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A General View of Graphene Reinforcements on Metal Matrix Composites (GR-MMC)

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Abstract:- Aluminum, magnesium, copper, iron, and other metals and alloys are utilised as matrix materials in composites, and each of these composites has a particular set of characteristics depending on the materials used for reinforcement. The strongest substance that has been tested to far, graphene, will significantly alter the material nature of composites. In this review work, several metal matrix composites incorporating graphene as a reinforcing material are thoroughly compared.

Keywords:- *Graphene, Metal Matrix Materials, Composites, Reinforcement Materials.*

I. INTRODUCTION

Development of improved composites for engineering and functional devices was made possible by advances in nanotechnology. Composite materials have distinctive, important, and diverse features. They have the unique mechanical, chemical, and physical characteristics. Graphene, strongest material with wear resisting property, high hardness and nature of lubricance [1]. This substance possesses a stunning mechanical strength, thermal conductivity, electrical conductivity, and a sizable specific surface area [2].

Metals, alloys are used as matrix for composite which give rise to metal matrix composite, application of different metals / alloys with graphene are done frequently due to outstanding results of graphene composition. Hence graphene as reinforcement material and different metals (Al, Cu, Ni, Mg, Fe) as matrix material, several composites are surveyed in a generalised view of characterisation in this work.

II. COMPOSITION

A. Graphene-reinforced Al matrix composites

A typical reason for this is that aluminium has expanding features including a high specific modulus, light weight, high strength, strong wear resistance, and a low thermal expansion coefficient. [3]. The multiple research initiatives to utilise the flexibility and high strength of Graphene Nanoplatelets (GNPs) without significantly sacrificing the natural ductility of Aluminium (Al) are driven by the desire to increase the strength of Al.

In most cases, powder metallurgy methods are used to create Al-GNP composites. For such methods, either mechanical agitation [4]/ ultrasonication [5, 6] are used to create mixed powders of GNP and Al. After that, the powder is condensed using high-temperature techniques like sintering or hot extrusion. Mechanical alloying [7-9], hot extrusion [10, 11], hot rolling [12], friction stir process [13, 14] , and other novel methods [15, 16] are included in these composite design and manufacturing process.

B. Graphene-reinforced Cu matrix composites

The relatively large disparity in density between the matrix and reinforcement phase makes it difficult to disperse graphene in copper matrix. The complex behaviour of the resulting composite is caused by the high interfacial contact area of graphene and the mismatch in thermal conductivities [3]. Due to the non-homogeneous distribution of multilayer graphene in the copper matrix, multilayer graphene copper nanocomposites with flake powder metallurgy, sintering, and the composite produced decreased density, enhanced hardness, and increased electrical conductivity [17]. Excellent electrical and thermal conductivity, low thermal expansion coefficient, superior lubricating property, and better mechanical qualities are all features of copper graphene composites [18, 19].

According to certain authors' investigations on bulk Cu-GNP composites [20, 21, 22], the observed density was 98 percent of the theoretical density [20, 23]. Since GNPs prefer to aggregate at greater volume fractions, it is observed that the relative density of compacts falls as a function of GNP[20]. After sintering, the GNP structure is unchanged according to the Raman spectra. However, Raman spectra show that after balling milling Cu-GNP powders, GNP flaws increased. The layers and sides of GNPs frequently distort, cold weld, and fracture during ball milling [20, 21, 23]. Peak broadening of XRD data showed that the Cu matrix grain refining occurred during ball milling [20]. No observable oxide or carbide generation has been found [20, 21]. With GNP concentrations of 8 volume percent, improvements in hardness, and Young's modulus (E) of Cu-GNP composite was noticed [20, 21, 22, 23]. Subsequent rises in GNP percentage lead to accumulation, which reduced the mechanical characteristics and caused porosity or flaws.

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C. Graphene-reinforced Mg matrix composites

The earth's crust has the eighth-highest amount of magnesium (Mg). Effects of graphene on Mg metal matrix and the consistent distribution of multilayer graphene in the matrix that tends to enhance mechanical characteristics [24]. Mg is one of the lightest metals utilised in structural applications. Due to its inferior strength, resistance to abrasion, and ductility when compared to other structural metals, it has a small number of uses. In order to ensure the conservation of other important physical features, it is therefore desirable to construct composites using reinforcements that can improve mechanical properties at low volume fractions.

By incorporating GNPs into the Mg matrix either by ball milling in liquid environments [25] or wet chemical methods [26,27], researchers have sought to synthesise Mg-GNP composites. Mg-GNP composites have been effectively created via slurry mixing [26,27], liquid state ultrasonic processing [25], or ball milling and SPS [28]. After sintering, Mg-GNP composites created using powder metallurgy methods reached a significant relative density of 97-99 percent [26,29,25,27], which is attributable to the easier atom diffusion at high sintering temperatures (about 450°C). The compaction attained in the Mg-GNP composite was up to 2% higher than pure Mg. This could be because graphene has higher thermal and electrical conductivity, which could lead to better heat transfer. Phase analysis shows that Mg and GNP are mostly present, with some instances showing signs of oxide generation [29]. However, no investigations have documented carbide production in this combination of materials. Combining liquid state ultrasonication and solid state stirring was used to produce this Mg-GNP compound [25]. The interface appears to be devoid of voids or reaction products, indicating that GNPs have been successfully incorporated into the Mg matrix [25]. The majority of the lack of flaws and excellent bonding between GNPs and [29], Mg-GNP composites synthesised by wet chemical techniques are revealed by microstructural analysis. With one research by Rashad et al. [26] reporting a considerable number of micropores in the Mg-GNP as the exception. Some Mg-GNP composites have shown oxidation-related sintering symptoms. Additionally, it was discovered that GNPs pin grains, improving the grain structure [26, 27]. Due to the unequal distribution of GNPs in the Mg matrix, the decrease in grain size is not uniform. GNPs frequently align along the extrusion direction when using directional processing methods like extrusion [26, 27]. Overall, the addition of GNPs is observed to increase the mechanical characteristics of magnesium. With a 2 volume percent GNP reinforcement, hardness increased by up to 78 percent.

