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Advancements in graphene reinforced metal matrix composites: A comprehensive review

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Abstract

The Present pollution norms insist automobile manufacturers to make use of ultra-high specific strength materials i.e., materials ahead of conventional metal matrix composites (MMCs) with micro-sized reinforcements. With the advent of nanomaterials, nanocomposites are being developed with properties that overcome the limitations for metals or composites with micro-sized reinforcements. In recent years, the family of graphene-based materials, in particular, graphene nanoplatelets (GNPs) reinforced MMCs offering promising solutions to revolutionize the industrial landscape owing to their excellent mechanical, thermal, chemical and electrical characteristics due to which they find applications in a wide variety of fields such as automotive, aerospace industry, power engineering and synthesis of anti-corrosive coatings among other biological and environmental applications for sustainability such as agriculture, energy storage and water purification. This article also sheds light on the factors that have slowed it down from becoming a mainstream industry, inspite of the plethora of benefits, offered by graphene nanoparticles and graphene derivatives reinforced metal matrix composites in terms of both commercial viability and ecological stability.

Keywords: *Graphene nanoplatelets, Metal matrix composites, Powder metallurgy, Stir casting, Strengthening mechanisms.*

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INTRODUCTION

Reduce and absorb are the taglines to save environment from greenhouse gases i.e., emissions need to be reduced through limiting the use of energy and simultaneously the harmful gases are to be absorbed by planting trees etc. In the current life style, energy consumption can only be reduced through effective use of technology in producing high specific strength materials. At present, carbon materials such as carbon nanotubes and graphene showing excellent potential for replacing high-density metals. However, every leap in technology is hindered by several challenges. In the same passion, here also the composites developed with carbon reinforcement materials encountering various challenges such as brittleness, non-uniformity in dispersion of reinforcement particles etc. This investigation presents the various synthesis routes and challenges in fabrication of graphene nano metal matrix composites with insights in to strengthening mechanisms involved and their applications.

As the world is moving towards light weight applications, there is huge scope and potential in the domain of processing and characterization of high specific strength materials in mechanical and thermal aspects in addition to its machinability [1]. In recent times, we witnessed the exponential growth in research towards graphene nanoplatelets (GNPs) as reinforcement phase of MMCs. Among all other types of graphene reinforcements, GNPs are favored owing to their ability to impart excellent mechanical properties to the composite due to their high surface area. Its 2-dimensional honeycomb structure formed by strong covalent bonds make it suitable as reinforcement for a wide variety of metal matrices. However, the empirical data obtained from fabricated GNPs/Al composites does not coincide with the theoretically predicted values of tensile strength and elongation based on electrostatic self-assembly due to low dispersion, poor wettability, inadequate structural retention and high-volume fraction of GNPs. In regard to this, most of the research work utilized a low volume fraction of GNPs, 0.5% and 1%, and have reported a significant improvement in the mechanical properties of Al [2].

The subsequent research too focused on improving dispersion of GNPs. Zhang et al. [3] studied the influence of GNPs reinforced Al5083 alloy by high energy ball milling and have identified adverse structural damage to GNPs inspite of improvement in the mechanical properties. An integration of ball milling and sonication was utilized by Khan et al. [4] to ensure uniform dispersion. One can observe that the majority of researchers resorted to powder metallurgy techniques to obtain uniform distribution of the dispersion phase. GNPs have platelet morphology and comprise a series of graphene sheets bound by Vander Waals forces. The bonding direction of these sheets differ from those of graphitic plates. GNPs are bound to have a disruptive effect as filler material owing to desirable properties such as high stability, ease of handling and low cost of production. Even with a low content of GNPs, formation of a 3-dimensional network occurs and as a result anisotropic attributes are imparted to the MMCs and enhanced electrical and thermal conductivities can be obtained [5]. Various exceptional properties of GNPs reinforcement are depicted in Fig. 1.

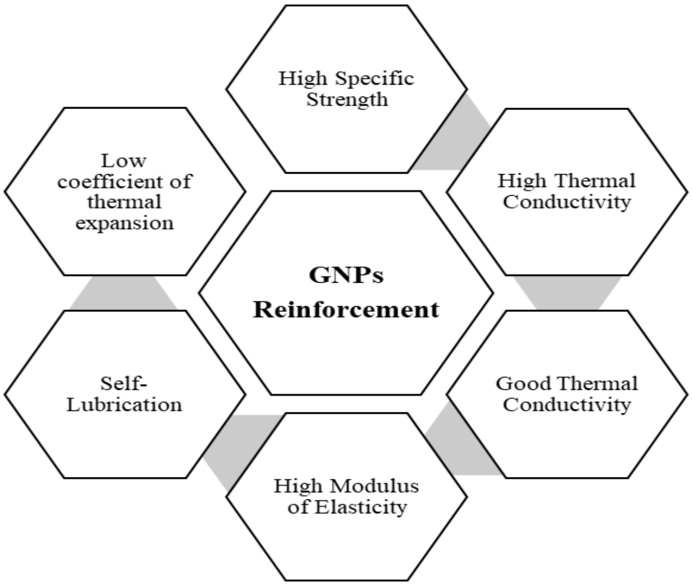

Fig. 1. Various properties of GNPs.

Summary of graphene nanoparticle reinforced MMCs fabrication techniques

The fabrication of graphene nanoparticle reinforced metal matrix composites can be achieved by a wide variety of techniques as illustrated below in Fig. 2. Srivastava et al. [6] fabricated graphene nanoparticle reinforced MMCs by stir casting with different weight percentages of graphene nanoparticles (0.4%, 0.8% and 1.2%) and established that with an increase in the weight percentage of dispersion phase, there is an increment in the yield strength and ultimate tensile strength at the expense of hardness. Abushanab et al. [7] fabricated nanocomposites with Al2024 alloy as matrix reinforced with varying graphene particles up to 2 wt.% and reported enhanced yield strength and microhardness.

