

Graphene: A State-of-the-Art Review of Types, Properties and Applications in Different Sectors

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Abstract

Being one of the most lightweight, toughest, and most flexible materials in the world, having exceptional mechanical, electrical, thermal, and tribological properties, makes graphene and its several based materials crucial applicants for biomedical, medical, aerospace, automotive, electrical, energy, sensing, food, and other industrial sectors. Graphene is classified as a carbon allotrope, with one-thick-atom planar sp^2 layers of attached carbon atoms tightly loaded within a crystal honeycomb lattice. Various techniques to produce graphene were established over a brief period of time, including top-down and bottom-up methods. Graphene itself can be used as a coating to improve other materials; likewise, it could be added to further composite materials. This review recaps the applications of graphene, its types, synthesis methods, and mechanical, tribological, and thermal characteristics, in addition to enhancement methods for graphene and its based materials.

Keywords- Graphene, Synthesis, Types, Properties.

1. Introduction

Graphene is a durable and adaptable 2D nanomaterial. It is categorized as an allotropic carbon form with a single layer of graphite. There are two major procedures to manufacture graphene: the initial is a top-down procedure through the cracking down of graphite into graphene utilizing exterior methods, though the next approach is bottom-up using graphene assembling from molecular structure blocks or carbon resources (Nassef et al., 2020). Long-scale π -coupling in graphene produces impressive thermal, mechanical, including electrical properties that have attracted the interest of various theoretical scholars and have lately become a thrilling field for experimentalists (Allen et al., 2010). Graphene lately has seemed to turn out to be one of the finest-promoting nanomaterials due to the fact that it has excellent incorporation of the following extraordinary characteristics: it is known as the thinnest and strongest material; likewise, it conducts heat well associated with further resources; it is a good power conductor; furthermore, graphene is optically transparent but so impassable that it is resilient to numerous gases, including helium, the smallest gas element might permit through it (Bae et al., 2010; Geim, 2012; McClure, 1956; Semenoff, 1984).

Others explained graphene as the mother of all graphite types. This outstanding substance offers a motivating stand regarding the consequent production knowledge expansion in several regions, including coatings, spectacularly fast microelectronics, enormously delicate sensors' medication, and multi-practical complexes, in addition to films, bioengineering, power storage, and collecting. A typical carbon molecule has a nanometers diameter nearly equal to 0.33, easily accessible just around 3 million graphene sheets within a 1 mm graphite-thick layer. In practical terms, the 2p detours are responsible for graphene's exceptional properties, which are responsible for shaping the π state straps, which delocalize throughout the carbon layer that defines graphene. Such a substance is considered tougher than diamond yet has more elasticity than rubber; it is tougher than steel although also smoother than aluminum, and graphene is the

strongest known material yet. Obligations to the unique graphene assembly, furthermore to stated characteristics, it likewise possesses additional amazing properties: it's astonishing electron elasticity is 100x faster than silicon; besides, its heat transfer is 2 times better than diamond; likewise, it has a 13 times better electric conduction compared to that of copper; likewise, this substance has an elevated surface zone equal to 2,630 m²/g (Döscher et al., 2021; Döscher & Reiss, 2021; Lee et al., 2008a; Luo et al., 2012; Papageorgiou et al., 2017; Zhang et al., 2014). The 2D shape of graphene is shown in Figure 1.

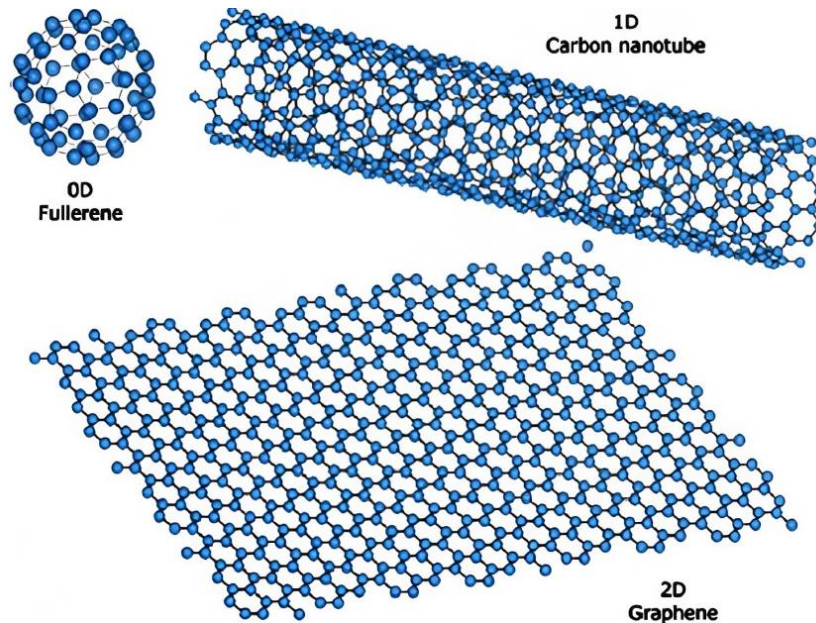


Figure 1. Fullerene (0D), carbon nanotube (1D), and graphene (2D) are low-dimensional carbon allotropes (Soldano et al., 2010).

Graphene was primarily introduced to the world in 2004 as quickly as Andre Geim and Kostya Novoselov controlled to split a certain carbon atomic sheet (Neto et al., 2006). Yet since then, this optimistic material has drawn the attention of numerous scientists contributing to the areas of materials science linked with manufacturing and mechanical engineering. Prior to graphene being mainly presented, two physicists from Manchester University (for this reason, they took the Nobel Prize in 2010) declared that the exact constituents of 2D crystalline graphene were considered thermodynamically unreliable and could not occur (Geim, 2012). Graphene was formerly been deemed theoretically in 1947 by Wallace (1947a), as a standard instance regarding computations within the solid-state physics field. He assumed the electronic elements, besides the linear diffusion relative, were indicated by him.

In 1956, the excitation wave equivalence was noted by McClure (1956), whereas the contrast to the Dirac equivalence was analyzed by Semenoff in 1984 (Semenoff, 1984). Just about 2002, Geim pointed out that he was interested in graphene; however, he also encountered a Ph.D. scholar who wanted to sparkle a portion of graphite into as few sheets as possible. He was able to create a graphite peel that was virtually 1,000 thick sheets (Yang et al., 2020). The major developments in graphene are presented in Figure 2. Table 1 shows the main abbreviations with their explanations.

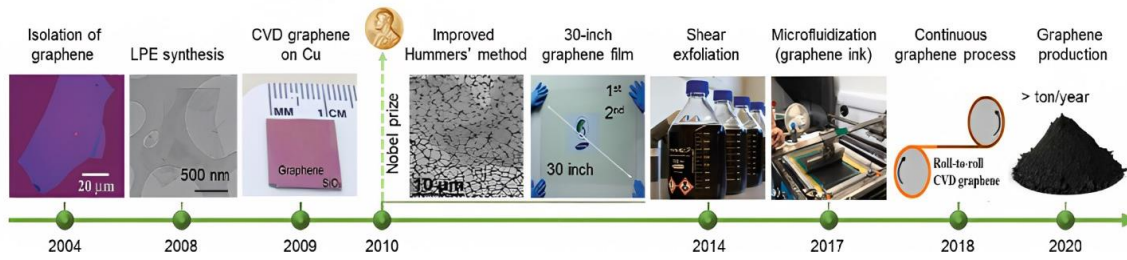


Figure 2. Major incidents within the investigation and growth of the graphene formulation timeline, starting in 2004 with the graphene isolation (Kumar et al., 2021).

Table 1. Abbreviation-explanation.

Abbreviation	Explanation
2D	2 Dimensional
3D	3 Dimensional
MLG	Multi-layer Graphene
GNP	Graphene Nanoplatelets
rGO	Reduced Graphene Oxide
GO	Graphene Oxide
FLG	Few-layer Graphene
FRET	fluorescence resonance energy transfer
GQDs	Graphene quantum dots
UV	Ultra violet
PDT	Photodynamic therapy
PTT	photothermal therapy
DSSCs	dye-sensitized solar cells
OPVs	organic photovoltaic cells
GICs	Graphite intercalation compounds
CVD	chemical vapor deposition
SLG	single layers of graphene
SiC	silicon carbide
GF	graphene fibers
GP	graphene papers
CTE	thermal expansion coefficient
PI	polyimide
CFs	carbon fibers
f-GNS	functionalized bisphenol nanosheets of graphene
PSS	poly-styrene sulfonate-polyaniline
HDPE	elevated-density polyethylene
3DGS	3D graphene skeleton
(T_g)	glass transition temperature
TEPA	tetra ethylene pentaamine
EPs	epoxy resins
PVDF/GNP/CNT	made poly (vinylidene fluoride)
CPRFs	glass fiber reinforced plastic
xGnP	graphite exfoliated nanoplatelets
LLDPE	linear small-density polyethylene
PVD	physical vapor deposition
MMC	metal matrix composites
UHMWPE	ultra-high relative molecular mass polythene
NMCs	Ni3Al matrix composites
PEEK	poly-ether-ether-ketone
COF	friction coefficient
GTMC	graphene aluminum titanium matrix composite
MGP	modified graphene platelets
SEM	scanning electron microscope

2. Types

In its finest form, graphene is illustrated as a specific atomic layer of hybridized sp² carbon atoms organized in a hexagonal configuration, the most perfect form. The simplest form is monolayer graphene, and corresponding to American carbon, it is the only authentic "graphene." However, as shown in the table below, several comparable orientations are neither as difficult nor as expensive to make but still display some highly desirable characteristics. Different types of graphene are shown in Table 2.

Table 2. Various types of graphene (Enyashin & Ivanovskii, 2011; Feicht et al., 2017; Rao et al., 2009; Tiwari et al., 2020).

Kind	Total of Sheets	Clarification	Estimated Uses
Monolayer Graphene	1	A particular thick sheet atom of hexagonally prepared carbon atoms. side dimensions are not related	Nanoelectronics, translucent conductive films, in addition to touch displays.
Few-layer Graphene (FLG)	2-5	Assembled graphene layers with a similar lateral dimension	Sensors, varnishes, nanoelectronics, along with batteries.
Multi-layer Graphene (MLG)	2-10	Identical to FLG however with a bigger variety of layers	Lubricants, conductive inks, composites, plastics additive material, etc.
Graphene Nanoplatelets (GNP)	More than 10	2D graphite substance having a thickness and/or lateral measurements fewer than 100 nm	An additive substance to plastics, conductive inks, lubricants, composites, etc.
Reduced Graphene Oxide (rGO)	NA	Like GO although lowered C/O atom ratio	further stable than GO, although even shifted following conductance
Graphene Oxide (GO)	NA	Altered graphene with an atom C/O ratio between 3.0 and 2.0	Very conductive, nevertheless it loses oxide every time conductivity appears

3. Applications

The massive quantity of procedures, products, and firms concerning which graphene can have a substantial influence all come about due to its remarkable characteristics.

- It is several times tougher than steel but extremely flexible and lightweight.
- It is thermally and electrically conductive, although also translucent.
- It is the globe's initial 2D substance, besides being thinner by one million times than a particular human hair diameter (Nag et al., 2018).

3.1 Domains of Application

No additional substance has the superlative breadth that graphene possesses, making such material the ultimate limitless product.

3.1.1 Biosensors

Biomolecules perform essential tasks within all life procedures involving disease development; hence, the precise recognition of biomolecules is crucial to disease analysis and treatment. The graphene-built substances were utilized to build numerous biosensors based on various sensing processes involving electrochemical and optical signaling (Liu et al., 2012). GO presents fascinating optical characteristics due to the fact that it could glow throughout a wide spectrum of wavelengths, from near-infrared to UV (Loh et al., 2010), in addition to likewise successfully quenching the fluorescence of further fluorescent dyes (Liu et al., 2008). Such properties make graphene a valuable substance for manufacturing fluorescence resonance energy transfer (FRET) sensors. Lately, a bunch of graphene-established FRET sensors have been established for target ssDNA monitoring (Yang et al., 2013).

