

## Review Article

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# Wear properties of graphene-reinforced aluminium metal matrix composite: A review

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**Abstract:** The recent advancement in graphene-reinforced aluminium matrix composites improves wear behaviour in the production of lightweight and high-performance nanocomposites. Considerable works have been devoted to using graphene nanoparticles as solid self-lubricants to increase wear resistance, minimise friction coefficients, improve service efficiency, and extend the lifespan of related sliding components. In general, wear behaviour often depends on the homogeneous distribution of graphene in the aluminium matrix. The non-uniform distribution of reinforcement due to the tendency of graphene to agglomerate in aluminium matrix and its poor wettability becomes a challenge in developing optimum functional of composites. The wettability of graphene can be enhanced by proper processing methods and sufficient addition of magnesium that can improve the wear and frictional properties of the produced composites. Hence, this review article provides recent findings and the influence of graphene as reinforcement materials in composites, including the effects on wear behaviour and friction properties. This

article also discusses new advancements in the effect of graphene in self-lubricating aluminium matrix composites and the impact of reinforcement on the wear mechanisms of the composites. The future direction of the wear properties of MMCs is also covered at the end of the review.

**Keywords:** aluminium, graphene, wear resistance, coefficient of friction

## Abbreviations

Al <sub>2</sub> O <sub>3</sub>	aluminium oxide
B <sub>4</sub> C	boron carbide
BN	boron nitride
BOD	ball-on-disk
CMC	ceramic matrix composite
CNT	carbon nanotube
COF	coefficient of friction
CTE	coefficient of thermal expansion
CVD	chemical vapour deposition
EDS	energy-dispersive spectroscopy
FLG	few-layer graphene
GNP	graphene nanoplatelet
GNS	graphene nanosheet
GO	graphene oxide
MLG	multilayer graphene
MMC	metal matrix composite
MMNC	metal matrix nanocomposite
MWCNT	multi-walled carbon nanotube
POD	pin-on-disk
rGO	reduced graphene oxide
SEM	scanning electron microscopy
SiC	silicon carbide
SiCp	silicon carbide particulate
Si <sub>3</sub> N <sub>4</sub>	silicon nitride
SPS	spark plasma sintering
Ta <sub>2</sub> C	tantalum carbide
VC	vanadium carbide
vol%	volume%
wt%	weight%

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## 1 Introduction

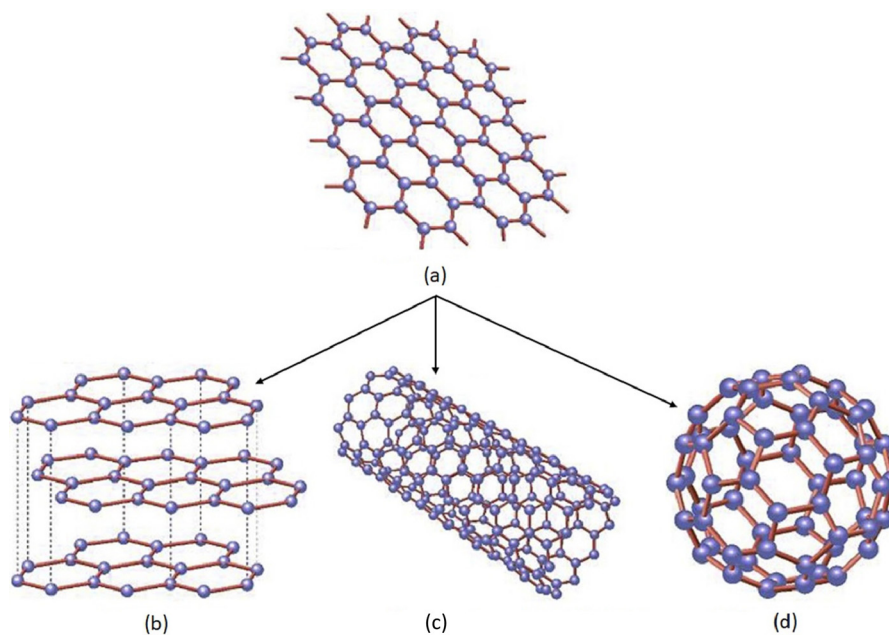
Composite materials can be classified into metal, ceramic, and polymer matrix composites. More research on ceramic matrix composites (CMCs) and polymer matrix composites has been conducted primarily due to the more straightforward fabrication routes of composites, which do not involve pressure and high-temperature requirements. Nevertheless, metal matrix composites (MMCs) are most commonly employed in the manufacturing industries, including aerospace, automotive, and construction, due to their enhanced engineering capabilities [1]. MMCs have been extensively explored in numerous branches of research owing to their high technological, structural, and functional capabilities for various industries and applications [2]. Innovative materials, such as composites, have been developed in response to the increasing need for structural components with improved operational life, increased in-service efficiency, and a high strength-to-weight ratio with an economical cost. These composites are formed by combining a minimum of two distinct chemical components with different interphases and separating the constituents in three-dimensional form to enhance the quality of the parent materials [3]. The matrix and reinforcement phases in MMCs are significant because they promote the dispersed phase, support load carrying, and offer integrity to the composite structure. The capability of stress transfer across the phases in the MMC interfaces significantly influences the properties and performance of

composites. Furthermore, the MMCs must be capable of bonding with the distributed material, endure the vicinity ambience, bend elastically under load, and prevent the formation and spread of cracks [4].

Aluminium alloys are the most commonly used materials in MMCs because of their low density, low melting temperature, good conductivity, excellent corrosion resistance, and low wear rate [5,6]. Furthermore, the benefit of lightweight facilitates the aluminium alloy, a significant finding of widespread application in automotive industries due to increased performance and fuel consumption. Although aluminium matrixes are preferred for a variety of reasons, they continue to face difficulties in terms of insufficient ductility, inadequate fatigue strength, and efficient control throughout processing [7]. Furthermore, the alloys face limited strength, which has piqued the interest of researchers who have attempted to integrate reinforcements, such as alumina oxide [8], silicon carbide (SiC) [9], boron carbide [10], carbon nanotube (CNT) [11] and graphene [12].

Graphene is one of the most abundant allotropes of carbon since Andre Geim and Kostya Novoselov discovered and successfully isolated graphene from graphite in 2004 [13–15]. Graphene is a single layer of carbon atoms tightly bound in a hexagonal honeycomb lattice, as shown in Figure 1.

Graphene was formerly classified mainly as a scholarly material. However, graphene has attracted the interest and curiosity of many experts due to its unique features,



**Figure 1:** Structure of all carbon allotropes in graphene. Reproduced from the study of Iqbal *et al.* [13]. (a) Graphene, (b) graphite, (c) carbon nanotube CNT, and (d) fullerene C<sub>60</sub>.

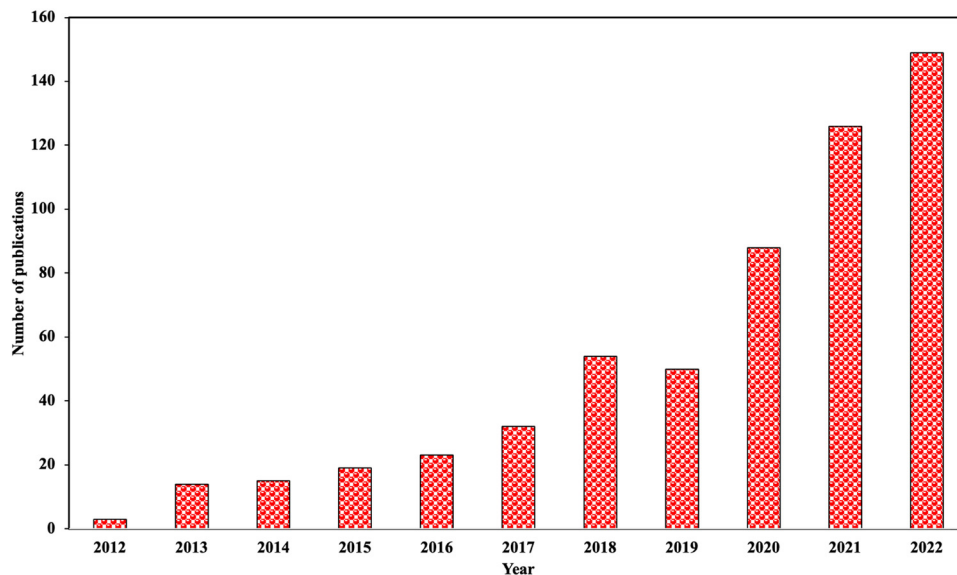
including outstanding thermal conductivity, mechanical properties, and self-lubricating ability [16–18]. Accordingly, graphene has become indispensable in a variety of applications and it rapidly gained much attraction in the publication with the related keywords graphene and tribology in the field of aluminium MMCs over the last 10 years due to its remarkable properties and unique structure (Figure 2). The unique structure in graphene enables it to exhibit a wide variety of intriguing features, such as excellent tensile strength with Young's modulus of 1 TPa, ultimate tensile strength (125–130 GPa) [16,19,20], exceptional stiffness [13], excellent thermal conductivity (1,000–5,300  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) [19,21], and generous specific surface area (2,600–2,630  $\text{m}^2\cdot\text{g}^{-1}$ ) [22]. These characteristics have led to the selection of graphene as an effective reinforcement for aluminium MMCs. Table 1 lists the unique properties of single-layer graphene.

Graphene as a carbon-based nanostructure exhibits excellent potential in enhancing the material properties of aluminium MMCs [23–25]. Several review articles have highlighted graphene-reinforced MMCs, such as their manufacturing process and behaviour, in recent years, as summarised in Table 2. However, the majority of the reviews focused on the fabrication process and its influence on mechanical properties with future perspectives from 2016 to 2022 (limited to the publications the authors could verify as applicable). The reviews addressed various main challenges of enhanced performance with the appropriate graphene dispersion without compromising the structure. The large van der Waals attractive forces and the  $\pi$  stacked between the graphene lamellae contribute to the insolubility of graphene in the matrix [26]. Furthermore, the weak

**Table 1:** Unique properties of single-layer graphene [15,21,22]

Properties	Value
Hybrid bond type	$\text{sp}^2$
Number of sheet layers	Single layer
Structure of crystal	Hexagonal lattice
Dimension	Two-dimensional
Purity degree level (%)	99
Bulk density ( $\text{g}\cdot\text{cm}^{-3}$ )	~0.3
Actual density ( $\text{g}\cdot\text{cm}^{-3}$ )	2.25
Thickness (nm)	~1–2
Specific surface area ( $\text{m}^2\cdot\text{g}^{-1}$ )	2,600–2,630
Ultimate tensile strength (GPa)	125–130
Young's modulus (TPa)	1
Melting temperature ( $^{\circ}\text{C}$ )	5727
Thermal conductivity ( $\text{W}\cdot\text{K}^{-1}\cdot\text{m}^{-1}$ )	1,000–5,300
Current electron mobility ( $\text{cm}^2\cdot\text{s}^{-1}\cdot\text{V}^{-1}$ )	$\sim 2.5 \times 10^5$

van der Waals bond between graphene causes the bond between graphene and the matrix to be difficult and challenging. The  $\pi$ -bond is present above and below each graphene layer and overlaps with neighbouring carbon atoms. Additionally, the  $\pi$ -orbitals also exhibit the behaviour of valence bands and conduction bands and activate the planar conduction mechanism [27]. Hence, the authors proposed various novel fabrications of graphene reinforcement with diverse MMCs to achieve a uniform distribution for more promising commercial applications and improve the properties. However, the recent advances in wear and friction applications for related industries have resulted in increased research including a critical review of tribological properties of these composites.



**Figure 2:** Number of publications of tribology for graphene in aluminium MMCs between 2012 and 2022 based on Elsevier database.

