Carbon Fibre Reinforced Composite Material: Review of Properties and Processing for various Metal Matrix Materials

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Abstract. Carbon Fibres (CF) are used as a reinforcing material from past few decades. Carbon Fibres are reinforced in Metal matrix composites (MMC), Ceramic matrix composites (CMC) & polymer matrix composites (PMC). Numerous Research work was done on Carbon Fiber Reinforced Polymer Composites (CFRP), but Carbon Fiber Reinforced Metal Matrix Composites (CFMMC) & Carbon Fiber Reinforced Ceramic Matrix Composites (CF-CMC) have wide scope to explore. This Paper reviews effect of Carbon Fibre reinforcement on Mechanical, Tribological and Morphological Properties of various Metal Matrix Materials. This paper also presents various processing techniques of Carbon Fibre Reinforced Composite Material.

1. Introduction

Composite Materials including Metal matrix composites (MMC), Ceramic matrix composites (CMC) & polymer matrix composites (PMC) are structural materials used for various Engineering applications. Composite materials combine best properties from two heterogeneous materials [1, 8]. Reinforcement and matrix are two basic constituent of composite materials. Properties of composite material depend upon selection of various types of reinforcement and matrix materials and also their manufacturing process [2-4]. From thousands of years human beings are making these combinations of reinforcement and matrix materials to obtain desired functioning properties [5]. Composite material family as MMC, CMC and PMC described very well in following Figure 1.

![Figure 1. The Combination for composites among metals/ceramics/polymers [5].](image-url)
Metal Matrix Composites are well known for high specific strength and specific stiffness. MMC were initially developed for aeronautics and space application but has limitations in automotive application due to its high cost. Now a day’s research and development in MMC is going on for its application in automobiles [6]. Various Techniques are used to study chemical characterization of Fibres for reinforcement in various matrix [7]. Chemical characterization of Fibres was carried to obtain desired properties among composite material. The reinforcement in ceramic matrix improves its tensile strength and toughness. Reinforcement in ceramics forms Ceramic matrix composites (CMC). CMC has wide applications in aeronautics, space and automobiles. Cost of composite materials as compared to conventional materials is high but still has more popularity due to Lightness, High specific properties, Design and processing flexibility, Cost effectiveness, Functional superiority and Durability [8, 9].

2. Carbon Fibre: History, Processing and Characteristics

Carbon Fibres have importance as a Reinforcing material in various matrix materials due to high modulus, strength to weight ratio and resistance to chemical reaction [10-22]. Earlier carbon fibers was used in the cotton and bamboo fibers carbonization for incandescent lamp filaments. Thomas Alva Edison had used carbon fiber filaments for light bulb experiments in 1879 for the first time. When the fibers were heat-treated from 1000°C to 1500 °C and proportion of graphite in fibers vary from 0 to 100% then they are known as Carbon Fibres [11,12]. Various precursor materials are available from which carbon fibers derived. Polyacrylonitrile (PAN), viscose rayon and pitch are precursor materials for carbon fibers. Polyacrylonitrile (PAN) has advantages over other materials such as no change in original structure, better orientation and high carbon content. Carbon fibers are derived from pyrolysis of polymer fibers [13, 19]. Carbon fiber reinforced composite materials are stronger and lighter than conventional material structural parts. Carbon fiber reinforced metal matrix composites have fatigue properties better than conventional metals. Carbon Fibres used in civilian aerospace industry such as in Boeing 7E7. Composite materials contribute 58% and which results in 20% less fuel consumption [16]. Carbon fiber reinforced polymer matrix composites with the proper resins are corrosion resistant materials. Strong covalent C-C bonds in layer increases strength and stiffness otherwise weak bonding allows thermal and electrical conductivity [14]. Carbon fibers are useful as reinforcing material due to its unique properties like low density, high tensile modulus and strength, low thermal expansion coefficient, thermal stability, excellent creep resistance, chemical stability, high thermal conductivity, low electrical resistivity and decreasing cost (versus time) [15, 21].Various types of carbon fibres are used for commercial application such as High and low-modulus fibers, PAN based fibers and Pitch based fibers. High-modulus fibers are weak during shear mode and low-modulus fibers are weak during buckling mode. If modulus for PAN based fibers increases then compressive strength decreases. As PAN based carbon fibers have particle-like structure results in higher tensile and compressive strength than pitch based carbon fibers [17]. PAN based and Pitch based Carbon fibres had wide applications in automobile, aerospace, construction, medical, sports equipment, electronics etc. Figure 1 and Figure 2 shows various properties of PAN based and Pitch based Carbon fibres [16-17].
3. Properties and Processing of Carbon Fibre Reinforcement in various Metal Matrix Materials