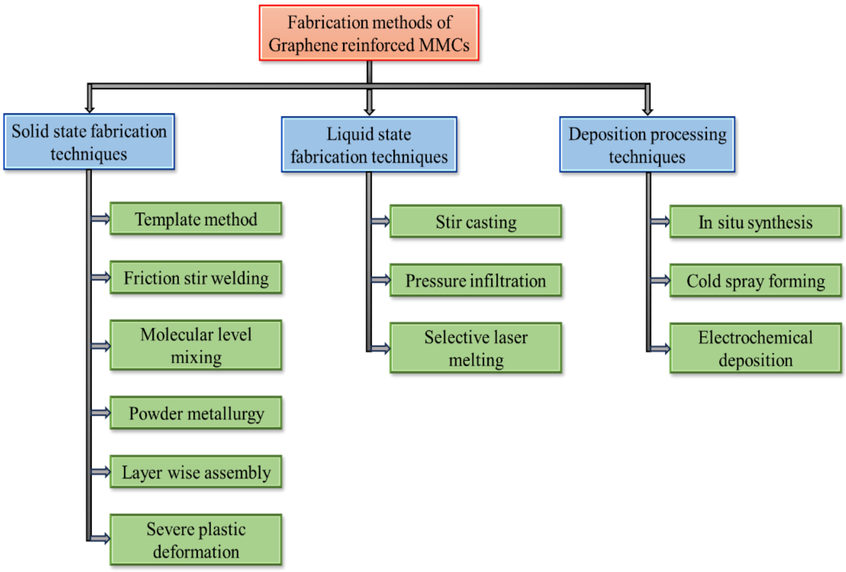

Fig. 2. Several fabrication techniques for developing GNPs reinforced MMCs.

In the context of the mechanical domain, fabrication and usage of high specific strength materials for domestic as well as commercial purpose can reduce the carbon emissions. Whereas in the view of environmental concern, carbon foot print of stir-casting is far superior to regular powder metallurgy route of fabricating nanocomposites. Usage of high specific strength materials may reduce the harmful emissions which helps in conserving the environment. Khobragade et al. [8] employed high-pressure torsion (HPT) method to fabricate graphene (5 and 10 wt.%) reinforced Cu composite that has twice the strength of pure copper, better hardness and considerable conductivity. Zhao et al. [9] have fabricated graphene strengthened-copper matrix composite. The spread of graphene in the matrix phase is found to be homogeneous and the composite has improved strength. Homogeneity of the dispersed phase is dependent on the level of premixing, properties of the matrix. In our recent studies [10], the usage of combined liquid and powder metallurgy helps us for significant enhancement in tensile strength and hardness of the Al/GNPs cast composites as depicted in Fig. 3. Nevertheless, 25% to 40% of insinuated GNPs are entangled in dross during casting process, phenomenal mechanical behaviour with an ultimate tensile strength (UTS) of 203 MPa and hardness of 81.5 BHN accompanied with exceptional uniform dispersion of nanoreinforcement particles with no witness of clusters and voids noticed for 1.5 wt.% GNPs composite sample.

Infiltration is also noticed as a significant processing technique that comprises inoculating the metal melt via absorbent ceramic structure (discharge). High-pressure die casting is being followed to fabricate the nanocomposites by inoculating a liquefied metal by introducing a porous structure established by the reinforcement phase particles. In Pressure infiltration casting, the molten metal is made to pass through a preform of reinforcement through an inert gas at high pressure, as shown in

Fig. 4. The limitations associated with other casting techniques such as poor wettability between matrix and reinforcement phase can be tackled by pressure infiltration. As it is a quick process, undesirable reactions and product formation can be prevented. The properties of MMCs fabricated by this technique are a function of the temperature of preheating, pressure of infiltration, time and speed of pressing. Exceptional electrical conductivity (EC) and mechanical properties have been observed in graphene reinforced aluminum metal matrix composites (AMMCs) fabricated by the route of pressure infiltration [11]. Moreover, Table 1 illustrates the salient features and enhancement in several properties of various GNPs reinforced MMCs processed with different strategies.

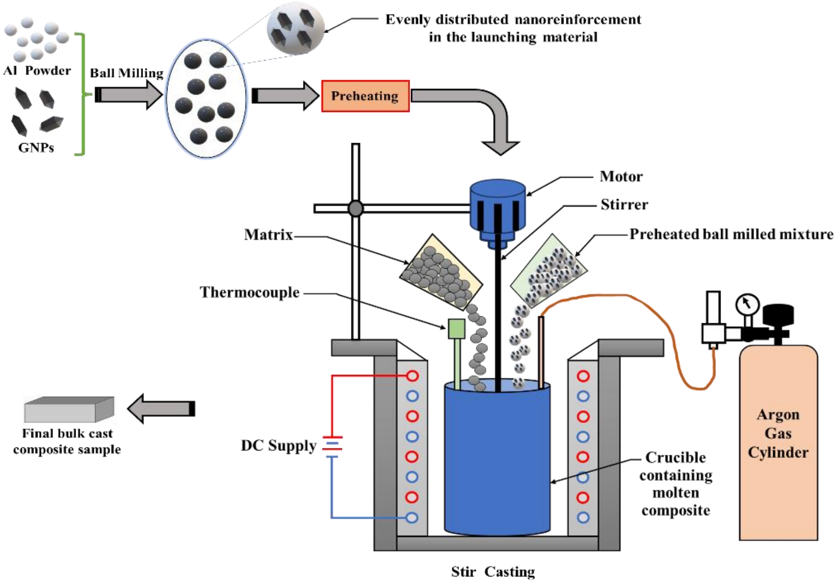

Fig. 3. Combined liquid metallurgy (stir casting) and powder metallurgy (ball milling).

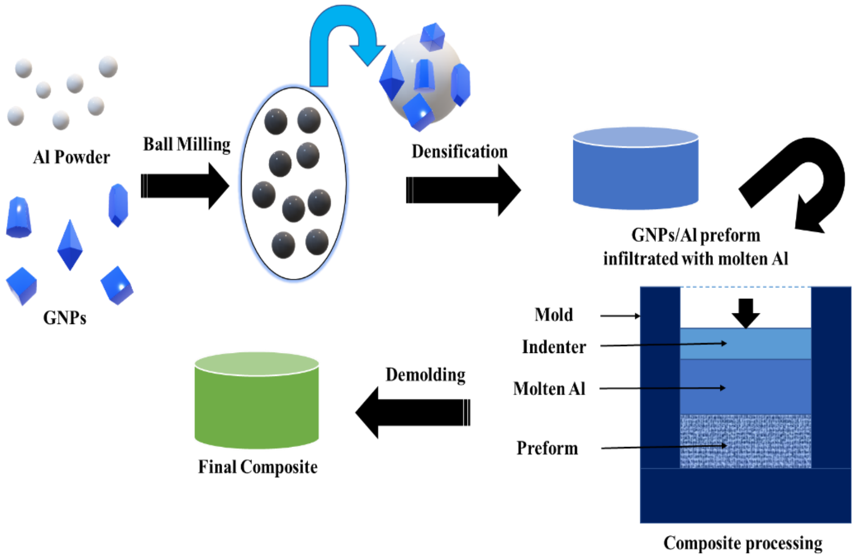

Fig. 4. Combined ball milling and pressure infiltration.