**Table 2:** Related review papers on graphene nano-reinforcement from 2016 to 2022

Year	Ref.	Remarks	Future perspectives
2016	[29]	<ul style="list-style-type: none"> <li>This article specifically focused on uniform dispersion due to sizeable surface differences between carbon nanofillers and metals by different current processing techniques and their impact on the mechanical and tribological properties of nanocomposites</li> </ul>	<ul style="list-style-type: none"> <li>Further understanding of new development in the fabrication of carbon-nanofillers reinforcing MMC approaches in increasing the strengthening mechanisms to produce future MMNCs with more versatile and demanding properties for various engineering applications</li> </ul>
2016	[30]	<ul style="list-style-type: none"> <li>This review article reported the microstructure and mechanical properties of various current processing fabrication and dispersing techniques of graphene in different MMCs to increase the strengthening mechanism. The majority of research was focused on pure metal matrixes, while the metals utilised in the industry are alloys</li> </ul>	<ul style="list-style-type: none"> <li>Future research focuses on developing dispersion and processing techniques to overcome the ongoing big challenge and fulfil future mass production. Numerical simulations combined with theoretical studies will play a critical role in achieving appropriate findings to avoid wasting time and money</li> </ul>
2017	[31]	<ul style="list-style-type: none"> <li>This review article focused on the mechanical behaviour, tribological performance, and functional properties (corrosion, high-temperature oxidation, biocompatibility, thermal properties, and electrical properties) of graphene reinforcement MMCs and CMCs based on different processing techniques, respectively</li> </ul>	<ul style="list-style-type: none"> <li>Graphene-reinforced metal and CMCs-based technologies are the potential for commercialisation in the near future. However, the control of the GNP dimension in advanced processing and its characterisation is still challenging. The advanced application, especially in extreme environments, such as high temperatures with scalable manufacturing, is requisite to driving further optimisation and enabling the use of GNP composites in novel and specific applications</li> </ul>
2018	[32]	<ul style="list-style-type: none"> <li>This article discussed the main challenges in the powder metallurgy fabrication technique of GNP reinforced to MMNCs due to limitations in liquid-based processes. Moreover, it also addressed the effort in producing new MMNCs to enhance the performance and properties of the composites and meet the challenges</li> </ul>	<ul style="list-style-type: none"> <li>The discussion still brings a significant challenge to the material and process field in order to achieve uniform dispersion and strong interfacial bonding of GNP with a particular fabrication technique without detrimental reactions. One of the suggestions is related to the preparation technique by proposing the post-processing techniques</li> </ul>
2018	[33]	<ul style="list-style-type: none"> <li>This review article contributed to research efforts focused on producing and characterising various MMNCs reinforced with graphene nanoplatelets (GNPs). It was demonstrated that the thermal conductivity and mechanical properties of the composites are substantially dependent on the graphene quantity, graphene dispersion in the matrix, and graphene-metallic matrix interfacial bonding</li> </ul>	<ul style="list-style-type: none"> <li>Technical obstacles should be addressed before or during the fabrication process to enable the production of novel MMNCs with superior thermal and mechanical properties and a reduced coefficient of thermal expansion (CTE). In contrast, various post-processing procedures can be used to eliminate residual porosity</li> </ul>
2019	[34]	<ul style="list-style-type: none"> <li>This review discussed less attention given to graphene dispersion and its interface bonding with the matrix. Hence, it emphasises the foundations of graphene's atomic structure as a role in the distribution and the bonding behaviour at the graphene-metallic interfacial region through powder metallurgy and their influence on mechanical properties</li> </ul>	<ul style="list-style-type: none"> <li>Conventional powder metallurgy is a well-known process of fabricating graphene with the MMC to achieve uniform distribution and strong interfacial bonding. However, obstacles still exist in the ball-milling process since it damages the surface of graphene sheets. Hence, novel methods, including coating, vacuum infiltration, alloying of matrix and plasma treatment, were introduced as alternative methods to conventional methods in the powder metallurgy route</li> </ul>
2019	[35]	<ul style="list-style-type: none"> <li>This review article presented recent research into the development of powder-based production, property characterisation, and application of matrix nanocomposites reinforced with graphene. On the other hand, it compared the graphene and CNT <i>via</i> the powder process route, respectively, and reflected mechanical, tribological, electrical, and thermal conductivity properties</li> </ul>	<ul style="list-style-type: none"> <li>The challenges in the fabrication step are found, such as the non-uniform distribution of graphene, poor interfacial bonding, and different orientation of graphene. To solve these issues, it is suggested to alter the fabrication technique and offer a post-processing method. However, it should also consider the stability and distribution of reinforcement. Hence, despite all efforts in developing new MMNC's, it needs more attempts to overcome the challenges in the industrialisation stage.</li> </ul>
2020	[15]	<ul style="list-style-type: none"> <li>According to this critical review article, graphene-reinforced composites with the same metal matrix demonstrate a range of properties due to changes in the manufacturing technique, graphene/matrix interaction, graphene dispersion, and graphene position in the matrix. As a result, it</li> </ul>	<ul style="list-style-type: none"> <li>Optimisation of variables and simplification of production procedures result in significant possibilities in a wide variety of applications. Thus, the manufacturing process and control variables can result in excellent reinforcement between graphene and MMCs with exceptional mechanical properties</li> </ul>

*(Continued)*

Table 2: Continued

Year	Ref.	Remarks	Future perspectives
2020	[36]	<p>addressed factors affecting graphene's properties, including graphene agglomerates, graphene alignments in a metal matrix, and the graphene–matrix contact</p> <ul style="list-style-type: none"> <li>This review article highlighted current breakthroughs in the critical mechanisms, production, fabrication, simulation, and utilisation of graphene MMNCs. It presented the current research trends and delivered the problems with reinforcing graphene and MMCs. The main strengthening mechanisms were discussed in relation with synthesis fabrication technology, including conventional and advanced methods. Analytical modelling and numerical simulation were addressed in order to understand the interface bonding and its performance on characteristics</li> </ul>	<ul style="list-style-type: none"> <li>This article presented the future prospect of research and explores the directions. Microwave sintering, SPS process, in situ growth chemical vapour deposition and electroless plating are proposed as modern rapid sintering methods to enhance the density and defects in composites. The modification of graphene also needs to be improved to increase the uniform distribution and dispersion of the metal matrix. The introduction of intermediate materials is a new concern in optimising and improving the interaction between graphene and metal matrix. Hence, all the current trends are still in the theoretical development stage, and the numerical simulation can be a new broad research prospect</li> </ul>
2020	[37]	<ul style="list-style-type: none"> <li>This systematic study presented synthesis techniques to fabricate graphene reinforcing with the metal matrix. This article summarised the effects of the graphene type and its content to enhance the electrical, mechanical, tribological, and thermal properties. Hence, graphene dispersion and interfacial interaction are highlighted, including the result of microstructures</li> </ul>	<ul style="list-style-type: none"> <li>A more systematic strategy for creating and analysing these composites is necessary to comprehensively understand their behaviour and response, as conflicting results about graphene reinforcing with different metal matrixes have been reported</li> </ul>
2020	[38]	<ul style="list-style-type: none"> <li>This critical article highlighted recent progress in fabricating graphene-reinforced metal nanocomposites using powder metallurgy techniques such as milling, compaction, and extrusion or rolling, emphasising graphene agglomeration, interfacial bonding, and reaction between the metal matrix and graphene. On the basis of existing theoretical models and experimental findings, the CTE mismatch and all strengthening mechanisms between graphene and matrix were explored, as well as their consequences on mechanical and tribological behaviour</li> </ul>	<ul style="list-style-type: none"> <li>The composite's fracture surface revealed an insufficient binding strength between the matrix and graphene and an issue that appeared to be resolved in a subsequent investigation. The mixture rule is incompatible with actual estimations based on the single-layer graphene assumption. Although a uniform distribution significantly affects strengthening mechanisms, it is still not practicable. Thus, creating advanced novel synthesis procedures is possible to achieve a robust anchoring mechanism for graphene to the metal matrix</li> </ul>
2021	[39]	<ul style="list-style-type: none"> <li>This article reviewed the fabrication process of nanocarbon reinforcing with light MMCs and focused on the characterisation and structures of interface nanocarbon with a light metal matrix. It was shown that coating of reinforcement GNPs to aluminium improves the mechanical properties. At the same time, depositing Ni or Cu improves the interface properties and promotes wetting. Hence, all the proposed methods aim to increase the strength and ductility of composites</li> </ul>	<ul style="list-style-type: none"> <li>The overview demonstrated that balancing strength and ductility is not simple and that increasing strength capability decreases ductility and formability. Proper design is necessary to ensure that nanocarbon is distributed uniformly throughout the matrix. The 3D network structure of reinforcement, atomic, and microstructural design is suggested as a few novel fabrication strategies to realise the composites with excellent properties. However, the casting method is suitable for large-scale manufacturing due to the low production cost required for actual material utilisation</li> </ul>
2021	[26]	<ul style="list-style-type: none"> <li>This article review outlined three critical topics related to the challenges of graphene as a reinforcement material, the strengthening mechanism of graphene in a metal matrix, and the factors limiting the enhancement of the properties. Structural integrity, interfacial bonding, and strengthening mechanisms are essential to overcome poor wettability, agglomerations, and non-uniform distribution of reinforcement in MMCs to achieve optimal and improved properties</li> </ul>	<ul style="list-style-type: none"> <li>Effective load transmission is critical for enhancing the mechanical qualities of the mechanism. Additionally, numerous fabrication techniques have been proposed to get a higher-quality result. Due to the increased potential of reinforcement distribution in the matrix, powder metallurgy is the most often used technology for creating graphene-reinforced aluminium composites. Nevertheless, there are new studies on the amount of graphene in the Al matrix and its effect on mechanical properties. Thus, prior to completing the manufacturing process, there is an opportunity to establish the criterion and optimise the composite's strength gain and ductility</li> </ul>

(Continued)



Table 2: Continued

Year	Ref.	Remarks	Future perspectives
2021	[40]	<ul style="list-style-type: none"> <li>The article had a particular focus and concern on the mechanical, tribological, and challenges associated with the fabrication of nanocomposites till-date available. The materials suffer from their fabrication and synthesis to achieve the uniform distribution of graphene reinforcement with the MMC. Hence, the discussion of challenges and factors is assisted along with solutions so the new research can be done with ease</li> </ul>	<ul style="list-style-type: none"> <li>The need for rectification of defects at the microscopic level is required because most of the work done is towards the strength enhancement of the composite</li> </ul>
2021	[41]	<ul style="list-style-type: none"> <li>This review article discussed the use of graphene/CNTs to strengthen aluminium in order to improve its mechanical qualities. As a result, it is critical to determine their effect on yield strength, hardness, ductility, and tensile strength using various primary and secondary production methods</li> </ul>	<ul style="list-style-type: none"> <li>According to published research, powder metallurgy is the most often utilised processing technology due to its simplicity and low cost, followed by mechanical stirring casting. Uniform dispersions of graphene/CNTs in a matrix remain a significant issue; hence, future research is required to produce materials with increased service life, sustainability, and dependability. Additionally, future manufacturing improvements should emphasise critical features such as oxidation behaviour, corrosion behaviour, and fatigue</li> </ul>
2022	[42]	<ul style="list-style-type: none"> <li>This article provided a comprehensive and critical review of the state-of-the-art research activities related to the processing, properties, and applications of aluminium reinforced with graphene-based nanomaterial composites for various applications. It also highlighted the processing challenges using various approaches. However, powder metallurgy, casting, and friction stir processes are common in fabricating reinforcement composites. The addition of graphene in aluminium composites alloy can improve the maximum strength and consistently improve tribology but there was less improvement in thermal and electrical conductivity</li> </ul>	<ul style="list-style-type: none"> <li>The agglomeration of various graphene derivatives in aluminium matrix composites is still one of the greatest challenges. Future efforts must consider low-cost synthesis and fabrication to produce high-quality graphene reinforced with aluminium composite alloy. <i>In situ</i> synthesis has shown encouraging results but needs further exploration. Additive manufacturing is another exciting area of future research and the available results show promising trends. The different heat treatment conditions should be considered for commercial aluminium to study the impact on physical and mechanical properties. The 3D microstructure can be considered a topic for future research to develop a new 3D-based model</li> </ul>
2022	[43]	<ul style="list-style-type: none"> <li>This review article elucidated the complex tribo-performances of MMNCs in their fabrication or manufacturing methods with various factors. In addition, it also summarised important factors in reducing friction and wear and is systematically linked with a fundamental understanding</li> </ul>	<ul style="list-style-type: none"> <li>The summarised article gave extended interdisciplinary applications of MMNCs in future directions, improvement pathways, and possible expected outcomes. Besides, the links of tribology to materials science, nanoscience, biomedical, and electronics have also been discussed</li> </ul>

Meanwhile, wear behaviours and friction of aluminium-based MMCs have always been critical issues. In general, wear is the gradual loss of material from two contacting surfaces that move relative to each other under a load [28]. During sliding applications, the component must operate under extreme heat and vacuum conditions when fluid lubrication is insufficient or complicated, and fluid lubricants are environmentally unfriendly, emitting pollutants into the atmosphere. To date, graphene is expected to positively influence wear and friction behaviour. This behavioural influence can be linked to its self-lubricating ability, which results from the squeezing of graphene sheets between sliding surfaces and its load-bearing capability, which

minimises the wear rates of MMCs. The materials can sustain a low coefficient of friction (COF) and a low wear rate without requiring additional lubrication. Hence, the demand for self-lubricating materials supplemented with MMCs is increasing for green tribology, endurability, and power efficiency. However, there are limited studies that discuss the effects of graphene reinforcement material as self-lubricating in the aluminium matrix on the wear and friction to identify the wear behaviour of composites. The wear behaviour for graphene-reinforced aluminium matrix composites includes wear rate, COF, and wear mechanism.