Conventional metal alloys possess some properties which limits its use in aerospace and automobile application. Numerous research papers are critically reviewed to study properties and processing of carbon fibre reinforcement in aluminium and magnesium alloys. Various properties of aluminium alloy were improved with carbon fibre reinforcement [23-39]. H. Chen, A.T. Alpas [23] studied Tribological properties of carbon fibre reinforced aluminium matrix composites. Aluminium alloy A356 was selected as matrix material. Carbon fibres were coated with nickel layer. Wear tests were carried out for A356 with 4%CF, unreinforced A356 and A30 grade cast iron. For the wear test constant load and constant sliding velocity was considered. Comparison on the basis of wear behaviour of A3564 with 4%CF, unreinforced A356 and grade grey cast iron was done. It was observed that A3564 with 4%CF had high wear resistance than conventional A356 alloy and A30 grey cast iron within the certain region. ZHANG Yun-he [24] compares interface structure and thermal expansion properties of PAN M40 carbon fiber reinforced 6061Al and 5A06Al composites. Composites were processed by the squeeze-casting technology. It is observed that M40/5A06Al
composite showed weaker interface reaction than M40/6061Al composite. It was found that weak interfacial reaction gives higher Coefficients of thermal expansion. M. Sánchez, J. Rams, A. Ureña [25] studied combination of centrifugal and investment casting like Centrifugal-force infiltration. Aluminium alloy composites reinforced with carbon fibre were obtained by the infiltration of preforms. In this study short carbon fibres were used in both coated and uncoated forms. Coated carbon fibres were used as reinforcement to increase wettability in aluminium alloy. This study concludes that Centrifugal-force infiltration were suitable fabrication technique, hardness of composite material increases as CF volume fraction increases and Ni-coated CF gives higher hardness than uncoated CF. H. Naji et al [26] investigated effects of aspect ratio of carbon fiber on fracture toughness of aluminium matrix composite. Aluminium matrix composite was produced using stir casting method. Al–8.5%Si–5%Mg selected as a metal matrix material. Three volume fractions (1, 2 and 3) and three aspect ratios (300, 500 and 800) were selected for specimen preparation. Fracture toughness was measured by three point bending test and scanning electron microscopy (SEM) was used to observe the fracture behaviour and crack deflection of composites. The results showed that the increase in CF percentage gives increased fracture toughness and also depend on volume fraction, aspect ratio of fibre. 0. PEREZ et al [27] also studied Interphases and mechanical properties of T800 carbon fibres reinforced in Al-4.5 Mg matrix composites. Al4C3 layer is formed with uncoated carbon fibres results in reduced strength. To avoid the same coated carbon fibres were used which gives improved strength and grain structure. Ki Hoon Jung et al [28] fabricated carbon fibre reinforced Al composite using spark plasma sintering technology. CF was reinforced in the wt% as 5, 10, 15 and 20. Mechanical testing was carried out using vickers hardness tester and Tribological test were carried out using ball on disc method. Scanning electron microscopy was used to study surface structure. It was observed that increase in CF % increases hardness and at 20wt% composite gives best wear performance.

