the oxide-coated steel can potentially replace mild steel fiber in friction composites.

Several researchers have studied the thermal behaviors of composite materials [75,76]. The thermal, mechanical, and dynamic behavior of the aluminum and copper wire mesh hybridized with jute epoxy composite was studied by Krishnasamy et al. [77]. The result expressed that the copper wire mesh provides more thermal stability than the aluminum wire mesh. Li and Qu [78] Designed, an experimental apparatus to measure the effective thermal conductivity at different pressures of porous stainless steel fiber felt by analyzing matrix heat conduction, matrix thermal radiation, and air natural convection. The results indicated that the total effective thermal conductivity was reduced with the increase of the diameter of steel fiber at fixed porosity, and the total effective thermal conductivity was reduced with the increase in porosity under fixed fiber diameter. In the same context, Li et al. [79] investigated the effects of the porosity and the fiber diameter of porous stainless-steel fiber felt saturated with paraffin of phase change materials on the surface temperature and the solid/liquid interface evolutions The results showed that the increase in steel fiber felt porosity reduced the effective thermal conductivity. However, a slight difference in the effective thermal conductivity was observed for different fiber diameters at fixed fiber porosity. The thermal and mechanical properties of the steel fibers reinforced composite discs were investigated at constant convective air cooling. It can be said that the fiber arrangements can be considered an effective parameter on thermo-mechanical behavior when residual stress and plastic strain in the circular fiber array were twice as more as those in the radial array [80]. It can say that the different functional properties can be added to polymer composites materials using metal fibers.

In the term of application of metal fibers reinforced polymer composites, various types of metal fibers are used for electromagnetic and electrostatic protection, signal transmission, heat exchange, abrasive media, filtering, and design. The need for some specific properties of technical textiles led to an increase in the use of metal fibers. Silver and copper are the most used and preferred smart, medical, and protective textiles. For example, the conductivity and antibacterial effect are the required properties for smart textiles and medicinal textures, respectively [81]. Ahmed [28] found that, in addition to thermal, mechanical, and tribological, the electrical properties of metal fibers make the fiber's inclusions more interesting. The exploitation of the electrical properties of metal fibers will broaden the design's horizon toward different applications including lightning electromagnetic shielding and strike protection. Tires for vehicles and trucks, blast-protective composite panels, composite bridges, and building repair solutions are all examples of steel fiber-reinforced polymer composite products that are now on the market. Yet, the difficulty of using it more is the complexity of machining steel fiber-reinforced composites [8].

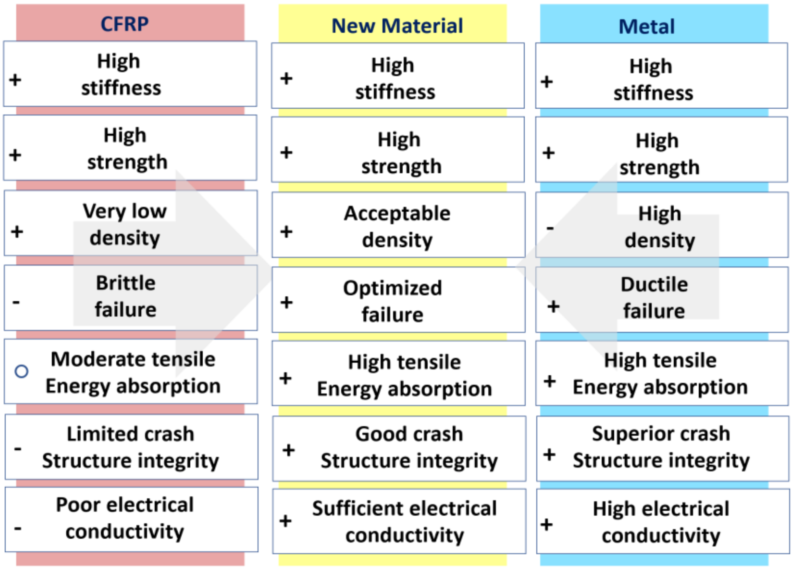
Carbon fibers reinforced polymers offer high weight-specific mechanical properties. However, their brittle failure restricts the structural safety and damage tolerance in impact events. Over and above that, the electrical conductivity is insufficient for main applications (e.g., lightning strike protection, signal transfer, grounding). A potential approach is the incorporation of highly conductive and ductile continuous metal fibers into the carbon fibers reinforced composites. In this context, the hybridization of steel fibers with carbon fibers reinforced composite materials has been investigated in many researches [82-89]. Figure 6 compares carbon fibers reinforced polymer, new material, and metal in terms of stiffness, strength, density, and failure. It also compares energy absorption, structural integrity, and conductivity. The new material has sufficient desired properties like electrical conductivity, high stiffness, strength, suitable density, etc., which are obtained as a result of a combination of carbon fibers reinforced polymer and metal [30].