D. Graphene-reinforced Fe matrix composites

Iron (Fe) matrix composites with graphene reinforcement have only received one attempt thus far. Laser sintering was used to create iron composites with graphene oxide (GO) reinforcement. The surface microhardness of the 2 wt-% laser sintered material When compared to the base material, the GO composite had an increase of 93.5 percent, or 600 HV. It was talked about the strengthening mechanism. Investigations into the GO-iron interfacial structure were conducted; the study documented cementite development and offered theoretical analysis as well as conclusive evidence of cementite production [30] Schematic view of GO–Fe nanocomposite layer on steel is shown in Figure 1.

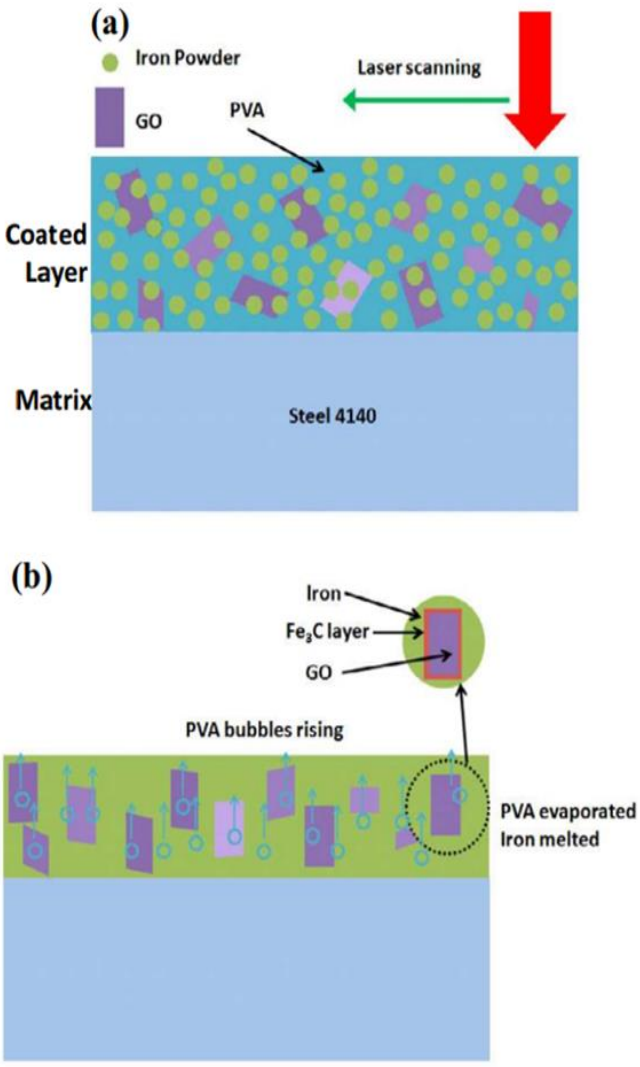

Fig 1 : Schematic cross-sectional view of GO–Fe nanocomposite layer on steel 4140 (a) after coating and (b) after laser sintering [30].

III. FABRICATION ROUTES

A. Processing and graphene dispersing techniques

Graphene-reinforced Metal Matrix Composites (GR-MMC) have been manufactured using a range of handling methods, according to the articles that have been published. M ajority of processing methods utilised to create Carbon NanoTube-reinforced MMCs may also be employed to create GR- MMCs. However, powder metallurgy, melting and solidification, and electrochemical deposition were the main methods documented for processing GR-MMCs. Processing GR-MMCs often presents challenges with homogenous graphene dispersion in metal matrix, porosity brought on by graphene dispersion, and high processing temperature [31]. (Sintering /melting process). Therefore, dispersing graphene

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evenly in metal matrix is crucial for obtaining good GR-MMCs.

B. Powder metallurgy techniques

The majority of the Al, Cu, and Mg composites with graphene reinforcement were created utilising the powder metallurgy approach. The three phases of this manufacturing method are typically combining graphene with the metal powder, compacting, and sintering. Compacting may occasionally be carried out in tandem with another stage or in a single step.

