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REVIEW ARTICLE

2D materials enhancing tribological performance in bulk and composite coatings: a review

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Abstract
The tribological properties of materials, such as wear, scratch resistance, corrosion resistance, and surface hardness, are heavily influenced by surface conditions. Therefore, understanding tribological behavior is a significant challenge in surface engineering. Typically, this behavior is controlled by applying protective coatings or layers post-fabrication of bulk components or by adding secondary reinforcements during manufacturing to enhance the performance of utilized bulk materials. These secondary reinforcements, including self-lubricating particles, ceramic particles, can also be incorporated into coatings to form composite layers. Particularly, developing 2D materials exhibit significant potential as secondary reinforcements for boosting tribological performance in both bulk materials and coatings. However, there is a lack of comprehensive understanding regarding their role in wear resistance and their interface interactions with various metal, ceramic, and polymer matrices. Furthermore, the production methods for incorporating 2D reinforcements into these matrices are not well-documented. This review addresses these gaps by emphasizing the importance of tribology and clarifying the essential role of 2D materials in enhancing the tribological behavior of composites. It explores the interface connection between 2D materials and different matrices, and examines various production techniques used to integrate these materials into bulk and coatings. This comprehensive review aims to provide insights that will facilitate the development of advanced tribological solutions in surface engineering.

Keywords Tribology · 2D materials · Composites · Coatings · Wear

Abbreviations

2DLMs	Two-dimensional layered materials
2DMs	2D materials
2DRs	2D reinforcements
ABS	Acrylonitrile butadiene styrene
BS	Bovine serum
CF	Carbon fiber
CFRP	Carbon fiber reinforced polymer
CMC	Ceramic matrix composite
CNT	Carbon nanotube
COF	Friction coefficient
DED	Directed energy deposition
GO	Graphene oxide
h-BN	Hexagonal boron nitride
LDH	Double-layered hydroxide
L-PBF	Laser powder bed fusion
MMC	Metal matrix composite
MOF	Metal oxide framework
PA	Polyamide
PAEK	Polyaryletherketone
PDA	Polydopamine
PEEK	Polyetheretherketone
PEO	Plasma electrolytic oxidation
PI	Polyimide
PMC	Polymer matrix composite
PMMA	Poly(methyl methacrylate)
PPS	Polyphenylene sulfide
PPTA	Poly(p-phenylene terephthalamide)
PS	Physiological saline
PTFE	Polytetrafluoroethylene
PU	Polyurethane
SBF	Simulated body fluid
SPS	Spark plasma sintering
Ti64	Titanium–6Aluminum–4Vanadium

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1 Introduction

1.1 Tribology and its importance

One of the importance of the studying the surface of components is to understand the tribology behavior of the system including friction, wear, scratch, and corrosion resistance. There are different factors that influence of the tribology performance, such as surface condition, loading condition, working atmosphere, chemical composition, which are well investigated in the literature [1–4]. The effect of the loading ratio and surface hardness was previously predicted and introduced as Archard equation to predict wear resistance as below:

$$Q = \frac{K \times W}{H} \quad (1)$$

where, Q is wear rate, and W presents the loading ratio and H represents the surface hardness. K implies the surface condition. The wear map of steel components, also known as Lim-Ashby wear map [5], was plotted by considering the normalized applied pressure and normalized velocity of contact surfaces regarding to each other. Three different areas can be detected on the wear map including: seizure, severe wear and mild wear. The active mechanism in each area are different and the severe and mild wears are categorized. The active mechanisms are melting, abrasion, adhesion, and fatigue wears in severe wear and oxidational and ultra-mild wear in the mild wear regime. The factor K in the above equation was considered as a constant because there was no advanced equipment to study the influence of the surface condition on wear rate in that time. The effect of the surface condition was investigated recently in reported studies e.g. by Tabrizi et al. to predict the wear rate of diffusive and precipitated coatings and layers [6–8].

While, there are commonly used approaches to enhance tribological behavior, such as surface modification and lubrication techniques, it is important to note that these are just a subset of the wide array of methods available for improving performance. Tribology encompasses a diverse range of strategies, including material selection, design optimization, surface coatings, and environmental controls, among others, each offering unique ways to enhance the efficiency and durability of mechanical systems. Frequently, there are two main common elucidations to boost the tribology behavior of components; the first one is to applying protective coatings such as chromium or nickel electroplating [9–11], carburizing or nitriding, oxidizing, plasma treatment, ion bombardment [12] and etc. The second solution is to insert particular reinforcement particles to the bulk materials fabrication procedure or applying a coating to obtained composite bulk and coatings. For this aim, hard particles such as carbides, nitrides, borides and oxides including SiC [13], TiO_2 [14], Al_2O_3 [15], TiN [16], TiB_2 [17], B_4C [18] and etc. are frequently utilized. Recently, utilization of the high entropy powders as a reinforcement is increasing too [19]. There is another group of materials, which is introduced recently as reinforcement for improving the tribology behavior called 2D materials [20]. Some of the 2D materials like h-BN and MoS_2 have self-lubricating feature, which makes them good candidate to reduce the friction coefficient and enhance the wear resistance [8]. These 2D materials can be utilized separately or as a mixture to illustrate the synergic effect [21]. For example, Xu et al. [22] reviewed the utilization of a mixture of graphene and MoS_2 in diverse nanocomposites.