3.1.2 Bioimaging Applications

Due to their great biocompatibility, remarkable physiological stability, minimal cytotoxicity, and

customizable fluorescence characteristics, graphene quantum dots (GQDs) have shown tremendous potential in bioimaging applications. Graphene quantum dots (GQDs), a unique 2D nanomaterial consisting of graphene nanosheet with a lateral dimension < 10 nm, have been the subject of significant research in recent years. GQDs typically exhibit high optical absorption in the UV range of about 230 nm (Lu et al., 2019; Tang et al., 2010).

3.1.3 Drug/Gene Delivery

The main benefit of graphene across additional nanomaterials is its sp^2 hybridized carbon area and ultra-superior surface area ($2630 \text{ m}^2/\text{g}$), this makes graphene on both sides of the single-atom layer sheet, an ideal drug carrier for packing several large drug molecules (Yang et al., 2013).

3.1.4 Photothermal Therapy

In addition to gene therapy and chemotherapy, phototherapy is another therapeutic methodology that might be utilized to deal with a range of diseases. Photothermal therapy (PTT) and photodynamic therapy (PDT) are two types of phototherapy that are capable of managing the disease through certain light irradiation. Graphene has lately taken a quiet interest in the PTT field, owing to its powerful optical adsorption within the reflectance near-infrared zone (Yang et al., 2010).

3.1.5 Multimodality Therapy and Theragnostic

All the excellent capabilities of graphene-established materials in cancer treatments (PTT, PDT drug/gene delivery, etc.) urged several scientists to merge various methodologies intended for cancer therapy (Zhang et al., 2016).

3.1.6 Tissue Engineering

Tissue engineering is an intersection of disciplines that employs knowledge from biological sciences, medicine, and engineering to create biomimetic tissue structures for organ transplantation and also for diagnostic and therapeutic investigations (Tamayol et al., 2013). Graphene and graphene-based substances have been used in tissue engineering techniques for nervous, cardiac, and bone tissues (Arkowski et al., 2021), due to their high electrical conductivity, stiffness, and mechanical strength (Shin et al., 2016; Yang et al., 2011). Figure 3 shows different medical applications of graphene.

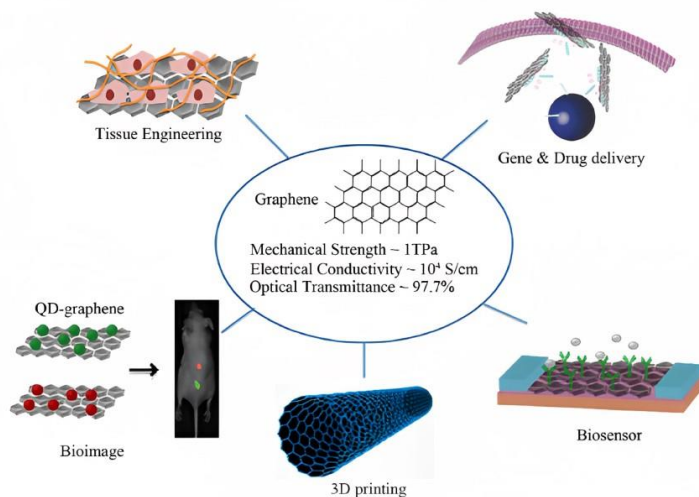


Figure 3. Different medical applications of graphene (Hu et al., 2012; Shin et al., 2016).

3.1.7 Electrotherapy

Innovative electrotherapy is established in the vascular system's presence of leads. Lead collapse, tricuspid valve deficiency, and diseases are the most frequent issues that arise. Due to the potential severity of these disorders in individuals with heart disease, there are many different leadless pacing strategies and a need to research novel chemicals. Graphene besides its based materials, with common antimicrobial characteristics, may be deemed important contender substances for electrotherapy tools (Arkowski et al., 2021).

3.1.8 Photovoltaic Cell

Super capacitors, fuel cells, batteries, and solar cells are just a few of the energy conversion and storage technologies that graphene has thoroughly investigated, to make use of its remarkable features. Among these uses, the creation of effective solar cells that can transform solar energy into electricity is highly desired to address growing energy- and global warming-related problems. The use of graphene to enhance a photovoltaic device's overall performance, such as that of dye-sensitized solar cells (DSSCs) and organic photovoltaic cells (OPVs) has received a lot of attention to date. According to reports, graphene can function as an electron acceptor, an electrode, an interfacial layer, and an active layer in solar cells, among other different but advantageous roles (Aïssa et al., 2015; Chang et al., 2014; Chapin et al., 1954; Wang et al., 2008). RGO transparent electrodes could be utilized for solar cell electrodes. Numerous analyses indicate that GO/RGO could also be applied as a hole transport layer in addition to a section of the active substance (Singh et al., 2011). Graphene and its derivatives in PSCs are represented in Figure 4.

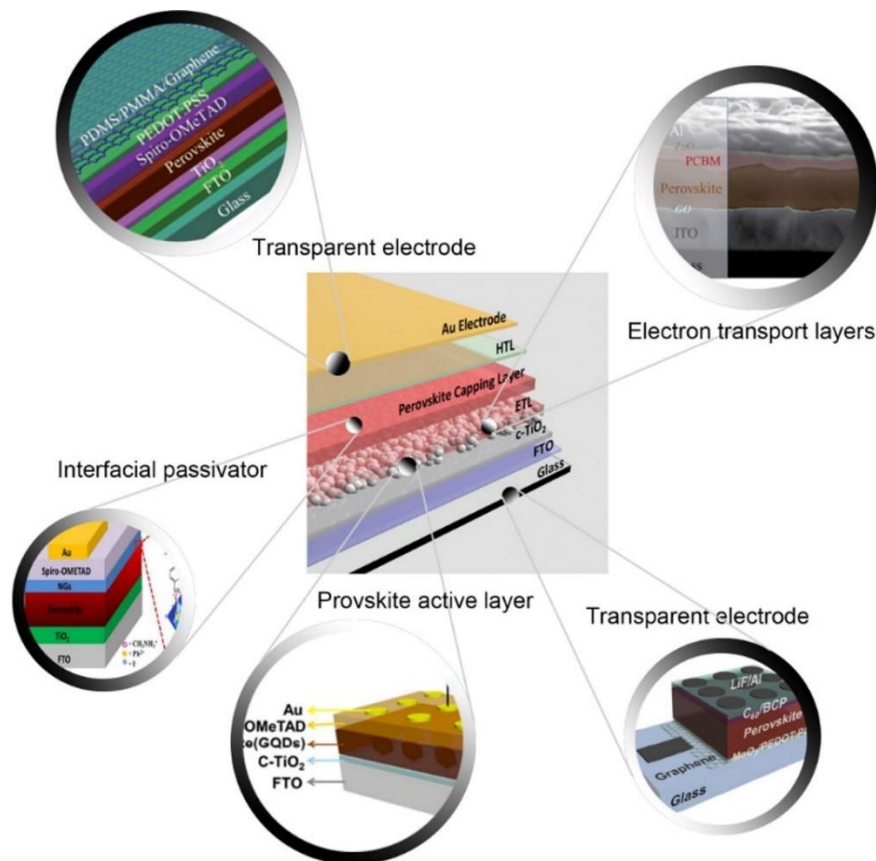


Figure 4. Graphene and its derivatives in PSCs are depicted schematically (Gong et al., 2021; Sung et al., 2016; Wen et al., 2016; You et al., 2015; Zhang et al., 2018).

3.1.9 Flexible and Transparent Electronics

Presently, the majority of the research by companies in the electronics tool manufacturing field is considering various ways to manufacture transparent and flexible electronic appliances concerning different categories of applications, such as solar cells, incorporating displays, smart windows, LEDs, IC cards, etc (Jo et al., 2012; Wager, 2003; Yu et al., 2011). Within materials, graphene is considered one of the viable options. It has all the necessary characteristics needed for such applications, such as mechanical flexibility and optical transparency, combined with elevated conductivity (Aïssa et al., 2015).

3.1.10 Graphene Transistors, Batteries, Supercapacitors

Graphene's outstanding thermal and electrical conductivity leads to minimal resistance losses, in addition to improved heat degeneracy compared to silicon. Subsequently, graphene transistors can deliver improved functioning and effectiveness (Lemme, 2010). Graphene and products made of it could be used in super capacitors through AC line filtering, flexible energy-storing tools, transparent capacitors and batteries, stretchable batteries, energy-storage appliances for wearable electronics, fast-charging batteries, lightweight batteries concerning ultrathin electronics, perm-selective membranes regarding safe batteries, etc. (El-Kady et al., 2016). Graphene and its based materials are also used in storing energy produced from wind and solar power sources (Hsu et al., 2016).

3.1.11 Graphene Coatings

Graphene coatings could be conductive, hydrophobic, and chemically resistant, thus gaining enormous marketability. However, there is considerable concern about the usage of graphene as a coating substance or, likewise, as an additive to improve the functioning of different coating knowledge (Cui et al., 2019; Teng et al., 2020). Graphene is further used in several fields such as sensors, crop protection, automotive applications, marine applications, reducing food waste, and more (Chen et al., 2016; Hill et al., 2011; Jena et al., 2020; Liu et al., 2012; Ramón-Raygoza et al., 2016; Wang et al., 2021).

3.1.12 Applications of Graphene in the Aerospace Sector

The superb conductivity and structural strength of graphene in the field of polymer composites make such a material a prospective applicant for aerospace products. Since graphene is very light and strong, it is suitable for solar sails in space (Matloff, 2012). Graphene is being investigated as a possible material to be used in space lift cables since it has a tensile strength equal to 130 GPa (Pugno, 2013). Graphene is used as a sensor for advanced corrosion monitoring (Li et al., 2021). Graphene is also used in various aerospace applications, including heat shields and thermal protection systems, charge dissipation layers, multifunctional electronic elements, etc. (Siochi, 2014).

4. Synthesis Methods

Synthesis or production of graphene implies any procedure concerning the fabrication or extraction of graphene, varying in purity and size, combined with efflorescence regarding the product. Within the previous period, several methods were discovered for creating thin graphite sheets. At the end of the 1970s, carbon was triggered in the structure of thin graphite sheets on transition surfaces of metal (Eizenberg & Blakely, 1979). In 1975, only a partial graphite layer was produced on a specific platinum crystal surface by chemical decomposition techniques, although due to a lack of characterization techniques, it was not classified as graphene or possibly owing to its restricted potential functions (Bhuyan et al., 2016; Edwards & Coleman, 2012; Muñoz & Gómez-Aleixandre, 2013).

4.1 Top-Down Approach

Within the top-down procedure, graphene or altered graphene layers are created through exfoliation or

separation of graphite or even graphite products (for example, graphite oxide (GO) besides graphite fluoride) (Bhuyan et al., 2016).

4.1.1 Mechanical Exfoliation

Throughout the history of graphene, the method of mechanical or micromechanical exfoliation has evolved. Because it produces high-value graphene layers of 5 to 10 m, as shown by AFM in addition to TEM evaluation, it is still the main synthesis method for obtaining superior-value graphene for research goals. Nevertheless, the unequal film thickness achieved through this technique and the elevated manufacturing expense owing to minimal yield makes this technique impractical for mass manufacture. These techniques are a major instance of the top-down methodology, in which a graphene ancestor (GO, graphite, etc.) is carried out sheet by sheet, creating graphene layers. This is considered a top-down procedure within nanotechnology, where transverse or longitudinal stress is made on the layered structure substance's surface. Graphite is produced while mono-atomic graphene sheets are assembled simultaneously through van der Waals's weak forces (Bhuyan et al., 2016; Shams et al., 2015).

4.1.2 Graphite Intercalation

Through intercalation, graphite might potentially be concentrated to form graphene. Graphite intercalation compounds (GICs) may be made by mixing different chemical types in the graphite's interlayer region. Due to the presence of these intercalates, the distance between graphite sheets widens. This additionally shifts the graphene characteristics, as the expanded interlayer gap impacts electronic coupling among graphene sheets. Various intercalates can lead to GIC with a distinct set of usable characteristics concerning products aimed at thermal and electrical operation, in addition to magnetic operation (Zhan et al., 2010).