Several articles [10, 32, 33, 34] described the use of this processing approach with various graphene dispersion techniques for Al matrix composites. The majority of them claimed to have used ball milling to mix graphene with metal powder. The Al powder and graphene were physically blended with graphene for 5 minutes before being subjected to an hour-long ball milling operation with 2 weight percent stearic acid. After that, it was condensed at 375°C for 20 minutes using instrumented hot isostatic pressing (I-HIP) [10]. The billets were then extruded after being warmed to 550°C for 4 hours. Similar to how the graphene dispersion process was different, graphene and Al-Mg-Cu powder were combined with ethanol before being ball milled [32]. This ball milling technique was also employed in another study to mix graphene with powdered aluminium alloy. However, they employed a two-step consolidation procedure, first performing a pre-compaction under 50 MPa at ambient temperature, and then hot pressing the material for 10 minutes at 100 MPa at 630°C. Approximately 18% of the product was liquid at this temperature. [33, 35] There was no extrusion stage. A comparable study but one that employed a different dispersal technique. Ball milling was used to create the aluminium flakes, which were then modified with 3 weight percent PVA. GO and the modified aluminium flakes were then combined with deionized water, and the mixture was stirred to ensure homogeneity. The GO/Al powder was then heated to create dry GNS/Al composite powder [36]. Another study created composites using hot extrusion after dispersing graphene using the cryo-milling method. Ball milling was said to be capable of evenly dispersing graphene in matrix particles. The length of the ball milling process is crucial. According to reports, greater milling times resulted in smaller graphene and larger matrix particle sizes. After ball milling, the amount of disordering and flaws in graphene increased. Longer ball milling times led to more uniform graphene dispersion in the matrix, which improved the mechanical performance of the corresponding composites [34, 37] Schematic view of SPS sintered Ni -GNS reinforced Al-GNP composites si shown in Figure 2.

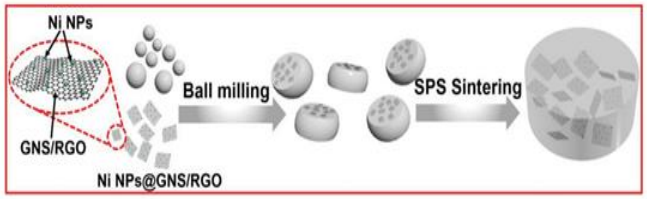

Fig 2 : Schematic diagram of the detailed processes for preparing Ni -GNS reinforced Al-GNP composites [37]

In order to disperse graphene in Cu powder, rolling is employed to create Cu matrix composites. Graphene and Cu powder are combined in ethanol, vibrated for an hour, and then subjected to a 4-hour ball milling process. It was then degassed at 673 K for an hour. A two-step rolling procedure was then used, starting with equal speed rolling and ending with high-ratio differential speed rolling. It was claimed that the sample produced via high-ratio differential speed rolling had improved mechanical characteristics. The composites were made with the aid of SPS. Once more, the graphene dispersion, a molecular level mixing process, made the difference. The crucial step included joining the functional groups of the GOs and the Cu ions to establish chemical bonds, which were subsequently reduced jointly to produce the Cu-graphene composite powder [38]. The two other studies described a procedure that was substantially similar. It was claimed that GNPs decorated with Ni nanoparticles offer an effective means of resolving graphene separation issues because the Ni nanoparticles can serve as a spacer to prevent graphene aggregation. Improvements in the mechanical characteristics of the comparable composites were reported in both articles [39]. By vacuum uniaxially hot pressing combinations of powders from a ball mill, graphene-reinforced Cu matrix composites were created [40, 41].

C. Electrochemical deposition

By electroless Nickel (Ni) plating, composites of Ni and graphene are created. They created Ni/graphene composites by stirring and carefully regulating the reaction conditions while mixing graphite, $NiSO_46H_2O$, and $NaBH_4$ in the appropriate ratio. Because there was no compacting technique used, the composite has a porous structure. The electrodeposition procedure was described in the other two articles on Ni/graphene composites [42]. GO was dispersed in a solution of $Ni(NH_2SO_3)_2$, H_3BO_3, and Cl_2 in water. The temperature was held at 55°C while the co-deposition process was run at a current density of 5 A dm^2. During the electrodeposition procedure, the solution was agitated using magnetic stirring [43]. To ensure that the graphene was distributed uniformly, Koltsova et al. used a different technique. By using CVD, they directly deposited graphene on the Cu particle surface. To get the compressed samples, they employed two-stage rolling (with an interim 900°C annealing) [44, 45] Schematic representation of Cu–gr composite is shown in Figure 3.

The bath solution's ingredients were altered, but the technique was impleted as before. Graphene $NiSO_4$ and Na_2SO_4 were employed in place of GO, $Ni(NH_2SO_3)_24H_2O$, and $NiCl_26H_2O$. Changed to 1 A dm^2 and 40 °C, respectively, for the solution's current density and temperature. Both of them reported improvements in hardness after successfully fabricating Ni/graphene composite. The fabrication of Cu/graphene composites using electrochemical deposition has received a lot of attention [46]. Cu/graphene composites are synthesised using a novel electrochemical technique termed PRED. Reverse pulses were believed to be able to distribute graphene evenly throughout the matrix and provide a better contact with copper [47]. Similar manufacturing method, but without the usage of reverse pulses. They concentrated their study on the thermal and electrical

characteristics. With practically minimal damage to graphene sheets, the electrochemical deposition technique may provide a highly uniform dispersion of graphene in the matrix [48]. Another benefit is that during manufacture, it may convert GO to graphene [47, 43].