Although the types of the reinforcements is effective on the tribological performance of the composites, there are other effective factors including reinforcement orientation and distribution, volume fraction, manufacturing process and interface connection between reinforcement and matrix. In other words, in the composite materials, friction coefficient could be categorized in three different terms as below:

$$\mu_t = \mu_r + \mu_m + \mu_i \quad (2)$$

where, μ_t is the total friction coefficient; μ_r and μ_m imply the share of reinforcement and matrix, respectively. The μ_i indicates the share of the interface between reinforcements and matrix. This term, μ_i, is a function of the average surface area of the each reinforcements (A) and the number of them (n) as shown in Eq. 3 as below:

$$\mu_i = f(A, n) \quad (3)$$

From the geometrical aspect of view, the surface area is a function of the size of reinforcements and shape of them. Therefore, it can be concluded that the size of reinforcements, shape, amount and distribution of them are key parameters that should be considered for improving the wear resistance of the composites. This statement reveals the reason of the eagerness to utilize the 2DMs to improve the tribology behavior. In other words, the surface area of 2DMs is higher compared to conventional reinforcement such as SiC due to their nano size, and random shape features. Therefore, more area is available at the interface of reinforcements/matrix, and a greater number of the 2DMs compared to conventional micron size reinforcements at the same loading ratio, which influence the μ_i based on Eq. 3. There is another mode of Eq. 2. By addition of the second phase reinforcements to the matrix of composites, new interfaces are commenced, which can strongly affect the friction coefficient. Thus, Eq. 2 can be rewritten as below Eq. 4:

$$\mu_t = \mu_r + \mu_m + \mu_{Sec.m} + \mu_i{'} \quad (4)$$

where, $\mu_{sec.m}$ indicates the friction between second reinforcements and matrix, and the μ_i' is the sum of the three different formed interface by addition of the 2D reinforcements including interfaces of matrix/reinforcement ($\mu_i^{m.r}$), matrix/2D reinforcement, ($\mu_i^{m.2D}$) and reinforcement/2D reinforcement ($\mu_i^{r.2D}$). The share of the interface between reinforcements and matrix is divided to three different parts because by addition of 2D reinforcement, the 2D particles placed self-preferably on any location in matrix separately or in touch with main reinforcements. The μ_i' can be written as below as Eq. 5:

$$\mu_i\prime = \mu_i^{m.r} + \mu_i^{m.2D} + \mu_i^{r.2D} \quad (5)$$

On the other hand, the manufacturing process should guarantee the bonding of 2D reinforcements with the matrix, while modern fabrication processes including wire arc additive manufacturing (WAAM) [23], additive manufacturing (AM), selective laser melting (SLM) [24], and plasma-enhanced processes, and help toward establishment [25] of better tribological performance. In other words, the integration of 2DRs into composites has demonstrated significant promise in improving tribological performance. Conventional manufacturing procedures such as forging, powder metallurgy, and casting are having problems in fabrication of composites with uniform distribution of reinforcements [26]. The employment of the modern fabrication techniques, particularly additive manufacturing, has revolutionized the fabrication of the composites. The critical challenges are related to dispersion and interface bonding, which are less understood for SLM [27]. The novel AM methods allow for precise control over the facilitating uniform distribution of 2DRs, for instance, Guo et al. [28] reported the in situ fabrication of Ti–6Al–4V–B_4C through SLM. Additionally, Zhao et al. [25] elaborated the main mechanisms of friction-reducing propertied of 3D printed structures are including reduction of actual contact area, availability of storage space for wear debris and continuous lubrication due to the formation tribofilm in the presence of solid lubrications.

2 2D materials

Since, the revolutionary discovery of graphene, the field of two-dimensional layered materials (2DLMs) has attracted significant scientific and industrial interest due to their unique properties and potential applications. 2DMs consists of materials that are only one or a few atoms thick, where the atoms are covalently bonded within the layers and stacked together through van der Waals forces. These materials demonstrate significant electrical, thermal, and optical properties that make them suitable for a wide range of applications, from electronic to energy storage [29]. Graphene, the first discovered 2D material, has established the way for exploring other 2DMs such as transition metal dichalcogenides (TMDs) (MX_2, M represents a metal element, X implies dichalcogenide like MoS_2 and WS_2), black phosphorus, complex metal oxides, and hexagonal-boron nitride (h-BN). Each of these materials possesses unique features. For instance, TMDs have a direct bandgap, making them excellent for electronic and optoelectronic devices, while h-BN is known for its exceptional thermal and chemical stability and also its self-lubricating feature and utilized in tribological applications. The general family of 2DLMs is shown in Table 1. Although there are well structured reported reviews available in the literature [30–33], there is a rare study in focusing on their applications in the tribology [34]. The assembly of these 2DLMs to each other with desired van der Waals interactions is called "heterostructure". In other words, a monolayer puts it on top of another mono- or a few layers. Indeed, a combination of any 2DLMs with 0D (plasmonic nanoparticles, quantum dots), 1D nanostructures

Table 1 Categorized of known family of 2D layered materials based on chemical composition and structural characterization