4.1.3 Nanotube Slicing

Additionally, graphene has been produced using carbon nanotubes as a precursor. This technique might lead to the production of tiny, micron-sized graphene nanoribbons (Mittal et al., 2015). Such techniques present superior yields in addition to decent graphene. Carbon nanotubes might theoretically be cut open to produce 2D layers of graphene (Kolahdouz et al., 2022). Numerous techniques were established, such as putting carbon nanotubes into a solution including sulfuric acid and potassium permanganate (Kosynkin et al., 2009) or plasma etching of partially embedded nanotubes in polymer film (Jiao et al., 2009). Superior graphene value could be achieved using nanotube slicing.

4.1.4 Pyrolysis Method

Pyrolysis is a simple procedure that may be increased in size for manufacturing. Nevertheless, they have a low yield, and impurities appear in the finished product. During this process, a molar ratio of 1:1 of sodium (2 g) plus ethanol (5 mL) is warmed at 220 °C in a sealed vessel reactor for a duration of 72 hours to acquire the graphene predecessor, which is solid solvothermal. Then it is pyrolyzed quickly, and the product remaining is cleaned with deionized water (100 mL). 24 hours of vacuum filtration and drying at 100 °C in a vacuum oven are applied to the suspended solids (Shams et al., 2015).

4.1.5 Reduction of Graphite Oxide (GO)

The chemical reduction of graphite oxide (GO) yields graphene powder or nanoflakes that range in size from an nm to an μm . This method produces graphene that may be used in polymer fillers, conductive paints and inks, battery electrodes, sensors, super capacitors, and other applications. GO reduction is frequently chosen for graphene decline because of the lesser exfoliation degree attained through expandable graphite in addition to graphite (Chen et al., 2003; Dreyer et al., 2009; Ramanathan et al., 2007).

4.1.6 Electrochemical Exfoliation

In order to produce graphene from graphite, electrochemical exfoliation is thought to be a promising bulk method; during this procedure, ionic types intercalate into graphite via a driving voltage, where they develop gaseous varieties that exfoliate and expand specific graphene layers. Still, a total of barriers have prohibited this methodology from developing a viable production path; the graphite electrode disintegration as the process develops is the principal obstacle (Achee et al., 2018).

4.1.7 Sonication

Superior values of un-oxidized graphene flakes and graphite could be achieved through sonication (Hernandez et al., 2008). This technique is a crucial instance concerning the top-down methodology for the synthesis of graphene because, in this method, simultaneous graphene sheets placed inside a precursor are divided using ultrasonic energy. However, since sonication is the only energy source used, this method requires a lot of power, which might be problematic when scaling up (Jayasena & Subbiah, 2011). Another obstacle that emerges throughout this technique is the removal of contaminants. Graphene achieved through this procedure might be used in polymer filler areas, sensors, and transparent electrodes (Mittal et al., 2015).

4.1.8 Ball Milling

In general, ball milling is regarded as a subset of mechanical exfoliation; however, numerous differences in this technique have been established, and thus this technique deserves to be reviewed individually. Ball milling has long been used for mixing as well as reducing the size of components. Researchers have exfoliated graphite and graphene layers using this element size-reduction technique, occasionally utilizing magnetic assistance (Shams et al., 2015) and from time to time utilizing solvent (León et al., 2011; Lin et al., 2013) or chemical help (Borah et al., 2014). Magnetic support offers metallic particle filtration, which is present within the precursors. At the same time, chemical aid prevents the layers from re-stacking through chemical interactions (León et al., 2011).

4.1.9 Radiation-based Methods

Rapid synthesis of graphene is possible with radiation-based techniques. This method allows for the production of high-value graphene, nevertheless, the yield is low.. Likewise, beliefs concerned with radiation will not permit such techniques to be applied industrially, although this method is economically not feasible for industrial development. By exposing GO to an electron beam, graphene layers might be created. According to the stated technique, an aqueous dispersal of isopropyl alcohol and GO was placed for 10 minutes in a plastic bag and irradiated under 2 MeV/10 mA conditions (doses of 140 kGy). The reduced GO was then centrifuged apart, repeatedly rinsed in alcohol, and dried under a vacuum at 60 °C (Pan et al., 2009). Laser scribing is a procedure similar to pyrolysis; however, the power supply used at this step is a laser (El-Kady et al., 2012). Other top-down synthesis methods of graphene include Graphite super acid dissolution (Behabtu et al., 2010), Micromechanical exfoliation (Novoselov et al., 2004), Graphene electrochemical exfoliation/functionalization (Liu et al., 2008), and Graphite direct sonication (Bourlinos et al., 2009; Hernandez et al., 2008).

4.2 Bottom-up Approach

Graphene could be formed through molecular development from small-scale carbon molecular precursors through epitaxial growth on a chemical vapor deposition (CVD) or substrate, where well-controlled thickness (amount of sheets) could be performed utilizing diverse growing parameters and substrate catalysts. Graphene produced through the CVD process has a larger area and superior quality, and this process has the finest capability concerning the mass production of elevated-clarity graphene (Tang et al., 2012).

4.2.1 Growth from Metal-Carbon Melts

In this basic procedure, a transition metal is heated to extreme temperatures in order to melt a carbon source (graphite powder) that is connected to it. The high temperature may cause a drop in carbon solubility once carbon starts to melt inside the molten metal, resulting in unneeded carbon precipitation. This precipitate might be scraped off in a way to produce other carbon forms, such as thick graphite and single layers of graphene. Nickel appears highly suitable for this procedure because it is non-Raman active (Amini et al., 2010). Ruthenium, besides iridium, is also common and practical, although the graphene value is not as excellent as whatever is attainable from copper and nickel (Pletikosić et al., 2009; Sutter et al., 2008).

4.2.2 Epitaxial Growth on Silicon Carbide (SiC)

This process advances to achieving epitaxial graphene, even though the graphene flake size remains dependent on the SiC wafer size. The SiC surface impacts the mobility and thickness, coupled with the graphene carrier density achieved within this approach, as noted in the study. Graphene achieved by this process manages to have low anti-localization, which is dissimilar from exfoliated graphene. Alternatively, like graphene gained through the peel-off approach or drawing, SiC-epitaxial graphene exhibits very large, independent temperature mobility but is not as superior as exfoliated graphene (Hibino et al., 2010; Mishra et al., 2016).

4.2.3 Dry Ice Method

As stated by the dry ice approach, graphene could be achieved by burning the Mg ribbon (3 grams) within a dried-up ice bowl, enclosed with further dry ice (solid CO₂) pieces. Mg needs to be burned in CO₂, then the remainder is stirred in 100 mL of 1 M HCl during the night. Together MgO and Mg are water-soluble. Thus, the blend is purified, and the excess is rinsed with deionized water until the pH becomes neutral (Chakrabarti et al., 2011).

4.2.4 CVD Deposition

The precursor, a chemical process in which molecules are warmed and changed to a gaseous phase, is a component in chemical vapor deposition. During this CVD procedure, a substrate is dispersed on disintegrated thermal precursors at an elevated temperature. It accumulates in thin layers of solid, crystalline, gaseous, or liquid precursors on the substrate surface. The superior-value graphene deposition as part of the CVD procedure is normally performed onto numerous transition-metal substrates similar to Ni (Kim et al., 2009a) Pd (Choucair et al., 2009), Ru (Sutter et al., 2008), Ir (Coraux et al., 2008), and Cu (Reina et al., 2009). The CVD development of graphene has occurred mostly on copper in addition to nickel substrates (Bhuyan et al., 2016). Other bottom-up graphene synthesis techniques, including their advantages and drawbacks, are shown in Table 3.

Table 3. Bottom-up graphene synthesis.

Process	Benefit	Drawback	References
Reduction of CO	Un-oxidized layers	Contamination with α -Al ₂ S and α -Al ₂ O ₃	Kim et al. (2009c)
Unzipping carbon nanotubes	Size manipulated via a selection of the initial nanotubes	High-priced starting substance; oxidized graphene	Jiao et al. (2009), Kosynkin et al. (2009), Hirsch (2009)
Epitaxial growth on SiC	Especially huge pure graphene area	Very little-scale	Rollings et al. (2005), Sprinkle et al. (2009)
Arc discharge	Could generate around 10 g/h of graphene	Small graphene yield; carbonaceous impurities	Karmakar et al. (2009), Li et al. 2010(a)
CVD	Huge size; superior quality	Modest production scale	Bhuyan et al. (2016)
Confined self-assembly	Thickness monitor	Presence of faults	Zhang et al. (2009)

5. Properties

Graphene is a fascinating substance. Theoretically, it has a large specific surface area, a high Young's modulus, and elevated intrinsic mobility, and is thermally conductive as well as optically transparent., as well as its good electrical conductivity, this highlights the interest of researchers for applications such as transparent conducting electrodes, among several additional prospective uses (Cai et al., 2010; Li et al., 2009; Zhu et al., 2010). Graphene's general properties are shown in Table 4.

Table 4. Graphene general properties (Cai et al., 2010; X. Li et al., 2009; Y. Zhu et al., 2010).

Properties	Predictable Value
surface area	~2630 m ² g ⁻¹
electrical conductivity	~1738 siemens/m
mechanical strength	Young' Modulus ~1100 GPa, Fracture strength ~125 GPa
Thermal conductivity	5000 Wm ⁻¹ K ⁻¹
Ease of functionalization	– stacking interaction Electrostatic interaction

5.1 Mechanical Properties

Due to the good mechanical properties of graphene and graphene-based materials, several studies were conducted to investigate these properties. Numerous numerical simulations, including molecular dynamics, have been used to examine the mechanical characteristics of monolayer graphene, including Young's modulus and fracture strength (Reddy et al., 2006; Van Lier et al., 2000). Su et al. (2022) investigated the mechanical performances of graphene poly crystalline at elevated temperatures, and tensile-shear biaxial strains were studied through dynamic molecular simulations. They demonstrated that shear strain ruled the poly crystalline graphene malfunction when shear and tensile loading were employed concurrently. The authors derived that as the temperature increases, the poly crystalline graphene's structural destruction varies from stress-controlled to temperature-controlled. The major structural records of poly crystalline graphene at simple shear strains are shown in Figure 5 (Su et al., 2022).

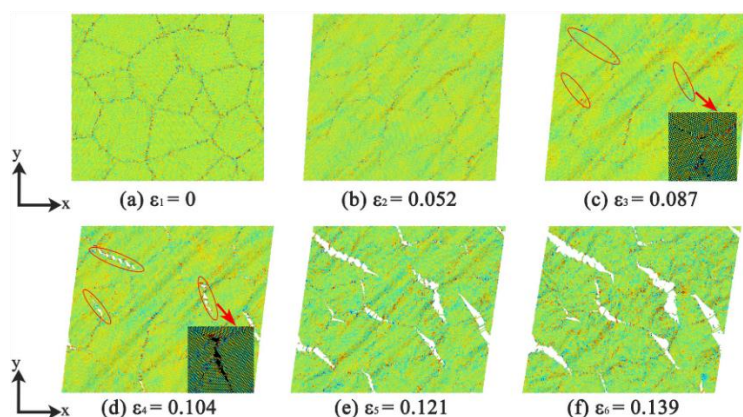


Figure 5. The most important polycrystalline graphene photographs from 0 to 0.139 with simple shear strains (Su et al., 2022).

Yang et al. (2021) analyzed the stress relaxation performance of graphene fibers. They concluded that the stress drops throughout relaxation diminished with crystallinity and orientation degree promotion. The plasticization stretching approach and graphitization procedure were introduced to lessen GF relaxation in

association with exceptional mechanical strength. The enhanced GF shows the finest stress-relaxation behavior, with 99 percent of stress persisting following relaxation. This effort shows the important relaxation performance of GFs in addition to developing successful procedures to conquer stress relaxation, producing GFs intended for functional purposes as structural substances. Figure 6 shows the graphene oxide characterization (Yang et al., 2021).