Hence, this article focuses on the important research gaps and supplies significant information on wear and

friction properties of graphene-reinforced aluminium matrix composites. In addition, this article also aims to highlight the influence of graphene on wear behaviour, including graphene content, fabrication process, and extrinsic factors such as the applied load and sliding speed.

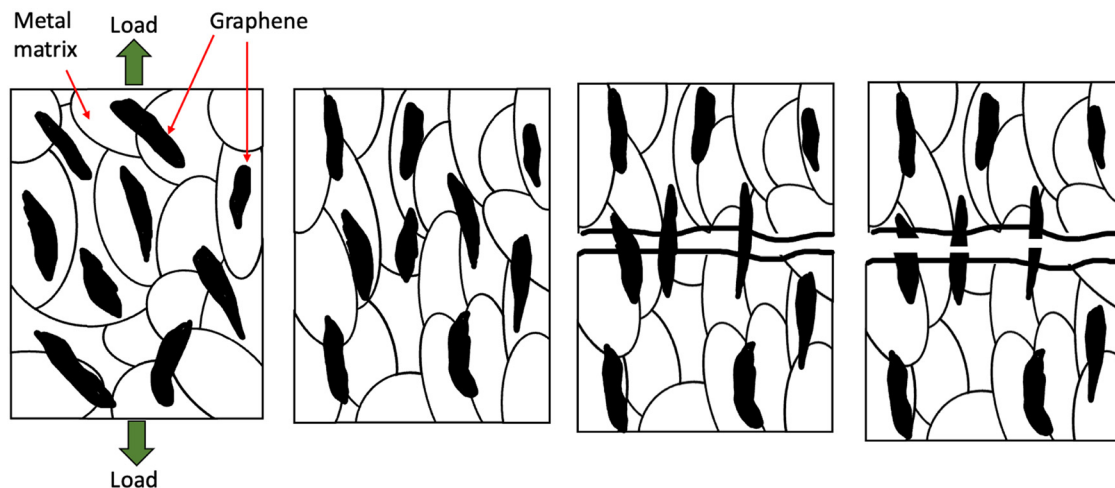
## 2 Graphene as a reinforcement material

The role of graphene in aluminium matrix composites has received increased attention across a number of disciplines in recent years. Graphene and graphene derivatives can be produced *via* several techniques, for example, CVD, epitaxial growth method, molecular beam epitaxy, arc-discharge method, and plasma etching technique [36]. Given the instability of graphene in its single-layer form in the free state, GNPs or graphene nanosheets (GNSs) are employed as reinforcements, which are thin stacks of platelet-shaped graphene sheets with an average thickness of 5–100 nm, and the sheets are peeled off to attain a single-layer distributed graphene in a matrix [44]. Accordingly, GNPs and GNSs have received extensive research into employing them as reinforcements in aluminium metal composites due to their low production cost and good cost-effectiveness [21,45]. Therefore, reducing the cost of the final material while improving the wear and barrier properties will increase its service life and allows its use in most industries. In addition, few-layer graphene (FLG) can be produced from the peeled GNPs or GNSs in some cases [46]. The thin structure of GNPs can retain the structural integrity and outstanding properties of single-layer graphene, especially in mechanical and tribological properties. Furthermore, the single-layer

graphene structure results in a lower Young's modulus with more defects compared with multilayer graphene (MLG). Zhang and Gu [47] compared Young's modulus between single-layer graphene and MLG with seven layers by simulation analysis. They found that single-layer graphene had a slightly lower value of this property compared with MLG. Therefore, they concluded that the interlayer interaction in MLG plays a positive role in Young's modulus of graphene.

In other studies, the amount of graphene in the matrix also determines the mechanical and tribological properties. Liu *et al.* [48] conducted an experiment on three different contents of a few layers of graphene (0.3, 0.6, and 1.0 wt%) with Ni metal composites and their effects on hardness and tribological performance. The data showed that only a small percentage of a few layers of graphene (as low as 0.3 wt%) was required in the matrix to improve the hardness and wear rate, while Essa *et al.* [49] identified the graphene nanoparticles with up to 5.0 wt%. The hardness deteriorated at this value due to porosities resulting from the interfacial reactions between solid lubricants and base alloy. Moreover, the wear resistance and friction are enhanced due to the presence of a lubricating tribolayer film and synergic action between the aluminium oxide and the graphene during sliding.

In a sound composite structure, graphene acts as a load transfer, as shown in Figure 3, to increase the strength and improve the wear resistance. Lian *et al.* [50] indicated that the presence of graphene oxide (GO) in the matrix alloy synergistically bears the load, which increases the hardness and improves the wear resistance of the composites. Jayaseelan *et al.* [51] explored the use of the composite material for the launch vehicle external fuel tank structural components for aerospace applications. They embedded the graphene with three types of aluminium

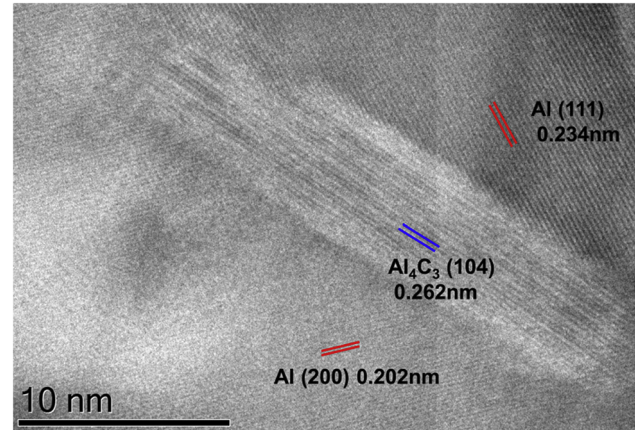


**Figure 3:** Schematic diagram of load transfer with an illustration of microstructure evolution of the graphene/MMC under load.

composites: AA2024, AA6061, and AA7075. The results show that the nano-graphene successfully integrates into the composites, where the pinning effect from the addition of graphene hinders grain growth in the aluminium composite and increases the strength of the composite material due to the fine grain structure, as shown in Figure 4. In addition, several studies report the presence of  $\text{Al}_4\text{C}_3$  due to the reaction between carbon and aluminium at high temperatures during the fabrication process [52,53], as shown in Figure 5. The excessive amount of  $\text{Al}_4\text{C}_3$  formation could damage the mechanical properties due to the intrinsic  $\text{Al}_4\text{C}_3$  phase, which is known to be brittle. Hence, an exceptional and homogeneous matrix of interfacial bonding with reinforcement is crucial to achieve the optimal performance of a composite.

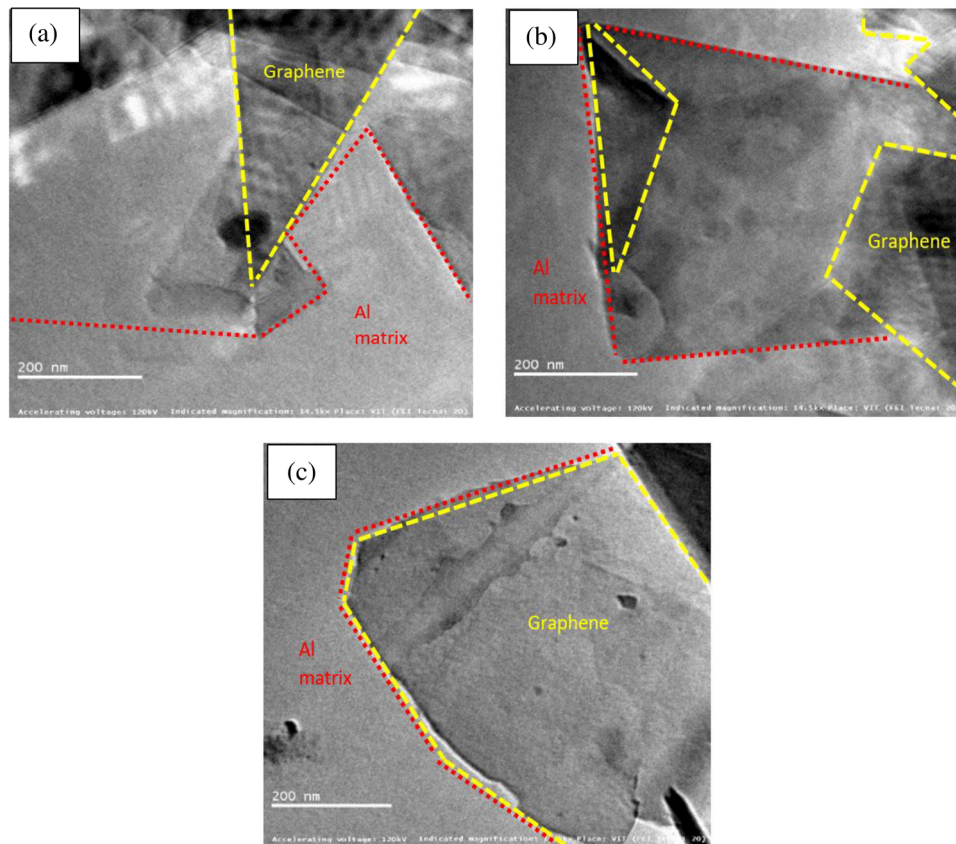
### 3 Wear characterisation

The advantages of graphene-reinforced matrix composites are their superior and excellent wear resistance in addition



**Figure 5:** TEM image shows the formation of needle-like  $\text{Al}_4\text{C}_3$  between aluminium grains. Reproduced from the study of Zhang *et al.* [54].

to their mechanical properties. Nowadays, extensive research has been conducted on the wear resistance of aluminium matrix composite reinforced with graphene [55]. The tribological behaviour of various graphene-reinforced aluminium matrix composites is summarised in Table 3. The wear



**Figure 4:** High-resolution transmission electron microscopy (TEM) for graphene-reinforced aluminium composite (a) AA2024, (b) AA6061, and (c) AA7075 for fuel tank structure in aerospace application. Reproduced from the study of Jayaseelan *et al.* [51].



Table 3: Tribological properties of graphene-reinforced aluminium composites

Matrix	Optimised reinforcement	Process method	Post-processing	Type of test	Load (N)	Sliding distance	Sliding speed (m·s <sup>-1</sup> or rpm)	Wear rate (mm <sup>3</sup> ·N <sup>-1</sup> ·m <sup>-1</sup> )	COF	Wear mechanism	Ref.
AA7068	0.5 wt% GNPs	Ball milling + stir casting	T6 heat treatment + hot extrusion	POD	20, 40	1,500 m	0.5 m·s <sup>-1</sup>	–	0.21	Delamination wear (both samples at early stages), abrasive wear for both samples	[60]
Al	2.0 vol% GNPs	SPS	–	BOD	1	~53 m	100 rpm	(1.9 ± 0.2) × 10 <sup>-5</sup>	0.79 ± 0.09	Adhesive wear (base alloy), delamination wear (composites) at RT	[61]
Al6061	10 and 15 vol % MLG	Spark plasma texturing	–	BOD	1, 3, 5, 10	–	0.1 m·s <sup>-1</sup>	~0.7 × 10 <sup>-2</sup> mm <sup>3</sup> ·m <sup>-1</sup> (15 vol%) at 10 N	–0.2 at 10 N for both vol% MLG	Fatigue and abrasion wear (base and composite)	[62]
Al-7Si	10 wt% SiCp/0.5 wt % rGO	Powder metallurgy	Hot extrusion	BOD	1, 2, 2.5, 3.2	1,500 m	1,500 rpm	~1.4 × 10 <sup>3</sup> mm <sup>3</sup> ·m <sup>-1</sup> at 3.2 N	0.5 at 3.2 N	Delamination wear (SiCp/Al-7Si composite), abrasive and adhesion wear at low load while delamination wear at high load (RGO/SiCp/Al-7Si composite)	[63]
Al	0.8 wt% GNPs	Powder metallurgy	–	POD	15	1,130 m	150 rpm	0.0256 g	–	–	[64]
Al	10 wt% SiC/0.5 wt. GNPs	Powder metallurgy	–	BOD	10, 50	–	10 mm·s <sup>-1</sup>	~0.128 at 10 N, ~0.442 at 50 N	–0.18 at 10 N, ~0.063 at 50 N	Adhesive wear at low load, abrasive wear at high load	[65]
Al	0.1 wt% GNPs	Powder metallurgy	–	POD	10, 20, 30, 40	500 m	200 rpm	12 × 10 <sup>-5</sup> at 10 N	0.32 at 20 N	Damage on the worn surface (base alloy, 0.3 and 0.5 wt% GNPs), low- depth groove (0.1 wt% GNPs)	[66]
Al6061	GNPs/SiC	Friction stir processing	–	BOD	20	5 m	20 rpm	~0.01	0.37	Adhesion and abrasion wear (composite), adhesion wear (matrix)	[67]
AA6061	0.6 wt% GNPs/10 wt% B <sub>4</sub> C	Ultrasonic dispersion + Powder metallurgy	–	POD	5, 10, 15, 20	600 m	0.4 m·s <sup>-1</sup> , 0.8 m·s <sup>-1</sup> , 1.2 m·s <sup>-1</sup>	–	–0.38 at 10 N and 0.8 m·s <sup>-1</sup>	Delamination wear (composite), erosion wear (matrix)	[68]
A355	5 vol% SiC/1 vol % GNSs	Powder metallurgy	–	BOD	20	43.96 m	43.96 mm·s <sup>-1</sup>	0.0015	0.5	Abrasive wear (SiC/A355), adhesive and abrasive wear (GNSs/SiC/A355)	[69]
Al	0.2 wt% rGO/0.2 wt% CNTs	Hot sintering	–	Block-on-ring	10	~458.67 m	200 rpm	0.022 mg·s <sup>-1</sup>	–	–	[70]
Al	0.1 wt% GNPs/9 wt % Si <sub>3</sub> N <sub>4</sub>	Powder metallurgy	–	POD	10, 20, 30	500 m	200 rpm	3.1 × 10 <sup>-5</sup> at 10 N	0.13 at 30 N	Abrasive wear for both samples	[71]

