Aluminium-Carbon Fibre Metal Matrix Composites: A Review
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Abstract
Manufacturing sector always demands superior materials that can cope up with the demand of improved mechanical properties to develop wide applications in diverse sectors. Carbon fibres (CFs) reinforcement in metals matrix is excellent in improving the properties resulting composites. The present review is emphasized on the major developments of using carbon fibres in recent years with aluminium (Al) metal as matrix to improve various mechanical properties. Several aspects (like tensile strength, hardness, shear strength etc.) contributing to the performance of Al-CFs composite have been discussed by covering several case studies. This review reveals that reinforcing CFs in Al matrix increases properties like tensile/shear strength, hardness, wear resistance etc. The mechanism involved in improving these properties is also discussed. Moreover, the remaining challenges in this field and future prospects are discussed in detail.

Key words: Carbon fiber; aluminium metal matrix composites; mechanical properties; dispersion; strengthening.

1. Introduction
Tremendous progress in the area of material science leads to the development of certain high performing materials which are extremely light in weight[1–3]. Composite materials, like polymer matrix composite and metal matrix composite (MMCs), played a pivotal role in this phenomenal development [4–6]. MMCs possess several unique properties such as low thermal expansion, high strength, higher temperature resistance, higher stiffness, e’ donor capability, and good thermal conductivity which are hard to obtain by monolithic materials [7–13]. Due to these wide range of properties, MMCs are used in many fields of engineering application where light weight and strong materials are heavily in demand, e.g., defence, automobiles, marines and aerospace [4,14–16]. The family of MMCs consists of different metals used as matrices (e.g., aluminium (Al), copper, magnesium, and titanium). Various micro/nano reinforcement has been used to achieve desired properties. Although, every metal has its unique applications that best suit their properties but out of all, Al-MMCs are most widely used composite materials [1,17–20] Al-MMCs have remarkable properties such as light weight, low density, very good corrosion resistance, high specific strength, low thermal coefficient of expansion good wear resistance, and ease of machining [10,21]. Many reinforcements are used with Al-MMCs such as macro reinforcements (e.g., SiC, Cr3N4, AlN, Al2O3, TiB2, ZrO2, and Y2O3) and nano reinforcements (like GO, CNT, SiC (nano particles), nano diamonds, carbon fibres; CFs, fullerene, and nano-ZrO2) [8,22–25] The nano reinforcement has been proved to give better results when compared to the macro reinforcements [26,27]. Like other nano reinforcements, CFs also possess excellent properties such as high modulus and high strength along with good wear and lubrication properties [28,29]. Therefore these reinforcements have been progressively used with Al-MMCs to increase the toughness and various tribological properties of the formed composite [30–33]
The present review is an attempt to study various developments based on Al-MMCs reinforced with CFs during the recent years. Impact on various mechanical properties along with reasons supporting their enhancement has been reviewed. Along with various applications, the scope for future outlooks has been also discussed.

2. Carbon fibres (CFs)
Carbon fibres (CFs) are fibres having a percentage of carbon more than 92 wt. % [34]. The structure of CF can be amorphous, crystalline, or partly crystalline and are available in both short and continues form [35,36]. The history of CFs started in 1878 when Thomas Edison took some CFs along with bamboo silvers and baked them at high temperatures to convert it into carbon for producing light emitting filaments. Later in 1958 and 1963, some more research was done at British research centre to develop polyacrylonitrile (PAN); this process was more economical in comparison to the earlier method and the potential of CFs was realized after this discovery [37,38]. Since then, a considerable reduction in CFs prices has taken place due to development in manufacturing process [39,40]. The CFs can be classified based on the precursor used for its synthesis. Nomenclature of CFs on the basis of mechanical performances are shown in Figure 1, respectively [41].

![Nomenclature of CFs](image)

**Figure 1: Nomenclature of CFs according to tensile strength and respective tensile modulus.[41]**

CFs possess excellent properties such as high stiffness, high tensile strength, good chemical resistance, low coefficient of thermal expansion, tolerant to high temperatures, and high weight to strength ratio [37,41,42].

CFs shows remarkable mechanical properties and are five times stronger, two times stiffer and four times lesser in weight than steel [43,44]. Due to this wide range of properties, CFs are used in various
engineering applications such as nuclear engineering, aerospace, automobiles, manufacturing of bearings, gears, and blades of helicopters [36,37,42,45].