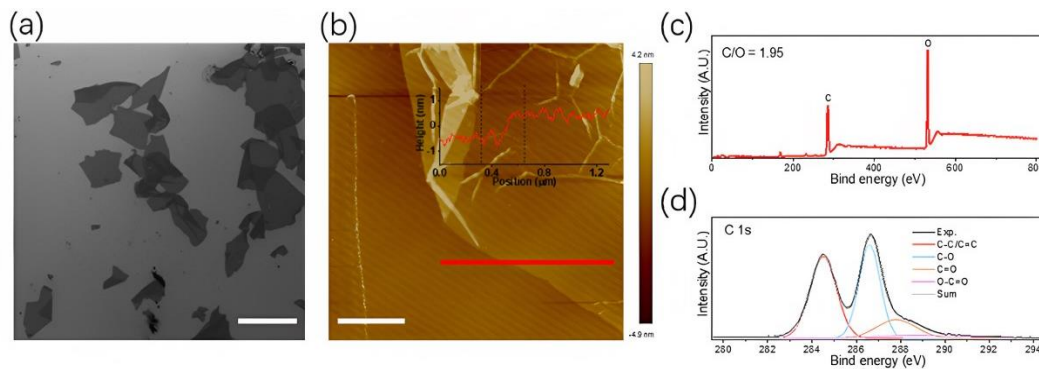


Figure 6. Graphene oxide classification. a). GO sheets SEM image. b). AFM images with an inset photo of the height profile. c). XPS spectrum survey in addition to d). C 1s GO XPS spectrum (Yang et al., 2021).

Ahmadi et al. (2021) performed an analysis using a multiscale hierarchical technique to examine the mechanical properties of composites of multilayer graphene reinforced with nano-epoxy. Biaxial loading was used for different representative volume components in order to get the surfaces of atomistic stress needed to evaluate the material's mechanical properties at a higher scale. The effectiveness and proposed technique applicability are offered via different numerical examples. It was indicated that the anticipated multiscale method was able to answer large challenges in the appropriate computational period, which is not feasible utilizing traditional molecular dynamics methodologies (Ahmadi et al., 2021). Facciolo et al. (2009) studied the electronic, structural, and mechanical characteristics of graphene zigzag nanoribbons under stress by employing the density functional hypothesis. The uniaxial stress was employed along the periodic path, permitting a unitary distortion within the scale of $\pm 0.02\%$. The mechanical characteristics within that range demonstrated a linear response, whereas, for superior strain, a nonlinear dependence was noticed. The important findings showed that Young's modulus was significantly higher compared to those found regarding carbon and graphene nanotubes. The geometric restoration at the edges of the C-C connections strengthens the nanostructure. The authors added that the electronic structure features within the linear elastic regime were not sensitive to strain, indicating the possibility of applying carbon nanostructures within nano-electronic applications in the near future (Faccio et al., 2009). Frank et al. (2007), evaluated the efficient spring constants of graphene layers (fewer than 5) suspended over defined photolithographically trenches in silicon dioxide. Calculations were done on layered sheets of graphene having a thickness between 2 and 8 nm. Dynamic and static measurements were performed, and spring constants varying from 1 to 5 N/m were noted concerning the suspended graphene layers fewer than 10 nm thick (Frank et al., 2007). Ranjbartoreh et al. (2011) explored the mechanical characteristics of as-arranged graphene papers (GP) via indentation, bending, and tensile experiments. Heat-preserved GPs reveal greater hardness, ten times more compared to synthetic graphite and twice as related to steel carbon; also, their yielding strength was considerably greater when contrasted to carbon steel. GPs exhibited exceptionally high levels of modulus of elasticity throughout the bending analysis, within the range of a little terapascal. The GP's superior stiffness and strength were assigned to the individual graphene nanosheet's interlocking-tile microstructure. These exceptional GPs' mechanical characteristics can lead to a broad engineering application range (Ranjbartoreh et al., 2011). Scarpa et al. (2009) suggested a material cellular mechanics

concept-established approach in addition to truss-form analytic models to define the in-plane elastic linear individual layer graphene sheet characteristics. The numerical and analytical findings of finite element simulations revealed a decent settlement with the present numerical standards in the open literature. An auxetic peculiarity concerning the C-C bonds was detected for individual graphene layers under natural shear loading (Scarpa et al., 2009).

5.1.1 T Young's Modulus and Ensile Strength

Graphene single-sheet was obviously discovered to be the most advanced nanofiller that was ever analyzed. The 2D material strength could differ significantly owing to the existence of Stone-Wales combined with the vacancy deficiencies inserted within it (Lee et al., 2008b). Zandiatashbar et al. (2014) through an experiment, the impact of the topological deficiencies in the graphene strength. 100 GPa breaking strength was anticipated for pristine graphene, whereas 80 GPa in addition to 75 GPa values were stated concerning armchair plus zigzag-sort graphene, correspondingly. The essential covalent bond mechanics that periodically spread along the grain boundary were the primary cause of this divergence. Because of the weakening of the bonds, graphene's overall strength decreased (Kumar et al., 2019). Wei et al. (2012) illustrated the comprehensive arrangement of flaws and ultimately showed their consequences for the stiffness and strength of graphene. It was noticed that the highest stiffness and tensile stress was a tilt angle function regarding both zigzag and armchair, with 0.980 TPA and 110 GPa, respectively. This was derived to happen owing to the heptagon-pentagon ring dipole disinclination, which is precisely opposed to the grain boundary strength (Wei et al., 2012). Using the strongest single-crystal graphene membrane, Rasool et al. (2013) estimated the graphene membrane's fracture strength and found that it was 94 GPa at a force of fracture equal to 6.8 lN. Although the top bound was reported to be 35 GPa, it was found that the breaking strength was 100 GPa. This variation was noted owing to the weakening influence of grain limits (Rasool et al., 2013). Suk et al. (2010) utilized AFM to determine the tensile strength and Young's modulus of rGO platelets and then assessed it as 39.7–76.8 MPa and 207.6 ± 23.4 GPa, respectively. Due to the weak cross-linking connections between the surfaces of the modifier and the graphene, estimated values were shown to have a less efficient mechanical characteristic through an experiment (Suk et al., 2010). Park et al. (2008) employed AFM to mechanically describe one, two, and three GO platelets in overlapping sheets. In further research, DMA outcomes displayed that the adhesive feature of pDop advances the elongation and tensile strength of pDop-rGO paper by 70% and 35 %, respectively (Lee et al., 2013). Gong et al. (2015) finished a series of bulge and tensile evaluations on graphene rGO sheets with a thickness between 0.5 and 100 lm. When compared to pure graphene (0.335 nm), such were higher. Separately, the fracture strength and Young's modulus were found to have decreased from 170.2 to 40 MPa and 44.6 to 8.5 GPa. Numerous studies have shown that GO paper with various thicknesses of 2.5–25 lm + 50–60 nm loses some of its mechanical properties (Dikin et al., 2007; Kang et al., 2013).

5.2 Thermal Properties

In addition to the mechanical properties that were reviewed in the preceding part, Additionally, graphene maintains thermal characteristics, particularly thermal conductivity, which is essential for the regulation of temperature in both electrical and mechanical systems. Due to its anisotropic bonding, durable, repeated structure, and small mass of carbon atoms, graphene exhibits unique thermal properties (Pop et al., 2012). The thermal conductivity of graphene was determined at ambient temperature in the range of 2000-5000 W m⁻¹ K⁻¹ using a Raman technique that included temperature and heating sensing (Balandin et al., 2008; Cai et al., 2010; Faugeras et al., 2010; Geim, 2009). Numerous studies on the thermal characteristics of numerous polymer nanocomposites were accomplished during the previous century; nevertheless, the glass transition temperature, melting temperature, and thermal expansion coefficient, in addition to the thermal conductivity of the nanocomposites, were revealed to remain the most significant. Baladin et al. (2008) calculated the thermal conductivity of suspended individual-layered graphene within the scale of 4800–

5300 W m⁻¹ K⁻¹, which is considerably superior to 2310 W m⁻¹ K⁻¹ intended for pure diamond, 3000 W m⁻¹ K⁻¹ concerning MWCNT (Kim et al., 2001), and 3500 W m⁻¹ K⁻¹ regarding SWCNT (Pop et al., 2006). At this moment, the graphene values considered above are around ten times the values placed for standard substances like copper (Balandin et al., 2008). The heat conductivity of single and multilayer graphene layers (ultrathin 7–10) was assessed by Jang et al. (2010), the researchers found that for single-sheet graphene, as the number of layers increases, the thermal conductivity rises at ambient temperature, showing suppression of less than 160 W m⁻¹ K⁻¹. The CVD method was used by Cai et al. (2010) to determine the single-sheet graphene's thermal conductivity at 3000 W m⁻¹ K⁻¹, which was less than that indicated in other quoted publications. This could occur as a result of the substrate's roughness and the smaller graphene suspension (Cai et al., 2010). Shaina et al. (2016) estimated the thermal expansion coefficient (CTE) of generated CVD graphene using temperature-dependent Raman spectroscopy. Regarding the entire temperature range of 90 to 300 K, they were able to attain a graphene-negative CTE value of -3.75×10^{-6} K⁻¹. The temperature was reported to be below 150 K, hence the value was zero (Shaina et al., 2016). Graphene tensioned membranes' 2D CTE and Young's modulus were examined by Storch et al. (2018) across the membrane static displacement. Laser interferometry was used for the testing, and it was shown that the modulus significantly lowers as temperature rises. This results in a favorable thermal expansion that is temperature-related (Storch et al., 2018).

5.3 Graphene-Modified and Reinforced Composite Characteristics

As stated before, graphene, in addition to adapted graphene, has exceptional mechanical characteristics associated with fracture toughness, elevated tensile strength, elevated elastic modulus, etc. These unique characteristics played a major role in the advancement of economical and superior-value nanocomposites. Asadollahi-yazdi et al. (2017) studied the mechanical characteristics of graphene-layered/polyoxymethylene nanocomposites made through the spray process. The findings of the research showed that the accumulation of 2.4 wt% graphene improved the tensile strength and Young's modulus by 64 and 103 %, respectively. Mo et al. (2015) finished the mechanical characterization of GO/PVA nanocomposites and discovered that the materials had a tensile strength of 280 MPa and Young's modulus of 13.5 GPa with a 50% modifier loading (Mo et al., 2015). Following a series of tensile tests on reinforced rGO nanocomposites, Kashyap et al. modifier (Kashyap et al., 2016) discovered a 150% improvement in tensile strength and elastic modulus for rGO/PVA 0.3 wt% nanocomposites. Due to the homogenous distribution of the fillers and the increased load transfer potential between the hydrogen bonds maintained by the matrix and modifier, this was predicted (Kashyap et al., 2016). Vlassioux et al. (2015) formed flat graphene layered laminates (sort 1) in addition to fibers (sort 2) through the request of layer-through-layer construction methodology in conjunction with layered structures' systematic progression, correspondingly. The resultant composite structures revealed that the graphene/PMMA laminates strength was twice that associated with pure PMMA having only a 0.13% graphene load. Nevertheless, pure graphene scrolls (fibers) mechanical characteristics are less notable (0.3 TPA modulus and 2.2 GPa strength), but they present a viable edge in contrast with the carbon fibers (CFs) (Vlassioux et al., 2015). Sainsbury et al. (Sainsbury et al., 2017) employed functionalized bisphenol nanosheets of graphene (f-GNS) to assemble PBE/GO-built nanocomposites in the manner of facilitating the improvement of 63 and 26 % in ultimate tensile strength and Young's modulus with concern to a 0.25 wt% filler loading (Sainsbury et al., 2017). Chhetri et al. (2018) stated that a 0.25 wt% dispersion concerning the GNS within the epoxy matrix enhances its flexural strength and fracture toughness, in addition to flexural modulus, by *46, 91, and 71%, respectively, when contrasted to the pure epoxy. Nevertheless, Young's modulus and tensile yield strength were attained to be 4.92 GPa and 66 MPa, respectively, in the case where PVA nanocomposites included a GO of 1.0 wt% (Goumri et al., 2017). Zhang et al. (2012) observed that individual-layer GO films (5.0 wt%) improved the tensile properties and interfacial of CF/epoxy composites (Zhang et al., 2012). Alexopoulos et al. (2017) examined how the size of the GNPs affected the characteristics of epoxy