(Continued)

Table 3: Continued

Matrix	Optimised reinforcement	Process method	Post-processing	Type of test	Load (N)	Sliding distance	Sliding speed (m·s <sup>-1</sup> or rpm)	Wear rate (mm <sup>3</sup> ·N <sup>-1</sup> ·m <sup>-1</sup> )	COF	Wear mechanism	Ref.
AA7075	0.5 wt% GNPs	Stir casting + ultrasonic vibrations	T6 heat treatment	POD	5	1,000 m	–	–	–0.35–0.42	Abrasive wear (matrix), adhesive wear (composite)	[72]
Al6061	0.25 wt% GNSS	High-frequency induction heat sintering	Hot extrusion	POD	19.60	126 m	500 rpm	~4.8 × 10 <sup>14</sup> m <sup>2</sup> ·Nm <sup>-1</sup>	0.65–0.75	Abrasive wear for both samples	[18]
A360	0.25 wt% GNPs	Ball milling + Stir casting	–	BOD	20	1000 m	273 rpm	–	–0.25 at RT and –0.225 at 150°C	Oxidation wear for both samples at 150°C, abrasive and adhesive wear at RT	[73]
Al	1.0 wt% GNPs/2.0 wt% Al <sub>2</sub> O <sub>3</sub>	Powder metallurgy	–	POD	5, 10, 15, 20	1,500 m	120 rpm	0.2 × 10 <sup>-5</sup> at 20 N	–0.21 at 20 N	Formation of GNPs tribofilm as a protective layer	[74]
AlSi18Cu-NiMg	1 wt% GNPs	Semi-powder metallurgy + stir casting	Ageing process	BOD	10, 20, 40	200 m	0.06 m·s <sup>-1</sup> , 0.07 m·s <sup>-1</sup> , 0.08 m·s <sup>-1</sup>	0.0046 at 10 N & 0.08 m·s <sup>-1</sup>	–	Delamination wear (matrix); abrasive and oxidation wear (composite)	[75]
Pure Al	2 wt% CNTs/3 wt% graphene	Stir casting	–	POD	10, 30	1,200 m	–	2.8711 × 10 <sup>-3</sup> mm <sup>3</sup> ·m <sup>-1</sup> at 10 N, 3.4479 × 10 <sup>-3</sup> mm <sup>3</sup> ·m <sup>-1</sup> at 30 N.	–	Adhesion wear (base alloy), abrasion wear (graphene/CNTs/Al composite)	[76]
Al5251	GNPs/BN	Friction stir processing	–	POD	10	–	0.1 cm·s <sup>-1</sup>	~0.013 mg·s <sup>-1</sup>	0.32	Delamination wear (Al5251), abrasive wear (composite)	[77]
Al	3 wt% graphene/2 wt% CNTs	Powder metallurgy	–	POD	10, 20, 30	1,200 mm	2 m·s <sup>-1</sup>	2.5 × 10 <sup>-3</sup> mm <sup>3</sup> ·m <sup>-1</sup>	–	Delamination wear (base alloy), abrasion and adhesion wear (composite)	[78]
Al-10Si	2 wt% FLG	Powder metallurgy	–	BOD	3	2,5000 mm	5 mm·s <sup>-1</sup>	0.00065	–	Abrasive wear for both samples	[22]
Al	0.25 wt% GO/10 vol% Al <sub>2</sub> O <sub>3</sub>	Powder metallurgy	Spark plasma sintering	BOD	3	100 m	0.1 m·s <sup>-1</sup>	~0.25 × 10 <sup>-3</sup>	–0.833	Severe adhesive wear (base alloy), abrasive wear (composite)	[79]
Al	0.5 wt% GNPs	Powder metallurgy	–	BOD	10	–	30 min	–	0.027	–	[80]

BOD, ball-on-disk; POD, pin-on-disk; RT, room temperature; SPS, spark plasma sintering.

performance of graphene-reinforced aluminium matrix composites is more favourable than the unreinforced aluminium matrix. Generally, the wear rate and COF of graphene-reinforced aluminium matrix composites are lower to a certain extent relative to unreinforced alloy and attractive for industrial applications. Consequently, tribological performance is influenced by many factors, such as the test method, counterface composition, reinforcing composition, sliding speed, load, processing method, and temperature [56–59].

### 3.1 Processing method

Graphene was introduced with aluminium in MMCs in 2011 and has grown in popularity in recent years [13]; however, due to variety of factors, including constrained output volume, it might impede graphene adoption. Although a variety of methods are available for fabricating various types of graphene reinforcing with aluminium matrix composites, the volume production of each approach remains limited. Consequently, material uniformity and production cost will have to be prioritised. Liquid and solid-route processing are the most common fabrication procedures for graphene-reinforced aluminium matrix composites [76,81]. Both processing routes are important to achieve graphene dispersion in aluminium matrix composites. Powder metallurgy is widely used in solid-route processing due to its versatility and ease of operation. However, significant deformation occurs during the particle powder mixing method due to frequent breakage between graphene particles and the aluminium matrix and promoting graphene dispersibility [36,82].

Wang *et al.* [80] used high-energy ball milling and powder metallurgy to form a composite using pure aluminium powder as a matrix and 0.5 wt% graphene powder as reinforcement. After the processing, delicate and globular particles accumulate in the composite powder and no aggregation of graphene is observed in the blended powder. The shear force of the stainless-steel ball may allow graphene to incorporate into the aluminium powder particles during the high-energy ball grinding operation, thus avoiding graphene agglomeration. It was found that the maximum COF was 0.126 and the average COF was 0.027, indicating high resistance to corrosion and wear compared with unreinforced aluminium. The findings demonstrate that the dispersion of graphene at grain boundaries influences effective load transfer. The interface load transfer and plastic deformation help in increasing the wear resistance to a particular level. Accordingly, the homogeneity of

graphene was considered to be enhancing the tribological characteristics in this scenario.

Nonetheless, the traditional powder metallurgy drives the shattering of graphene structures, increasing the rate of defects, and lowering the properties of the material. The use of high temperature and long duration time in the sintering technique generates the coarsening in the microstructure of graphene-reinforced aluminium composite and deteriorates the tribological and mechanical properties. Hence, numerous advanced sintering techniques have been created with the traditional method of powder metallurgy, such as SPS [83], laser sintering [84], and microwave sintering [85,86] to overcome the drawbacks associated with extended sintering durations. Moreover, these new advanced techniques can productively prevent deficiencies such as macro-pores, which reduce the density and lead to impairment of strength and tribological properties by altering the temperature and duration of the sintering process. However, new advanced development procedures add to the complexity and cost of the process. Hence, process optimisation is required to achieve the optimum parameter, especially in temperature and duration of sintering without compromising the integrity of graphene and the strength of the composite.

Zheng *et al.* [87] fabricated the aluminium powder reinforced with GO by using solution mixing and powder metallurgy to ensure that a homogeneous graphene distribution and clean metallurgical interface in the aluminium matrix were achieved. Meanwhile, Kostecki *et al.* [62] used the SPS and spark plasma texturing to fabricate MLG/AA6061 composites with 2–15 vol% of MLG and examined the effect on the wear rate and COF. The COF and wear rate of the MLG/AA6061 composites show a decreasing trend and higher hardness with the spark plasma texturing process compared to the SPS technique for the unreinforced AA6061 and MLG/AA6061 composites. The spark plasma texturing process decreases the density of agglomerates in MLG and the amount of porous throughout these particles' agglomerates. Meanwhile, the number of particle boundaries that the solid lubricant covered increased simultaneously. This condition facilitates access to the carbon flakes during the sliding process and retains the tribofilm development mechanism. In another experiment, Mohammed *et al.* [79] conducted a ball-on-disc wear test to evaluate the wear behaviour on the GO/Al<sub>2</sub>O<sub>3</sub>/Al hybrid nanocomposites produced by the SPS technique. Reinforcing the Al<sub>2</sub>O<sub>3</sub>/Al with GO increased the hardness by 48.4% and enhanced the wear behaviour by 55.6% of hybrid nanocomposites compared with the aluminium matrix due to the hard alumina nanoparticles. In addition, the lubricating characteristics of GO and reinforcement uniformly distributed throughout the aluminium matrix

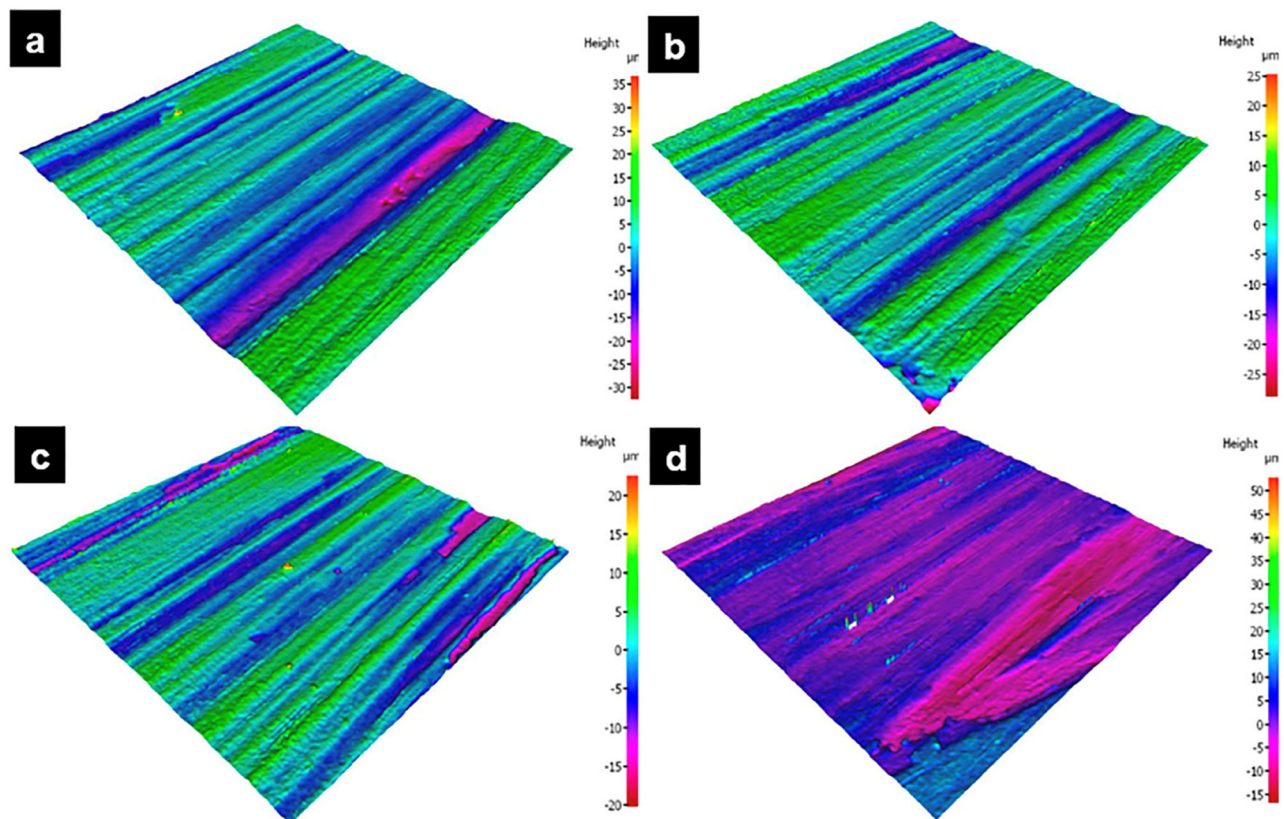
enhanced the wear behaviour and strength. Furthermore, the most prevalent wear mechanism is abrasive wear owing to plastic deformation, with fine surface features and much fewer debris particles for hybrid nanocomposites.