Mechanical properties of Carbon fiber reinforced 2024 aluminium composites were improved than conventional Al 2024 alloy [29, 30]. E. Hajjari et al [29] used PAN based carbon fibre as reinforcement in Al 2024 metal matrix. Composite material was fabricated using squeeze casting method under different pressure. Mechanical properties, morphological properties and fracture surface were studied. The results showed improvement in tensile strength using nickel coating carbon fibers. As the pressure increases during the manufacturing leads to decrease in composite strength. Jacek W. Kaczmar et al [30] also studied microstructure and mechanical properties of CF-2024 aluminium alloy composite. CF-Al2024 composite material was strengthened with Al2O3 Saffil fibers using direct squeeze casting method. Synthesized composite showed better wear resistance at dry condition. Pull-out of fibers was rarely observed during mechanical testing. CF-Al2024 alloy composite materials reinforced with 20% of fibers exhibited highest improvement of strength. Xiong Cao et al [31] fabricated Carbon fiber reinforced AA5052 alloy composite using multi-pass friction stir processing (FSP). Microstructural, mechanical and tribological behaviour of the composites were observed. The results showed that hardness of the composites increased by 46.8% and wear volume loss was reduced by more than 70%. Mechanical and tribological behaviour of Carbon fiber reinforced Al6061 alloy composite were improved than conventional Al6061 alloy [32-35]. Al6061 alloy was used as metal matrix material due to its wide applications in aerospace, automotive and defence sectors. C.S. Ramesh et al [32] studied tribological behaviour of carbon fiber rod Al6061 alloy metal matrix composite. Carbon fiber rods of 4 mm and 6 mm diameters were used as reinforcement. Composites were fabricated using casting route. A pin on disk configuration was used to study tribological behaviour of composite. Scanning electron microscopy (SEM) studied the morphological properties. Composites exhibit higher wear resistance and lower coefficient of friction than conventional Al6061 alloy. Higher wear resistance and reduced density composite material had potential automotive applications. K.M. Sree Manu et al [33] used PAN-based bidirectional carbon fiber fabric was used as the reinforcement in Al 6061 alloy of composition Al-1.2 Mg-0.8 Si (wt%). CF-Al6061 alloy composite was fabricated by squeeze infiltration process. The infiltrated composite showed close
control on the formation of aluminium carbide (Al4C3) phase results in improved properties. Self-lubrication had enhanced the wear resistance. Bi directional CF reinforcement showed increased hardness than conventional alloy. B. Bhav Singh et al [34] selected chopped carbon fibres (4–8mm length and 6µm diameter) as a reinforcement and Al6061 alloy as a metal matrix. CF-Al6061 alloy Composite material was fabricated by using stir casting method. CF coated with copper to avoid interfacial reaction and coating was done by electroless coating method. Results showed that tensile strength and yield strength of the CF-Al6061 alloy composites was found to be increasing up to 4wt% carbon fibre. Yiping Tang et al [35] studied interface and mechanical properties of short CF reinforced Al6061 alloy composite material. Different types of coating on short CF such as Ni, Cu and Al2O3 were done. Results showed that compared to non-coating short CF, Ni and Cu coated short CF improved wettability in Al alloy. Compounds such as Al3Ni or CuAl2 are formed on short CF surface and in matrix. These compounds increase the hardness but damage the tensile strength and decreases plastic properties.