Graphene family	Graphene
	h-BN
	BCN
	Fluorographene
	Graphene Oxide
	Borophene
2D chalcogenides	MoS_2, WS_2, $MoSe_2$, WSe_2
	Semiconducting Dichalcogenides $MoTe_2$, WTe_2, ZrS_2, $ZrSe_2$
	Metallic Dichalcogenides $NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$
	Layered Semiconductors GaSe, GaTe, InSe, Bi_2Se_3
2D oxides	Micas, BSCCO, MoO_3, WO_3, TiO_2, MnO_2, V_2O_5, TaO_3, RuO_2
	Layered Cu Oxide
	Perovskite-Type $LaNb_2O_7$, $(Ca, Sr)_2Nb_3O_{10}$, $Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$
	Hydroxides**:** $Ni(OH)_2$, $Eu(OH)_2$

(nanowires and nanoribbons), and other 2DLMs shown in Table 1 leads to the formation of heterostructures. Furthermore, some definitions considered 2D-3D bulk materials as a heterostructure beyond these combinations and developed them for diverse applications. The mechanical robustness of heterostructures can be engineered to create flexible, high strength, materials as reinforcements of composites suitable for different applications, where tribology performance is important.Wu et al. [35] reviewed the formation mechanism of graphene/h-BN heterostructure synthesized by in situ chemical vapor deposition method, or Aghjehkohal et al. [36] reported the synthesis of CNT/h-BN heterostructure through self-assembled hydrothermal technique. The specification of some of the well-known and most used 2DMs for enhancing the tribological properties are shown in Table 2. Regarding the aforementioned issue about the effect of the interface connection and interaction, surface area has a critical impact. A higher surface area provides more contact points between interacting surfaces, which can distribute the load more evenly and reduce localized stress concentrations, which can impact positively on reducing of the friction. Additionally, the higher surface areas can dissipate heat more effectively, and leads to prevent localized overheating, and avoid the accelerating wear processes such as abrasion, and adhesion. Furthermore, the mechanical properties including Young's modulus and tensile strength of 2D materials have a critical impact on stiffness, durability and wear resistance. On the other hand, higher tensile strength ensures the coherency of the materials and less prone to delamination or spalling. The nanotribology features of 2DMs such as their thin thickness, lubricity and chemical stability, have been determined as key factors in their effectiveness [37].

Moreover, the frictional behavior of 2DMs at the nanoscale level haven investigated with focus on the effects of atomic structures and external factors [38]. It is reported that the atomic structure of 2DMs has a significant role in determining their tribology performance such as interlayer interactions, commensurability, defects and functionalization, environmental factors, matrix effects, mechanical strength and flexibility, electronic and thermal properties. For instance, the thermal properties such as heat dissipation during sliding contact through in-plane and out-plane directions of 2D reinforcements, thermal expansions of utilized 2DRs and phonon-electron coupling may influence the friction and wear behavior [34]. The capability of 2DMs to resist wear is relatively dependent on their thermal properties. Materials that can conduct heat away from the contact area more effectively may undergo less thermal damage and thus exhibit better wear resistance.

2.1 2D materials in metal composites

Metals are the most common engineering materials used for diverse applications in bio, automobile, aerospace, chemical, petrochemical, etc. Steel, aluminum, copper, and titanium are the most common metals and alloys to devote in the fabrication of desired parts. Regarding their favorite properties, including high mechanical properties and good corrosion resistance, they suffer from low wear resistance, limiting their applicability [7, 47]. Therefore, applying a protective coating [48] and adding second elements to fabricate a composite [49] are the two most common solutions for enhancing wear resistance. As mentioned earlier, graphite, MoS_2, and h-BN are the three most widespread self-lubricating additives [8] that drop the coefficient of friction, but under humidity, the performance of graphite and MoS_2 is diminished.

Moreover, Eqs. 2 and 3 are valid for metal matrix composites, and most studies have been conducted to evaluate the effect of amount, size, shape and distribution of the reinforcement on the achieved properties. Sahoo et al. [50] fabricated the Al/SiC/h-BN self-lubricating hybrid composites and studied the effect of the amount of addition of h-BN. Results showed that Al-5 wt.%h-BN-4 wt.%SiC demonstrated the best wear resistance. The presence of hard SiC particles in the composite restricts metal flow during sliding, leading to a decrease in the CoF. Additionally, the hBN reinforcement acts as a solid lubricant, reducing the wear rate by forming a thin solid lubricating layer.

