ENHANCING GRAPHENE IN INGREDIENT OF PAINTS COATING

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Abstract

The excellent flexibility of graphene materials that allows them to adjust to the curvature of the substrate surface, chemical surface inertness, and impermeability have attracted considerable attention in the past decade as a blending material and an additive in anti-corrosion coatings. In this paper, we present the role of graphene in enhancing the protective properties of anti-corrosion coatings on metal surfaces with the aim of improving the anti-corrosion performance and extending the life of the coating on metal structures, comparing the anti-corrosion ability of graphene with some types of metal oxide materials such as zinc oxide, titanium dioxide. The methods of graphene fabrication and the method of blending graphene into the coating composition give results on mechanical properties, wettability, antibacterial properties, anti-corrosion properties, fire resistance and current research trends in graphene-based coating materials and explore optimal solutions for applications in the paint industry.

Keywords: anti-corrosion, graphene, mixing and modified graphene, paint coatings, synthetic methods

1. Introduction

Graphene is a special form of Carbon, they have the thinnest two-dimensional hexagonal structure with a thickness of atomic size (Ding et al., 2018). Their characteristic properties are also gradually discovered. Graphene has the ability to allow electrons to move freely through the structure thanks to π bonds, so graphene has a high electrical conductivity of about 6.10^5S/m, the highest thermal conductivity of all materials equal to diamond and carbon nanotubes and 12 times higher than copper, an electrical conductivity of about $3000Wm^{-1}.K^{-1}$, mechanical tensile strength is 130Gpa, 311 times higher than steel and a high Young's modulus of up to 1TPa, a specific surface area of $2600m^2/g$ (Kulyk et al., 2022; Ding et al., 2018). Graphene absorbs very little visible light, about 2.3%, making it almost transparent (Xia et al., 2013).

The coating industry has promoted the development of new material technology with the provision of optimal material solutions to provide effective coatings while providing economic benefits and environmental concerns. Several factors affect the effectiveness of coatings such as coating quality, substrate characteristics, interface properties between coating and substrate, and corrosiveness of the environment (Tong et al., 2013). Studies on graphene have shown that graphene (G) is a material with higher water and oil repellency than graphene oxide (GO), which is suitable for coating materials with water and oil repellency (Tong et al., 2013; Zhan et al.,2025). In the study of Lin et al. (2011) a test of friction properties and wear resistance of multilayer graphene films was performed using AFM images. This result demonstrates that graphene has the potential to be a protective coating against scratches or surface damage to the substrate. The anti-corrosion effect is also explained by graphene being an inert material under the chemical reaction conditions of the substrates because of the stable structure of graphene, carbon atoms are linked together by strong covalent bonds and the structure is very stable and difficult to break under the influence of most chemical reactions. In addition, graphene can withstand extremely high temperatures without decomposing. Graphene flakes can be blended with paints such as acrylic, enamel, and varnish to create composite materials, enhancing the mechanical strength and antibacterial properties of the coating (Bartczak et al., 2023; Calovi et al., 2020). Self-healing polymer/graphene anti-corrosion coatings have superior advantages in overcoming metal corrosion compared to traditional coatings due to the reduced risk of penetration of corrosive molecules such as water, oxygen, and ions (Cui et al., 2021). Graphene-reinforced epoxy coatings (GREN) using 1-5wt% graphene synthesized by electrochemical separation make the coating surface hydrophobic with water contact angles of 94^0 for 3% graphene and 102^0 for 5% graphene, respectively (Ali et al., 2024). Recent advances include the presence of graphene in self-healing polymer nanocomposites, imaging materials, and coatings (Yadav et al., 2025; Da Luz et al., 2020; Idumah & Odera, 2020). New self-healing techniques that have been studied include metal coordination bonds, boron ester bonds, acyl-hydrazone bonds, dynamic imine bonds, and disulfide bonds (Idumah & Odera, 2020). The ability of graphene nanoparticles (GNPs) and other two-dimensional materials (2DM) such as tungsten disulfide (WS_2), molybdenum disulfide (MoS_2) and hexagonal boron nitride (hBN) to act as protective barriers against fading of architectural paints and also inks/paints used in art (Kotsidi et al., 2023; Zhu et al., 2018). Zinc oxide (ZnO), silica (SiO_2), titania (TiO_2), alumina (Al_2O_3), zirconium oxide (ZrO_2) nanoparticles have also been studied for their anti-corrosion properties such as resistance to water and corrosive ion penetration, improved adhesion (Ezzeddin & Al-khalidi, 2024; Zhang et al., 2020), antibacterial and UV absorbing properties, which help protect the paint from the effects of sunlight and at the same time extend the life of the coating (Javadi et al., 2019). One way to improve the durability of materials such as epoxy resins is to add fillers such as graphene nanoparticles, graphene oxide, and carbon nanofibers (Zotti et al., 2022). These facts make it necessary to develop new coatings with environmentally friendly additives. The popularity of graphene is notable for its electrical properties and mechanical strength, so it is encouraged to be used in the coating industry (Tong et al., 2013). An example is a polyester coating containing 2% graphene that shows higher thermal stability and mechanical strength than pure polyester (Pojnar et al., 2024). However, the production of paints with graphene-based coatings is limited due to the poor dispersion of graphene in organic solvents or in water, and poor compatibility in many polymers. Therefore, oxidized graphene (rGO) and graphene oxide (GO) have been proposed in the production of polymer composites (Gudarzi & Sharif, 2013).