Anıl Alten et al [36] carried out mechanical characterization and fabrication of Carbon fibre reinforced Al6063 alloy composite material. Composite was processed by using squeeze casting method and Ni coating on CF was done to improve wettability. SEM, EDS and XRD methods used to determine morphological properties. Mechanical behaviour of CF-Al6063 alloy composite was carried out using three-point bending, Charpy impact and Vickers hardness tests. Results showed that increase in hardness and bending strength but impact strength reduces as CF reinforcement. 258 MPa of high strength was observed for 0.9 mm Ni coated 2wt% CF reinforced composite. The alloy Al 7075 is found to be pollution free, low energy requirements and excellent machinability. Above properties increases the tool life results in reduced production time during its fabrication process. Carbon fibre reinforced Al7075 alloy composite material showed improved properties than conventional alloy [37-39]. CF-Al7075 alloy composite was fabricated by using hot press [37], stir casting [38] and liquid metallurgy with vortex flow [39]. Madhuri Deshpande et al [37] focussed on Powder Metallurgy route that would give uniform distribution of carbon fibers in composite in the present work. Ni coated carbon fibers were reinforced in Al7075 aluminium alloy powder using hot press. Single action and double action hot press was used. Effect of volume fraction of carbon fibers on hardness was studied. Optical and Scanning electron microscopic used to study surface structure. Fabricated composites showed uniform bonding between CF and Al7075 alloy. As uncoated CF % increases hardness decreases and coated CF % increases hardness also increases. Powder Metallurgy route eliminates interfacial reaction therefore possesses a great potential to fabricate composites. Prof. S. R. Nimbalkar et al [38] reviewed fabrication of CF-Al7075 composite material using Stir casting on the basis of various parameters. Corrosion behaviour of carbon fibre reinforced Al7075 alloy composite material was studied by Nithin Kumar et al [39]. Scanning Electron Microscopy (SEM) was used to study corroded surface of composite specimen. Short carbon fibre increases then leads to more corrosion due to electrochemical between the matrix alloy and CF. Corrosion rate in NaCl solution reduces with time.

Carbon fibres were also reinforced in Al-Ni alloy and Al-Zn alloy [40, 41]. Carbon fibre reinforced Al-Ni alloy composite was fabricated by Atmospheric-pressure infiltration. This route had given reasonable mechanical properties and better control to avoid residual porosity [40]. CF-Al-Zn composite material was processed by pressure infiltration method at relatively low temperature. The tensile strength of the CF-Al-Zn composite material increased by 103% compared with that of AZ31 alloy [41]. Carbon fibre reinforced magnesium matrix composite (CF-Mg) showed better mechanical and thermal properties [42-44]. Distribution of carbon fibres in magnesium matrix had great influence on its thermal properties. Hardness and compressive strength of the composite increases by 86.6% and 42.0% as compared to conventional magnesium [42]. CF-Magnesium composite had high fatigue resistant [43]. CF-magnesium matrix composites were fabricated by using powder metallurgy method [42] and liquid-solid extrusion processed by vacuum pressure infiltration technique [43, 44].
4. Concluding Remarks

Fascinating properties of carbon Fibres makes them potential reinforcement material for various matrix materials. Carbon Fibre Reinforced polymer matrix composites (CF-PMC) had already replaced conventional material from various application. Carbon Fibre Reinforced metal matrix composites (CF-MMC) has great potential to replace existing metals and alloys from automobile application. CF-MMC has superior mechanical, tribological, morphological properties than conventional materials. CF-MMC has high strength and modulus, corrosion and wear resistance. Poor wettability of carbon fibres leads to deteriorate the composite materials. Coating is required for carbon fibres before reinforcement. Further research is required to select appropriate carbon fibre coating technique. CF-MMC has wide applications in Automobile and Aerospace industries. Potential area of research is to select suitable application in automobile that can replace by CF-MMC results in weight reduction and less fuel consumption.