nanocomposites and GNPs. At low filler concentrations (0.25 wt% GNPs), the findings demonstrated a rise in fracture toughness and UTS of 12 and 15%, respectively, and an increase in the nanocomposites' Young's modulus of 30 and 35% with the accumulation of GO with particle sizes of 1200 nm and 130 nm, respectively (Huskić et al., 2018). The researchers also discovered a decrease in mechanical characteristics while using a high filler concentration (5 wt% GNPs) because of particle agglomeration (Alexopoulos et al., 2017; Huskić et al., 2018). Likewise, an advancement of 127 and 39 % in the tensile toughness and UTS of polystyrene sulfonate-polyaniline (PSS)/rGO under a loading equal to 0.5 wt% was evaluated by Lin et al. (2019). By incorporating a novel filler, a core-shell-produced hybrid (SiO₂-GO), into the polymer epoxy matrix, Chen et al. (2012) created a high-performing polymer composite. High-density polyethylene (HDPE) nanocomposites with functionalized GO (FGO) showed a consistent dispersion inside the nanocomposites, increasing the strain and stress at the HDPE nanocomposites break by 130 and 28.7%, respectively, with no more than 0.2 weight percent of FGO loading (Li & Xie, 2018). Ni et al. (2015) manufactured epoxy-established composites strengthened by a 3D graphene skeleton (3DGS) through the RTM process to prevent complexity in the orientation and dispersion of graphene layers. The investigators applied the direct mixing process and noticed that specimens have exceptional thermal stability and mechanical characteristics when linked to EG/epoxy composites (Ni et al., 2015).

5.4 Thermal Characteristics

Frequent research on the thermal characteristics of diverse polymer nanocomposites has previously been performed within the previous decade; nonetheless, studies on glass transition temperature, melting temperature, coefficient of thermal expansion, and thermal conductivity concerning the nanocomposites remained essential (Kumar et al., 2019).

5.4.1 Glass Transition Temperature

One important viscoelastic feature of epoxy and its composites, which is normally defined by a point, is the glass transition temperature (T_g). A point like this shows how the polymer behaves, from being brittle to glassy to rubbery. The amount of free energy required by the atoms to move from their initial places in the lattice to more significant positions, which often results in a glassy toward a rubbery state, might as well be taken into consideration in order to determine the T_g more precisely. Li et al. (2016) included GO in a matrix epoxy to detect that the nanocomposites T_g developed at 33.05 °C through a filler of 1.0 fraction wt%. Nevertheless, relating to GO/epoxy nanocomposites, T_g changed to a smaller temperature variety when associated with the neat resin, as of 164.8 towards 157.1 °C (Ferreira et al., 2018). Zaman et al. (2011) produced two epoxy nanocomposite forms strengthened with GNP plus surface-improved GNP. They noticed that the interface adjustments had enhanced the T_g concerning the neat epoxy from 94.7 to 108.6 °C, showing a 14.7% increase (Zaman et al., 2011). Layek et al. (2010) likewise stated that the T_g growth from modulus loss records was not substantial. Though, while executing estimates utilizing the $\tan\delta$ plot, results observed revealed that there existed a 21 °C progress in T_g and elevated damping effects within the PMMA-functionalized 5.0% graphene (FG)-strengthened nanocomposites. Despite this, the basic epoxy resins (EPs) revealed a T_g of 153.9 °C. The incorporation of thermally condensed FG and GNPs in the epoxy raised the T_g toward 169.8 and 167.6 °C, respectively (Naebe et al., 2014). Ribeiro et al. (2015) researched the T_g of GO-TEPA (tetra ethylene pentaamine)- epoxy-reinforced composites and GO utilizing the DMA experiments. They assessed that the T_g rates improved by 15 to 20 °C regarding GO besides GO-TEPA epoxy composites (0.5 wt%), correspondingly, in contrast to the basic polymer (Ribeiro et al., 2015).

5.4.1 Thermal Conductivity

Utilizing an accumulation of nanocarbon fillers increased the thermal conductivity of epoxy nanocomposites (Zhou et al., 2013). Nevertheless, the thermal conductivity increase could be efficiently completed by adding nanosheets of 2D graphene, not including 1D rod-like CNT (Ganguli et al., 2008).

Free electron interactions and lattice vibrations among two or further contacted surfaces have been noticed to be responsible for carrying out the thermal energy transfer according to Kaptiza resistance. Consequently, poor interactions at epoxy or nanofiller interfaces greatly impacted the thermal resistance (Pollack, 1969). Therefore, a solid epoxy or nanofiller interface was essential to attaining sufficient thermal conductivity (Martin-Gallego et al., 2011). Kostagiannakopoulou et al. (2016) studied the consequences of GNPs and MWCNTs on nanomodified CPRFs in addition to the nano-strengthened polymer's thermal conductivity behavior. They showed that the addition of GNPs of 15 wt% to the epoxy enhances the thermal conductivity of nano-modified CPRFs and nano-reinforced polymers by 48 and 176 %, respectively (Kostagiannakopoulou et al., 2016). Gu et al. (2016) assembled the f-GNPs/E-51 and GNPs nanocomposites by utilizing the casting process. They observed that f-GNPs/E-51 nanocomposite's thermal conductivities existed to be enlarged by the f-GNPs content rise, besides being bigger than that regarding GNPs/E-51 nanocomposites, while the coefficient of thermal conductivity concerning f-GNPs/E-51 combined with a 30 wt% of f-GNPs was larger by 8 times compared to the pristine E-5 (Gu et al., 2016). Liu et al. (2022) investigated the influence of doping in addition to deficiencies in the thermal conductivity regarding the graphene/Si structure interface, centered on dynamic molecular simulation. In conjunction with the boron and nitrogen doping deficiency ratios, the heterostructure's thermal conductivity showed a decreased tendency. However, the effect of boron doping on thermal conductivity was greater compared to nitrogen doping. It was determined that, owing to the distinct mass of boron and nitrogen, the lattice vibration harmonic impact occurs to a certain extent. The authors added that the fundamental deficiencies of graphene would significantly lessen the individual-sheet graphene/Si interface's thermal conductivity, though single vacancy deficiencies have the ultimate effect on thermal conductivity. The weakness region of graphene is shown in Figure 7 (Liu et al., 2022).

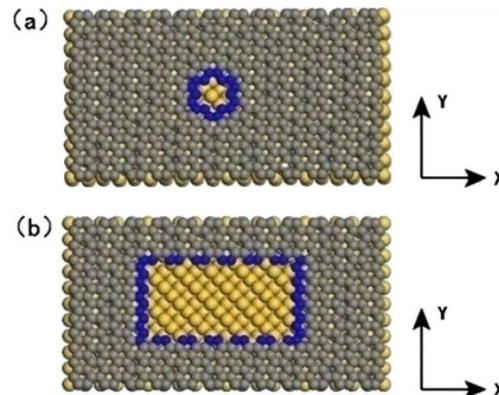


Figure 7. The silicon heterostructure contact is just one instance where graphene has deficiencies according to the CPK model. (a) The defect area of the circular hole-doped material is 3%. (b) A flaw with a square shape and a 35% defect area (Liu et al., 2022).

5.4.1 Coefficient of Thermal Expansion

A low thermal expansion coefficient and decent stability have been considered important aspects that a composite must possess, especially in such climatic circumstances where the temperature shifts considerably. This can be utilized to reinforce the aircraft's surfaces, aerospace products, and buildings (McQuade et al., 2021; Shi et al., 2016). Kano et al. (2020) excluded the contamination impacts, measured the substrate impact, and then accomplished evaluating the thermal expansion coefficient of suspended single-layer graphene (SLG) under temperatures varying between ambient and 900 °C. It was observed that the CTE of the SLG was positive, and the values were linked to an SLG lattice spacing that might specify compressive or tensile stress concerning the SLG specimen (Kano et al., 2020).

5.5 Tribological Properties

Energy supplies are diminishing at an especially rapid pace worldwide, and inventors and engineers are under immense pressure to discover all accessible options to create modern and innovative technologies to preserve energy and substances, in addition to preserving the environment. Weak wear and friction characteristics of a substance culminate in elevated energy expenditure, an elevated wear rate, and additional emissions to the environment. Consequently, it is predictable not merely to lessen friction but also to raise the material's wear resistance, which is utilized for the fabrication and design of elements in addition to mechanical procedures (Wani & Anand, 2010). One of the oldest and most highly efficient techniques of lowering the wear and friction behavior of elements and mechanical systems is done through the usage of mineral oil-established lubricants at the tribo-system interface (Farhanah & Syahrullail, 2016; Willing, 2001). Liquid lubricants decrease friction by inhibiting contact sliding interfaces on severe or more common metal-to-metal surfaces or by forming a small-shear, elevated durability film boundary on rubbing surfaces (Bartz, 1998; Mercurio et al., 2004; Nuraliza et al., 2016). For instance, by varying the sliding velocity in addition to additional working circumstances, engine oils could essentially split the contacting tribo-pairs surfaces and thus avoid the direct metal-metal connections, which lead to low wear and friction. When there is a metal-metal interface, the additives within such oil lubricants create a small shear, extremely protective boundary film to offer supplementary protection. Additionally, decreasing wear and friction implies superior fuel investments and extended tribo-systems durability. Oil lubricants are supplied to sliding surfaces over a pump or else by more types of oil supply processes, though solid lubricants need to be employed as light films utilizing physical vapor deposition (PVD) along with chemical vapor deposition (CVD) techniques. Owing to their fixed thickness, lubricant solid films eventually wear out and hence lose their efficiency. They are too incredibly susceptible to the surroundings; in reality, a few of them, similar to MoS₂, would not lubricate or hold up longer in case oxygen or water particles appeared; in fact, boric acid and graphite would not operate with no humidity within the nearby air. Consequently, the highly attractive characteristics of solid lubricants are that they are ecologically inconsiderate, very durable, and simple to provide to the contact interfaces (Beerschwinger et al., 1994; Holmberg et al., 2012; Kim et al., 2009b; Kim et al., 2012; Kim et al., 2011; Penkov et al., 2012; Penkov et al., 2013; Woo & Kim, 2011). Graphene has drawn the attention of researchers, designers, and engineers in numerous functions worldwide (Avouris & Dimitrakopoulos, 2012; Geim & Novoselov, 2007; Novoselov, 2011; Park et al., 2009; Peng et al., 2008; Ramanathan et al., 2008; Schwarz et al., 1997; Singh et al., 2011; Stankovich et al., 2006; Taghioskoui, 2009; Wintterlin & Bocquet, 2009; Young et al., 2012; Yu et al., 2000). Due to its exceptional electrical, mechanical, physical, and optical characteristics, graphene has lately been utilized within the area of tribology (Chen et al., 2011; Li et al., 2005; Prasai et al., 2012; Smolyanitsky et al., 2012; Spreadborough, 1962).

Furthermore, scientists have similarly applied numerous techniques concerning graphene synthesis to also develop its tribological and mechanical characteristics. It is consequently essential to comprehend the fabrication procedure of graphene completely and likewise conduct a comprehensive literature study to comprehend its wear and friction features for gaining the profits popular in the tribology field, like solid lubricant or as an additive strengthening trendy non-metals and metals.