Table 2 Mechanical properties of 2D materials

2D materials	Surface area ($m^2\ g^{-1}$)	Density ($mg\ m^{-2}$)	Band-gap (eV)	Young's modulus (GPa)	Tensile strength (MPa)	Thermal conductivity ($W\ mK^{-1}$)	Refs.
Graphene	700	0.763	0	250 ± 150	360	2275	[39]
h-BN	260	2.2	6	500–600	20,000 <	400	[40]
MoS_2	600	5.06	1–2.5	265	35,000	340	[41, 42]
WS_2	600	7.16	1–2.5	302	15,000	350	[43]
MXene	700–1500	2.1–3.5	< 0.2	300–500	10,000	50–100	[44, 45]
2D Oxides	50–300	6.3–7.3	1.55–2.32	100–500	10,000	0.3–50	[46]

The formation of this thin lubricating layer between the pin and the sample during sliding contributes to a decline in the wear rate of the composites. The CoF value is lower for the hybrid composites compared to aluminum alloy, Al–SiC, and Al–hBN composites, with the minimum CoF observed for the hybrid composite with 5 wt.% hBN and 4 wt.% SiC. This is due to the lamellar hexagonal crystalline structure of hBN, which creates a thin lubrication film on the pin surface, resulting in reduced friction. The wear rate is also least for the Al–SiC–hBN hybrid composites compared to the aluminum matrix phase, indicating higher wear resistance. The improvement in wear resistance is attributed to the high load-bearing capacity of the reinforcement particles and the excellent interface bonding between the matrix and reinforcement. In another study, Loganathan et al. [51] studied the wear behavior of AA2024/h-BN composite synthesized by powder metallurgy route and sintering at 525 °C under an argon atmosphere. Results demonstrated the rise in microhardness value up to 68%, and wear resistance improved even up to 74.9% compared to pristine AA2024. The maximum hardness and best wear resistance were achieved in 7.5 wt. % of h-BN. Furthermore, Rajkumar et al. [52] studied the mechanical behavior of AA2024/h-BN composite synthesized by stir casting, where the highest tensile and compression strength were obtained with 15 wt. % of h-BN. The application of some of the common 2D reinforcements in metal matrix composites and coatings are shown in Table 3.

There are several factors, which can be attributed to the enhancement of tribological properties. Firstly, the addition of the reinforcements increase significantly the hardness and strength, which improves the wear resistance. The addition of the reinforcements causes the crack bridging, crack pinning and activation of load transfer mechanism, which avoid further crack propagation. Additionally, the formation of self-lubricating tribofilm in the presence of 2DRs, reduces the mass loss within wear. By reviewing the literature data, it can be concluded that effectiveness of the 2D reinforcements can be categorized in their self-lubricating feature, thermal stability and loading ratio. The self-lubricating feature is available in all layered structures; however, due to the heat generation within the wear, the thermal stability is another key factor on enhancing the wear resistance. Finally, the amount of the reinforcement, which can be named the loading ratio is a crucial factor, which can influence the mechanical properties negatively by too much addition. In other words, there is an optimum amount of the 2D reinforcement just before constructing a 3D network in the metal matrix and decrease the mechanical properties.

2.2 2D materials in ceramic composites

Ceramic matrix composites (CMCs) have excellent properties, including corrosion resistance, high hardness, resistance to oxidation, and non-pollution, which expand their application with accelerating slope. Nevertheless, their poor tribological properties, brittleness, and poor machinability limit their application [6, 69, and 70]. One of the most efficient solutions for improving these drawbacks is to use self-lubricating compounds like graphite, h-BN, or MoS_2 [71]. For example, Chen et al. [72, 73] studied the wear behavior of Si_3N_4/h-BN composite for different applications respectively in the marine atmosphere and against Ti–6Al–4V in

Table 3 The Summary of the Application of 2DR in MMCs

2D Reinforcement	Matrix	Manufacturing process	Loading ratio	Average COF	Wear Rate (10^{-4} $mm^3.N^{-1}$)	Coating Thickness (µm)	Refs.
Graphene@SiC	Al	Hot press	5 vol. %	0.0015	0.5	–	[53]
hBN/NiTi	Al7075	Squeeze casting	3 wt. %	0.20	125	–	[54]
Graphene	Cu	Hot press	–	0.25	0.57	–	[55]
B_4C	Al5083	Powder metallurgy	15 wt.%	0.4	0.1 mg	–	[56]
B_4C	Cu	Powder metallurgy	6 vol.%	0.24	20	–	[57]
MoS_2	Cu	Sintering	20 wt.%	0.27	18	–	[58]
WS_2	30CrMnSi	Laser cladding	10 wt. %	0.3	–	–	[59]
WS_2	Cu	Hot press	25 wt. %	0.21	0.15	–	[60]
WS_2+MoS_2	Ag	Hot press	10 wt.%	0.14	–	–	[61, 62]
WS_2	Ni-W	Electrodeposition	0.3 $g.l^{-1}$	0.14	–	18	[63]
WS_2	Al	SPS	10 wt.%	0.56	28	–	[64]
MgAl Coating	2195 Al-Li	Hydrothermal	–	0.41	–	17.8	[65]
MoS_2	Al	Sintering	2 vol. %	0.4	0.25	–	[66]
MoS_2	Al	Plasma sprayed	5 wt. %	0.2	0.25	450	[67]
MoS_2+B_4C	Al7075	Stir casting	3 wt. %	0.48	–	–	[68]

three other lubricating conditions of simulated body fluid (SBF), physiological saline (PS), and bovine serum (BS) for simulating the bearing pair in artificial joint prosthesis designs. The study revealed that the mechanical properties of the composite ceramics decreased with the addition of hBN, leading to an improvement in machinability. The optimal hBN content was identified as 20 vol%, which maintained the tribological performance of Si_3N_4 and improved its processability. However, excessive hBN content, such as 30 vol%, resulted in extensive wear of the ceramic pin due to the deterioration of its mechanical properties. The results demonstrated that the optimal content of h-BN is 20 vol. % and an excessive amount of h-BN leads to extensive wear. In another study, Wang et al. [74] studied the wear and corrosion behavior of Si_3N_4/h-BN composite in seawater conditions. They reported that Si_3N_4-30 wt. % h-BN/Ti64 sliding pair displayed friction coefficient as low as 0.403 due to the lubricous tribo-chemical films composed TiO_2, SiO_2, and $Al(OH)_3$ were formed on the worn surfaces during the sliding process in seawater.