In this paper, we present the role of graphene in enhancing the protective properties of anti-corrosion coatings on metal surfaces with the aim of improving anti-corrosion performance and extending the life of the coating on metal structures, comparing the anti-corrosion ability of graphene with some types of metal oxide materials such as zinc oxide, titanium dioxide, the method of mixing graphene into the coating composition for the results of mechanical properties, wettability, antibacterial properties, anti-corrosion properties and current research trends on graphene-based coating materials and application solutions in the field of coatings.

2. Methods

Typical carbon materials include fullerenes, carbon nanotubes, graphite, and graphene. Depending on the arrangement of carbon atoms, they have their own characteristic molecular structures. Fullerenes are spherical with carbon atoms arranged in hexagonal and pentagonal structures. Graphene is a single hexagonal layer, the carbon atoms are arranged in a honeycomb lattice, the distance between carbon atoms in the crystal lattice is 0.142nm, which helps create outstanding mechanical strength and extremely unique electronic properties (Xia et al., 2013). This structure gives graphene outstanding properties. Carbon nanotubes have a cylindrical structure made of graphene sheets. Numerous graphene layers are piled on top of one another to form graphite.

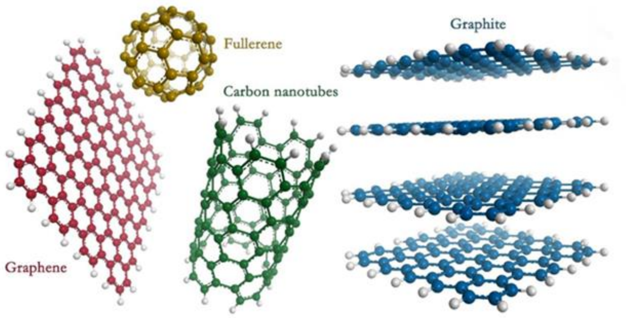

Figure 1. Structural description of carbon materials (Tong et al., 2013)

2.1. Graphene synthesis method

Currently, there are many methods of graphene fabrication, each suitable for different applications and technical requirements. Specific methods are presented below.

2.1.1. Mechanical Exfoliation

A simple mechanical exfoliation method is to use adhesive tape to peel off graphene layers from graphite (Kulyk et al., 2022; Moosa & Abed, 2021). Repeat the process of sticking and peeling several times to obtain thinner graphene layers, then transfer the graphene to the desired surface, usually using a silicone substrate. This method, called the Scotch tape method, is easy to perform but difficult to control the size of the graphene layers, not suitable for large-scale production and can only be used for research purposes (Tong et al., 2013; Moosa & Abed, 2021). Figure 2 illustrates the Scotch tape method for peeling graphite layers from graphite sheets.