Table 1: Salient features of various graphene nanoplatelets reinforced MMCs.

Author and Year of publication with Reference	Salient features	Optimal weight fraction of GNPs	Matrix	Enhancement
Saha et al. (2023) [12]	1. High Energy Mechanical Alloying 2. Cold Spray Additive Manufacturing	1.0 wt.%	AA6061	Improved deformability and better mechanical interlocking at the interface
Zhou et al. (2021) [13]	1. Synchronization of in-situ exfoliation and dispersion of GNP 2. Three-dimensional vibration milling 3. Spark plasma sintering	0.1 wt.%	Pure Nickel	24.8% increase in ultimate tensile strength 29.5% increase in yield Strength
Polayya et al. (2023) [14]	1. Stir-casting 2. Scanning electron microscopy	1.0 wt.%	AA6061	Increase in tensile strength by 37% and compressive strength by 34%
Kabir et al. (2023) [15]	1. Powder metallurgy 2. Energy-dispersive X-ray spectroscopy, Raman spectroscopy	0.2 wt.%	Pure Zinc	Increase in ultimate compressive strength by 28%
Munir et al. (2020) [16]	1. High-energy ball-milling processes 2. Powder metallurgy 3. Transmission electron microscopy, Scanning electron microscopy 4. Energy dispersive X-ray spectroscopy, XRD, Raman	0.3 wt.%	Pure Magnesium	Ultimate tensile strength increased to 126 MPa

	spectroscopy			
Lopez et al. (2022) [17]	1. Additive friction stir deposition 2. Optical and scanning electron microscopy 3. Raman spectroscopy	2.5 wt.%	AA6061	Microhardness increased significantly to the range of 45-70 HV

APPLICATIONS

Automotives

A large percent of MMCs, roughly 50% of the world’s production is being utilized in the automobile sector, owing to their excellent strength and their effect in reducing overall vehicle weight. Graphene reinforced MMCs form a special class of this extensively used materials owing to their remarkable wear resistance and lighter weight and are suitable for manufacturing pistons, cam shafts, cylinder liners, rockers, various components of the brakes, bearings and tappets [18]. Thus, in the near future, nanocomposites that possess high specific strength would replace high density materials like steels to make automobiles lighter thereby decreasing the fuel consumption and hence contributing immensely to environmental conservation.

Aeronautical

Owing to its excellent thermal conductivity, graphene reinforced MMCs are being widely used in aeronautical and military applications. Aerospace and other aviation related industries are the pioneers of implementing graphene reinforced MMCs in cutting edge, live saving technologies such as de-icing systems which play a crucial role in prevention of surging of the aero plane engines which could ultimately lead to a fatal failure, protection from a lightning strike and other thermoelectric systems without compromising the streamlined structure of the air-craft [19]. Required stiffness and low coefficient of thermal expansion for space exploration are offered by GRMMCs. Stringers are the aluminum components that join cross sectional frames to form a semi-monocoque fuselage in airplanes. These stringers are subjected to tension and compression loads produced by varying pressure between cables and atmosphere surrounding the aircraft. Strengthening the stringers using advanced aluminum composites improve the reliability of the airplane.

Anti-Corrosive coatings/Anti-Corrosion properties

Improving barrier properties and providing anodic and cathodic protection are essential for the life of any metal or composite material. A synergistic anti-corrosion effect of the two alloying elements while developing the tailor-made composite is needed for enhancing corrosion resistance. Wang et al. [20] fabricated graphene reinforced aluminum composites and have reported a significant rise (31%) in corrosion resistance. However, when the reinforcement phase exceeded 0.5 wt.%, the anti-corrosive nature is not exhibited. Pure graphene anti-corrosive coatings are not effective in the sense that once the graphene layer is worn off, the corrosion of the inner metal accelerates. To address this problem, graphene composite nano-coatings are introduced as they have the dual advantage of strong adhesion properties of graphene and the film-forming properties of the coating matrix resulting in an improved performance [21]. Anti-corrosive properties of nanoplatelets have been overridden owing to the cathodic nature of graphene with respect to the matrix, which in the presence of electrolyte would lead to galvanic corrosion. Prevention of corrosion deters the possibility of corrosion-related detrimental effects on the environment such as leaching of metal oxides into water bodies and by increasing the longevity of the products it lowers the production demand associated with replacing the old ones and hence reduces the carbon footprint associated with metallurgical industry.

Power Engineering

The power generation industry is on a constant lookout for materials that can minimize the losses associated with electricity transmission and to achieve a substantial increase in the current carrying capacity of the transmission lines. After copper, aluminum is the second most widely used metal in the field of electrical engineering due to its unparalleled electrical properties. It was found that, due to graphene reinforcement in Cu and Al wires produced by extrusion, there is a slight increase in the resistivity and strength. This makes Gr reinforced wires a suitable material for the core segment of the transmission wires [22].

STRENGTHENING MECHANISMS

There are two prominent components of the strengthening system, viz, direct and indirect mechanisms of strengthening. The former arises from the incorporation of hard nanoparticles into the soft matrix phase, while the latter is a result of difference in the coefficient of thermal expansion (CTE) between the dispersed phase and the matrix phase. Owing to an increase in the temperature, thermal stresses are induced in the matrix and the accompanying increment in the density of dislocation contribute to strengthen the composite [23]. Further, interface quality, processing techniques, dispersion at grain boundaries, along with the intrinsic attributes like geometry, size of grains and aspect ratio have a profound impact on the strengthening effect. Various phenomena associated in strengthening mechanism of nanoparticle reinforced MMCs are as follows.