B_4C is another known example of CMCs, the third hardest artificial material but has poor tribological behavior. Studies have been conducted to evaluate the effect of the addition of h-BN to the B_4C composite. For example, Li et al. [75–79] studied the effect of the addition of h-BN and synthesis of B_4C–h-BN ceramic composite by hot press method with different ratios of h-BN. The results showed that by increasing the h-BN content and due to its self-lubricating feature, the coefficient of friction is decreased from 0.385 down to 0.008 as the h-BN content was raised to 30 wt. % from zero. It is shown that it is a tough challenge to accomplish mechanical and tribological advantages in a ceramic matrix composite by adding h-BN. Thus, the other compounds must be accompanied to optimize the desired features. In another study, Kitiwan et al. [80] investigated the synthesis of TiN–TiB_2–h-BN composite through the spark plasma sintering method. The optimum sample with 15 wt. % of h-BN illustrated excellent results, including 20.1 GPa as hardness and 4.3 MPa. $m^{1/2}$ as fracture toughness.

Tian et al. [81] utilized the nitride boronizing process using TiN and amorphous boron as raw material to synthesize TiN–TiB_2–h-BN composite. Results showed that in this process, B atoms began to diffuse into TiN and substitute the N atoms to form TiB_2 at a high temperature of 1400 °C and the replaced N flowed outwards, and upon contact with B, formed h-BN at the surface of TiB_2. Therefore, TiN–TiB_2–h-BN composite powders with a core–shell structure of layered h-BN-wrapped TiB_2 were achieved. Misra et al. [82] evaluated the optimum range of h-BN and SiC additions to obtain the highest improvements in lubrication and wear resistance of applied ceramic composite coating TiB_2-TiN on AISI 1025 steel substrate. The results showed an optimum amount of h-BN addition, and a higher amount of h-BN decreases the COF due to the weakening of bond strength between coating matrix and reinforcement, which overweighs the influence of solid lubrication, causing easier dislodgement of particles. The synthesis of hydroxyapatite/ZrO_2/h-BN bio-composite for bone regeneration applications is also reported by Gautam et al. [83], where excellent mechanical, tribological and biological improvement was reported due to the addition of h-BN. The application of the different 2DMs as reinforcements in ceramic matrix composites are shown in Table 4.

Table 4 The Summary of the Application of 2DR in CMCs

2D Reinforcement	Matrix	Manufacturing process	Loading ratio	Average COF	Wear Rate (10^{-4} $mm^3.N^{-1}$)	Refs.
Graphene	Al_2O_3-WC-TiC	Hot pressing	0.5 wt. %	0.1	–	[15]
Graphene	Al_2O_3	SPS	2.5 wt. %	0.45	1.74E-4	[84]
Graphene	FeCoCrNiAl	SPS	10 wt. %	0.47	0.22	[85]
Graphene	c-BN	Sintering	0.01 wt.%	0.38	–	[86]
Graphene	WC-Al_2O_3	Hot press	0.3 wt. %	0.28	0.013	[87]
Graphene	Si_3N_4	Sintering	1 wt. %	0.07	0.34	[88]
hBN@Ni	CoCrNi	Sintering	–	0.4	8	[89]
hBN	Ni-SiC	Electrodeposition	6 wt. %	0.15	2.44	[90]
hBN	ZrO_2/SiC	SPS	30 wt.%	0.54	0.49	[91]
hBN	ZrO_2/SiC	SPS	70 wt. %	0.32	18.9	[92]
hBN	SiO_2	Hot Press	60 wt. %	0.20	–	[93]
WS_2	CoCrFeNiMo	Laser cladding	10 wt.%	0.25	0.2	[94]
WS_2	YW1/NiCoCrAlY	Laser cladding	7 wt.%	0.35	–	[95]
WS_2	NiMoAl-Ag	Plasma spray	10 wt. %	0.16	0.9	[96]
WS_2	Al-Al_2O_3-SiC	Sintering	9 wt. %	0.13	0.67 mg	[97]

2.3 2D materials in polymeric materials

One of the challenges in the automotive and space industries is the development of lightweight components to improve fuel efficiency [98]. Weight reduction, specific strength, corrosion resistance, cost-efficiency, formability are some notable features of polymer matrix composites that make them an excellent candidate for the fabrication of components in these industries. However, polymer matrix composites' poor mechanical properties and especially wear resistance restrict their application. Proper fibers should be added to the polymeric matrices to compensate for these drawbacks and the extent of their application. The 2DRs can be added to the reinforced fibers or polymer matrix such as epoxy through different techniques like grafting, electrospraying, or coating methods. Due to the self-lubricating feature and high strength, h-BN, GO, MoS_2 and etc. could be added to thermoset and thermoplastic matrices to fabricate components with desired mechanical properties [99]. For example, Chen et al. [100] studied the effect of the addition of h-BN to Si_3N_4 ceramic composite to evaluate the wear behavior against PEEK in artificial seawater. They reported achieving 0.05 average COF, which can indicate excellent wear resistance in some special cases.