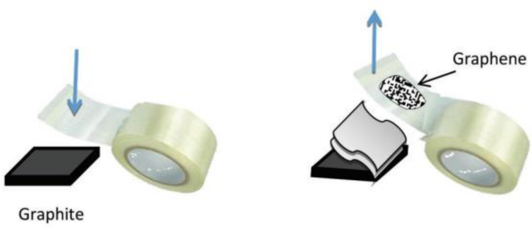

Figure 2. Scotch tape method for separating monolayer graphene (Moosa & Abed, 2021)

2.1.2. Chemical Vapor Deposition

Chemical vapor deposition is one of the advanced techniques for producing high-quality graphene. Materials such as copper (Cu), silver (Ag) or nickel (Ni) are often used as catalyst substrates (Kulyk et al., 2022; Ding et al., 2018). Before deposition, the substrate must be cleaned and heat treated to remove impurities. Precursors including hydrocarbon gases (such as methane CH_4) and hydrogen gas (H_2) are provided to minimize the formation of impurities on the surface of the deposition substrate. The reaction chamber is heated to a temperature of about 800-1000^0 C (Machac et al., 2020). The hydrocarbons decompose and release carbon atoms, which are then deposited on the surface of the catalyst substrate to form graphene (Tong et al., 2013; Cui et al., 2019). When the deposition process is finished, the system is slowly cooled to avoid damaging the structure of graphene. Graphene is separated from the catalyst substrate by chemical or mechanical exfoliation methods.

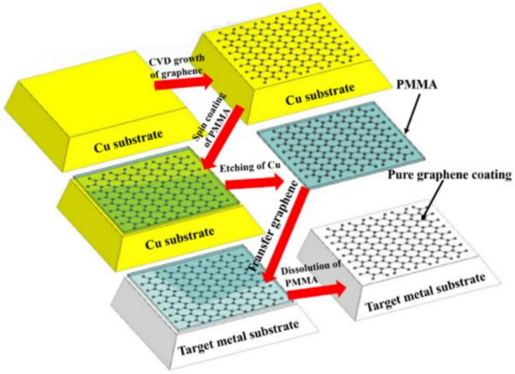

Figure 3. Dynamic process of graphene formation using CVD method (Cui et al., 2019)

The steps involved in this method are as follows: (1) A polymethyl methacrylate (PMMA) layer is deposited onto the graphene surface, forming a PMMA/graphene/Cu interlayer; (2) The Cu foil is dissolved using an etchant; (3) The PMMA/graphene layer is transferred onto the target metal surface and then dried; and (4) The PMMA layer is removed using acetone, leaving a graphene coating on the target metal surface (Cui et al., 2019).

2.1.3. Chemical Reduction

Strong reducing agents including hydrazine (N_2H_4), ascorbic acid (vitamin C), and sodium borohydride ($NaBH_4$) are used in the chemical reduction process from graphene oxide to eliminate the oxygen group on GO (Tong et al., 2013). Thermal reduction at 600-1000^{0}C in an inert atmosphere can also remove the oxygen group, but this method can partially destroy the original structure of graphene (Moosa & Abed, 2021). Electrochemical reduction is also a way to produce reduced graphene (rGO). The reduction method can produce graphene with high purity and few defects (Chua & Pumera, 2014; Guex et al., 2017). Most researchers focus on the reduction process of GO because GO and rGO can be synthesized easily. GO disperses well in many solvents, especially in water, creating good conditions for subsequent processing (Tong et al., 2013). An example of using Benzoyl peroxide (BPO) to synthesize graphene oxide by reduction method.