Orowan looping of nanoparticles

In general, Orowan looping estimates the discharge of impinging induced by fine grain size particles inside the dislocation zone. Even though micro sized reinforcement particles are giving far superior properties than conventional metals, that is not up to the mark due to the wide range of intermolecular separation. Nevertheless, when nanoreinforcement particles are dispersed in metal matrix, Orowan looping phenomenon imparts a predominant strengthening contribution. Usually, the reinforcement of nanoparticles reacts to discontinuity out-turns in Orowan looping [24]. The GNP particles act as hindrances to dislocation motion and thereby prevent the agglomeration of dislocation. This causes the dislocation loops thus generated to move via particles resulting in adequate back stress and imparts them the tendency of bending, prompting them to assume a semi-circle geometry. The back stress thus developed enhances the strength of the composite and the associated phenomena is termed as Orowan looping. Equation (1) represents the strength attained by means of Orowan looping mechanism. In which α indicates Taylor element, μ and b denotes modulus of rigidity and burger aspect of metal matrix categorically, whereas x represents the average gap in between the dispersed grains of reinforcement inside the matrix and v indicates the fraction of volume.

$$\delta\sigma_{\mathrm{orowan}} = \frac{\alpha\mu b}{x\,(\sqrt[3]{\frac{v}{2}}-1)}\ \ln\frac{x}{2b} \text{ ----------(1)}$$

With the exception of grain size and shape, uniformity in distribution of nanoparticles plays a momentous part in the strengthening system. Graphene nanoplatelets need to dissipate uniformly inside the matrix in the view of interrupting the dislocation motion. Nevertheless, weight percentage of graphene tends to agglomerate at a definite edge, thereby degradation of mechanical parameters which in turn entails to enhance various supplements [25]. Detailed investigation and studies of Xiong et al. [26] on strengthening of the nanoreinforcement on various MMCs revealed that due to the nano sized reinforcement of GNPs added in the aluminum matrix, composite enhances the Orowan looping. Authors discussed about the influence of interfacial retort in several variations in terms of volume ranging from 0.3 to 1.2% with an interval of 0.3% of GNPs embedded AMMCs processed through spark plasma sintering. However, recent findings highlighted the interphase reaction converted from mechanical to adverse chemical adhesion due to the formation of closely packing in between aluminum carbide and Al matrix; thereby the reinforcement anchors to the matrix then. In connection with the outcomes, authors suggested to consider the whole volume fraction of GNPs and aluminum carbide for understanding the Orowan strengthening due to the following aspects such as closely packed Al_4C_3 with GNPs, fact of Orowan strengthening phenomenon doesn't depend on the mechanical variables of the reinforcement particles and nano size of reinforcement.

Load transfer from the metal matrix to graphene reinforcement

Shear lag model [27] is employed to explain the load transfer from the metal matrix to nanoparticle reinforcement and also illustrates the phenomenon of strengthening in detail. Interfacial shear stress and strength are two major effects that come from the load transfer and depend highly on interfacial bonding between matrix and composites. It was formulated by Tyson and Kelly to determine the ultimate tensile strength in terms of many process parameters as depicted from the equations (2) and (3). Where σ_m and σ_r represents the tensile strength of matrix and reinforcement phases, υ_r indicates the percentage of reinforcement phase in terms of volume and l_c denotes the critical length.

In accordance with the equation (4), the numerical model developed includes critical length (l_c). Where, τ indicates the maximum shear strength and d is the diameter of the reinforcement particles. However, applied loads have been transferred from the matrix phase to the GNPs reinforcement phase through shear/tangential stress included between two faces through the tensile direction. More precisely, if the nanoreinforcement surpasses the critical length as represented in equation (2), the particle reinforcement tends to fail by the way of sudden fracture. Whereas if the length of graphene nanoplatelets appeared to be shorter than its corresponding critical length as illustrated in equation (3), it seems to be pulling out of nanoplatelets of graphene via interfacial de-bonding.

$$\delta\sigma_{\mathrm{load}} = \sigma_r v_r \left(1 - \frac{1}{2l_c}\right) - \sigma_m v_r \text{ ; for } l > l_c \text{ ----------(2)}$$

$$\delta\sigma_{\mathrm{load}} = \sigma_r v_r \left(\frac{1}{2l_c}\right) - \sigma_m v_r \text{ ; for } l \leq l_c \text{ ----------(3)}$$

$$l_c = \frac{d\sigma_r}{2\tau} \text{ ----------(4)}$$

CTE difference induced dislocation

During the cooling phase from high temperatures that follows heat treatments such as annealing, generation of misfit strains take place and these are adequate to cause dislocation at the interface of metal matrix and GNPs interface owing to the difference between thermal contractions. The thermal stresses induced during contraction further elevates the dislocation density than that caused by the ones due to addition of GNPs. These dislocations promote strain hardening and thereby enhancing the strength of the composite. In certain cases, the CTE mismatch induced thermal strains can be overcome due to the formation if dislocation nucleation. This mechanism is also referred to as thermally activated dislocation. It is predominantly dependent on the particle size, as it results in a large surface area which contributes to increment the dislocation density [28]. The lower coefficient of thermal expansion of graphene (1×10^{-6}) in comparison to the higher value of aluminum (23.6×10^{-6}) results in a dislocation.

Grain refinement strengthening

The yield strength of MMCs can be increased by grain strengthening mechanism by refining the grains and thereby lowering the stress concentration at the sites of dislocation. Introducing GNPs into the matrix phase accelerates the grain refinement by the inception of sites of nucleation at the time of recrystallization. The Hall-Petch mechanism elucidates the phenomena in which the presence of graphene has a profound effect on altering the grain size of aluminum [29]. The growth of aluminum grains is shunted by the GNP particles resulting in the formation of a grain boundary with high density, which in turn increments the strength by affecting the dislocations and also transmitting them to the nearby grains.

COMPREHENSIVE COMMENTS ON BEHAVIOUR OF GRAPHENE REINFORCED MMCS

Microstructure and morphological progression effected by graphene nanoreinforcement preceded to equivalent variations in its mechanical, thermal, tribological, corrosion and electrical characteristics of metal matrix nanocomposites.

Mechanical behaviour

Many research articles emphasize on hypothetical responses of mechanical behaviour of graphene nanosheets reinforced AMMCs estimated by the law of mixtures are remarkable only because of exceptional properties of graphene such as tensile strength (130 GPa) and young's modulus (106 N/mm^2). In particular, the hypothetical value of maximum tensile strength of AMMCs reinforced with 0.3 wt.% of graphene nanosheets is escalated as 500 N/mm^2 where the reinforcement sheets are situated alongside of tensile direction [30]. Nevertheless, the responses obtained through tensile strength evaluation are substantially less values in comparision with hypothetical values. The relative error in between the experimental outcomes and theoretical responses can be accredited to non-uniform distribution, irregular alignment of graphene nanosheets and poor articulation bonding in between matrix and reinforcement phase. It is evident from the literature that the wt.% of graphene influences the accomplishment of GNPs reinforced AMMCs. Also, it is possible to strengthen the MMNCs by adding less content of graphene as reinforcement phase; whereas deterioration starts with stimulated extent of graphene particles. However, degree of nanoreinforcement distribution influences the strengthening mechanism; i.e., phenomenal reduction in mechanical characteristics of GNPs/AMMCs is observed due to the formation of graphene clusters within the metal melt. In detail, Islam et al. [31] highlighted that around 36% of enhancement in hardness exhibited by the 0.5 wt.% GNPs/AMMCs and is resembled with 5 wt.% SiC/AMMCs.