3. Aluminium-Carbon fibre (Al-CF) nano composites

A composite structure was prepared by reinforcing carbon-fibre–reinforced thermoplastic (CFRTP) in Al (A5052) matrix by the method of friction lap joining [46]. In the results, the effect of joining speed on the tensile shear strength was calculated. It was observed that as the maximum tensile shear strength of 2.9 kN was obtained at joining speed of 1600 mm min\(^{-1}\). As the speed was further increased to 2000 mm min\(^{-1}\), the tensile shear strength decreased to \(~2.1\) kN. This reduction in the value of tensile shear strength was due to lack of input heat.

**Figure 2. Interfacial scanning electron micrograph Al-CFs composite.** [47]

In a similar study, laminate squeeze casting method was used to fabricate composite of CFs reinforced Al6061 composite [47]. Content of the CFs was varied between 7 to 14 vol%. The fabricated composite showed good bond between reinforcement and the matrix (Figure 2). The maximum value of Vickers micro hardness was obtained at 7.4 vol% of CFs. The obtained value was 59 and 135 HV at the matrix and carbon matrix interface, respectively. By further increasing the CFs to 13.5 vol%, the micro hardness value decreased up to 38 HV at the matrix and carbon matrix interface. This was due to the poor flow of liquid in the work samples with high carbon percentage. Poor interface attachment between carbon fibre and matrix was reported too. In another report, Al-CFs were synthesised using multi pass friction stir processing (FSP) [48]. Various samples were treated at different FSP conditions and the best results were obtained with composite fabricated at 1000 rpm and 75 mm min\(^{-1}\) FSP. The value of ultimate tensile strength and elongation obtained was 283 MPa and 13 %, respectively which was 18.6 % and 13 % higher in comparison to the corresponding values obtained for the base metal. The reason for the strengthening of the composite was induction of large amounts of geometrically necessary dislocations (GNDs) during FSP and the homogenous dispersion of reinforcement in the matrix.

Al6061 matrix was used along with CFs reinforced plastic (CFRP) as reinforcement to fabricate a composite by the method of laser joining [49]. Al alloy was pre-treated with phosphate anodizing before joining. The shear strength obtained from the joint before and after anodizing was 5.3 and 40 MPa, respectively. It was postulated that the surface of anodized Al was covered with porous nanostructure, which was majorly responsible for enhanced wettability of CFRP and Al, thus
strengthening the joint. In a similar study, acrylic adhesive (AO420) was used as a binding agent to fabricate joint between CFRP and Al alloys [50]. To enhance the strength of the joint made by the adhesives, ultrafast picosecond infrared (IR) and excimer ultraviolet (UV) lasers methods were used to pre-treat the samples. It was observed that the shear strength of the IR and UV laser-pre-treated samples was 24.8 and 21.9 MPa as compared with the non-treated adhesive joint for which the value was 5.6 MPa. In another study, ultrasonic metal welding was used to join Al AA5754 as a matrix with CFs reinforced epoxy resin as reinforcement [51]. To conduct this experiment, a different set of welding forces (140 N or 280 N) and welding energy (2160 J, 2300 J or 2500 J) were used. The maximum value of tensile shear strength of 34.8 ± 3.9 MPa was obtained at 280 N welding force and 2300 J welding energy. Presence of good mechanical interlocking between CFs and Al during the welding attributed to superior results. Al alloy (A7050) matrix and CFRP were used to fabricate a composite by the method of laser joining [52]. Al alloy was pre-treated by Surfi-Sculpt procedure. The shear strength of pre-treated samples with Surfi-Sculpt procedure was found to be 39.0 MPa, which was four times more than the shear strength of non-treated samples. It was further observed that, due to pre-treatment of the matrix, protrusions and grooves were formed on the surface of the composite which led to the improvement in its properties.

Adhesive bonding method was also tested to fabricate a composite of CFRP and Al alloy [53]. Two types of CFRPs (CFRP-A and CFRP-B) with different configurations were used to develop abovementioned composites. CFRP-A had fibre orientation of (0/45/90/-45) while CFRP-B has a stacking sequence of (0, 90). Both CFRP-A and CRRP-B were pre-treated with IR and UV lasers before the bonding process. The composites fabricated with CFRP-A was found to holds high tensile shear strength as compared with the composites fabricated by CFRP-B. The maximum value of tensile shear strength for CFRP-A composites was 20 MPa while it was 16.5 MPa for CFRP-B composites.

Figure 3. CFs (a) Woven, (b) Microstructure, (c) Copper coated and (d) Al-CFs composite after SPS process. [54]
The overlap composite joints were fabricated using CFs-reinforced poly(phenylene sulphide) (CFs-PPS) and Al alloy AA6181-T4 using friction spot joining method [55]. The results of mechanical properties were investigated by using Taguchi method and ANNOVA technique. It was further stated with the help of the Taguchi method that the proper combination of factors like rotational speed and joining time would always increase the mechanical performance of the composite. In another study, friction spot joining process was used to fabricate a composite of CFs-PPS and Al alloy 2024-T3 [56]. The ultimate shear force of the joints was found between 2700 ± 115 N and 3070 ± 165 N which was 20%–55% more than parent materials. The reason for increase in the properties of composite was good load distribution, improved interlocking and larger bonding area.