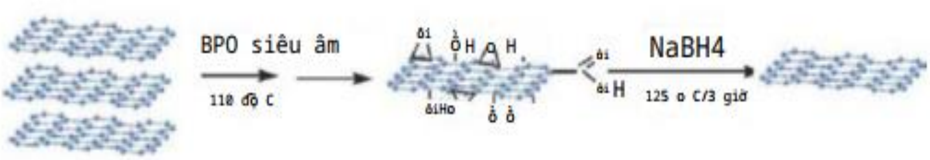

Figure 4. Synthesis of graphene from BPO (Tong et al., 2013)

2.1.4. Epitaxial Method (Epitaxial Growth)

Epitaxial growth is an advanced technique for producing high-quality materials that can be used to produce high-quality graphene by growing graphene on a suitable substrate, typically a silicon carbide (SiC) substrate (Ollik et al., 2020; Cui et al., 2019). Graphene is formed by heating SiC at high temperatures of 1200-1600^{0}C in an inert atmosphere. The silicon atoms evaporate, leaving behind a self-organized carbon layer that forms graphene. Another method is to use a carbon molecular beam to deposit graphene on a substrate such as nickel or copper. This method allows for fine control over the thickness and structure of graphene (Ollik et al., 2020; Moosa & Abed, 2021). Epitaxial growth of graphene on SiC substrates is considered an ideal material for advanced electronic devices that can outperform Si in terms of electron transfer rate, dimensional characteristics, and power consumption. Although it can produce high-quality graphene, the epitaxial growth process is unable to reach feasible production rates. Below is the process of growing graphene on SiC substrate with thermal impact (Moosa & Abed, 2021).

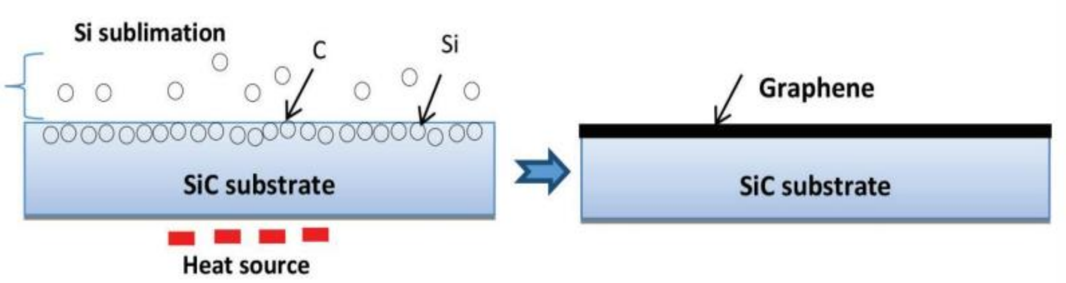

Figure 5. Epitaxial growth of graphene on SiC hot substrate (Moosa & Abed, 2021)

2.1.5 Liquid Phase Exfoliation

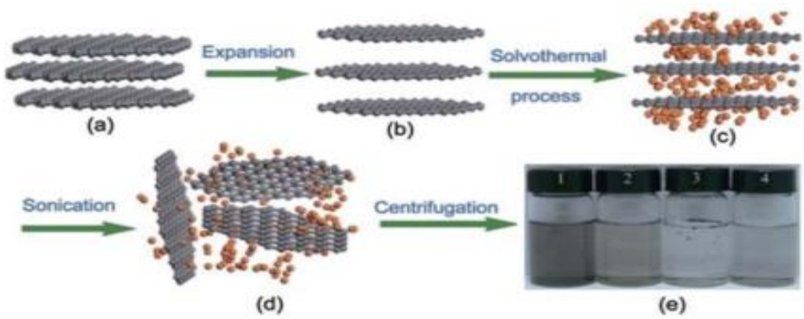

Figure 6. Solvent thermal exfoliation process: a) pure graphite; b) EG; c) insertion of ACN molecules into EG layers; d) GNS peeled in ACN; e) samples under different ultrasonic speed conditions (1-600rpm, 2-2000rpm with thermal impact process; 3-600rpm, 4-2000rpm with non-thermal impact process) (Cui et al., 2011).