Various liquid state fabrication routes, such as casting, compo-casting or rheo forming, squeeze casting, spray forming, and liquid metal infiltration have been identified to disperse the reinforcement material in aluminium nanocomposites [41,88]. The melt casting method is frequently used in liquid-route processing due to its simple process and is preferred in the manufacturing industry [89], where the graphene is supplied into the melt aluminium matrix to obtain graphene-reinforced aluminium matrix composites through solidifying. However, it was discovered that the reinforcement material floated on the top layer of the molten metal surface after adding reinforcement because of the extremely high interfacial tension and weak wettability. Hence, a permanent or temporary mixing or stirring unit is installed in the melting system, and the mixing period is controlled to ensure that all the reinforcing elements are thoroughly mixed. Accordingly, the reinforcing particle size and shape have a more significant influence on molten state dispersion. Moreover, the cooling condition

and solidification rate during casting significantly impact the resulting performance of the case product [90,91].

For example, Alipour and Eslami-Farsani [60] synthesised the graphene/AA7068 nanocomposites by combining powder metallurgy and stir casting with ultrasonic waves with T6 heat treatment as a secondary process with graphene concentrations of 0.1, 0.3, 0.5, 0.7 and 1.0% by weight. The finding demonstrates that an addition of 0.5 wt% GNPs to the AA7068 matrix considerably affected the COF due to the adequate quantity of solid lubricant at the pairing surfaces of the sliding part.

Additionally, magnesium (Mg) powder is frequently used in liquid-state fabrication to promote the wettability between aluminium and graphene [92]. Chak and Chattopadhyay [93] added 1 wt% of Mg as a wettability agent to improve the wettability of GNPs in the base Al7075 matrix alloy and revealed exploits of the stir casting technique's capacity to produce uniform distribution GNP-reinforced Al7075 metal composites following T6 heat treatment. Furthermore, incorporating self-lubricating graphene in the Al7075 matrix greatly reduced the wear rate and COF of the manufactured nanocomposites, and the average surface morphology of the worn surfaces was evaluated



**Figure 6:** Image analyser of surface roughness for (a) aluminium matrix, (b) 0.1 wt% GNP/Al composites, (c) 0.3 wt% GNP/Al composites, and (d) 0.5 wt% GNP/Al composites. Reproduced from the study of Chak and Chattopadhyay [93].



with an image analyser, as shown in Figure 6. Figure 6 shows that the graphene-reinforced composites exhibit smoother surfaces due to the presence of fewer asperities than base matrix composites.

### 3.2 Effect of applied load

The aluminium nanocomposites experienced significant wear rate when the applied normal load varied [94]. A load or pressure exerted at the interface region is one of the most significant parameters and must be included because the product of load and velocity represents the severity of the tribological condition. Turan *et al.* [75] observed an increase in the wear rate up to 0.0127 and 0.0176 mm<sup>3</sup>·m<sup>-1</sup> for GNP-reinforced AlSi18CuNiMg and unreinforced AlSi18CuNiMg, respectively, for load 40 N with a sliding distance employed in dry ball-on-disc. The composite materials are reported to exhibit abrasive and oxidative wear mechanisms because of the heat generated by friction from the repeated load. However, the unreinforced materials experienced a delamination wear mechanism where a transition from mild abrasive wear to severe abrasive grooves occurred when the normal loads increase to 40 N.

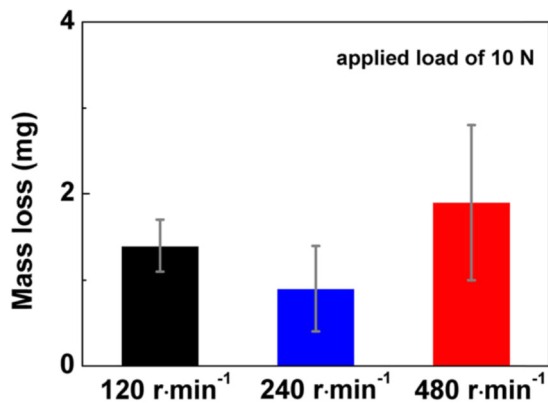
Zhang *et al.* [55] observed that GNPs/Zr-reinforced Al10SiMg underwent increasing wear loss with the increase in applied loads at relatively low load variation (5, 10, and 15 N). The main wear mechanisms under a low load of 5 N are adhesive and mixed abrasive wear, while fatigue and abrasive wear dominate the wear mechanisms under a load of 15 N due to the appearance of cracks and deep wear scars along the parallel surface for the GNPs/Zr-reinforced Al10SiMg. They discovered that the aluminium and oxide elements were evenly disseminated above the cleft of the crack, confirming the appearance of a mechanically mixed layer (MML) produced by Al<sub>2</sub>O<sub>3</sub> on the worn surface. Although graphene has good lubricating characteristics that decrease wear, fatigue damage is inevitable under continuous and severe loads. Chak and Chattopadhyay [93] recorded a similar observation in the wear rate increase for the GNP-reinforced Al7075 matrix composites while increasing normal loads under 5, 10, and 15 N by pin-on-disc. However, smoother surfaces and less delamination are detected for reinforced composites compared with craters detected on the Al7075 alloy, and the GNP reinforcement depicted smooth tribolayers. The wear loss of the base alloy was observed to be higher than that of the composites because the outer protective layer of the reinforced composites prevents the plastic deformation flow of the material under higher loading conditions. However, the composites performed

remarkably similarly to unreinforced alloy and delaminated when intermediate loading was applied to the sliding surfaces. Under these conditions, the addition of hard reinforcing contributed to creating a three-body abrasive tribosystem.

Islam *et al.* [65] investigated the tribological effect on aluminium reinforced with SiC nanoparticles and GNPs with 10 and 50 N normal loads. The results showed that the material loss rate significantly decreased for the specific wear rates. Meanwhile, the wear rate further decreased for the 10 N normal load and narrowly increased for the 50 N normal load because of the abrasive influence of the hard SiC nanoparticles that were possibly detached from the composite during the early phase of wear. By contrast, the presence of GNPs as an additional reinforcement material facilitates the dispersion of SiC nanoparticles compared with the individual GNP reinforcement through packing aluminium particles. Accordingly, GNPs assist in conformal reorganisation during dry lubrication of sliding wear. It also explains that the adhesive wear process resulted in a decreasing wear rate at a low load of 10 N with substantial plastic deformation through dry sliding. Naik *et al.* [78] found that the increase in wear rate with an increasing normal load is consistent with Archard's principle, which states that the wear rate tends gradually increases with a normal load. From a load perspective, the increment in load assists the counterface asperities infiltrating the aluminium surface and its hybrid composites. It is known that aluminium is quite soft and tends to easily wear in terms of material removal rate, especially for unreinforced aluminium. Hence, additional nanocarbons, such as graphene, significantly improve the hardness of ductile aluminium alloy because the hardness properties are a crucial factor in determining the material weight loss during engagement with other moving interfaces.

### 3.3 Effect of sliding speed

Gao *et al.* [95] reported the dry sliding wear characterisation of pure aluminium reinforced with GO particles. They investigated the behaviour of the matrix composites with the difference in the sliding speeds of 120, 240, and 480 rpm under variation normal loads. The reinforcement composites maintained their wear resistance; however, they had undesirable outcomes beyond the speed limitations, as shown in Figure 7 for the 0.3 wt% GO/Al composite for sliding speeds of 120, 240, and 480 rpm. The removal rate of the composites significantly increased as the sliding speed reached a transformation to a denser worn surface



**Figure 7:** Tribological properties of the 0.3 wt% GO/Al composite for mass loss at different sliding speeds. Reproduced from the study of Gao *et al.* [95].

at 480 rpm, indicating that the characteristics of the composite sample deteriorated at a high speed. This phenomenon occurs as the transfer layer of the surface of the composite becomes thick, originating in an excessive temperature and friction heating at a higher sliding speed [96]. As a result, the increased weight loss and reduction in abrasive wear of the composite occur at 480 rpm. This may be attributed to the more amount of worn debris protruding out from the counter disc at 480 rpm than at 240 rpm and reducing the adhesive wear of the composite at a higher speed. However, the wear resistance remains for composites under high sliding speed compared with the base aluminium. This phenomenon occurs because the introduction of graphene in the aluminium matrix enhances the hardness of the composite. When the graphene and matrix particles are pulled out of a composite, they generate a transition layer at the surface contact area, preventing the aluminium matrix from plastic deformation. Meanwhile, excellent self-lubrication properties of graphene on the contact surfaces enhance wear resistance and prevent oxidation.

Prashantha *et al.* [97] identified the decreasing trends in the wear loss of AA6061 reinforced with graphene and multi-walled carbon s (MWCNTs) on increasing the sliding speeds to  $0.15 \text{ m}\cdot\text{s}^{-1}$ . However, graphene/AA6061 composites with the same 0.5 wt% reinforcement addition are shown to have greater hardness compared to monolithic alloys and MWCNT-reinforced composites. The enhanced hardness is due to the homogeneous distribution and better dispersion strengthening mechanism with graphene reinforcement, and more heat is generated as the sliding speed increases. However, the high thermal conductivity in both reinforcements in the composite will result in thermal energy dispersing through the specimen at a rapid rate.

This phenomenon is also connected to the variance in interfacial bonding caused by different surface areas, where 2D graphene exhibits a large surface area, resulting in significantly higher wear resistance compared to that of MWCNTs.

### 3.4 Effect of graphene reinforcement

Graphene was chosen to strengthen self-lubricating metal nanocomposites because of its exceptionally high strength, lightweight, and lubricating characteristics [44]. In addition, adding graphene to an aluminium matrix should significantly increase its tribological and mechanical performance [98]. Accordingly, various researchers have added reinforcements to a variety of aluminium alloys to investigate the predicted impact on the tribological behaviour. Some researchers also revealed that the mechanical properties and wear performance of composites were increased compared with the basic aluminium alloy [99].

Sharma *et al.* [67] investigated the effect of the hybrid composite (GNP/SiC/Al, graphite/SiC/Al and CNT/SiC/Al) on the wear rate of the self-lubricating Al6061 hybrid nanocomposites by friction stir processing. The results demonstrate that the self-lubricating hybrid nanocomposite by GNP/SiC/Al has a better wear resistance in the dry sliding wear test compared with the as-received Al6061 alloy, unreinforced Al6061 alloy, graphite/SiC/Al, and CNT/SiC/Al, as shown in Figure 8. GNP/SiC/Al has an approximately 50% increase in wear resistance compared with the unreinforced alloy. The GNP tribolayer in the hybrid composite generates the consistency spread film in the matrix alloy instead of getting arrested in the surface asperities owing to the GNP's layered structure, large specific area, and wrinkled morphology of graphene flakes. The scanning electron microscopy (SEM) micrographs and energy-dispersive spectroscopy (EDS) spectrum reveal that the worn morphology of GNP/SiC/Al has a delicate parallel groove in the sliding route, as shown in Figure 9. However, Figure 10 shows coarse and large depth grooves with a delamination wear mechanism on the CNT/SiC/Al wear, as displayed in the SEM micrographs. The tubular structure and particles experience rolling of the CNT resulting in three-body mechanisms rather than shearing and squeezing out in the stacking of layers. The mechanism explains the non-appearance of a preventive barrier (protective layer) between the substrate and the wear track counterface due to distortion with a shortened length and damaged ends/tubular structure of the CNT.