References

[1] Bayraktar, E., 2015: Chapter 04108 - Section 12 Composites Materials and Technologies. Ref. Modul. Mater. Sci. Mater. Eng., 1–3.
[2] Mohammed, O., and E. Suleiman, 2017: HANDBOOK.
[3] Lynch, C. T., and J. P. Kershaw, 2018: Metal matrix composites. Met. Matrix Compos., 4, 1–170.
[4] Douglas Kiser, J., K. E. David, C. Davies, R. Andru lonis, and C. Ashforth, 2018: Updating composite materials handbook-17 volume 5, ceramic matrix composites. Ceram. Trans., 263, 413–423.
[5] Haghs henas, M., 2016: Metal–Matrix Composites. Ref. Modul. Mater. Sci. Mater. Eng., 0–28.
[6] Chawla, N., and K. K. Chawla, 2013: Metal matrix composites. Met. Matrix Compos., 9781461495, 1–370.
[7] Park, S. J., and M. K. Seo, 2011: Composite Characterization. 631–738 pp.
[8] Information, D. S., and M. House, 1990: composite.
[9] Park, S.-J., 2018: Carbon Fibers. Fiber Technol. Fiber-Reinforced Compos., 210, 123–151.
[10] W. S . Smith, 1987: Engineered Materials Handbook- Vol. 1, p. 49.
[11] Park, S.-J., 2018: Carbon Fibers. Fiber Technol. Fiber-Reinforced Compos., 210, 123–151.
[12] Www.polycomposite.ir acceeded on date 2/6/2019.
[13] Jean-Baptiste Donnet, Tong Kuan Wang and Jimmy C. M. Peng, 1998: carbon Fibres, third edition, revised and expanded, CRC press, Taylor and Francis Group.
[14] Paul J. Walsh, 2001: Carbon Fibres, article from ASM Handbook, Volume 21, Composites, Copyright© ASM International.
[15] Christensen, R. M., 1994: Properties of carbon fibers. J. Mech. Phys. Solids, 42, 681–695.
[16] Minus, M. L., and S. Kumar, 2005: The processing, properties, and structure of carbon fibers. Jom, 57, 52–58.
[17] Chand, S., 2000: Carbon fibers for composites. J. Mater. Sci., 35, 1303–1313.
[18] Baker, A. A., 1975: Carbon fibre reinforced metals - a review of the current technology. Mater. Sci. Eng., 17, 177–208.
[19] Dorey, G., 1987: Carbon fibres and their applications. J. Phys. D. Appl. Phys., 20, 245–256.
[20] Huang, X., 2009: Fabrication and properties of carbon fibers. Materials (Basel), 2, 2369–2403.
[21] Prashanth, S., S. Km, K. Nithin, and S. Sachhidananda, 2017: Journal of Material Sciences & Engineering Fiber Reinforced Composites - A Review. 6.
[22] Mathur, R. B., V. Gupta, O. P. Bahl, A. Tressaud, and S. Flandido, 2000: Improvement in the mechanical properties of polyacrylonitrile (PAN)-based carbon fibers after fluorination. Synth. Met., 114, 197–200.
[23] Chen, H., and A. T. Alpas, 1996: Wear of aluminium matrix composites reinforced with nickel-
coated carbon fibres. Wear, 192, 186–198.
[24] Zhang, Y. H., and G. H. Wu, 2010: Interface and thermal expansion of carbon fiber reinforced aluminium matrix composites. Trans. Nonferrous Met. Soc. China (English Ed.), 20, 2148–2151.
[25] Sánchez, M., J. Rams, and A. Ureña, 2010: Fabrication of aluminium composites reinforced with carbon fibres by a centrifugal infiltration process. Compos. Part A Appl. Sci. Manuf., 41, 1605–1611.
[26] Naji, H., S. M. Zebarjad, and S. A. Sajjadi, 2008: The effects of volume percent and aspect ratio of carbon fiber on fracture toughness of reinforced aluminum matrix composites. Mater. Sci. Eng. A, 486, 413–420.
[27] Perez, O., G. Patriarche, M. Lancer, and M. H. Vidal-Setif, 1993: Interphase and mechanical properties in carbon fibers/Al matrix composites. J. Phys., 3, 1693–1698.