Liquid phase exfoliation is highly effective in the preparation of graphene from graphite by using solvents and mechanical or chemical energy. This process can be understood as graphite being stirred in a solvent such as NMP (N-Methyl-2-pyrrolidone) or DMF (Dimethylformamide) to weaken the binding force between the layers (Ciesielski & Samorì, 2014; Du et al., 2013). Some other studies use distilled water combined with surfactants such as Tween-80 to support the exfoliation process. Alternatively, it is also possible to exfoliate using mechanical or chemical energy such as ultrasound to break the bonds between the graphite layers, helping the graphene to disperse better; or using strong acids or mild oxidants. After the exfoliation process, the graphene is filtered through a nanofilter to remove impurities. The resulting product is dried or stored in solution (Moosa & Abed, 2021; Du et al., 2013). For example, to reduce the oxide defect in graphene, pure graphite is dispersed and peeled in some organic solvents such as NMP, DMF; ultrasonicated for about 30 minutes; then centrifuged for 90 minutes at 500rpm. The graphene dispersion concentration can reach 0.01mg/ml, with a monolayer yield of approximately 1 Wt% in NMP. Further treatment enhances this yield to 7-12 Wt% (Cui et al., 2011). Alternatively, solvothermal exfoliation or non-ultrasonic liquid phase exfoliation can also be used. The solvothermal process is shown below with acetonitrile (ACN) as the solvent used (Cui et al., 2011).

Summary table of graphene fabrication methods:

TABLE 1. Synthetic methods of graphene

Method	Description of method	Pros and Cons	Literature References
Mechanical Exfoliation	Using tape to peel graphene layers from graphite	Pros: simple method Cons: difficult to produce in large quantities	(Moosa et al., 2021; Kulyk et al., 2022)
Chemical Vapor Deposition	Use hydrocarbon gas to deposit on metal surfaces such as copper or nickel	Pros: produces high quality graphene and is suitable for industrial applications Cons: high cost	(Cui et al., 2019; Kulyk et al., 2022; Tong et al., 2013; Yadav et al., 2025)
Chemical Reduction	Reduction of graphene oxide (GO) to produce graphene	Pros: simple and economical method Cons: graphene quality is not as high as other methods	(Agarwal et al., 2021; Chua et al., 2014; Guex et al., 2017)
Epitaxial Growth	Separation and crystallization of graphene on substrates such as silicon carbide (SiC)	Pros: produces high-purity graphene, suitable for high-end electronics Cons: does not meet practical production speed	(Ollik et al., 2020; Cui et al., 2019; Moosa et al., 2021)
Liquid Phase Exfoliation	Using solvents to peel graphene layers from graphite	Pros: This method is cost effective and easy to implement Cons: difficult to control size, inconsistent, low efficiency	(Ciesielski et al., 2014; Du et al., 2013; Guex et al., 2017; Cui et al., Zhang et al., 2011)

2.2. Method of mixing graphene into coating composition

Graphene can be combined with many other materials to create optimal coatings depending on the intended use. Combining graphene with polyurethane creates a polyurethane/graphene coating that is more corrosion resistant and durable than pure polyurethane, especially in harsh environments such as marine environments (Tong et al., 2013). Graphene enhances the mechanical properties and corrosion resistance of epoxy coatings, providing more effective protection for metal surfaces. Graphene can also combine well with silicone to create coatings with high heat resistance and UV resistance. Graphene and metal oxide nanoparticles such as ZnO, TiO_2 can create coatings with superior anti-corrosion, antibacterial and UV resistance (Javadi et al., 2019; Xia et al., 2013). To increase the environmental friendliness and self-healing ability of the coating, graphene is combined with chitosan or biopolymers (Xia et al., 2013). Below are some methods of combining graphene and other materials to create effective anti-corrosion coatings.