5.5.1 The Friction and Wear of Graphene at Microscale

The wear performance of a substance is the interface that happens among the surfaces that leads to the elimination and distortion of the substance on the sliding faces. This constraint is additionally described as dimension loss owing to plastic deformation. Chemical processes, corrosion, erosion, or even the sequence of such advances to wear (Gupta et al., 2022a). Various experiments have explored graphene's frictional properties using a scratch microscale experiment. Unlike nanoscale scratch experiments performed using an AFM tip, the contact pressure within the microscale scratch experiment could be considerably superior

(Cho et al., 2013; Filleter & Bennewitz, 2010; Lee et al., 2010; C. Lee et al., 2009; Lee et al., 2009; Li et al., 2010b; Lin et al., 2011). Shin et al. (2011) inspected the coefficient of friction concerning exfoliated and epitaxial graphene through a few sheets under a normal load ahead to 0.5 μN utilizing an AFM radius tip equal to one meter. They discovered that the thickness of the graphene layer was not significantly influenced by the coefficient of friction. One, two, and three graphene sheets were found to have a coefficient of friction of around 0.03. The authors also looked at how structural flaws caused by graphene coatings affected tribological properties. It was shown that in both exfoliated and epitaxial graphene, the presence of flaws increased the friction by two times (Shin et al., 2011). Marchetto et al. (2012) analyzed the friction and wear of a single graphene sheet by means of many-asperity contacts, which are convenient for relatively tough substrates. It was established that tiny asperities burst the layer of graphene during the initial limited sliding phases at small loads (Marchetto et al., 2012).

Won et al. (2013) have likewise proved the effect of deficiencies that happened as a result of the friction on the graphene's tribological characteristics. The writers stated that the wear processes and friction of grown CVD graphene on copper substrates at a load equal to 20 μN besides 1 mm diameter balls of chrome steel have been utilized as an anti-surface. It emerged that concerning certain deposition parameters set in addition to the deficiencies number, the number of average layers in the coatings of graphene was reliant on the growth time (Won et al., 2013). Hasan et al. (2022) studied the influence of graphene on friction, and substance characteristics, coupled with wear concerning aluminum self-lubricating-established metal matrix composites (MMC), were associated with the graphite influence as strengthening. Noteworthy improvements in friction and mechanical characteristics, in addition to wearing behavior, were noted with the addition of friction (Hasan et al., 2022).

5.5.2 Tribological Performance of Graphene at Room Temperature as Reinforcement

A composite made of graphene oxide (GO) and ultra-high relative molecular mass polyethylene (UHMWPE) was studied by Tai et al. (2012). GO/UHMWPE and pure UHMWPE composites' mechanical and tribological properties were examined using a micro-hardness testing tool in addition to a reciprocating high-velocity tribometer. The outcomes demonstrated that as the substance of GO nanosheets was around 1 wt%, the composite's hardness and wear resistance were enhanced considerably, whereas the coefficient of friction would rise swiftly (Tai et al., 2012). Zhu et al. (2014) studied the tribological analyses at dry sliding concerning Ni3Al matrix composites (NMCs) having a graphene nanoplatelets (GNPs) concentration equal to 0.5 wt% sliding counter to various counter balls. The test was conducted under an applied load equal to 10 N and a sliding speed of 0.234 m s⁻¹. The authors stated that in the case of NMC sliding versus GCr15 steel, a thick and reliable friction sheet was developed, causing a smaller friction coefficient. While in the case of the NMCs sliding counter to Al₂O₃ in addition to Si₃N₄, the stability, and formation of the friction sheets were limited in the severe wear regime, and thus the NMCs showed greater wear rates and friction coefficients (Zhu et al., 2014). Min et al. (2018) investigated the tribological performance of graphene oxide (GO) and polyimide (PI) nanocomposite layers by means of in situ polymerization under various conditions, including pure water lubrication, seawater lubrication, and dry friction. The GO/PI presented well-defined outcomes in the case of lubricated seawater when compared to additional circumstances, for the reason that the superb influence of lubricating seawater. The strengthening of GO significantly enhanced the composite's thermal stability (Min et al., 2018). Zhou et al. (2022) investigated the tribological behaviors and mechanical properties of a graphene/metallic glass film with a laminated structure and discovered that the GR combination could lead to large shear band interfaces and shear band interactions. In association with the MG monolithic film, the wear rate and friction coefficient regarding the multilayer was reduced by means of ~ 65% and 35%, respectively, which was credited to the improved mechanical characteristics in addition to the lubricating influence caused via the GR layer. The cross-sectional photo of the sample is shown in Figure 8 (Zhou et al., 2022).

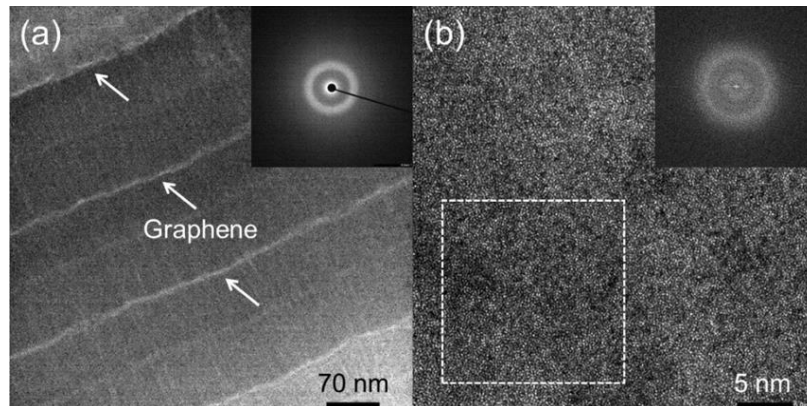


Figure 8. (a) The electron pattern diffraction exhibited inset in the MG/GR multilayer cross-sectional TEM image. (b) HRTEM picture regarding the MG layer displaying the amorphous structure (Zhou et al., 2022).

Gonzalez et al. (2015) compared a graphene/alumina (Al_2O_3) sample's dry sliding performance to that of alumina. A reciprocating tribometer was used to conduct the experiments, with a sliding distance of 10 km and a load of 20 N, in addition to a 0.06 ms/1 sliding velocity. During the assessment, the sample revealed a 10% smaller coefficient of friction and nearly half the wear rate compared to monolithic alumina. In addition, it was also revealed that such performance was connected to the existence of adhered graphene nanoplatelets on the friction surface beside the GNPs procedure, a self-lubricating sheet that delivers sufficient lubrication and is subsequently efficient to decline both wear rate and coefficient of friction while associated with the $\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3$ blend (Gutierrez-Gonzalez et al., 2015). Kalin et al. (2015) analyzed the effects on tribological and mechanical properties of the morphology of fine-suspended solid lubricant nanoparticles and the substance type of poly-ether-ether-ketone (PEEK) samples. The attained consequences in dry sliding tribological situations displayed that the nanoparticle's morphology and material have a significant consequence on the wear and coefficient of friction, mainly through influencing their thickness, macroscopic hardness, and so their transfer film surface coverage (Kalin et al., 2015). Zhang et al. (2019) investigated graphene's influence on the tribo-layer of aluminum matrix composite throughout wear dry sliding. A lubricious and shielding tribo-layer was established among the sliding interfaces. It was observed that a 1 vol% GNS's incorporation decreased the friction and wear by 39.1% and 85.0% correspondingly. The wear scar images are shown in Figure 9. The experimental results micrographs are shown in Figure 10 (Zhang et al., 2019).

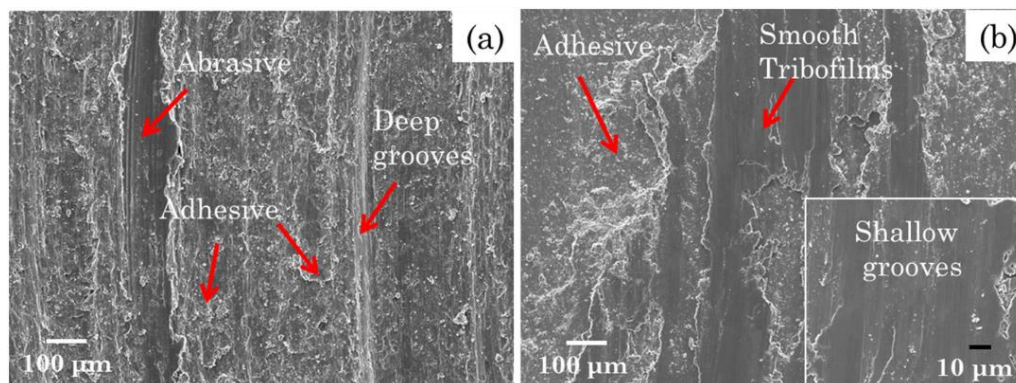


Figure 9. Wear scar micrographs concerning (a) Al alloy in addition to (b) Al-GNSs composite having an expanded view within the inset (Zhang et al., 2019).

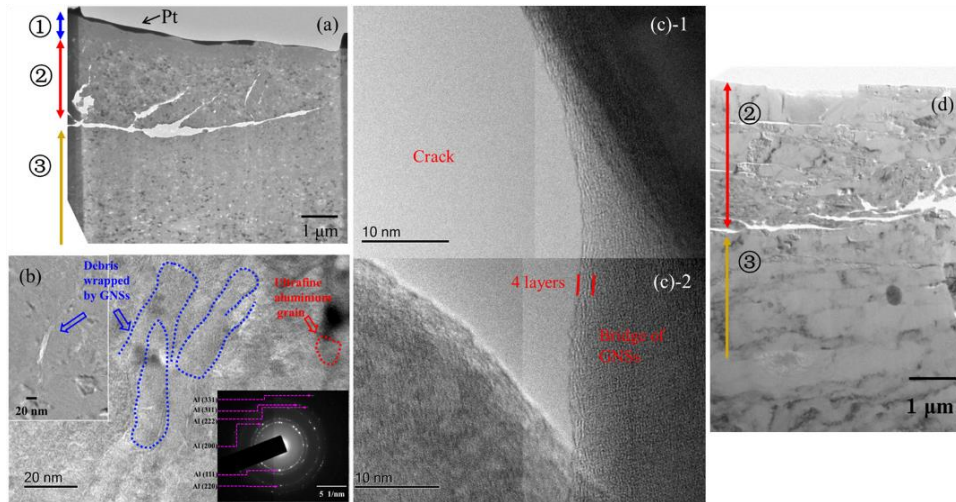


Figure 10. (a) A TEM micrograph shows a three-layered microstructure beneath the wear scar. (b) A top tribolayer high-resolution morphology with arrowed aluminum ultrafine grains; (c) A high-level-resolution morphology for the fractured layer. (d) The fractured sheet and the matrix are made of the alloy AlSi. (Zhang et al., 2019).

5.5.3 Graphene's Tribological Properties as a Reinforcement at Elevated Temperature

Shukla et al. (2021) analyzed the tribological performance of sprayed plasma graphene nanoplatelets reinforced with cerium oxide coatings at high temperatures. Curiously, distinct from standard coatings in case the wear characteristic decomposes at elevated temperature, the CG wear characteristics kept on enhancing from room temperature to 873 K. The highest wear rate decline (260%) and coefficient of friction (26%) were seen at 873 K. It is assumed that such a coating can overlay the route concerning designing coatings working at elevated temperatures. The wear track of various coatings, Raman spectra, and elemental mapping is shown in Figure 11 (Shukla et al., 2021).

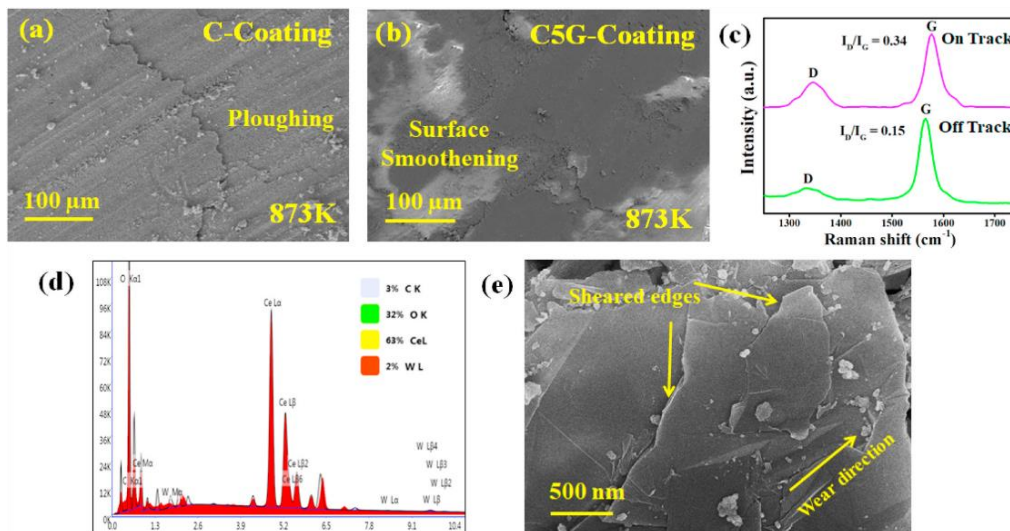


Figure 11. SEM photo of the wear track of (a) C coating (b) C5G coating. (c) Raman spectra of the C5G coating at 873 K, both on and off-track, (d) At 873 K, elemental mapping was completed over the wear track of the C5G coating, (e) SEM depiction of GNPs in C5G coating at higher magnification for subsequent wear evaluation (Shukla et al., 2021).