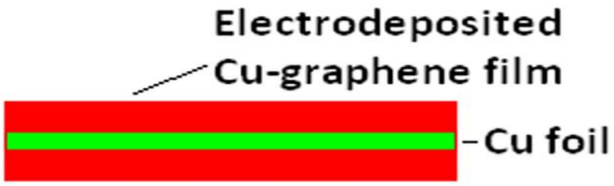

Fig 3 : Schematic representation of the Cu foil in the middle with thickness 135 lm and the Cu–gr composite film deposited outside [45].

D. Melting and solidification

Typical MMC fabrication techniques include melting and solidification. Stir casting was a common fabrication method for graphene-reinforced MMCs, but the melting and solidification method presents challenges for particulate-reinforced MMCs. Because graphene is so light, it can float on the top of liquid metal with ease. This has two detrimental impacts as a result. Firstly, graphene is easily able to aggregate due to its huge surface area and high surface energy, and secondly, graphene will be destroyed by the high temperature of melting metals. Only a few articles have so far documented the synthesis of Mg matrix graphene composites utilising melting and solidification processes [49, 14] Schematic process procedure for liquid state ultrasonic process in obtain graphene nanoplatelets reinforced metal matrix nanocomposites shown in Figure 4. The melting and solidification processes were actually only a small portion of the overall fabrication process, the research claims. To create the Mg/graphene composite plates, molten magnesium was mixed with graphene using an ultrasonic method, and the resulting slurry was then poured into a plate mould. The composite plates were given a solid state stir to better the dispersion of graphene in the composites. Al matrix composites were later reported to be manufactured via different fraction stir procedures [50, 51]. On the metal matrix's surface, the GO/water colloid was evidently applied directly. At the point where the revolving tool meets the Al matrix, it has been claimed that the water in the colloidal suspension evaporates nearly immediately.

The fabrication of graphene-reinforced MMCs by melting and solidification was also described. They first created Cu-decorated graphene, which they then mechanically stirred into molten aluminium. The graphene-reinforced MMCs were abricated after solidification. Cu-decorated graphene is easily coupled with the Al matrix due to Cu's strong wetability with the Al matrix, and when compared to pure graphene, Cu-decorated graphene was easier to disperse in liquid Al [52]. Another attempt at melting and solidification was done by combining PVA, GO, iron powder, and deionized water while utilising PVA as the dispersion agent. It was stirred using magnetic stirring [53]. The steel 4140 substrate was then coated with the solution. The sample surface was scanned with a laser beam using the correct technical conditions after the coating layer had sufficiently dried. The GO was able to endure the melting and solidification processes because to laser sintering, which involves fast heating and cooling. In fact, a very encouraging outcome was seen; the composites now contain GO uniformly, and their mechanical characteristics have improved [53].

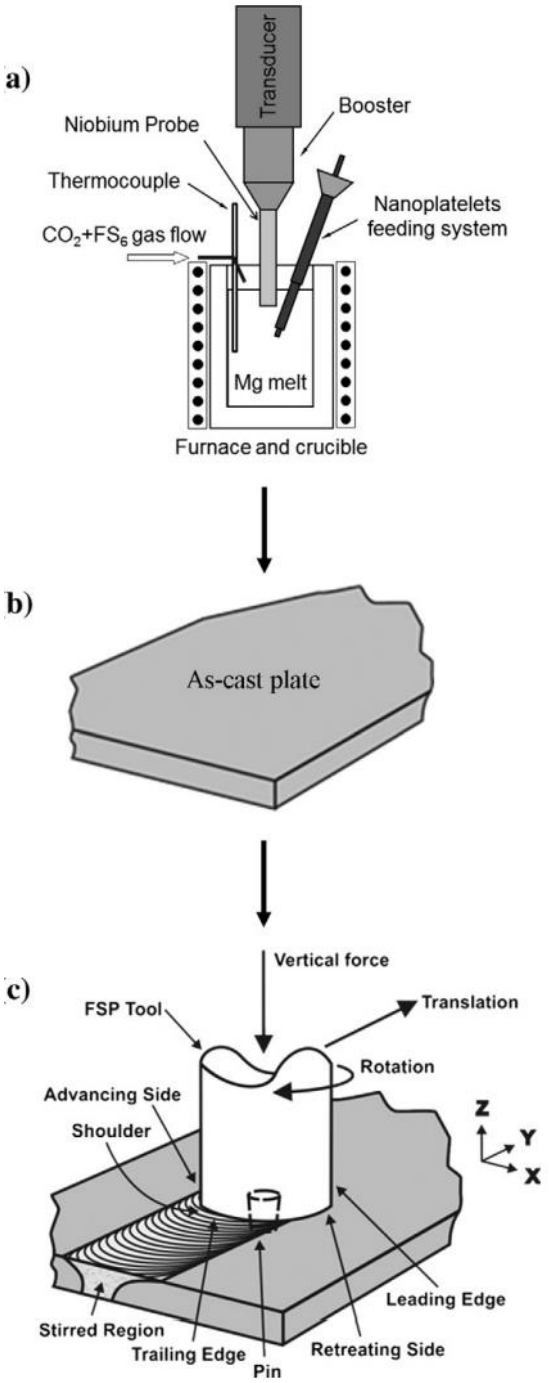

Fig 4: Schematic process procedure for liquid state ultrasonic process in obtain graphene nanoplatelets reinforced metal matrix nanocomposites [49].