2.2.1. Method of combining graphene with epoxy

Dispersing graphene in epoxy with solvents, graphene is dispersed in organic solvents such as acetone or ethanol before mixing with epoxy for the purpose of creating uniformity and adhesion of the coating (Gudarzi et al., 2012). Enhancing graphene with functional groups like carboxyl (-COOH) or hydroxyl (-OH) to improve its compatibility with epoxy. In addition, it can be combined with metal oxide nanomaterials to enhance optical properties (Zhang et al., 2020). Finally, using the ultrasonic stirring method helps to disperse graphene evenly in epoxy, avoiding clumping, keeping graphene from settling, while ultrasonic technology helps maintain the original properties of graphene (Zotti et al., 2022). The result is a multifunctional epoxy/graphene composite coating material with anti-corrosion, anti-UV, and antibacterial properties.

2.2.2. Method of combining graphene with polyurethane

Combining graphene with polyurethane is a way to create composite materials with outstanding properties in terms of corrosion resistance, mechanical strength, and electrical conductivity. Graphene is dispersed into the solution by ultrasonic stirring. The ultrasonic stirring process usually lasts for about 30-60 minutes with an ultrasonic frequency of 20-40Hz. After dispersion, start mixing graphene with the polyurethane solution by magnetic stirring or mechanical stirring. Next, heat the polyurethane/graphene mixture at 60-80^{0}C to remove the solvent and completely polymerize. Finally, the material is cured (Tong et al., 2013).

2.2.3. Method of combining graphene with nano Zinc oxide

TABLE 2. Graphene modification methods

Method	Description of method	Pros and Cons	Literature References
Improved Hummers Method	Graphene was treated with a mixture of sulfuric acid (H_2SO_4) and potassium permanganate ($KMnO_4$) to produce graphene oxide (GO), then a reduction process was carried out to retain some of the hydroxyl groups on the GO surface, helping to improve dispersion in the solvent.	Pros: high performance, good control of structure Cons: uses strong chemicals, long reaction time, difficult to control oxidation level	(Alam et., 2017)
Electrochemical method	Graphene is treated with an electric current in a solution containing a hydroxylating agent such as H_2O_2 or NaOH	Pros: good control of the degree of denaturation and keeping the structure of graphene intact Cons: difficult to control electrochemical parameters	(Yu et al., 2020)
Reaction with hydroxylating agents	Graphene can react with compounds containing hydroxyl groups such as glycerol or polyvinyl alcohol (PVA) to form chemical bonds.	Pros: increased adhesion and corrosion resistance of the coating Cons: can change the atomic structure of graphene, affecting some important properties such as electrical conductivity and mechanical strength	(Yu et al., 2020)

Graphene and nano zinc oxide (ZnO) are two advanced materials that can be combined to create coatings with superior corrosion resistance (Rekha et al., 2019; Wang et al., 2025). Graphene creates a physical barrier while ZnO acts as a semiconductor that protects the metal from oxidation. Graphene increases the toughness and adhesion of the coating, while ZnO enhances the hardness and tensile strength and UV absorption to protect the coating material from the effects of sunlight (Albiter et al., 2020). The process of creating graphene/ZnO coatings begins with dispersing nano ZnO in organic solvents such as ethanol or acetone to ensure homogeneity, then the mixture is mixed with graphene to create a highly adhesive coating (Ali et al., 2014). To increase compatibility with ZnO, graphene must be modified and then mixed with nano ZnO by ultrasonic drying (Ali et al., 2014). Methods of graphene modification include oxidation by the improved Hummers method, electrochemical modification, and reaction with hydroxylating agents (Alam et al., 2017).