Exceptional rate of impact strength should be possible by incorporating graphene particles with in the metal matrix [32]. In the course of crack promulgation towards the reinforcement phase, that should be hindered by the graphene particles. To a greater extent, the crack promulgation across the indigenous path would be typical to carry on with, subsequently the cracks had to avert towards the region of graphene absence. The accumulation of over-stretch at the crack edge had slowly discharged, thereby the composite strength enhanced up to certain stretch.

In materials and machining technology, ductility is the capability of a medium that can endure large durable distortion while applying tensile load before gets failure; on other words, the corresponding propensity of a material to be long-drawn-out plastically at ambient level temperature without damaging and it had been taken in to consideration by many engineers as essential parameter in the time of design [33]. If we can discuss about the ductile nature of Al-graphene MMCs, it tends to reduce due to the addition of graphene as reinforcement in the aluminum metal matrix [34]. Recently, some researchers addressed that strength of the composite improved without losing its ductility; also, ductility is even ameliorated with respect to its related metal matrix because of the uniform distribution of nanoreinforcement particles on one hand and the improved wettability in between the aluminum matrix and graphene phase [35].

Thermal behaviour

In recent times, thermal properties of tailor-made composites garnered significant importance due to their huge scope and potential in avionic applications where high strength to weight ratio is desirable. Metal matrix nanocomposites at higher weight fraction rate are adorable in the point of imminence for improving thermal conductivity and also pliability to achieve suitable coefficient of thermal expansion by varying the wt.% of reinforcement phase. Even though higher thermal conductivity materials such as aluminum, copper etc. are used as matrix by incorporating various carbon reinforcements, the fabricated composites confronting several difficulties. It is evident form the statistics that AMMCs are offering higher specific thermal conductivity than CuMMCs; thereby, AMMCs are identified as significant material for aerospace applications. On other hand, the augmented demand inflicted on high temperature resisted components in micro electronics and semiconductor devices accelerate the evolution of state-of-the-art tailor-made composites with exceptional thermal conductivity to adequate heat dissipation and suitable thermal expansion coefficient to reduce thermal stresses and oxidation of heat [36].

To encounter the demand of exalted temperature applications, GNPs/AMMCs need to attain tailorable thermal properties in order to forbid the agglomeration of heat lead to impairment of configurational integrity of the material. In general, aluminum is intended to be a good thermal conductive metal having 237 $Wm^{-1}K^{-1}$ thermal conductivity whereas its thermal expansion coefficient around 24 x 10^{-6} K^{-1} limits its usage in commercial applications. Earlier, the traditional ceramic reinforcement particles of silicon carbide and titanium diboride were taken in to consideration for minimizing the coefficient of thermal expansion of AMMCs, whereas thermal conductivity is to be reduced contemporarily. To get the better of this contrary, graphene particles have been advised as a favorable reinforcement for AMMCs because of its remarkable thermal conductivity and contrary values of thermal expansion coefficient [37].

Tribological behaviour

As it is known that tribology is the salient study of engineering of interacting the surface texture in equivalent motion and encloses the evaluation and discharge of wear, coefficient of friction, lubrication and various characteristics of design. Also, investigations on tribological studies are very much essential in recent times owing to the fact that high amount of energy is vanished due to friction in slipping interfaces of impulsive devices. However, in the context of tribological studies on graphene reinforced MMCs; as a substantial lubricant, graphene is ready to configures a withstandable lubricant rheological surface subjected to wear constraints [38]. Throughout the tests of tribological study, excessive shear forces were applied to the worn surface of the specimen, where graphene nanosheets tended to interweave because of feeble Vander walls forces among the reinforcement layers lead to the depletion of coefficient of friction subject to consequences of self-lubrication [39]. Due to the incorporation of graphene as a reinforcement phase in the metal melt, the composites offer promising tribological behaviour. AA6082 metal matrix composites with nano flakes graphene reinforcement fabricated with friction stir processing [40] revealed that the composite exhibits minimal wear compared with unreinforced AA6082 sample. Also, pointed that the dissipation of Magnesium silicide particles previously existed at cereal extremities at the time of fabrication assists to decrease the coefficient of friction, thereby wear resistance can be enhanced in the course of grain evacuation.

Corrosion behaviour

The effect of addition of graphene to aluminum is debatable, with some researchers suggesting that galvanic corrosion can be initiated due to the presence of graphene and resulting in accelerated corrosion in case of Gr reinforced AMCs, whilst others are of the opinion that friction stir processing enables a finer grain structure which leads to enhanced mixing of the reinforcement and thereby improving the resistance to corrosion. The study of Gr reinforced Al5083 was undertaken by Prabhakar et al. and they have revealed an acceleration in the corrosion rate due to the tendency of aluminum to act as the anode and graphene as the cathode [41]. Whereas, slower corrosion rates can also be attributed to the lowering of sites for galvanic coupling owing to the dissolution of secondary phase [42]. Therefore, it can be concluded that the resistance of graphene reinforced AMCs is a function of both microstructural development of the matrix phase and distribution of graphene and hence controlling the development of microstructures is pivotal to ensure that anti-corrosive properties are imparted to the composite.

Electrical behaviour

Modern technology requires materials with good electrical properties, as aluminum is the second most widely used material in electrical industry next to copper, the effect of graphene addition to aluminum matrix on the electrical properties is of considerable interest. In general, the electrical conductivity of Graphene reinforced AMMCs is expected to be superior to pure aluminum owing to the high EC of graphene of 9.6 x 10^{7} Sm^{-1} [43]. At par from the literature, [44] some deflections in electrical conductivity observed due to the following hindrances such as lack of interfacial bonding and uniform dispersion, the role of processing techniques and the associated intrinsic defects.