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E. Other techniques

There have been attempts to create graphene reinforced MMCs using techniques other than those discussed above. An approach was to fabricate graphene-reinforced MMCs by alternately layering graphene and metal in a sandwich shape [54, 55]. The Cu substrate was first covered with GO, and then, using laser pulse vapour deposition, Cu was added to the GO (LPVD). To lessen GO transfer to graphene, this was then heated in a safe environment. To create multilayered composites, this was performed numerous times [54]. Another method of fabrication; it first created a porous Cu structure resembling firewood, filled the holes with graphene oxide (GO), and then used heat pressing to produce the final composites. The test findings were rather positive, as was already said. That proves that this processing method worked. In the future, there will be further conventional procedures or cutting-edge methods. Graphene and CNT may both be used to strengthen MMCs. It follows naturally that the processing methods utilised to create CNT composites should also work well to create composites of graphene. Other methods include thermal spray, which was particularly effective in creating the CNT composite [56, 57]. In order to heat the green compacted Al2O3/TiC/GPLs samples at low temperatures and prevent oxidation, silicon carbide and graphite powder were added to the powder bed. The experiment was then carried out in a 2.45 GHz microwave furnace with a power output of 0–6 kW. Sintering of the samples was place in a high-purity argon environment at 1700 °C for 10 minutes while being held at that temperature. The samples that had been sintered were then cooled to room temperature [58].

IV. CHARACTERISATION

A. Mechanical behaviour of graphene–metal composites

To increase mechanical qualities including tensile strength, young's modulus, and hardness, graphene is mostly added to MMCs. The production method, graphene content, dispersion, and particle shape are just a few of the variables that affect how the characteristics may be improved. The effectiveness of stress transmission or strengthening is governed by the dispersion of the reinforcement phase, carbide formation, and interfacial interactions, which are all influenced by manufacturing procedures in addition to the degree of consolidation. Tensile/compressive strength, yield strength, elastic modulus, hardness, and flexural strength are the main mechanical parameters covered in all of the GNP-MMC investigations that have been published to yet. Only a few recent research have put forth micromechanical models to forecast how GNP reinforced composites would behave when subjected to mechanical loadings, comparing experimental results to theoretical forecasts. In several Cu, Al, and Mg matrices reinforced with graphene, the impact of GNP addition on Ultimate Tensile Strength (UTS), Yield Strength (Y-S), E, and failure strain has been thoroughly investigated [12, 11, 22, 25, 59]. With a maximum improvement of up to 117 percent of Y-S [29], 131 percent in E [60], 68 percent of UTS [27], and up to 84 percent in ductility [15], the majority of experiments utilised very modest quantities of GNP (8 present of volume). Due of the difficulties in homogenously spreading GNPs, which results in inferior mechanical characteristics, the low GNP concentration was recommended. Although several new fabrication methods have been created in recent years to address this issue, GNP-MMCs have not shown a substantial improvement in GNP dispersion, particularly at increasing volume fractions. Additionally, despite utilising compositions that are identical, different groups have observed a variety of features. Such variances indicate the improvement in elastic modulus in various MMCs as a function of GNP content and may be attributed mostly to changes in processing procedures or parameters and the variable morphologies of the synthesised composite GNP/metal powders. Mg-GNP was the subject of most investigations on elastic moduli. Due to its low elastic modulus, magnesium might considerably benefit from graphene's orders-of-magnitude greater elastic modulus. With the exception of a few findings on UTS, it is usually claimed that adding GNPs improves all of the mechanical characteristics of GNP-MMCs. In one such work, the Al-GNP composite was treated via ball milling, hot extrusion, and lower strength was found to be caused by the creation of Al4C3 at the Al-GNP interface, which was thought to be aided by the wrinkled morphology and flaws present in thermally reduced GNPs [10]. In almost all the trials, the failure strain decreased as strength rose. Given that the majority of strengthening processes in GNP reinforced MMC result in either dislocation pile up or increased dislocation density, which causes strain hardening and decreased ductility, it is to be anticipated. There is a limiting content of GNP for improving qualities, above which a considerable switch-over is detected, according to a general pattern shown for all mechanical properties. Such behaviour can be explained by the high concentration of GNPs that aggregate to form flaws that concentrate stress. Such agglomerates encourage the creation of pores and the beginning of microcracks. Except for one work on Mg-GNP composites treated by ball milling and SPS [28], the literature to date suggests that adding GNP to various metal matrices enhanced the compressive strength. Figure 2 shows SEM micrographs of Mg-GNP composites that broke during compression and exhibit shear lines at 45° angles to the loading axis. Compared to pure Mg, the fracture surfaces of Mg-GNP were rougher. Micro-voids and microcracks that were present as a result of inadequate GNP dispersion and poor interfaces with the metal matrix led to decreased strength.