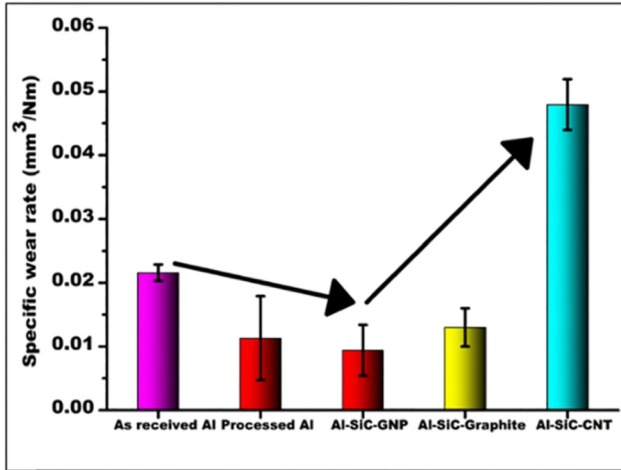


Figure 8: Variation of specific wear rates. Reproduced from the study of Sharma *et al.* [67].

Moustafa *et al.* [100] revealed an almost similar finding when they investigated ceramic particles Ta<sub>2</sub>C and VC with GNP and Al<sub>2</sub>O<sub>3</sub> nanoparticle-reinforced AA5083 with four different combinations of reinforcement materials, namely, Al<sub>2</sub>O<sub>3</sub> + Ta<sub>2</sub>C (H1), GNPs + Ta<sub>2</sub>C (H2), Al<sub>2</sub>O<sub>3</sub> + VC (H3), and GNPs + VC (H4), on the tribological behaviour of AA5083 using friction stir processing. According to the wear rate as assessed by the weight loss and the wear volume approach, the results showed that the GNPs/AA5058-Ta<sub>2</sub>C (H2) and GNPs/AA5058-VC (H4) hybrid composites experienced maximum wear resistance than the other fabricated hybrid composites. The reinforcement using GNP particles obstructs the pin of the wear tool from penetrating the wide regions. Consequently, incorporating GNPs with VC or Ta<sub>2</sub>C improves the tribology behaviour of the studied alloy. A proportion of GNPs might adhere to the surface during the wear testing and

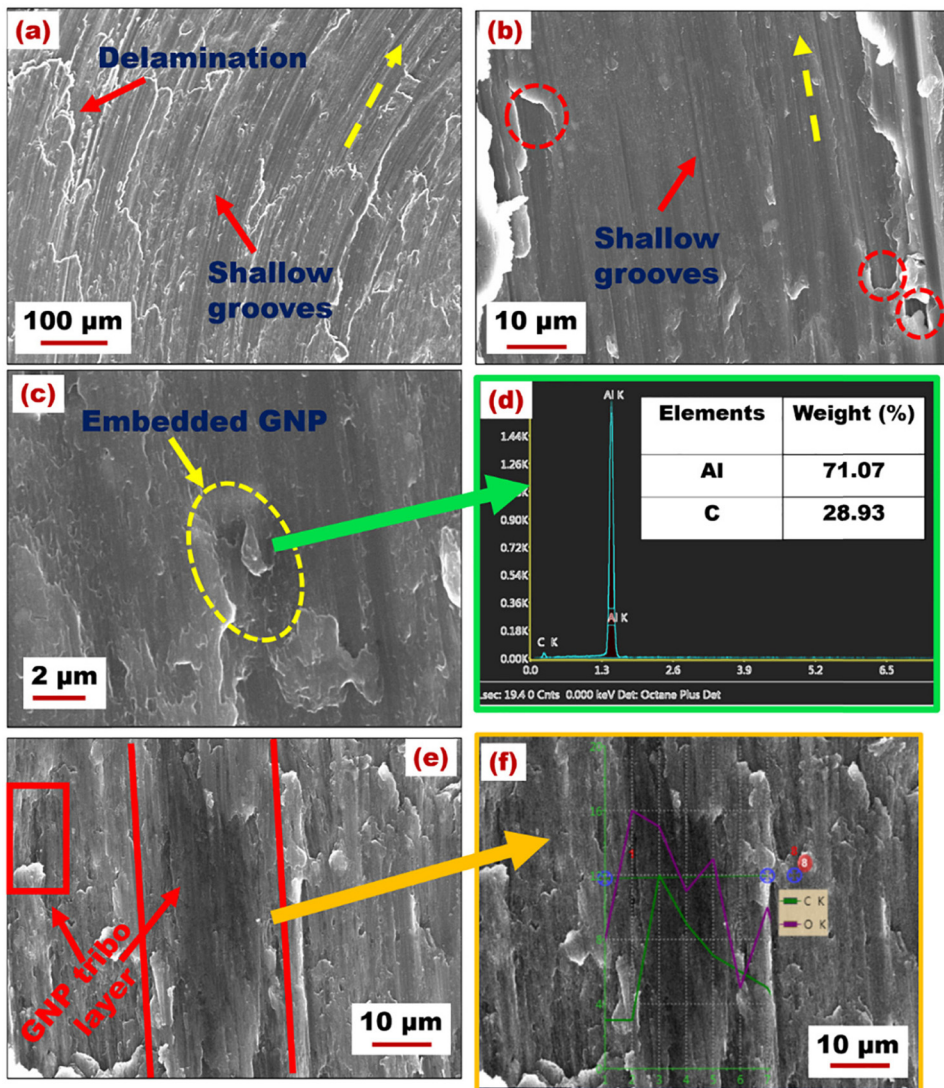
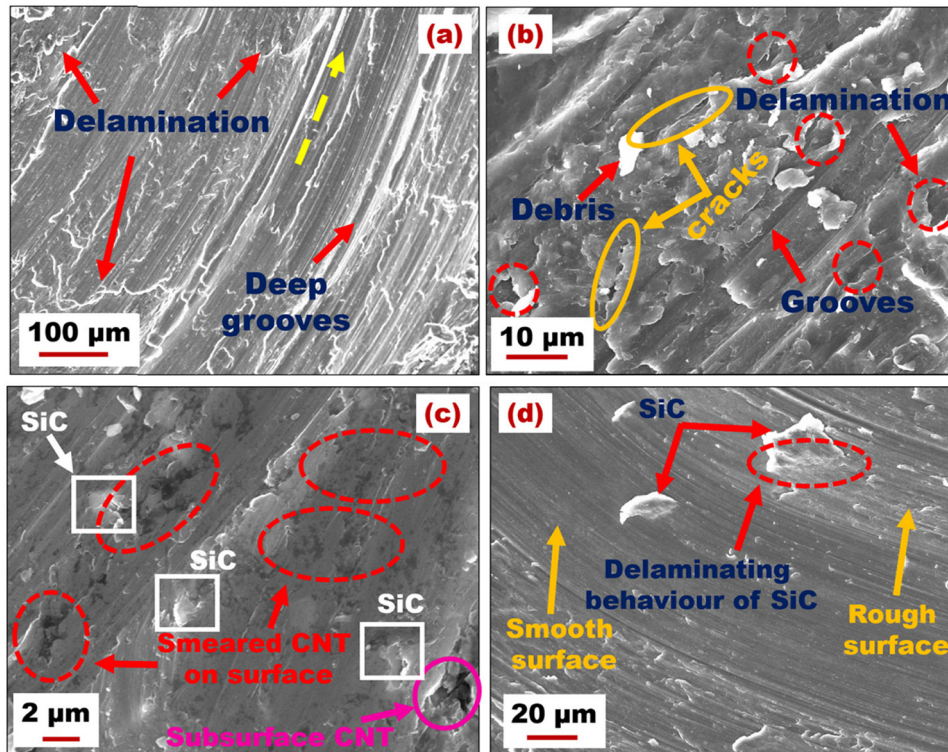


Figure 9: (a–c) Wear track morphology on the hybrid GNP/SiC/Al composite surface, (d) EDS analysis of the reinforcement GNP, (e) tribolayer graphene developed at the composites’ surface, and (f) confirming line shows the appearance of the tribolayer by EDS analysis. Reproduced from ref. [67].



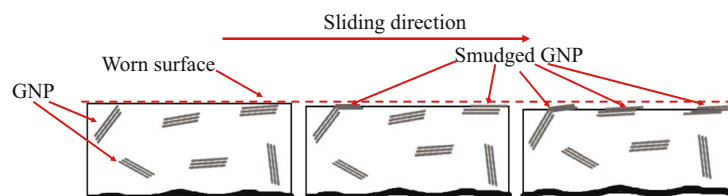


**Figure 10:** Morphology of worn track of the CNT/SiC/Al hybrid composite: (a–b) Deep groove with large debris with micro-sized on wear track due to the absence of protective layer. (c–d) SiC was pull-out from the CNT's subsurface region. Reproduced from the study of Sharma *et al.* [67].

present a lubricated surface, resulting in increased wear resistance. Furthermore, the layers in GNPs demonstrated weak van der Waals connections, allowing for simple sliding under shear forces and creating a self-lubricating composite [29,100]. Accordingly, the GNPs were force-pulled out and marked on the worn surface, as shown in the illustration in Figure 11. Thus, the wear behaviour of the nanocomposites containing GNPs was enhanced.

According to Sahoo *et al.* [101], the tribological study shows that more than 50% of the wear resistance of Al1100 reinforced with MLG is enhanced compared with graphite particles with a constant sliding speed of 20 rpm and a normal load of 20 N. This notion explains that MLG and graphite possess layered structures and exhibit self-lubricating characteristics. However, graphite requires a humidity surrounding so that the graphite particles are able to absorb water or lubricant molecules. The shearing activity is easier

when the absorption of water or lubricant molecules decreases the shear strength of the particles. However, the presence of MLG minimises wear and friction regardless of the surroundings. At the same time, El-Ghazaly *et al.* [102] analysed the significance of the reinforcements ratio on the tribological behaviour of Al2124 reinforced with graphene composite with graphene ratios of 3 and 5 wt%. They discovered that adding 5 wt% graphene did not affect the crystallite size due to the uneven distribution in the Al2124 composites compared with the homogeneous dispersion of 3 wt% graphene particles inside the Al2024 matrix. The agglomeration of 5 wt% graphene particles reveals the increasing wear rate and presents severe delamination compared with the mild delamination at high magnification for 3 wt% graphene particles. However, plain Al2124 reveals a severe abrasive wear mechanism but a mild abrasive one for 3 and 5 wt% graphene-reinforced Al2124



**Figure 11:** Illustration of the squeezed-out and smudged GNPs on the layer surface of the nanocomposite during the wear test process.



composites. Akçamlı *et al.* [22] investigated the wear rate of few-layered graphene (FLG)-reinforced Al10Si composites. FLG in different amounts (0.25, 0.5, 1, 2, and 5 wt%) affects the improvement of wear rate compared with the Al10Si matrix. However, the highest wear resistance is demonstrated by the composites reinforced by 2 wt% FLG. FLG-reinforced composites exhibit greater wear resistance than matrix structures during reciprocal wear testing due to the intervention of the reinforcement phase network in resisting the wear forces acting on the samples. The presence of graphene addition significantly affects the production of its lubricant and reduces wear.

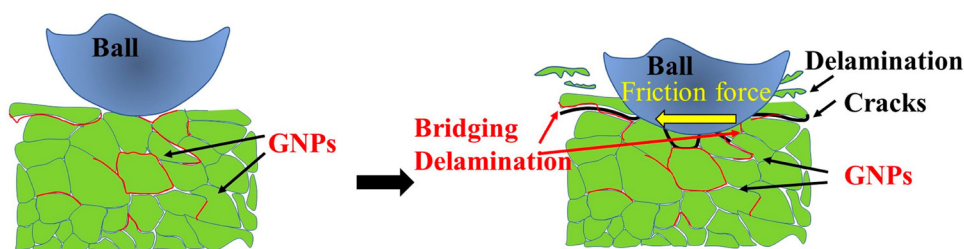
Daha *et al.* [103] experimentally examined the tribological behaviour of pure aluminium hybrid composites reinforced with varied contents of reduced GO (rGO) and alumina oxide ( $\text{Al}_2\text{O}_3$ ). The wear resistance decreased with the increase in rGO and  $\text{Al}_2\text{O}_3$  contents. However, the specimen with a high rGO content shows the least mass loss than the hybrid reinforcement. The decrease in wear resistance with a high  $\text{Al}_2\text{O}_3$  content shows that the specimen experiences considerable agglomeration, resulting in porosities and cavities. The nano-sized reinforcement particles are practical in the level of self-lubrication compared with the micro-sized particles in the reinforced composites. Abbas Shafiqat *et al.* [68] presented the tribological results in terms of the wear rate for GNPs/10 wt%  $\text{B}_4\text{C}/\text{Al6061}$  with different GNP contents (0.25, 0.6, and 1.2 wt%). Wear loss was reduced by approximately 69 and 54% in 0.6 wt% GNPs compared with unreinforced Al 6061 alloy and Al 6061/10 wt%  $\text{B}_4\text{C}$  composite, respectively. This significant decrease in wear loss is ascribed to the use of reinforced composites, providing dry lubrication and a slight layer between contact surfaces. However, the wear rate decreased with the addition of 1.2 wt% due to agglomeration.