In recent years, an improvement in EC was observed by Yu et al. [34] in case of Gr reinforced Al6063 composite fabricated by a combination of squeeze casting and ball milling. Increase in EC is only noticed when the milling time is 3 hours, any other milling time is of no consequence. High-resolution transmission electron microscopy images of the composite processed by 1 hour milling time revealed the formation of amorphous alumina film at the interface owing to the gas atomization of aluminum. Whereas, for milling time greater than 3 hours, occurrence of aluminum carbide has an insulating effect and effectively lowering the EC. But, milling time of 3 hours resulted in the rupture of oxidation layer and established direct contact with Al matrix, thereby significantly enhancing the electrical conductivity. To sum up, better electrical conductivity can only be achieved with strong interfacial bonding between graphene and Al. Apart from that, the following factors are crucial in determining the electrical conductivity of the composite: Preventing aluminum oxide and intermetallic carbide formation, obtaining direct contact with graphene, retaining its structural integrity, and ensuring the uniform dispersion of graphene.

CHALLENGES WITH GRAPHENE AS REINFORCEMENT IN MMCS

Carbide formation, poor dispersion, low interfacial bonding and structural integrity are the main hindrances for the rapid development of graphene reinforced MMCs [24]. Regarding graphene-reinforced aluminum composites, the formation of Al-carbide can be attributed to a lower value of Gibbs free energy. Formation of carbides in Al matrix detrimentally affects the strength, since they are prone to stress concentration which may ultimately lead to brittle failure [45]. Li et al. [46] conducted a study on bulk nanostructured aluminum-graphene composites prepared via cryo-milling. They reported a 20% drop in tensile strength, attributing it to carbide formation in 6.34 vol.% GNP. The difference in the bonding nature of Gr and Al is the cause of poor dispersion in GNPs reinforced composites; GNPs being a derivative of carbon possess Vander Waals forces while aluminum has metallic bonds, but it enhances the thermal conductivity of the resulting composite. Rashad et al. [47] have observed a drop of 8% in compression strength of 0.39 vol.% GNP owing to the agglomeration of GNPs. Poor dispersion results in formation of cracks and pores which may induce premature failure.

Effect of low interfacial bonding is not clearly understood because of contradictory results exhibited by the various studies, as some research work points towards the fact that it promotes carbide formation and has adverse effects on the composite strength, while other debate that it may have positive effect. Ju et al. [48] processed GNPs/Al composites by pressure infiltration method and have reported a tensile strength of 303 MPa in case of Al_2O_3 interfacial bonding, 30% higher than that of Al_4C_3 and Al_2OC interface. The strengthening efficiency is highly dependent on structural integrity. Baig et al. [49], utilized powder metallurgy to fabricate GNP reinforced Al Matrix composites and have found a negative effect on the structural integrity which in turn effects adversely other mechanical properties and have proposed solvent dispersion and ball milling (SDBM) to counteract this problem.

CONCLUSIONS

Graphene reinforced metal matrix composites with emphasis on various synthesis techniques along with their applications potential in mechanical, thermal and electrical properties have been reviewed at length. Mechanical properties are further correlated with strengthening mechanisms involved in MMCs. Furthermore, the challenges encountered in this process have been identified and suitable methods to overcome them have been explored. However, this can be attributed to the ability of graphene reinforcements to enhance the mechanical properties of MMCs to suit extreme operating conditions. Among all other types of graphene reinforcements, GNPs are favored owing to their ability to impart excellent mechanical properties to the composite due to their high surface area. Inspite of the extensive research in this regard, defects such as porosity and wettability are to be dealt with. With the ever-growing demand for light-weight materials with high strength, economical methods such as stir casting have been devised, making GNPs reinforced MMC affordable. Also, it helps to facilitate the improvement of wettability between the matrix and reinforcement if GNPs are introduced in to the crucible with launching material in terms of ball milled mixture. Thus, graphene nanoplatelets reinforced MMCs are set to revolutionize the fields of electrical power transmission, machinery, automobiles, aviation and anti-corrosive components. On a concluding note, GNPs reinforced MMCs possess unique properties and have enormous potential to ensure sustainable development by facilitating eco-friendly applications.

REFERENCES

[1] Kotteda TK, Kumar M, Kumar P, Chekuri RB. Metal matrix nanocomposites: future scope in the fabrication and machining techniques. The International Journal of Advanced Manufacturing Technology. 2022 Aug 25:1-9. doi.org/10.1007/s00170-022-09847-0.

[2] Gao X, Yue H, Guo E, Zhang H, Lin X, Yao L, Wang B. Preparation and tensile properties of homogeneously dispersed graphene reinforced aluminum matrix composites. Materials & design. 2016 Mar 15;94:54-60. doi.org/10.1016/j.matdes.2016.01.034.

[3] Zhang H, Xu C, Xiao W, Ameyama K, Ma C. Enhanced mechanical properties of Al5083 alloy with graphene nanoplates prepared by ball milling and hot extrusion. Materials Science and Engineering: A. 2016 Mar 21;658:8-15. doi.org/10.1016/j.msea.2016.01.076.

[4] Khan M, Amjad M, Khan A, Ud-Din R, Ahmad I, Subhani T. Microstructural evolution, mechanical profile, and fracture morphology of aluminum matrix composites containing graphene nanoplatelets. Journal of Materials Research. 2017 Jun;32(11):2055-66. https://doi.org/10.1557/jmr.2017.111.

[5] Zhao Z, Bai P, Du W, Liu B, Pan D, Das R, Liu C, Guo Z. An overview of graphene and its derivatives reinforced metal matrix composites: Preparation, properties and applications. Carbon. 2020 Dec 1;170:302-26. doi.org/10.1016/j.carbon.2020.08.040.

[6] Srivastava AK, Saxena A, Maurya NK, Dwivedi SP. Microstructural and Mechanical Properties of AZ31B/Graphene Nanocomposite Produced by Stir Casting. Revue des Composites et des Matériaux Avancés. 2021 Feb 1;31(1). doi.org/10.18280/rcma.310107.

[7] AbuShanab WS, Moustafa EB, Ghandourah E, Taha MA. Effect of graphene nanoparticles on the physical and mechanical properties of the Al2024-graphene nanocomposites fabricated by powder metallurgy. Results in Physics. 2020 Dec 1;19:103343. doi.org/10.1016/j.rinp.2020.103343.

[8] Khobragade N, Sikdar K, Kumar B, Bera S, Roy D. Mechanical and electrical properties of copper-graphene nanocomposite fabricated by high pressure torsion. Journal of Alloys and Compounds. 2019 Mar 5;776:123-32. doi.org/10.1016/j.jallcom.2018.10.139.