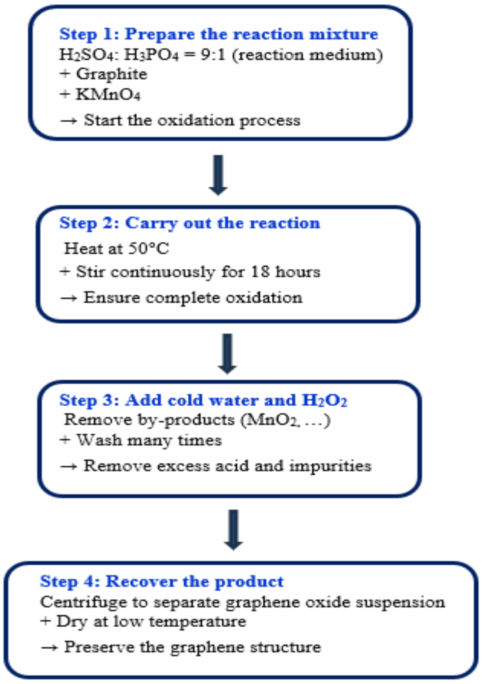

Figure 7. Schematic diagram showing the steps undertaken for the synthesis of GO and rGO by the Hummers method (Alam et al., 2017).

The Hummers method is considered a popular graphene modification method presented with the following specific steps (Alam et al., 2017):

- Step 1: Prepare the reaction mixture (use sulfuric acid H_2SO_4 and phosphoric acid H_3PO_4 in a ratio of 9:1 to create the reaction medium, add graphite and potassium permanganate $KMnO_4$ to the mixture to start the oxidation process)
- Step 2: Carry out the reaction (the above mixture is heated at 50^0C and stirred continuously for 18 hours to ensure complete oxidation)
- Step 3: Add cold water and hydrogen peroxide (H_2O_2) to remove by-products such as MnO_2. Wash the mixture several times to remove residual acid and impurities.
- Step 4: Product recovery (centrifuge the mixture to separate graphene oxide in suspension, then dry the product at low temperature to preserve the structure of graphene)

3. Results and discussion

3.1. Some research results on coating materials containing graphene

3.1.1. Mechanical properties

The research results showed that for the acrylic coating containing 2% graphene, there was a 52% increase in Young's modulus and 24% increase in hardness (Gudarzi et al., 2012). Using graphene nanoplatelets (GNPs) to improve the tensile strength and hardness of TPU/PP blend. The results showed that the blend containing 0.05% GNPs achieved the highest tensile strength, an increase of 30% compared to the blend without using compatibilizers (Nhan et al., 2025). With a graphene ratio of 1%, the mechanical properties of the paint film reached the highest value corresponding to an adhesion of 1.84MPa and an impact strength of 190kg.cm. At the same time, this ratio also corresponds to the best anti-corrosion protection ability of the polyurethane/graphene paint film compared to the surveyed samples. Thus, 1% graphene with the ability to evenly disperse interlayers has the ability to enhance the mechanical properties and anti-corrosion protection ability of the polyurethane paint film (Vu et al, 2023).

3.1.2. Wetness properties

Graphene can modulate wettability when incorporated into polymers (Carbone et al., 2019). Depending on the surface treatment and structure, graphene can increase or decrease the wettability of coatings (Belyaeva et al., 2020). This is useful in applications such as anti-fouling or protective coatings. Hydrophobic siloxane-acrylic organic resins were prepared by solution polymerization of acrylic monomers and graphene, the addition of functionalized graphene nanosheets increased the hydrophobicity, water contact angle of 151.5% and increased surface conductivity indicating compatibility of the coating components and the substrate (Uzoma et al., 2021).

3.1.3. Antibacterial properties

Graphene has natural antibacterial properties due to its two-dimensional structure and unique chemical properties. It can inhibit bacterial growth by disrupting cell membranes or inducing oxidation reactions (Alimardani et al., 2019). When combined with polymers, graphene enhances the antibacterial properties of materials. Graphene-based antibacterial materials are functionalized with silver nanoparticles, various metal ion/oxide nanoparticles, polymers, antibiotics, and enzymes. Their multicomponent functionalization has demonstrated the biosafety of graphene-based antibacterial applications (Kumar et al., 2019). Natural shellac-derived graphene oxide (GO) coatings exhibit superior antibacterial properties when applied to metal films such as Zn, Ni, Sn, and steel. Studies have shown that antibacterial activity is directly correlated with the electrical conductivity of GO-metal systems – higher conductivity leads to better antibacterial effects. The enhanced antibacterial performance of naturally derived metal-GO films results from a combined effect of a non-oxidative electron transfer mechanism and reactive oxygen species (ROS)-induced oxidative stress on bacteria (Panda et al., 2018).