## 4 Worn surface morphology

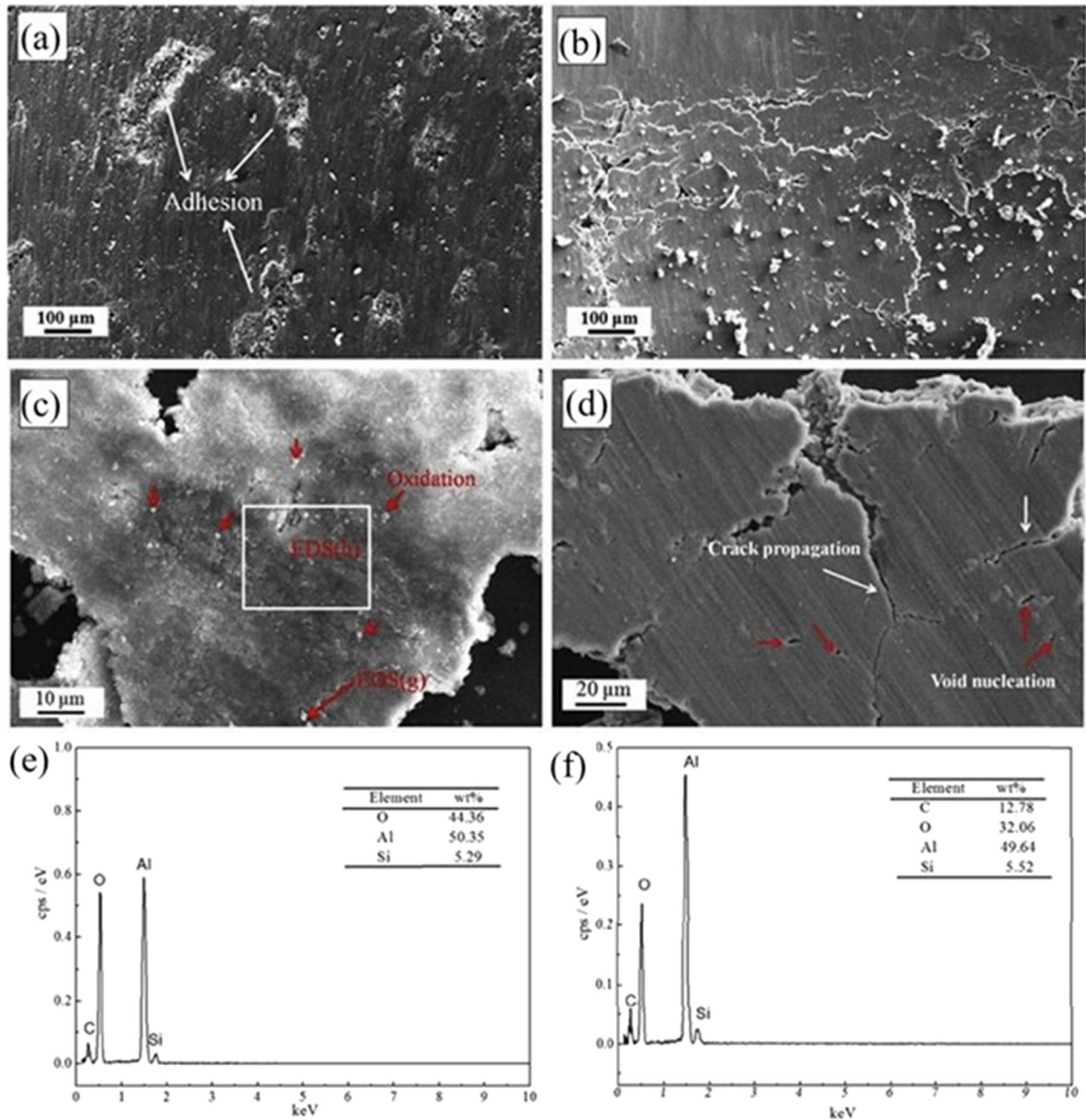
Several wear mechanisms, such as delamination, adhesive, abrasive, and fretting, have been observed in the case of

graphene-reinforced aluminium MMCs. Moreover, wear and friction response may differ to a certain extent depending on the test factors, loading conditions, weight or volume of reinforcement fraction, interfacial bonding, dispersion quality, and microstructural impurities [43]. Aluminium alloys basically have different wear mechanisms, which are mild because of oxidation and severe metallic wear. However, adhesive and abrasive wear mechanisms are the most common in the tribological application of aluminium MMCs, while some cases reported the mechanism of delamination wear in nanoparticle-reinforced composites [98]. Figure 12 illustrates the delamination mechanisms due to poor bonding in the reinforcement and matrix interfacial region. Hence, this phenomenon impaired the mechanical characteristics of composites due to an inhomogeneous mixture of the matrix and reinforcement materials. The absence of thin laminates characterises delamination wear as wear debris resulting from instability crack initiation at the bottom layer of the tribosurface [98,104]. Meanwhile, the appearance of pits and a prow after plastic deformation is defined as adhesive wear. The adhesive bond between the sliding surfaces causes adhesive wear. However, the pits on the surface of the composites exhibited adhesive wear that was less than that exhibited by the delamination mechanism. The abrasive wear was characterised by parallel grooves resulting from microploughing and microcutting.

According to the analyses of tribology conducted at varied normal loads, the increase in the applied load significantly affected the wear mechanisms by accelerating the surface deterioration under *in situ* sliding conditions. Zeng *et al.* [63] found that the oxidation layer was formed on the worn surface of the rGO/SiCp/Al-Si hybrid composites at a load of 1 N with shallow grooves, scratches, and craters (Figure 13(a) and (c)). The EDS spectrum in Figure 13(e) shows the high formation of the oxidation layer, indicating that abrasive wear is the main wear mechanism and is accompanied by adhesive wear at a low load. However, the rGO/SiCp/Al-Si hybrid composites form coarse flake-like worn debris with crack propagation, as shown in Figure 13(b) and (d), at a load of 3.2 N. In this finding, the severe plastic deformation causes



**Figure 12:** Schematic illustration of the delamination wear mechanism for the influence of GNPs on the wear resistance. Reproduced from the study of Wu *et al.* [105].

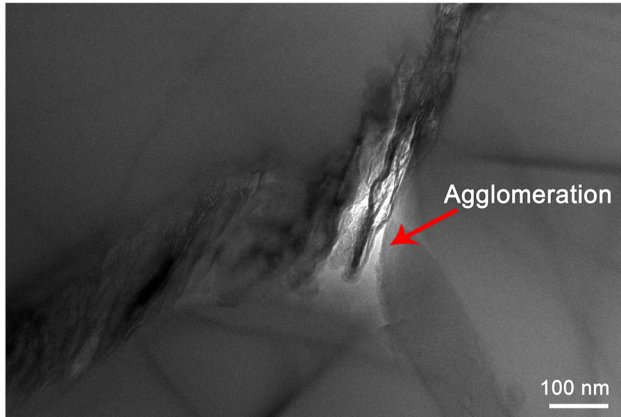


**Figure 13:** Worn surface and wear debris at high magnification images of the rGO/SiCp/Al-Si hybrid composite under normally applied loads of 1 N (a and c) and 3.2 N (b and d); the surface of the rGO/SiCp/Al-Si hybrid composite using the EDS spectrum under an applied normal load of 1 N at (e) and (f). Reproduced from the study of Zeng *et al.* [63].

ductile shearing and results in delamination wear at a high load due to aggregation of rGO near the subsurface region.

The amount of graphene also influences the wear mechanisms of the self-lubricating aluminium composites. Generally, the increase in graphene led to an increase in the strength of the composite. However, increasing the amount of graphene led to agglomeration due to the

increasing graphene layer as shown in Figure 14 [106]. This situation affects the strength where the cracks will be promoted and deteriorate the mechanical properties and wear resistance. Du *et al.* [107] analysed the worn surface of the 0.25 wt% SiC/Al7075 composite with various graphene content (0.25 and 0.5 wt%) with constant load (10 N), speed ( $0.02 \text{ m}\cdot\text{s}^{-1}$ ), and sliding distance (24 m). In



**Figure 14:** TEM image of agglomeration of rGO-reinforced aluminium composites with excessive rGO. Reproduced from ref. [106].

this finding, a large amount of wear debris and more furrows are observed on the worn surface of SiC/Al7075 than on the graphene-reinforced composites due to the deformation of the matrix during sliding, while the presence of furrows is related to the abrasive wear mechanism. However, the increasing graphene content changes the wear mechanism from abrasive wear to delamination wear since there is an increased potential for cracks near the agglomerated graphene, which causes a transition to the severe wear stage. This phenomenon occurs because graphene is compressed under load and entrapped with some wear debris due to its lubricity and large specific surface area; hence, graphene materials are gradually exposed to the worn surface. Consequently, more graphene accumulates on the wear surface to form a dry lubrication layer because the wear progresses with the occurrence of frictional activity. Nevertheless, wear mechanisms may also vary based on the number of variables involved, such as the wear condition, manufacturing process, and reinforcement size and type.

## 5 Friction behaviour

The COF between aluminium MMCs and hardened steel counterface greatly varies from low to high values. Friction is the resistance to movement between two contact surfaces and is often characterised by the dimensionless COF [98]. After sliding for a short duration, the surface of the tribolayer is protected with graphene-rich lubricating tribofilms due to the overspread of graphene in the aluminium reinforced with graphene composites [69]. However, interlayer sliding of graphene frequently occurs after a long sliding owing to the weak van der Waals connection between graphene,

significantly reducing the frictional force and COF of graphene-reinforced aluminium matrix composites. Moreover, due to the absence of multilayer sliding, the self-lubricating function cannot be accomplished by integrating single-layer graphene into aluminium. Mohammadi *et al.* [108] performed the simulations for molecular dynamics and discovered that adding a single-layer graphene into an aluminium matrix resulted in a significant COF. Therefore, the increased COF value by adding MLG such as GNPs, GNSs, or FLG is more advantageous for generating appealing self-lubricating characteristics. The presence of graphene layers results in the formation of a sustained solid-lubricating graphene coating at the surface contact and lowers the actual area of the roughness contact between the composites and the counterface.

Graphene-reinforced aluminium MMCs are projected to have a low overall COF because the friction for the deformation and adhesive parts is expected to decrease. Furthermore, the addition of graphene to an aluminium matrix improved the material characteristics such as hardness, tensile strength, and ductility. However, with various conditions in wear behaviour, a combination of factors, such as test variables, reinforcement content, and material properties, that are affected by the process greatly influences the friction properties. Therefore, various researchers have reported different values that either support or conflict with each other's information but no general principle can be determined.

A few researchers investigated a load range of 5–20 N [109,110] and a high load range of 30 N [111] up to 50 N [112] and 100 N [113]. They found that the COF of the aluminium alloy is higher than that of nanocomposites with different contents of reinforcements and sliding speeds. Şenel *et al.* [66] reported an interesting COF value decreasing with increasing load in the range of 10–40 N for unreinforced aluminium and reinforced composites. However, the friction value of unreinforced aluminium is higher than that of the reinforced composites. Hence, adding GNPs as a solid lubricant was persuasive due to their self-lubricating characteristics.

Omrani *et al.* [74] reported an increase in COF with increasing load for unreinforced aluminium alloys due to ploughing. However, a slight decrease in the COF was observed with an increasing normal load for the GNPs/Al<sub>2</sub>O<sub>3</sub>/Al hybrid nanocomposite. This situation reflects that higher wear releases more solid lubricant into the contact area due to the reinforcing lubricant behaviour. Specifically, substantial wear initially occurs when a normal load is increased. The larger quantity of worn composite materials consequently transfers more mixture of graphene as lubricant and alumina onto the contact surface area. Thus, these



freed mixture particles can generate a protecting tribofilm. Fathy *et al.* [114] reported that the COF increases with the increased normal load for the  $\text{Al}_2\text{O}_3/\text{Al}$  and  $\text{GNPs}/\text{Al}_2\text{O}_3/\text{Al}$  nanocomposites at a constant sliding speed of  $1\text{ m}\cdot\text{s}^{-1}$ . However, the COF of the  $\text{GNPs}/\text{Al}_2\text{O}_3/\text{Al}$  composites is lower than that of  $\text{Al}_2\text{O}_3/\text{Al}$  because the stronger GNP reinforcement particles act as asperities to resist the load, leading to reducing the contact area between the pin and composites counterface and resulting in lowering the COF.