[9] Zhao X, Tang J, Yu F, Ye N. Preparation of graphene nanoplatelets reinforcing copper matrix composites by electrochemical deposition. Journal of Alloys and Compounds. 2018 Oct 25;766:266-73. doi.org/10.1016/j.jallcom.2018.06.309.

[10] Kotteda TK, Kumar M, Kumar P. Experimental insights and micrographical investigation on graphene nanoplatelet–reinforced aluminum cast composites. The International Journal of Advanced Manufacturing Technology. 2023 Sep 6:1-2. https://doi.org/10.1007/s00170-023-12270-8.

[11] Yang W, Zhao Q, Xin L, Qiao J, Zou J, Shao P, Yu Z, Zhang Q, Wu G. Microstructure and mechanical properties of graphene nanoplates reinforced pure Al matrix composites prepared by pressure infiltration method. Journal of Alloys and Compounds. 2018 Jan 25;732:748-58. doi.org/10.1016/j.jallcom.2017.10.283.

[12] Saha DC, Sripada JV, Saha GC, Jahed H. Microstructure and interfacial bonding evolution of cold spray deposited graphene-reinforced composite feedstock on AZ80 magnesium substrate. Journal of Thermal Spray Technology. 2023 Apr;32(4):984-1001. doi.org/10.1007/s11666-022-01524-8.

[13] Zhou S, Zhang W, Ma S, Yang Y, Ren W, Shi L, Zhou Q, Liu M. Fabricating graphene nanoplatelets/nickel composites of balanced strength and ductility. Materials Chemistry and Physics. 2021 Apr 1;262:124254. doi.org/10.1016/j.matchemphys.2021.124254.

[14] Polayya C, Rao CS, Veeresh Kumar GB, Surakasi R. Synthesis and mechanical properties of graphene nanoparticles reinforced with aluminium alloy matrix composites. Nanotechnology for Environmental Engineering. 2023 Jan 18:1-2. doi.org/10.1007/s41204-022-00305-6.

[15] Kabir H, Munir K, Wen C, Li Y. Microstructures, mechanical and corrosion properties of graphene nanoplatelet–reinforced zinc matrix composites for implant applications. Acta Biomaterialia. 2023 Feb 1;157:701-19. doi.org/10.1016/j.actbio.2022.11.060.

[16] Munir K, Wen C, Li Y. Graphene nanoplatelets-reinforced magnesium metal matrix nanocomposites with superior mechanical and corrosion performance for biomedical applications. Journal of Magnesium and Alloys. 2020 Mar 1;8(1):269-90. doi.org/10.1016/j.jma.2019.12.002.

[17] Lopez JJ, Williams MB, Rushing TW, Confer MP, Ghosh A, Griggs CS, Jordon JB, Thompson GB, Allison PG. A solid-state additive manufacturing method for aluminum-graphene nanoplatelet composites. Materialia. 2022 Jun 1;23:101440. doi.org/10.1016/j.mtla.2022.101440.

[18] Stojanović B, Ivanović L. Application of aluminium hybrid composites in automotive industry. Tehnički vjesnik. 2015 Feb 23;22(1):247-51. doi.org/10.17559/TV-20130905094303.

[19] Kausar A, Ahmad I, Eisa MH, Maaza M. Graphene Nanocomposites in Space Sector—Fundamentals and Advancements. C. 2023 Mar 3;9(1):29. doi.org/10.3390/c9010029.

[20] Wang J, Guo LN, Lin WM, Chen J, Liu CL, Zhang S, Zhen TT. Effect of the graphene content on the microstructures and properties of graphene/aluminum composites. New Carbon Materials. 2019 Jun 1;34(3):275-85. doi.org/10.1016/S1872-5805(19)60016-8.

[21] Cui G, Bi Z, Zhang R, Liu J, Yu X, Li Z. A comprehensive review on graphene-based anti-corrosive coatings. Chemical engineering journal. 2019 Oct 1;373:104-21. doi.org/10.1016/j.cej.2019.05.034.

[22] Knych T, Mamala A, Kwaśniewski P, Kiesiewicz G, Smyrak B, Gniełczyk M, Kawecki A, Korzeń K, Sieja-Smaga E. New graphene composites for power engineering. Materials. 2022 Jan 18;15(3):715. doi.org/10.3390/ma15030715.

[23] Srivyas PD, Charoo MS. Role of reinforcements on the mechanical and tribological behavior of aluminum metal matrix composites–a review. Materials Today: Proceedings. 2018 Jan 1;5(9):20041-53. doi.org/10.1016/j.matpr.2018.06.371.

[24] Md Ali A, Omar MZ, Hashim H, Salleh MS, Mohamed IF. Recent development in graphene-reinforced aluminium matrix composite: A review. Reviews on Advanced Materials Science. 2021 Oct 20;60(1):801-17. doi.org/10.1515/rams-2021-0062.

[25] Sharma A, Sharma VM, Gugaliya A, Rai P, Pal SK, Paul J. Friction stir lap welding of AA6061 aluminium alloy with a graphene interlayer. Materials and Manufacturing Processes. 2020 Feb 17;35(3):258-69. doi.org/10.1080/10426914.2020.1718694.

[26] Xiong B, Liu K, Xiong W, Wu X, Sun J. Strengthening effect induced by interfacial reaction in graphene nanoplatelets reinforced aluminum matrix composites. Journal of Alloys and Compounds. 2020 Dec 10;845:156282. doi.org/10.1016/j.jallcom.2020.156282.

[27] Seyed Pourmand N, Asgharzadeh H. Aluminum matrix composites reinforced with graphene: a review on production, microstructure, and properties. Critical Reviews in Solid State and Materials Sciences. 2020 Jul 3;45(4):289-337. doi.org/10.1080/10408436.2019.1632792.

[28] Li J, Zhang X, Geng L. Effect of heat treatment on interfacial bonding and strengthening efficiency of graphene in GNP/Al composites. Composites Part A: Applied Science and Manufacturing. 2019 Jun 1;121:487-98. doi.org/10.1016/j.compositesa.2019.04.010.

[29] Boostani AF, Yazdani S, Mousavian RT, Tahamtan S, Khosroshahi RA, Wei D, Brabazon D, Xu JZ, Zhang XM, Jiang ZY. Strengthening mechanisms of graphene sheets in aluminium matrix nanocomposites. Materials & Design. 2015 Dec 25;88:983-9. doi.org/10.1016/j.matdes.2015.09.063.