[28] Jung, K. H., S. Nam, S. S. Kang, B. C. Ku, Y. H. Bang, and J. Y. Hwang, 2017: Tribological properties of carbon fiber-reinforced aluminum composites processed by spark plasma sintering. Carbon Lett., 21, 103–106.
[29] Hajjari, E., M. Divandari, and A. R. Mirhabibi, 2010: The effect of applied pressure on fracture surface and tensile properties of nickel coated continuous carbon fiber reinforced aluminum composites fabricated by squeeze casting. Mater. Des., 31, 2381–2386.
[30] Kaczmar, J. W., K. Naplocha, and J. Morgiel, 2014: Microstructure and strength of Al2O3 and carbon fiber reinforced 2024 aluminum alloy composites. J. Mater. Eng. Perform., 23, 2801–2808.
[31] Cao, X., Q. Shi, D. Liu, Z. Feng, Q. Liu, and G. Chen, 2018: Fabrication of in situ carbon fiber/aluminum composites via friction stir processing: Evaluation of microstructural, mechanical and tribological behaviors. Compos. Part B Eng., 139, 97–105.
[32] Ramesh, C. S., H. Adarsha, S. Pramod, and Z. Khan, 2013: Tribological characteristics of innovative Al6061-carbon fiber rod metal matrix composites. Mater. Des., 50, 597–605.
[33] Sree Manu, K. M., L. Ajay Raag, B. C. Pai, V. Petley, and S. N. Verma, 2019: Self-lubricating bidirectional carbon fiber reinforced smart aluminum composites by squeeze infiltration process. J. Mater. Sci. Technol.
[34] Bhav Singh, B., and M. Balasubramanian, 2009: Processing and properties of copper-coated carbon fibre reinforced aluminium alloy composites. J. Mater. Process. Technol., 209, 2104–2110.
[35] Tang, Y., L. Liu, W. Li, B. Shen, and W. Hu, 2009: Interface characteristics and mechanical properties of short carbon fibers/Al composites with different coatings. Appl. Surf. Sci., 255, 4393–4400.
[36] Alten, A., E. Erzi, Ö. Gürsoy, G. Hapçı Ağaoğlu, D. Dispınar, and G. Orhan, 2019: Production and mechanical characterization of Ni-coated carbon fibers reinforced Al-6063 alloy matrix composites. J. Alloys Compd., 543–550.
[37] Gondil, R., 2016: Processing of Carbon fiber reinforced Aluminium ( 7075 ) metal matrix composite. 5–14.
[38] Rnimbalkar, P. S., and M. Satpute, 2015: Aluminiumalloy Al-7075 reinforcement and Stir casting -a Review. 3, 38–46.
[39] Kumar, N., H. C. Chittappa, R. K. B, and S. E. Vannan, 2017: Corrosion Behaviour of Nickel Coated Short Carbon Fiber Reinforced Al Metal Matrix Composites. 12, 659–669.
[40] Da Silva, C. C., G. M. Volpato, M. C. Fredel, and U. Tetzlaff, 2019: Low-pressure processing and microstructural evaluation of unidirectional carbon fiber-reinforced aluminum-nickel matrix composites. J. Mater. Process. Technol., 269, 10–15.
[41] Hao, X., H. Nie, Z. Ye, Y. Luo, L. Zheng, and W. Liang, 2019: Mechanical properties of a novel fiber metal laminate based on a carbon fiber reinforced Zn-Al alloy composite. Mater. Sci. Eng. A, 740–741.
[42] Hou, L. G., R. Z. Wu, X. D. Wang, J. H. Zhang, M. L. Zhang, A. P. Dong, and B. D. Sun, 2017: Microstructure, mechanical properties and thermal conductivity of the short carbon fiber
reinforced magnesium matrix composites. *J. Alloys Compd.*, **695**, 2820–2826.

[43] S. Li, T. Zhang, J. Zhou, and H. Li, 2019: An analysis of the factors affecting strengthening in carbon fiber reinforced magnesium composites. *Compos. Struct.*, **209**, 328–336.

[44] Qi, L., L. Ju, J. Zhou, S. Li, T. Zhang, and W. Tian, 2017: Tensile and fatigue behavior of carbon fiber reinforced magnesium composite fabricated by liquid-solid extrusion following vacuum pressure infiltration. *J. Alloys Compd.*, **721**, 55–63.