It's interesting to note that the same study [61] found that GNP content rises with larger relative density, which is contradictory with the microstructure and mechanical characteristics shown. Less porosity is indicated by higher relative density, which should result in greater strength, but this was not the case in the research in question [61]. GNP addition often results in increased compressive strength. GNPs take up space between matrix particles, which makes dislocation movement more challenging [61,62,26,29]. The flexural characteristics of GNP reinforced MMCs have only been the subject of one publication. For Al-1.28 vol.-percent GNP composites synthesised through the powder processing technique, flexural strength is reported as a function of various milling times [8]. The composite is weaker than pure Al alloy at a shorter milling time of 10 minutes. This shows that not enough GNPs were properly dispersed throughout the

milling process. A 50 percent increase in strength was recorded for milling times longer than one hour, which was attributed to more effective GNP reinforcement due to greater homogeneity and higher strain hardening. Consolidated

Fabrication and mechanical properties of GNP–MMC is shown in Table 1.

Table 1: Fabrication and mechanical properties of GNP–MMCs.

Composition	Fabrication routes	Mechanical properties	Ref.
Al– GNP			
Al–0.13 vol.-% GNP	Al powder and GNP were blended, milled, pressed and then hot extruded at 550 °C. The pure Al was also processed in the same manner	Improvement in hardness 19.2% in as pressed condition but decreased by 14.2% after extrusion. Reduction in UTS 24% failure strain 55% with 0.13 vol.-% GNP	[10]
Al–0.39 vol.-% GNP	Al powder was ball milled – treated with PVA – added to deionised water to form slurry. GO solution was prepared and added to Al slurry – filtered and dried at 550°C in Ar atm. for 2 h to form GNP – compacted and sintered at 580°C – hot extrusion at 440°C	Improvement in UTS 62% Reduction in failure strain 51% with 0.39 vol.-% G+NP	[11]
Al–x vol.-% GNP (x = 0, 1.28, 3.82, 6.34)	GNP was dispersed in acetone - slowly added into Al slurry in acetone and mixed for 1h – filtered, dried and compacted at 500 MPa for 5 min – sintered at 400, 500 and 600°C for 5h	Improvement in ● compressive strength – 22% ● hardness ~ 34% ● with 6.34 vol.-% GNP	[14]
Al–1.28 vol.-% GNP	Al powder and GNP were mixed and ball milled. The powder was then compacted in two stages first pre-compaction at 50 MPa and then hot pressed at 100 MPa for 10 min.	Improvement in flexural strength ~ 47% with 1.28 vol.-% GNP and 60 min milling	[8]
Al-GNP	GO/water colloid directly applied to the surface of Al sheet – friction stir processing – water evaporates, GO gets reduced to GNP and gets dispersed.	Reduction in UTS ~ 12% while improvement in failure strain ~50.5% with GNP addition	[13]
Al–0.39 vol.-% GNP	Al powder dissolved in acetone and mechanically agitated while GNP ultrasonicated in acetone – both mixed and mechanically agitated together – mixture is filtered and vacuum dried overnight at 70°C – the powder is compacted, sintered at 600°C and hot extruded at 470°C	Improvement in ● Tensile YS ~14.7%, UTS ~ 11.1%,Hardness ~11.8%. ● Reduction in failure strain ~ 28.8%. ● Reduction in compression mode UCS ~ 7.8% failure strain ~16.8% with 0.39 vol.-% GNP	[6]
Al–x vol.-% GNP (x = 0.32, 0.64 and 1.28)	Al powder and GNP was ball milled for 1, 3 and 5 h – compacted at 950 MPa – sintered in Ar atmosphere for 0.5, 1, 2, 3, 4 and 5 h at 500°C	Improvement in hardness ~138% with 1.28 vol.-% GNP for 5 h milling and 3 h sintering	[7]
Al–x vol.-% GNP (0.3, 0.5 and 0.7)	Al powder and GNP was ball milled–milled powder was containerised in Cu tube – compacted – hot rolled at 500°C	Improvement in YS ~ 75% with 0.7 vol.-% GNP over pure Al (milled)	[12]
Al–x vol.-% GNP (0.64, 1.28, 1.92 and 2.56)	Al powder and GNP were mechanically mixed in blender for 24 h – blended powder was cryomilled for 2 h and finally degassed – hot extruded at 300°C – annealed at same temperature for 2 h	Improvement in YS ~ 55.2%, UTS ~ 68%, Reduction in failure strain ~ 52% with 1.28 vol.-% GNP	[9]