Ranjan et al. (2020) investigated the mechanical and microstructure, in addition to the high-level temperature tribological performance, of graphene nanoplatelets strengthened with plasma-sprayed coatings of titanium nitride. Progress of 18%, 300%, and 19% within elastic modulus, fracture toughness, and hardness were attained through the simple accumulation of GNP equal to 2 wt. %. The supplement of GNP appearing in TiN likewise lowered the wear rate and wear volume loss regarding the coatings at the full temperature range (293–873 K). Furthermore, GNPs also demonstrated the friction coefficient (COF) of the coating. The high FE-SEM magnification illustration of a GNP following wear analysis revealing the sheared edges is shown in Figure 12 (Ranjan et al., 2020).

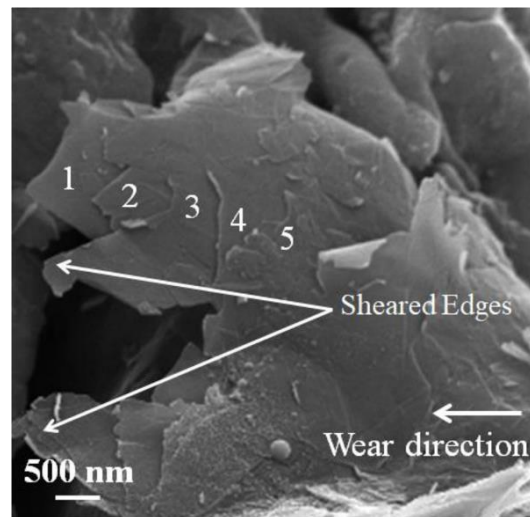


Figure 12. High FE-SEM magnification illustration of a GNP following wear analysis revealing sheared edges. Numbers on top of the GNP signify various layers (Ranjan et al., 2020).

Xu et al. (2015) inspected the self-lubrication properties of multi-sheet graphene plus the elevated-temperature tribological characteristics of graphene aluminum titanium matrix composite (GTMC) aimed at the primary period from 100 to 700°C by means of ball-on-disk apparatus under a 0.2 ms/1 constant velocity and a 10 N applied load. MLG's self-lubrication capabilities were lost due to the formation of the oxide layer, which improves GTMC oxidation resistance by blocking oxygen access all the way through the grain boundaries and restricting the grain boundaries (Xu et al., 2015).

5.5.4 Graphene's Tribological Performance as Lubricant Additive

There are several papers that mentioned the tribological behavior of various materials under different condition including the usage of lubricant additives (Çamlı et al., 2022; Demirsöz et al., 2022; Etri et al., 2023; Gupta et al., 2023; Gupta et al., 2022a; Gupta et al., 2022b; Korkmaz, 2022a; Korkmaz et al., 2021, 2023; Korkmaz, 2022b; Krolczyk et al., 2022; Ross et al., 2023; Ross et al., 2022a; Ross et al., 2022b). Wu et al. (2018) investigated the tribological properties of graphene oxide nanoplates utilized as oil additives in ceramic/steel contacts. With GOPs of 0.5 wt% lubrication, friction reduction, wear resistance, and load-carrying capacity were increased by 14.7%, 34%, and 18.2%, respectively. At each of the analyzed rotational velocities, GOPs improved wear resistance and friction lessening concerning the sliding sets. Associated with the small loads applied, the samples demonstrated improved tribological characteristics at superior loads. The optical images of the WSDs and Raman spectra of the sample are shown in Figure 13 (Wu et al., 2018).

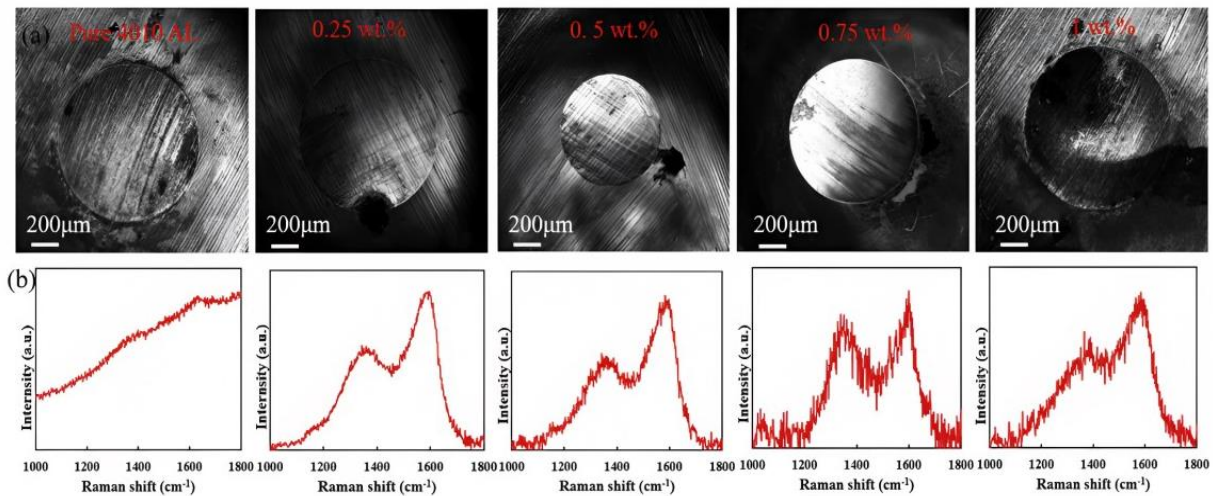


Figure 13. (a) Optical images of WSDs and corresponding (b) the Raman spectra of the rubbing surface of GCr15 steel balls with varied GOP lubrication concentrations at 392 N plus 1450 r/min (Wu et al., 2018).

Lin et al. (2011) evaluated the tribological performance of the modified graphene platelets (MGP) created in oil using a four-ball apparatus. The findings demonstrated that the lubricant comprising just 0.075 wt% of MGP obviously decreased the load-carrying and wearability of the substance (Lin et al., 2011). The tribological properties of graphene oxide nanosheets in mineral oil were investigated by Senatore et al. (Senatore et al., 2013) under mixed lubrication and boundary conditions, as well as elastohydrodynamic regimes. The tests were conducted on a ball-on-disc tribometer. The findings obviously proved that graphene platelets established an oil-protecting film to avoid the direct connection among mating steel surfaces, in addition to enhancing the base oil's frictional performance (Senatore et al., 2013). Yu et al. (2022) studied the tribological characteristics of alkylated diminished graphene oxide as an oil additive by applying a ball-on-plate device; later worn surfaces were analyzed through Raman spectra, an optical microscope, and a scanning electron microscope (SEM). At the 10 N load applied, it was revealed that ODA-RGO was beneficial for friction reduction and lubrication. The superb tribological performance promoted the development of ODA-RGO protecting film, which can prevent links among tribological pairs. The SEM images of the worn surfaces are displayed in Figure 14 (Yu et al., 2022).

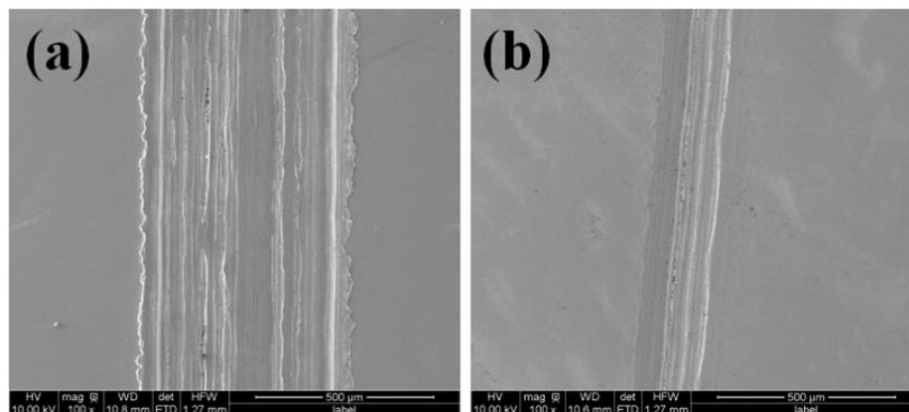


Figure 14. SEM illustrations on worn surfaces following lubrication with (a) base oil in addition to (b) base oil with ODA-RGO (0.075 mg/mL) (Yu et al., 2022).

5.6 Properties of Hybrid Composites Reinforced and Modified by Graphene

5.6.1 Graphene-Fiber-Hybrid Composites

The properties of the fiber-matrix interface often determine how carbon fiber-reinforced composites (CFRP) behave. To enhance the CF/epoxy composite's interfacial characteristics, immediate f-GNS dispersed or graphene introduction onto the individual CFs surface within the fiber sizing was completed. Throughout interface enhancements, graphene single- and double-layer sheets have been seen in randomly chosen regions (Kumar et al., 2019). Papageorgiou et al. (2016) investigated the impact of GFs, GNPs, and hybrid fillers on the characteristics of PP. The evaluations of tensile experiments on PP-GF, PP-GNP, and PP-GF-GNP composites were finished by the authors, and they assumed that the addition of hybrid filler increased Young's modulus of the composite (Papageorgiou et al., 2016). Glass fiber (GF)/epoxy composites with hybrid-coated GO/CNT were reported to form by Hua et al. (2017). Results revealed that compared to the value calculated under the conditions of a single GO in addition to CNT coating, the strength of the interfacial bond regarding the hybrid-coated fiber was enhanced by 128% (Hua et al., 2017). Dhananjaya et al. (2020) examined the corrosion and mechanical properties of hybrid composites made of 2024 aluminum and R-glass fiber. Experiments like compression and tension experiments were performed on the specimens based on the reinforcement's weight percentage. The authors concluded that the ultimate strength boosts with the rise in the percentage reinforcement composition of the aluminum alloy; likewise, the rise in the ultimate strength was anticipated by the graphene addition, which provides strength to the aluminum sample by improving tensile strength resistance. It was noticed that the compressive strength was similarly boosted in conjunction with the reinforcement percentage weight. The hybrid composite's SEM pictures were created at various conditions are shown in Figure 15 (Dhananjaya et al., 2020).

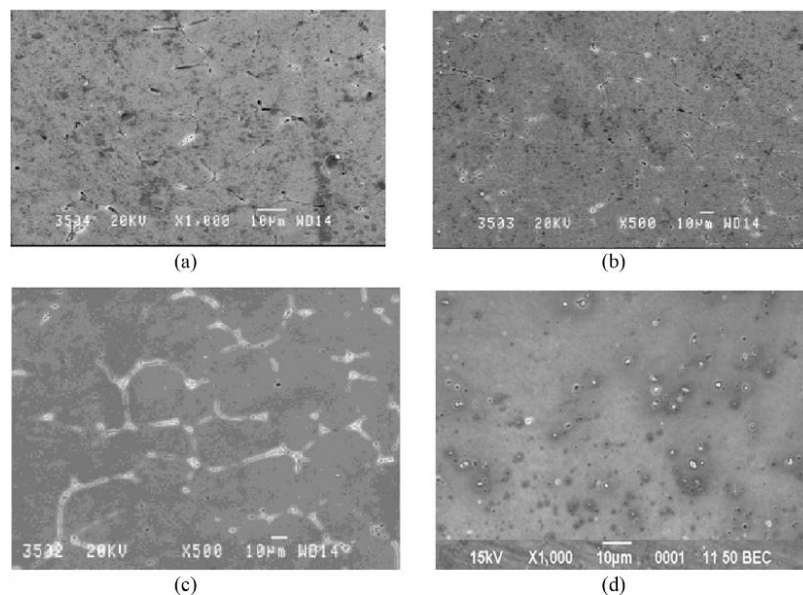


Figure 15. a) SEM photos hybrid generated composite with exposure periods of 24 hours in HCl solution, b) 48 hours, c) 72hrs, d) 96hrs (Dhananjaya et al., 2020).