Huang et al. [101] studied the effect of the addition of nanosheets of h-BN and TiO_2 on tribological properties of epoxy resin. They showed that the addition of two-dimensional materials like h-BN could provide friction reduction by interlayer slippage. Additionally, the results displayed the synergic effect of the addition of h-BN and TiO_2. The h-BN/TiO_2/EP composites demonstrated outstanding wear-resistant (both lower weight loss and lower coefficient of friction) attributed to the load-carrying ability of TiO_2 and the reduction of self-lubricating effect on the size of debris. In another study, Bijwe et al. [102] studied the synergic effect of the addition of h-BN and natural graphite on the tribology behavior to the PAEK polymer composite. Both h-BN and natural graphite have the self-lubricating feature. Although results showed that none of them has a remarkable effect alone, the best tribological behavior was obtained by combining them and observing the synergic effect. The Lancaster-Ratner factor is a parameter utilized in the field of tribology to predict the wear resistance of materials. It is based on the concept that wear resistance is proportional to the product of ultimate tensile strength and the elongation at break of a material. This factor is often used to correlate the wear resistance of a material with its mechanical properties. The calculated Lancaster-Ratner factors for each ratio of h-BN (B) and natural graphite (T) are shown in Fig. 1. The highest value was obtained for sample T15B5, indicating better wear resistance due to the higher tensile strength and/or elongation, which can better withstand the mechanical stresses and deformations that lead to wear.

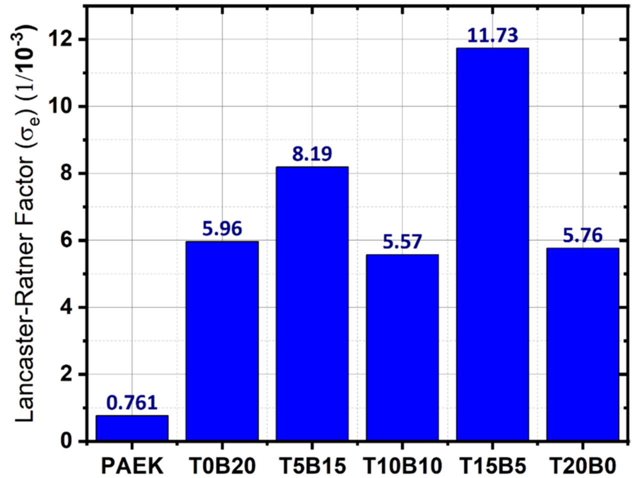

Fig. 1 The calculated Lancaster-Ratner factors for each ratio of h-BN (B) and natural graphite (T) redrawn from the data presented by Bijwe et al. [102]

Furthermore, Panda et al. [103] studied the synergic effect of using simultaneously glass fiber, natural graphite, and h-BN in the PAEK matrix, where the friction coefficient was 0.046. In a study reported by Mittal et al. [104], the effect of surface functionalizing of h-BN on the tribological properties of PMMA/PI composite was evaluated. The results illustrated that by applying a silane surface functionalizing method on h-BN powders before composite synthesis, the friction coefficient was decreased from 0.651 to 0.553. This indicates that the matrix becomes more compatible by applying a silane treatment on h-BN particles. Furthermore, the voids were filled by h-BN properly, because the better dispersion and interfacial properties were improved. The brief study of the application of the 2DRs in PMCs is shown in Table 5.

2.4 2D materials in composite coatings

As mentioned in the previous part, applying a protective coating is one of the solutions to improve the tribological properties, including corrosion, wear resistance, surface hardness, and scratch resistance. Combining the applying protective coating and adding the second phase leads to achieving a composite layer, which causes more improvement in the tribological properties [9]. There are various second phases reported to add to different coating like graphene oxide [11], Al_2O_3 [114], TiO_2 [115], and SiC [116]. Also, h-BN is used to increase oxidation and corrosion resistance in the literature. Wang et al. [117] increased the oxidation resistance of Ti_2AlNb composite coating by applying plasma electrolytic oxidation (PEO) treatment and adding h-BN. The pure Ti_2AlNb composite coating is not proper for temperatures higher than 800 °C. Still,

Table 5 The summary of the application of 2DR in PMCs

2D Reinforcement	Matrix	Manufacturing process	Loading ratio	Average COF	Wear Rate (10^{-4} $mm^3.N^{-1}$)	Refs.
–	ABS	3D printing	–	0.22	–	[105]
Carbon nitride	ABS	Solution casting	0.5 wt. %	0.18	–	[106]
Graphene	Epoxy	Vacuum impregnation	2.9 wt. %	0.20	–	[107]
Ti_3C_2@ZnO	PA	Spray	–	0.65	0.39	[108]
Graphene	Epoxy	Curing	1 vol. %	0.2	0.2	[109]
GO	PPTA/PTFE	–	0.5 g	0.061	0.18	[110]
CaAl	PTFE	Press molding	10 wt.%	0.2	–	[111]
Ti_3C_2 + h-BN	PPS + PTFE	Hot press	25 Mass Fraction	0.045	0.01×10^{-6}	[112]
MoS_2	PTFE	Cold press	10 wt.%	0.14	2.5	[113]
g-C_3N_4	PTFE	Cold press	10 wt.%	0.18	1	[113]