Al–3 vol.-% SiC–1 vol.-% GNP	SiC and GNP powder was ball milled for 0.5 h – Al was added and mixture milled – mixture added to molten Al – brought to 605°C and stirred	Improvement in YS ~ 45%, UTS ~ 54%, Failure strain ~ 84% with 1 vol.-% GNP addition	[21]
Cu– GNP			
Cu–x vol.-% GNP (0, 3, 5, 8 and 12	Ball milling of GNP and Cu for 3 h in presence of argon and petroleum ether – hot pressing and sintering at 800°C for 15 min and pressure of 40 MPa	Improvement in YS ~114% E ~37% with 8 vol.-% GNP	[20]
Cu–x vol.-% GNP (4.11 and 7.98)	Ball milling of Cu and GNP powder for 5 h – hot pressed at 510°C at 10−2 bar vacuum	Improvement in hardness is 48% higher for finer GNP than coarser with 7.98 vol.-% GNP	[15]
Cu–x vol. % GNP (0.5 and 1)	Cu and GNP mixed in ethanol and ultrasonicated at frequency of 10 kHz for 1 h – dried and ball milled for 4 h under argon atmosphere – high-ratio differential speed rolling	Improvement in YS ~14.7% UTS ~10.7% strain hardening exponent ~ 71% Reduction in failure strain ~ 34.6% with 1 vol.-% GNP	[23]
Cu–Ni/GNP (1 vol.-%)	GO prepared from graphite powder by modified Hummers method – GO , $NiSO_4 \cdot 6H_2O$) and DI water were mixed and sonicated for $N_2H_4 \cdot H_2O$ was slowly added under by adjusting pH 10.5, precipitated through centrifugation, filtered and dried – Ni–GNP/Cu was sonicated in ethanol – dried and consolidated by SPS at 580°C for 2 min at 50 MPa	Improvement in E ~61% · YS ~ 94% · TS ~ 39% · Reduction in failure strain ~ 63% with 1 vol.-% GNP	[22]
Mg– GNP			
Mg–0.64Al–0.24Sn–0.15 vol.-% GNP	Mg powder dissolved in ethanol with Al and Sn is agitated in GNP ultrasonicated in ethanol – mixture is filtered and dried overnight at 70°C – then compacted, sintered at 630°C and extruded at 350°C	Improvement in · YS ~ 29.2% · UTS ~ 14% · Reduction in failure strain ~34.7% with 0.15 vol.-% GNP	[70]
Mg-0.64 Al-0.5 vol.-% GNP	Mg powder dissolved in ethanol with 0.64 vol.-% Al and mechanically agitated while GNP ultrasonicated in ethanol – the mixture is filtered and vacuum dried overnight at 70°C – the powder is compacted, sintered at 630°C and hot extruded at 350°C	Improvement in tension mode ● E ~ 34.3%, YS ~ 31.6%, UTS ~31.1%, Hardness ~26%, Reduction in failure strain ~ 42% Improvement compression mode ● E ~ 52%, YS ~ 130%, UCS ~ 8% ● Reduction in failure strain ~ 27.7% with 0.5 vol.% GNP (Mg– 0.64Al–0.5 vol.%), as compared to Mg–0.64 vol.% Al	[26]
Mg–0.20 Cu–x vol.-% GNP (0.15, 0.30 and 0.45)	Mg powder dissolved in ethanol along with 0.20 vol.-% Cu and mechanically agitated while GNP ultrasonicated in ethanol – the mixture is filtered and vacuum dried overnight at 70°C – the powder is compacted at 600 MPa, sintered at 630°C & hot extruded at 350°	Improvement in tension mode ● E ~ 89%, YS ~ 117%, UTS – 58.5% ● Hardness ~ 41.75%Reduction in failure strain ~ 29.2%. Improvement compression mode ● E ~ 22.2%, YS ~ 35%, UCS ~ 59% failure strain ~ 61.1% with 0.45 vol.% GNP as Compared to pure Mg	[29]

Mg–0.64Al–x vol.-% GNP (x = 0.07, 0.15 and 0.30)	Mg powder dissolved in ethanol along with Al and agitated while GNP ultrasonicated in ethanol –the mixture is filtered and vacuum dried overnight at 70°C – powder is compacted, sintered at 630°C and hot extruded at 350°C	Improvement in ● Hardness ∼34% ● E ∼ 131% ● YS ∼50% failure strain ∼ 74.2% with 0.3 vol.-% GNP	[60]
Mg–x vol.-% GNP (1, 2 and 5)	Ball milling for 15 min at 350 rev min−1 – pre-pressed at 5 MPa – sintered at 450°C, 50 MPa	Improvement in hardness ∼ 37% Reduction in compressive strength ∼8.6% with 2 vol.-% GNP	[61]
Mg–1.2 vol.-% GNP	GNP dispersed in Mg at 700°C through ultrasonication – the melt is casted into plate – friction stir processing to improve dispersion further	Improvement in hardness ∼ 78% with 1.2 vol.-% GNP	[25]

B. Tribological behaviour of metal–GNP composite

A prevalent issue is mechanical failure caused by wear and friction of moving or rubbing elements of components. Because they are chemically inert, have great strength, and may readily shear due to their layered structure held together by weak van der Waals connections, GNPs can be used as a solid or liquid lubricant. Regular liquid or solid state lubricants must be replaced since they deplete rather fast. Due to their limited thickness, conventional lubricants are also susceptible to the working environment and loading circumstances. In order to provide continuous lubrication while in use and when the material gradually wears down, GNP-MMCs have a supply of solid state lubricant that may be discharged in situ.The impact of GNPs on tribological behaviour was explored in a research on Mg-GNP [61]. For Mg and Mg-GNP, the wear test was conducted against an alumina counter body (with 1, 2 and 5 volume percent of GNP). The depth and width of the Mg-5 vol.-% GNP wear tracks were reduced by 40 and 60 percent, respectively, according to the 3D surface profiles. With 5 volume percent GNP, material buildup at the worn track's margins was also decreased by around 65 percent, showing lessened plastic deformation. Between Mg and Mg-GNP, there were no discernible variations in the coefficient of friction (COF) [61]. The wear track of the composite surface also exhibits traces of exposed GNP. When Mg comes into touch with a moisture-containing environment, it oxidises owing to frictional heat and turns into a hydroxide. The alumina counter surface becomes worn as a result of these oxides, producing oxide debris that acts as third-body abrasive particles and exacerbates abrasive wear. Due to their superior shear qualities, pulled out GNPs on the worn track operate as solid state lubricants in the case of Mg- GNP, decreasing wear [61]. Due to their outstanding qualities, including low density, strength retention, and dimensional stability at high temperatures, intermetallics have attracted a lot of interest for structural applications. Intermetallics' poor performance in terms of friction and wear is one of its drawbacks, though. Because of this, GNPs have lately been employed to strengthen and improve the wear performance of composites made of TiAl [63-65] and Ni_3Al [66,67,68,69] intermetallic materials. Simple ultrasonic or mechanical mixing [65, 68, 69] or a combination [63,64] for dispersion is utilised for the construction of intermetallic-GNP composites, which is then followed by consolidation through SPS [66, 69].