5.6.2 Graphene/Nanofiller Hybrid Composites

To improve the overall qualities of hybrid epoxy nanocomposites, the filler's chemical compatibility is crucial. Recently, a number of tests were carried out to evaluate the increase in the interphase between the matrix as well as the fillers. Moosa et al. (2016) examined the mechanical characteristics of CNTs and GNPs epoxy nanocomposites that had 0.1, 0.2, 0.3, and 0.4 weight percent of CNTs and GNPs mixed 1:1.

According to the investigation, a 0.4% CNTs and GNPs hybrid filler, the UTS rises 36% while the elasticity modulus doubles that of the plain epoxy (Moosa et al., 2016). Min et al. (2018) produced reinforced hybrid PI nanocomposites formed of carboxyl functionalized MWCNTs and GO nanosheets. They concluded that the tensile strength has been observed to be raised by 25.1 % at a 3:1 GO/MWCNTs ratio when associated with pure PI (Min et al., 2014). Ribeiro et al. (2018) examined hybrid nanocomposites' thermal and mechanical characteristics. In conjunction with the accumulation of hybrid filler of 0.5 wt%, the authors noticed a 32, 177, and 140 % rise in elastic modulus, ultimate strain, and tensile strength of the epoxy nanocomposites, respectively. The thermal conductivity, in contrast, occurred to be enhanced by around 142 % while GO/h-BN2.0 wt% was included (Ribeiro et al., 2018). Chatterjee et al. (2012) investigated the effect of the CNT/GNP hybrid filler on hybrid nanocomposite properties. They noted that with a 9:1 ratio of CNT/GNP, the fracture modulus and fracture toughness of the specimen had risen considerably by 17 and 77 %, respectively (Chatterjee et al., 2012). Mechanical characteristics of a cross-linked hybrid GO/CNT aromatic PI nanocomposite have been studied by Wang et al. (2017). The authors noted that a substantial rise in modulus and strength, in addition to fracture toughness by 94, 118, and 138%, was correspondingly observed while matched to pristine PI (Wang et al., 2017).

5.7 Electronic Properties

Prospective uses for electronics based on graphene are quite promising. In addition to its enormous technological potential, graphene's relativistic charge carriers offer the chance to solve basic condensed matter physics issues that are not accessible to other materials (Castro Neto, 2010; Craciun et al., 2011; Geim & MacDonald, 2007; Neto et al., 2006). In graphene, electrons, and holes follow a linear energy dispersion relation and act as Dirac fermions, which are chiral massless particles (Castro Neto et al., 2009; Wallace, 1947b). Numerous unique physical behaviors, including Klein tunneling (Beenakker, 2008; Katsnelson et al., 2006), a novel quantization sequence in the quantum Hall regime (Novoselov et al., 2005; Zhang et al., 2005), and Veselago lensing (Cheianov et al., 2007), have their roots in these unique features.

Graphene π electrons offer a perfect 2D system: a single atom thickness, with the π and π^* states non-interacting with each other. The conduction band is formed by the π^* states, and the valence band is formed by the π states. These bands come together at 6 positions known as neutrality or Dirac points. Due to symmetry, these six points may be reduced to a pair, K and K', which are independent of one another. The bands show linear dispersion, and the structure of the bands may be compared to two cones coming together at E_{Dirac} if we restrict ourselves to minimal energies that are of the greatest significance for electron transport. This is due to the fact that the orthogonal π^* and π states avoid interacting, allowing for their crossing. Because these bands overlap at E_{Dirac} , graphene has no band gap and is hence frequently referred to as a zero-gap semiconductor (Avouris, 2010). Graphene has exceptional transport characteristics. Carriers in the ballistic transport regime move with a v_F 106 ms⁻¹ Fermi velocity (Bolotin et al., 2008; Du et al., 2008).

5.8 Optical Properties

Graphene's peculiar electrical dispersion results in very desirable optical and plasmonic characteristics that have a wide range of potential applications in optical electronics. As coupled photon-electron excitations in graphene, plasmon-polaritons exhibit 2D massless fermion behavior and are able to be imaged and gate-controlled, opening the way for the creation of novel and small Optical innovations, such as metamaterial and transformation optics devices, that operate from terahertz to visible frequencies (Capaz, 2022).

The quantum Hall effect, high carrier mobility at ambient temperature, a sizable theoretical specific surface area, exceptional optical transparency, and outstanding thermal conductivity are just a few of the unusual qualities that graphene has demonstrated. In graphene, certain astounding optical characteristics have also

been seen. For instance, despite being only one atom thick, it is optically observable. Its fine structure constant may be used to express its transmittance. Due to Pauli blockage brought on by the Dirac electrons' linear dispersion in graphene, which was previously found, graphene is suited for use in ultrafast mode-locked lasers. Additionally, luminescence may result from the chemical or physical manipulation of graphene as well as nonequilibrium carriers. It is the optimum photonic and optoelectronic material due to these characteristics (Zhibo et al., 2012).

6. Improvement Procedures

Several advancement techniques were used to enhance graphene and its derivative materials, Table 5 shows recent advances concerning graphene improvement.

Table 5. Recent advances concerning graphene improvement.

Author(s)/Reference	Title	Findings
Marcano et al. (2010)	Enhanced Graphene Oxide Synthesis.	The enhanced technique for producing GO has substantial benefits compared to Hummers' approach; it generates a better fraction of good-oxidized hydrophilic carbon substance.
Benzait et al. (2021)	The enhanced synthesis method of graphene oxide.	The rGO films that were produced have mechanical, rheological, and electrical properties that support the improvement of Tour's procedure.
Cano et al. (2013)	Optimizing the mechanical properties of materials based on graphene oxide by attaching covalent polymer chains.	Both the modulus combined, with strength raised by 40% compared to the pure polymer.
Li et al. (2018)	Enhancing mechanical characteristics and graphene distribution of GNP/Al composites via cold drawing.	The cold drawing method has a substantial impact on reducing pores and GNP aggregates.
Pathak et al. (2016)	Improved mechanical properties of hybrid carbon fiber/graphene composites.	Graphene oxide use is one of the methodologies for enhancing carbon fiber polymer composite characteristics.
Satti et al. (2010)	Chemical crosslinking is used to improve the mechanical properties of composites made of poly(allylamine) and graphene oxide.	The filtering technique was improved to produce solid GO layers, which were then crosslinked with PAH in situ to produce very intense composites with tensile strengths as high as 146 MPa.
Jing et al. (2020)	Introducing decreased graphene oxide to enhance cement composites' thermal properties.	Achieved outcomes determine doping rGO is a favorable method for decreasing the thermal stress and limiting the growth of thermal cracks.
Imran et al. (2018)	Graphene nanoplatelets are used to increase the thermal and electrical conductivity of polypropylene.	In the instance of the coating method, a graphene network developed on the polypropylene pellet's outer surface has a solid influence on electrical conductivity enhancement; though, it did not alter the thermal conductivity.
Anno et al. (2017)	Engineering of defects to improve the thermoelectric performance of graphene.	Establishing a controlled level of defects in graphene is an effective way to reduce its thermal conductivity, which will enhance the performance of thermoelectric devices based on graphene.
Wang et al. (2016)	Dramatic improvement of graphene oxide/silk nanocomposite membranes: through interfacial structures annealing.	Improved multilayer packing shear strength results from the development of nanofibrils in solid hydrophobic-hydrophobic relationships between GO sheets and SF.
Zhang et al. (2014)	Designing structures of graphene with precise topological defect distributions.	The distributed and curved topology deficiencies provide growth to an essential toughening process and lead to a fracture toughness rate nearly twice that of pristine graphene.
Khalil et al. (2019)	Functionalization with polyvinylpyrrolidone to improve the biocompatibility of graphene oxide-silver nanocomposite.	The findings showed that the decoration with AgNPs indicated a substantial rise in the antimicrobial action of GO in addition to FGO sheets.

7. Conclusion

In this article, the synthesis, types, applications, mechanical, thermal, and tribological characteristics of graphene besides graphene-established substances have been assessed. Graphene is considered a crystalline carbon 2D formation with different types depending on the number of layers; graphene having one layer of

carbon atoms forms a honeycomb shape. There are only two main methods to produce graphene: the preliminary method is a top-down process by the breakdown of graphite into graphene employing exterior techniques, while the following methodology is a bottom-up approach by means of graphene assembling from molecular structure blocks or even carbon resources. The formation of graphene in a cost-effective and high-value manner is vital for several industrial sectors and fields, as it is used in various applications including medical, biomedical, aerospace, electrical, automotive, and energy, in addition to other purposes. The complete analysis of graphene characteristics has uncovered that such material performs an essential function within the development of total polymer nanocomposite properties that could also be utilized in various fields of products. This assessment covers a serious investigation of the research studies that were comprehensively accomplished for evaluating the thermal, tribological, and mechanical characteristics of graphene, as well as the characteristics of graphene-built nanocomposites. Moreover, the characteristics of hybrid nanocomposites containing graphene as a major filler were also analyzed. Hereafter, this comprehensive review paper exposes the consequences of practically various kinds of graphene besides its derivatives on the thermal, tribological, and mechanical behavior of nanocomposites. Additionally, new developments concerning the enhancement of graphene properties and fabrication methods were also illustrated.

8. Future Scopes and Challenges

Despite recent attempts to produce and utilize GR and its materials in the biomedical sector, significant challenges still need to be solved. The first one concerns the mass manufacture of these materials to satisfy the escalating demand. It has been claimed that the expenses related to the manufacturing of GR-based products have decreased in the previous few decades, dropping from around US\$250. kg⁻¹ to US\$20. kg⁻¹. Consequently, it is evident that a significant drop in the manufacturing cost of GR and its based materials has resulted from the progress of innovative knowledge and methodologies In the last few years. Furthermore, we must know that nanocomposites frequently have a small nanofillers concentration, which offers a significant cost-saving. Due to this situation, GR is a strong contender for usage in a variety of industrial applications (Souza et al., 2022).

Without increased spatial resolution, it will be difficult to examine the Raman signals of individual faults in graphene in a short period of time. Improvements in patterned nanostructure quality and reproducible results, expanding the plasmon tunability toward the vis-NIR range, and effective light coupling through and out of graphene are plasmonic and optical challenges of graphene. The difficulty of creating regulated manufacturing methods that consequence in devices is a key factor in graphene spintronic and electrical applications. In fact, scalability and wafer-scale integration are also significant concerns. Even though twisted graphene systems have unusual superconductivity, we don't know exactly how it works. This is a big problem for scientists studying graphene. Other 2D materials and their mixtures now have the option of exploring the twist degree of freedom. Predicting and designing structures for desired electrical or optical characteristics is another issue brought on by the large range of conceivable configurations—combining different materials and twist angles. This enormous undertaking unquestionably requires the use of artificial intelligence methods. In fact, scalability and wafer-scale integration are also significant concerns. Improved quality control, uniformity, and stability of graphene flakes, as well as an increase in production rate and scalability for CVD graphene, are difficulties for industrial-scale graphene synthesis. The need to establish a single standard or grading scheme is essential since varying quality across various manufacturers is often a problem. In contrast to competing technologies, graphene applications face challenges in overcoming manufacturing costs and volume limitations. Recognizing the relationships between graphene materials' structure and activity in regard to health as well as the environment in greater detail and developing creative mitigation strategies for any negative consequences are challenges in this subject (Capaz, 2022).

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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