[30] Wang J, Li Z, Fan G, Pan H, Chen Z, Zhang D. Reinforcement with graphene nanosheets in aluminum matrix composites. Scripta Materialia. 2012 Apr 1;66(8):594-7. doi.org/10.1016/j.scriptamat.2012.01.012.

[31] Islam M, Khalid Y, Ahmad I, Almajid AA, Achour A, Dunn TJ, Akram A, Anwar S. Microstructural evaluation of inductively sintered aluminum matrix nanocomposites reinforced with silicon carbide and/or graphene nanoplatelets for tribological applications. Metallurgical and Materials Transactions A. 2018 Jul;49:2963-76. doi.org/10.1007/s11661-018-4625-0.

[32] Wang S, Wei X, Xu J, Hong J, Song X, Yu C, Chen J, Chen X, Lu H. Strengthening and toughening mechanisms in refilled friction stir spot welding of AA2014 aluminum alloy reinforced by graphene nanosheets. Materials & Design. 2020 Jan 15;186:108212. doi.org/10.1016/j.matdes.2019.108212.

[33] Han T, Li J, Zhao N, He C. Microstructure and properties of copper coated graphene nanoplates reinforced Al matrix composites developed by low temperature ball milling. Carbon. 2020 Apr 15;159:311-23. doi.org/10.1016/j.carbon.2019.12.029.

[34] Yu Z, Yang W, Zhou C, Zhang N, Chao Z, Cao Y, Sun Y, Shao P, Wu G. Effect of ball milling time on graphene nanosheets reinforced Al6063 composite fabricated by pressure infiltration method. Carbon. 2019 Jan 1;141:25-39. doi.org/10.1016/j.carbon.2018.09.041.

[35] Zhang S, Chen G, Qu T, Fang G, Bai S, Yan Y, Zhang G, Zhou Z, Shen J, Yao D, Zhang Y. Simultaneously enhancing mechanical properties and electrical conductivity of aluminum by using graphene as the reinforcement. Materials Letters. 2020 Apr 15;265:127440. doi.org/10.1016/j.matlet.2020.127440.

[36] Su J, Teng J. Recent progress in graphene-reinforced aluminum matrix composites. Frontiers of Materials Science. 2021 Mar;15:79-97. doi.org/10.1007/s11706-021-0541-0.

[37] Chu K, Wang XH, Li YB, Huang DJ, Geng ZR, Zhao XL, Liu H, Zhang H. Thermal properties of graphene/metal composites with aligned graphene. Materials & Design. 2018 Feb 15;140:85-94. doi.org/10.1016/j.matdes.2017.11.048.

[38] Dorri Moghadam A, Schultz BF, Ferguson JB, Omrani E, Rohatgi PK, Gupta N. Functional metal matrix composites: self-lubricating, self-healing, and nanocomposites-an outlook. Jom. 2014 Jun;66:872-81. doi.org/10.1007/s11837-014-0948-5.

[39] Ghazaly A, Seif B, Salem HG. Mechanical and tribological properties of AA2124-graphene self lubricating nanocomposite. Light Metals 2013. 2016:411-5. doi.org/10.1007/978-3-319-65136-1_71.

[40] Peddavarapu S, Veerappan AM, Raghuraman S. Tribological study of Graphene reinforced AA6082 surface composite processed through Friction Stir Processing. Materials Today: Proceedings. 2020 Jan 1;27:2225-9. doi.org/10.1016/j.matpr.2019.09.101.

[41] Prabhakar GV, Dumpala L, Ravi Kumar N. Investigating mechanical properties, corrosion resistance and machining characteristics of Al5083-graphene composites produced by friction stir processing. Transactions of the Indian Institute of Metals. 2020 Dec;73:2955-64. doi.org/10.1007/s12666-020-02098-1.

[42] Surekha K, Murty BS, Rao KP. Microstructural characterization and corrosion behavior of multipass friction stir processed AA2219 aluminium alloy. Surface and Coatings Technology. 2008 May 25;202(17):4057-68. doi.org/10.1016/j.surfcoat.2008.02.001.

[43] Zhou W, Mikulova P, Fan Y, Kikuchi K, Nomura N, Kawasaki A. Interfacial reaction induced efficient load transfer in few-layer graphene reinforced Al matrix composites for high-performance conductor. Composites Part B: Engineering. 2019 Jun 15;167:93-9. doi.org/10.1016/j.compositesb.2018.12.018.

[44] Khan M, Din RU, Wadood A, Syed WH, Akhtar S, Aune RE. Effect of graphene nanoplatelets on the physical and mechanical properties of Al6061 in fabricated and T6 thermal conditions. Journal of Alloys and Compounds. 2019 Jun 25;790:1076-91. doi.org/10.1016/j.jallcom.2019.03.222.

[45] Jiang Y, Tan Z, Fan G, Zhang Z, Xiong DB, Guo Q, Li Z, Zhang D. Nucleation and growth mechanisms of interfacial carbide in graphene nanosheet/Al composites. Carbon. 2020 May 1;161:17-24. doi.org/10.1016/j.carbon.2020.01.032.

[46] Li JL, Xiong YC, Wang XD, Yan SJ, Yang C, He WW, Chen JZ, Wang SQ, Zhang XY, Dai SL. Microstructure and tensile properties of bulk nanostructured aluminum/graphene composites prepared via cryomilling. Materials Science and Engineering: A. 2015 Feb 25;626:400-5. doi.org/10.1016/j.msea.2014.12.102.

[47] Rashad M, Pan F, Tang A, Asif M. Effect of graphene nanoplatelets addition on mechanical properties of pure aluminum using a semi-powder method. Progress in Natural Science: Materials International. 2014 Apr 1;24(2):101-8. doi.org/10.1016/j.pnsc.2014.03.012.

[48] Ju B, Yang W, Shao P, Hussain M, Zhang Q, Xiu Z, Hou X, Qiao J, Wu G. Effect of interfacial microstructure on the mechanical properties of GNPs/Al composites. Carbon. 2020 Jun 1;162:346-55. doi.org/10.1016/j.carbon.2020.02.069.

[49] Baig Z, Mamat O, Mustapha M, Mumtaz A, Sarfraz M, Haider S. An efficient approach to address issues of graphene nanoplatelets (GNPs) incorporation in aluminium powders and their compaction behaviour. Metals. 2018 Jan 25;8(2):90. doi.org/10.3390/met8020090.