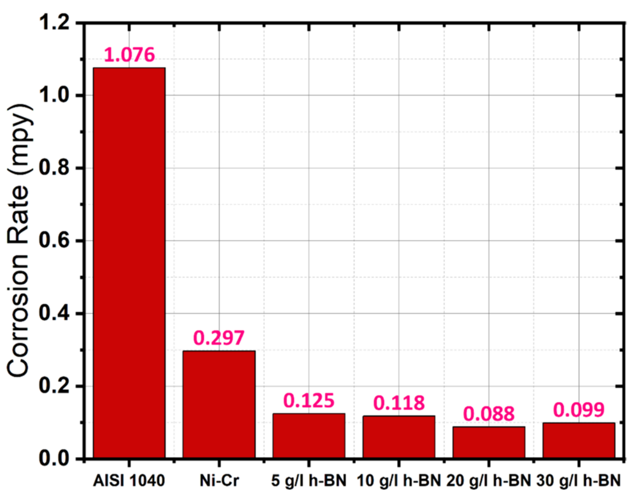

Fig. 2 Calculated corrosion rate of Ni–Cr composite coating by addition of h-BN redrawn from the Data reported by Demir et al. [118]

by applying PEO/h-BN to composite coating, oxidation resistance is increased up to 1000 °C for 100 h due to the formation of dense oxide and nitride layer. These achieved layers are avoiding oxygen diffusion. In a reported study by Demir et al. [118], the electrodeposited composite coating of Ni–Cr with the addition of h-BN was investigated on AISI 1040 steel. The corrosion resistance of that as one of the tribological performance was studied. Among the composite coatings (0, 5, 10, 20, and 30 g.lit^{-1} h-BN), the corrosion resistance of the coating with 20 g.lit^{-1} h-BN was measured to be 12, and it is 3.3 times higher than the uncoated steel substrate and Ni–Cr alloy, respectively. The variation of corrosion rate is shown in Fig. 2. The coating has improved corrosion resistance since h-BN particles fill cracks, voids, and micron-sized voids on the Ni–Cr composite coating surface and avoid the reaching of corrosive agents to the interface of coating and substrates by reducing the active surface areas.

Furthermore, adding h-BN particles to the electroplating bath plays a significant part in avoiding hydrogen formation reactions on the cathode surface and diminishing the active surface of the particles adsorbed on the cathode surface. Corrosive anodic and cathodic electrochemical reactions are reduced by h-BN particles scattered in the Ni–Cr composite coating. Adding h-BN particles displays the modification in anodic dissolution and cathodic hydrogen formation reaction mechanisms. Reduction of the corrosive reactions indicates that the distribution of the added h-BN particles and their size are important factors that should be considered to increase the desired properties. Improving the corrosion resistance by adding h-BN is against what was reported by Goncu et al. [119]. No morphology changes were seen by adding h-BN to obtain a composite coating of hydroxyapatite/h-BN coating by the electrophoretic deposition method, which was attributed to the size of the utilized h-BN particles. It is important to note that by decreasing the h-BN particles' size, diffusion of them to the cracks is more accessible and could hinder the diffusion of the corrosive agent properly. Still, parameters should be optimized to avoid agglomeration in coating bathes. In another study reported by Unal et al. [71, 72], the effect of ultrasonic agitation on Ni–B/h-BN co-deposited composite coating was studied and reported that the coating contains 10 g.L^{-1} h-BN has a better corrosion rate equals 0.0045 mm per year (mpy). In an additional study, Ao et al. [120] studied the tribological properties of TiO_2/h-BN composite coating on Ti–6Al–4V achieved by the micro-arc oxidation method. Results displayed that by adding h-BN, the less porous coating was obtained, which led to improvement of the achieved wear behavior of coatings, which is evident in SEM images shown in Fig. 3. However, the shown morphology in Fig. 3 demonstrate the porous structure, which is decreased with addition of the h-BN as a 2D reinforcement. The presence of porosities and pores in the morphology is playing an important role, when the component is subjected to wear. While wear