In contrast with other published studies, Alipour *et al.* [115] demonstrated that the COF of the AA7068 aluminium alloy reinforced with GNPs decreases with increasing normal loads in all cases. The observation shows that the COF experiences a significant decrease at higher normal loads (40 N) compared to lower normal loads (10 and 20 N). The refinement of the grain size and finer distribution of second phases in T6 heat-treated 0.5 wt%  $\text{GNPs}/\text{AA7068}$  nanocomposites, probably from the uniform distribution and dispersion of GNPs, contribute to reducing the friction coefficient at high load.

Meanwhile, sliding speed is one of the crucial test parameter factors affecting the tribological behaviour of graphene-reinforced aluminium matrix composites. The effect of the sliding speed on wear can decrease when the wear resistance and the temperature at the interface between the surfaces increase. This effect softened the matrix phase and led to increased oxidation rates and reduced the flow stress in the composite. Consequently, various sliding speed impacts on graphene-reinforced MMCs can be observed with different sliding speed parameters.

Tabandeh-Khorshid *et al.* [94] reported the influence of different sliding speeds (50, 100, and 150 rpm) on the COF of pure aluminium reinforced by 1.0 wt% GNPs. The sufficient formation of the self-lubrication graphene film during a 100 rpm sliding speed was attributed to the decrease in the COF of 1 wt%  $\text{GNPs}/\text{Al}$  compared with 50 and 150 rpm sliding speeds. Wu *et al.* [105] reported that the increasing sliding speed of  $0.9\text{ m}\cdot\text{s}^{-1}$  decreases the COF of  $\text{GNPs}/\text{AlSi10Mg}$  due to the self-lubrication property of GNPs. The self-lubricating characteristics in GNPs facilitate the interlayer sliding formation and efficiently reduce friction. The distribution of the oxidation content at a  $0.9\text{ m}\cdot\text{s}^{-1}$  high sliding speed due to the high temperature between the sliding interface produces a thick and stable MML as composites and protects the sliding interface. This situation prohibits direct contact of the counter body with the surface of the reinforced composites. Prashantha Kumar *et al.* [109] conducted the tribology test on Al6061 and graphene at various sliding speeds of 0.4, 0.8, and  $1.2\text{ m}\cdot\text{s}^{-1}$  at room temperature. They also observed similar behaviour in that the COF is reduced at a higher sliding speed of  $1.2\text{ m}\cdot\text{s}^{-1}$ ,

where the excessive wear debris on the worn surface is formed at a high sliding speed due to the increased frictional temperature at a high sliding speed.

Most investigators [62,68] have found that the COF decreases with an acceptable amount of nanoparticles. Moreover, the increase in graphene increases the surface area of the tribofilm on the surface of the composite. They attributed this phenomenon to the enhanced hardness caused by particles consistently dispersed in the aluminium matrix. A consistent dispersion can maintain the load while reducing the contact area between the counter surface and the composite, where contact and adhesion between the surfaces are reduced. The chips generate the three-body abrasive wear, and microplothing wear makes both wear the main wear mechanisms. These phenomena encourage the formation of a solid and protective surface layer on the worn morphology and increase the wear resistance. Hence, the COF of the reinforcement composites is significantly lower compared with the unreinforced composites.

Chak and Chattopadhyay [72] reveal that the graphene amount (0.1, 0.3, and 0.5 wt%) affects the friction with a significant reduction by 24.78% in COF for 0.5 wt% GNPs as the optimum percentage compared with the basic alloy. The coefficient variation revealed the COF between reinforcing material and base alloy, where the self-lubricating graphene reduces the abrasion of wear. Liu *et al.* [116] reported that the COF of aluminium is decreased after adding the multilayer of rGO with copper coating. However, the COF decreased when the content of the multilayer of rGO/Cu was up to 4%, while the other contents (1, 2, and 3%) increased after 30 min of sliding with 20 N of load. This phenomenon was related to grain refinement and the increasing hardness when the content of a multilayer of rGO/Cu where the graphene lubrication film formed increased. Such a situation can be explained by the fact that thin multilayers of graphene can easily access the cavity of the composite and reduce the roughness of the contact surface. Therefore, the COF tends to decrease.

However, Martin *et al.* [73] found an increased COF of A360 with an increasing content of 0.5 wt% GNPs at room temperature, 150 and 300°C compared with 0.25 wt%, which has minimal average COF values. This phenomenon can be attributed to the nonhomogeneous distribution and agglomeration that occurred at 0.5 wt% GNPs across the composite. Hence, the agglomeration results in the absence of reinforcement in the material, resulting in a larger surface contact area under the load, while increasing temperature contributes to the ductility on the contact surface during sliding.

Srivivas and Charoo [117] revealed the decreasing COF of  $\text{SiC}/\text{Al-Si}$  with different GNP percentage hybrid composites with the increase in temperature until 300°C. The COF



of 5 wt% GNP/6 wt% SiC/Al-Si enhances the friction behaviour and presents lubrication even at elevated temperatures. This is due to the presence of an oxide layer due to excessive thermal stress. The development of the oxide layer at low temperatures between two contact surfaces provides the opportunity to avoid direct hardened steel and matrix composite contact, resulting in a reduced COF. However, the transition from mild to severe wear occurs at temperatures greater than 200°C. High temperatures soften and weaken the matrix due to plastic deformation. Accordingly, changes at high temperatures allow delamination wear to remove the inactive oxide layer. Although passive oxide film formation occurs with the increase in temperature, only a small amount of the hard phase is exfoliated from the worn surface due to the presence of lubricants in composites.

The continuous sliding leads to the wear resistance of composites for all GNP contents to decrease at 400°C owing to the removal of coarse wear particles through crack propagation, sub-surface crack nucleation, and plastic deformation of the surface layer. The worn debris stuck at the edges of the crack ascribed to the matrix softening was easily removed at high temperatures, resulting in an increased COF. Accordingly, the COF relies on the fraction of energy dissolved in the counterface and composite surface or on the large interaction of contact asperities varying within any specific parameter range during the entire duration of the wear test. This condition is also affected by particle decohesion, which enhances the roughness of the surface and leads to higher friction [118].

## 6 Summary

Graphene nanoparticles have revealed a significant improvement in dry self-lubricating wear characteristics. Numerous studies on wear and friction have been analysed and compared from various perspectives. Table 3 exhibits that previous studies mostly used powder metallurgy and friction stir process in their work, while stir-casting or squeeze-casting methods were also considered. This notion indicates that solid-based fabrication processes have been widely studied and used in many fields due to their excellent stability and performance. Powder metallurgy has also been extensively used in composite manufacturing owing to its flexibility in producing components with precisely controlled weight or volume fractions.

Stir casting is the secondmost used skilled thermal or melting process for composites after powder metallurgy. The contributing factors include the ease of casting, low cost,

improved performance, increased manufacturing capacity, and versatility of those liquid state processes. Nonetheless, the fabrication techniques with correct parameters can further expand if typical drawbacks that damage mechanical and tribological qualities, such as poor wettability, reinforcement agglomeration, and non-uniform distribution of graphene in the matrix. Furthermore, Mg is frequently employed as a wetting agent to reduce the surface tension of graphene and serve as the intermediate bridge between matrix and reinforcing material. Moreover, the secondary process such as semisolid metal processing, forging, extrusion, and rolling can further improve the mechanical properties and tribological behaviour of the composites. Hence, efficient manufacturing is essential because it enables the generation of considerable grain refinement and heterogeneous nucleation, which are necessary for achieving the strengthening mechanism between graphene and an aluminium matrix.

The following factors contribute to the strengthening mechanism of graphene-reinforced aluminium matrix composites:

- 1) Orowan looping of graphene particles,
- 2) load transfer from aluminium matrix to graphene,
- 3) mismatch in the elastic modulus or in the CTE,
- 4) grain refinement strengthening [26].

Every strengthening mechanism may play a role in the process of further strengthening the composites but this will depend on the process parameters that were utilised to create the composites.

Recent years have witnessed a significant increase in interest in the use of hybrid reinforcements, and considerable effort has been devoted to investigating composites with at least two hybrid reinforcements, including graphene. The goal of hybridisation might greatly vary. For instance, two reinforcing elements will be utilised, with one serving to strengthen and the other serving to lubricate the hybridised material. Accordingly, a self-lubricating hybrid aluminium MMNC with improved wear and mechanical properties can be generated. Hybridisation is a potentially useful technology that can be a highly effective approach for wear applications on aluminium matrix composites, even when using the same reinforcement type with various sizes. Lin *et al.* [119] examined the microstructure of hybrid aluminium matrix nanocomposites and discovered that those nano-reinforcing agents are typically found in the base  $\alpha$ -aluminium, whereas micro-sized particles tend to resolve in eutectic phases at intragranular regions; similarly, the strengthening mechanisms in different loading conditions. For instance, composites reinforced with nano-sized particles may possess excellent wear resistance compared with

those reinforced with micro-sized particles [120]. According to capture theories, reducing particle size allows the reinforcement to be captured or engulfed more effectively by a particular melt matrix. Thus, increasing the amount of nanofillers could significantly improve the mechanical and tribological properties because long particles are well-dispersed and uniformly distributed in the matrix alloy.

Considering the summary above, the effect of graphene on the wear resistance of aluminium matrix composites has been found and classified according to the various test criteria. The effects are then thoroughly discussed to understand their wear behaviour extensively. Additionally, the three primary regulating mechanisms studying the wear behaviour of nanocomposites are abrasion, delamination, and adhesive, which have been extensively covered in earlier reviews [121,122]. The surface of the composite may become harder and more refined with the addition of graphene reinforcement equally disseminated throughout the host matrix, and the regulating mechanisms from adhesion and delamination may change to abrasion.

## 7 Conclusion and future directions

This review overviews the influences various researchers contributed to the wear properties and characterisations for the wide application of aluminium MMCs incorporated with graphene reinforcement as self-lubricating materials. Graphene reinforcement particles enhance the wear resistance and strength of aluminium matrix composites. Additionally, the wear resistance is increased by inserting more graphene reinforcement particles. However, the wear or mechanical qualities begin to deteriorate after reaching a certain weight percentage due to the agglomeration development of graphene in the aluminium matrix. Furthermore, powder metallurgy is the most popular process for producing graphene-reinforced aluminium matrix composites due to its advantages in adjusting the weight fraction and achieving good distribution of graphene in the matrix. Meanwhile, the casting method is also regularly used owing to its straightforward process, flexibility, and great potential for mass production.

The wear and friction performance of graphene-reinforced aluminium matrix composites were dependent on the intrinsic variables, such as the content of graphene and the manufacturing method, and the extrinsic variables, such as applied normal load and sliding speed. A comprehensive examination reveals that the intrinsic parameters have a longer-lasting influence on the wear performance of graphene-reinforced aluminium matrix composites compared to extrinsic parameters.

The wear rate and COF increase when the sliding speed and normal load are increased due to the expansion in the surface contact area. Oxidation and abrasive wear were shown to be the prevalent wear mechanisms at higher normal loads, while the low normal load dominated adhesive wear. The oxide layer ruptures when a critical pressure load exceeds the crucial value, resulting in high friction with a high wear rate and generating delamination. Graphene-reinforced aluminium matrix composites experience significant pressure loading when the wear mechanism is suddenly transformed from moderate to severe wear. In this case, graphene might be used as a nanoparticle coating for the protective layer, increasing its resistance to damage and allowing it to withstand greater loads before failing under extreme conditions.

From the industrial view, the demand for composite, especially in the automotive and aviation industry, is on an increasing trend because of the excellent properties offered by these materials. The excellent self-lubricating properties of graphene also offer continuous development in the wear resistance of composites. Therefore, a significant amount of work must be directed into industrialising graphene-reinforced aluminium matrix composites for use in such applications. Producing commercially and affordable graphene-reinforced aluminium matrix composites with enhanced mechanical and tribological performance should be prioritised. Overall, the inconsistency of the results reported thus far in the review can be attributed to the large number of wear variables included in graphene-reinforced aluminium MMNCs. The discrepancy also arises from the dissimilar graphene derivatives utilised, the type of wear test, the processing method, and the graphene amount used. Therefore, a more systematic method is necessary for their production and tribological characterisation to have a thorough comprehension of the behaviour and responsiveness of these composites.

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