Under room temperature, the tribological characteristics were examined using a variety of counter surfaces, including Al_2O_3, GCr15 steel, WC-6Co, and Si_3N_4 [66, 64, 68], at various loads [65], and at temperatures ranging from 100 to 700 °C [69]. When TiAl/GNP composites and Ni_3Al-GNP composites were put through wear testing, it was discovered that the wear behaviour varied depending on the type of counter surface material used [64, 68]. It was observed that when the counter surface's hardness decreased, COF and wear rate did as well. Three body abrasive wear and micro-plowing from chipping or delamination were the predominant wear mechanisms. With various counter surface materials at room temperature, GNP reinforcement decreased the COF by 0.5–0.6 times and the wear rate by around 3–11 times for TiAl and NiAl [63, 68]. Due to the superior lubricating capabilities of GNP up to 550°C, GNP reinforced composites demonstrated decreased COF and wear rate when compared to the base material [63, 64]. Due to GNP oxidation at 600°C, COF and wear rate sharply did rise and exceeded that of the base material [63, 69]. Microhardness testing further demonstrated that GNPs cause the worn track to become harder as a result of work hardening that occurs during the sliding test [66, 70]. Greater wear resistance often directly correlates with higher hardness.

V. SUMMARY

A composite with strong and exceptional mechanical and other characteristics will result from the reinforcement of graphene on a metal matrix. There are several challenges and limitations in producing and processing this sort of composite, despite the widespread use of graphene reinforcement. These limitations, benifits and challenges that this survey highlighted are as follows:

- Improving mechanical and functional qualities, one must be aware of the ideal GNP lateral dimensions and thickness. Additionally, even with the most efficient methods, control of GNP dimensions is not now totally possible. Ball milling, which decreases GNP dimensions, was used to reduce GNP in the majority of cases.
- Ensured uniform dispersion and structural retention/control of GNPs, more advancements in composite powder mixing procedures are required. There are efforts being made to create graphene coated nanoparticles with layers and coverage. The usage of

graphene-coated nanoparticles might increase the problem of dispersion and enable the role of GPL thickness, both of which need to be thoroughly explored before a decision is taken.

- The development of various interface types will make it possible for processing methods to engineer and control interfaces. A measurable technique is required to assess interfacial strength and ascertain which is most desirable for metal composite systems from an application standpoint, even while the overall features of the desired interfaces are known, i.e., not too strong/brittle or weak.
- The sorts of interface design also depend on a better comprehension of the mechanisms that reinforce and toughen the GNP. Despite being challenging to scale, molecular mixing methods have produced microstructures where GNPs may concurrently offer strengthening and toughening. Even though the molecular mixing technique has many benefits, it is typically used to create ceramic-type composites, and these mechanisms are necessary to create composite microstructures that are suitable for a variety of applications.
- The study of the tribological performance of GNP reinforced metal is still in its early phases, and some of the early papers have produced contradictory findings. According to the encouraging investigations, the development of a lubricating and protecting tribofilm is essential for preventing sliding wear. To further characterise the film and regulate its onset, more research is needed to comprehend the creation process of this tribofilm.
- Due to the fact that GNPs are often located at grain borders in GNP-MMCs, the number of grain boundaries and, consequently, the size of the grains, have a substantial impact on the reinforcing effects and matrix-reinforcement interactions. Further research into the ideal grain sizes for metal composites is necessary, taking into account the effects of GNPs on the processing-induced microstructural development.
- High uniaxial pressure processing of GNP composites has a preferential alignment, resulting in anisotropic mechanical and functional characteristics. Advanced applications that harness directionality, such as heat sinks and dampening devices, may result from controlling and using anisotropic characteristics. Anisotropy may be controlled and designed in such a way as to create gradient structures, which have lately showed great promise for improving ductility and strength.
- Further research is needed to determine how greater fracture toughness affects wear resistance, especially whether it plays a primary or secondary role in tribofilm formation's ability to reduce wear rates.
- The GNFs/Metal matrix nanocomposites have the notable advantage that, when compared to traditional metal matrix composites, they have an enormous potential for fabricating composites reinforced with Graphene, which has important properties and high levels of stiffness and strength. As a result, the finished composites will have exceptional mechanical properties.
- Graphene reinforced metal matrix nanocomposites have shown some promising results, but there are still many unknown influencing factors that need to be explored. Future research will concentrate on the optimization of processing parameters to improve the content and dispersion of GNFs in the metal matrix, as well as sintering and extrusion parameters.

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