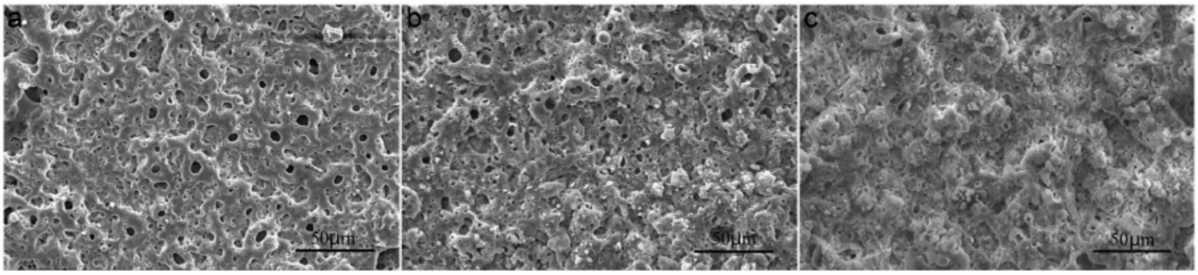

Fig. 3 Morphology of the TiO2/h-BN composite coating, where it is shown with the increasing h-BN content, less porous structure was formed [120]

debris can be trapped in these pores, reducing the quantity and size of pores leads to the wear debris acting as abrasive particles, so intensifying wear. Therefore, addition of the 2D reinforcements have two distinct impacts on the morphology and wear resistance. The first one is to improve the wear resistance by reducing the number of pores and the second one is to weaken the wear resistance by activating the abrasive wear mechanism. Thus, it can be concluded that the there is an optimum amount of 2D reinforcements that should be added to the matrix to balance these effects effectively. Other applications of h-BN coating include seal coating of Al/h-BN in the compressor of aero engines [121]; h-BN thin film as gate dielectric [122] in metal/insulator/semiconductor AlGaN/GaN as high electron mobility transistors (IMISHEMTs) on sapphire were reported in literature too.

3 Perspective and outlook

In considering the outlook of tribology research, it is essential to explore into the field of developing two-dimensional materials (2DMs) that have potential beyond those currently explored. Alongside established materials like graphene and hexagonal boron nitride, exploring the potential of emerging 2DMs such as MXenes and transition metal dichalcogenides could illuminate new pathways in tribology. These materials offer unique structural and chemical properties such as high conductivity, excellent mechanical strength, and tunable surface chemistry that could change various applications in friction and wear reduction. By discussing their potential benefits and applications, the outlook section gains depth, opening paths for further exploration and innovation. MXenes, with their metallic conductivity and hydrophilic nature, and TMDs, famous for their layered structures and semiconducting properties, offer diverse benefits that can be exploited to develop advanced solid-state lubrication and wear-resistant coatings. Considering their particular properties and possible applications in detail will provide a more robust outlook and promote further investigations.

Furthermore, the concept of synergistic effects presents a fascinating prospect in enhancing tribological performance. Combining different 2DMs or mixing them with other reinforcements could yield composite materials with superior mechanical properties. For example, hybrid composites that benefit the strengths of both MXenes and graphene could result in unique enhancements in wear resistance and friction reduction. By exploring these possibilities, researchers may unlock novel strategies to alleviate friction and wear, leading to the development of more robust and efficient tribological systems.

However, alongside opportunities come challenges that must be addressed to fully realize the potential of 2DM-reinforced composites. Significant issues such as dispersion, interfacial bonding, and the balance between wear resistance and other mechanical properties pose noteworthy obstacles. Acknowledging these challenges in the outlook section promotes a comprehensive understanding of the field and encourages researchers to plan multidisciplinary solutions through experimentation of advanced synthesis techniques, computational modeling, and advanced characterization techniques. By handling these obstacles head-on, the tribology community can cover the way for the successful integration of 2DMs into next-generation composite materials, shaping the future of friction and wear mitigation, in other words, 2DMs in tribology.

4 Conclusion

Looking ahead, the future of 2DM-reinforced composites in tribology is full with potential. Additional research on emerging 2DMs and investigating synergistic effects with other reinforcements hold enormous capacity for achieving modified tribological properties. However, addressing challenges like dispersion, interfacial bonding, and potential trade-offs between properties is crucial. Computational modeling and simulations can be valuable tools in optimizing material design and processing techniques.

By overcoming these challenges and continuing to explore new borders, researchers can unlock the full potential of 2DMs. This will cover the way for the development of next-generation tribological materials with exceptional performance, leading to advancements in various fields. The synergic effects of combining 2D materials can be a practical procedure to enhance the tribological performance and balance the targets features to maximize the advantage of each 2D reinforcements. For instance, simultaneously application of one 2D materials with self-lubricating feature such as h-BN and the another one with higher conductivity and mechanical properties such as newly developed Mxenes can improve friction and wear resistance, respectively. This can lead to fabricate components with improved tribological performance like reduced wear rate and enhanced durability to surpass the harsh working conditions. Additionally, the stability and long-term durability of 2D materials are two crucial factors influencing their practical implementation. Aforementioned, loading, surface condition and interaction and environmental exposure can impact their performance over time. For ensuring sustained effectiveness and reliability by developing effective strategies, conducting comprehensive researches are necessary to assess the degradation mechanisms.

Finally, to achieve a reliable tribological performance, optimizing manufacturing proves to effectively integrate 2D reinforcements into composite matrix is an essential step. The dispersion and bonding of 2D reinforcements within desired matrix should be ensured through production method, whether the bulk materials or coatings are exploited. Advanced fabrication methods such as additive manufacturing (3D printing, wire arc additive manufacturing and etc.) and plasma enhanced techniques could facilitate the customized scheme for improved tribology properties. Furthermore, implementing scalable and economical synthesis routes and optimizing process parameters can help diminish production costs without compromising the quality or performance of 2D material-based tribological systems.

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Declarations

Conflict of interest The authors declare no competing interests.

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