The pressure infiltration method was also effective for the synthesis of high performing Al-CFs composites [57]. The properties of Al-CFs composite developed with pressure infiltration method can be further improved with Z-pinning method. AISI 321 steel wire was used as a Z Pin with different diameters as 0.3, 0.6, and 0.9 mm. It was observed that the interlaminar shear strength for Al-CFs composite without Z pin was 13.8 MPa, while the values of interlaminar shear strength with Z Pin of dia. 0.3, 0.6, and 0.9 mm was 23.8, 38.5, and 45.9 MPa, respectively which was 70% to 230% more than the value of Al-CFs composite without Z pin. Figure 3 shows Cu-coated woven Al-CFs composites fabricated by Spark Plasma Sintering (SPS) method [54]. The mechanical properties of the developed composite were studies and it was found that the elongation of the fabricated composite increased from 4.5% to 13.5% after addition of woven CFs. Likewise, the tensile strength also increased slightly from 168 to 202 MPa after addition of woven CFs in the original Al alloy. The good deformation ability of CFs with the Al matrix is mainly postulated for an increase in the abovementioned mechanical properties. The synthesis methods employed for Al-CFs-based composite and their strength applications are summarized in Table 1.

### Table 1. Carbon fibre reinforcement in various aluminium metal matrix composites.

| Sr. No | Nano material | Metal matrix | Fabrication Method | Strength Enhancement | Ref. |
|--------|---------------|--------------|--------------------|----------------------|------|
| 1.     | CFRTP         | Al (A5052)   | Friction lap joining. | Strength 2.9 kN      | [46] |
| 2.     | CFs           | Al6061       | Laminate squeeze casting process | Micro hardness 135 HV (50%) | [47] |
| 3.     | CFs           | Al5052       | Multi-pass FSP      | Ultimate strength 283 MPa (18.6%) Elongation 13 % | [48] |
| 4.     | CFRP          | Al6061       | Fibre laser joining | Shear strength 40 MPa (800%) | [49] |
| 5.     | CFRP          | Al           | Acrylic adhesive Bonding | Shear strength 24.8 MPa(IR Treated) 21.9 MPa (UV treated) | [50] |
| 6.     | CFs/epoxy     | Al5754       | Ultrasonic metal welding | Tensile shear strength 34.8 ± 3.9 MPa | [51] |
| 7.     | CFRP          | Al (A7050)   | Fibre laser joining | Shear strength 39.0 MPa (400%) | [52] |
| 8.     | CFRP          | Al           | Adhesive            | Tensile shear strength 20 MPa | [53] |
bonding.

|   | CFs-PPS | Al6181-T4 | Friction Spot Joining | Mechanical performance increased from 2107 N to 3523 N | [55] |
|---|---------|-----------|----------------------|----------------------------------------------------------|------|
| 9 | CFs-PPS | Al 2024-T3 | Friction Spot Joining | Ultimate shear force 2700 ± 115 N and 3070 ± 165 N (20%–55%) | [56] |
| 10 | CFs (metal z-pine) | Al | Pressure infiltration method | Shear strength 45.9 MPa | [57] |
| 11 | Cu-coated woven carbon fibres | Al | Spark plasma sintering | Elongation 13.5% Tensile strength 202 MPa | [54] |

4. Conclusion and Future Prospects

From the present review, it can be concluded that the area of Al-CFs MMCs has fascinated the researchers in recent years. There is significant progress in the field of high performing CFs. Improvement in performance of composites can be achieved with CFs as reinforcement in the Al matrix. Commercial use of CFs started in 1970s, since then the prices of CFs has dropped significantly thus increasing the application of CFs in various engineering applications such as automobile, aerospace, defence etc. Despite the good research achievement in this field, there are some challenges left unattended for Al-CF MMCs. Some factors need to be considered which are restricting the use of CFs as reinforcements in Al composites such as difficulty and high cost involved in processing techniques, effects of size on strength, tolerance in dimensions, impact strength etc. Surprisingly, only a few processing techniques are in use for the fabrication of this composite structure. More research is required to develop some novel and low cost processing techniques for the development of Al-CFs composites. Since the research in the field of Al-CFs MMCs is at its early stages, some novel numerical and computer simulations techniques should also be developed for the progressive growth of Al-CFs composites field. These simulation techniques could be helpful in the accurate prediction of final results, which can reduce the processing time and expenditure.

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