The effect of incorporating copper, steel, and aluminum fibers into friction materials was investigated in terms of friction and wear performance. The maximum wear was recorded in the friction material containing steel fibers. While the produced materials with the incorporation of copper fibers exhibited the lowest value [90].

4. Conclusions

The use of metal fibers has gained extensive importance in recent years. In this review, the applications, methods of production, and different types of metal fibers currently used in the research, as well as in various applications were reviewed. Moreover, the properties and applications of metal-reinforced polymer composite materials have been reviewed in detail. The following salient points can be drawn based on this survey:

1. Various manufacturing methods emerged, where different lengths and cross-sections of metal fibers can be formed. Steel fiber is the most common metal fiber used due to its cost-effectiveness, high performance, and availability despite its heavy weight.



CFRP	New Material	Metal
+ High stiffness	+ High stiffness	+ High stiffness
+ High strength	+ High strength	+ High strength
+ Very low density	+ Acceptable density	- High density
- Brittle failure	+ Optimized failure	+ Ductile failure
○ Moderate tensile Energy absorption	+ High tensile Energy absorption	+ High tensile Energy absorption
- Limited crash Structure integrity	+ Good crash Structure integrity	+ Superior crash Structure integrity
- Poor electrical conductivity	+ Sufficient electrical conductivity	+ High electrical conductivity

Fig. 5. Comparison between CFRP, new material, and metal [30]

2. The applications of metal fibers are linked to their functional properties. The potential of fine wires and mesh metal forms, which are partially exploited, seems to have excellent mechanical, thermal, electrical, and tribological properties.
3. The use of metal fibers as single reinforced composite materials was studied by many researchers, where the results show different results regarding the effect of metal fibers to improve their properties. Moreover, different synthetic and natural fibers can be combined with metal fibers to form a new hybrid material to improve their properties, as well as the possibility to overcome the limitations that restrict the applicability of metal fibers in some applications. Although metal-reinforced hybrid composites are widely synthesized and investigated by researchers, more work is needed to exploit their potential in many more applications.

Just like in any review article, conducting additional searches in the literature helped shape the future perspective. Metal fibers have potential, but that potential hasn't been fully realized, so there's still an opportunity to grow. The most typical metal fiber is steel, although more research needs to be done on other metal fibers. To improve the performance of metal fiber hybrid composites, numerous researchers have put in a lot of effort. To find the best fiber for a given application, though, considerable investigation is necessary. Moreover, more practical applications and representation can be made possible by metal fiber-reinforced composites that are filled with different particle additives. Since numerical modeling for high-end engineering applications of metal fiber-reinforced composites is useful, more time and effort must be put into creating precise models. As the bonding between the fiber and matrix affected how well the metal fiber-reinforced polymer composite performed, more study is needed to improve the bonding through surface treatment.

Nomenclature

FRP	Fiber-reinforced polymer composite
FML	Fiber Metal Laminate

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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