3.1.4. Anti-corrosion properties

In addition to the mechanical properties evaluated, the anti-corrosion properties of the coating were also evaluated by impedance modulus through electrochemical impedance spectroscopy (EIS). The greater the impedance modulus value, the stronger the coating material's anti-corrosion capability (Pojnar et al., 2024). The low-temperature powder coating based on graphene oxide modified acrylic resin, the result is a copolymer acrylic resin of HEMA (2- Hydroxyethyl methacrylate), MA (Methyl methacrylate), BA (n-Butyl acrylate) with a molar ratio of 1:5:2 for high hardness and scratch resistance. Dispersing GO into acrylic resin by in situ method at the resin synthesis stage has a more positive effect on the properties of the coating than blending at the raw material stage (Pojnar et al., 2024). A GO/poly-hexamethylene diisocyanate composite film deposited on a copper (Cu) substrate by electrochemical deposition (ECD) and then reduced with 0.1M borohydrate ($NaBH_4$) showed strong corrosion resistance in salt water with an inhibition efficiency of more than 94.3%. However, the degree of reduction affected the corrosion inhibition due to the hydrophilic nature of GO. A simpler method is to fabricate a graphene layer on a copper substrate by rapid thermal annealing (RTA) with a drop of acetone on the surface. The coating produced in this way showed 37.5 times higher corrosion resistance in sea water than the uncoated copper substrate. The corrosion resistance efficiency reached 97.4% (Nine et al., 2015).

3.2. The role of graphene in optimizing coating material properties

To ensure the long-term corrosion resistance of pure graphene coatings, it is necessary to remove the conductivity to inhibit the corrosion process by doping heteroatoms, searching for new composite materials or stacking configurations (Zhang et al., 2021). The application of doping agents alters the electronic density of graphene. For example, conductive graphene can be adjusted to insulating graphene by hydrogenating its two sides. Complete hydrogenation of graphene results in the formation of graphane, in which every carbon atom forms a covalent bond with a hydrogen atom. Figure 8 shows the structures of three stable graphane isomers: chair, boat, twist boat, of which chair is the most stable, besides the zigzag structure and aimchair structure. In these configurations, hydrogen atoms are adsorbed alternately above and below the graphene sheet (Wang et al., 2015). The electrical structure and characteristics of graphene are entirely altered when hydrogen atoms are present in the lattice structure.

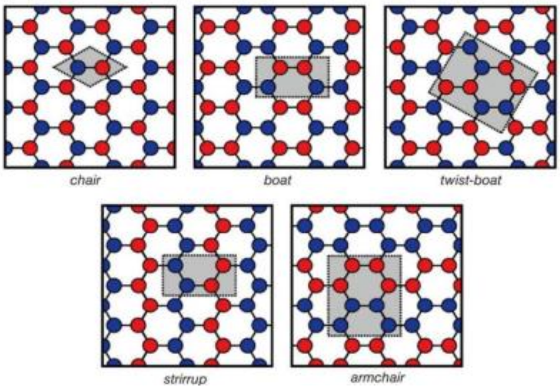

Figure 8. Graphane isomers. Blue is carbon atom and red is hydrogen atom (Wang et al., 2015)

Another important function of graphene that needs to be addressed is improving its dispersion inside the coating matrix. The surface of pure graphene has no functional groups, they are easy to aggregate and do not disperse well in the composite coating, leading to the coating not showing its anti-corrosion ability. Physical dispersion (ultrasonication, magnetic stirring, ball milling) and surface chemical modification (chemical coupling agent with a hydrophilic group that can combine with inorganic filler particles and an organophilic group that can react with the organic coating matrix) are required to improve the dispersion of graphene in the coating matrix in order to solve this issue (Ding et al., 2018). After modification, graphene is more compatible in the coating matrix, and at the same time, the modified graphene has the characteristics of a polymer, which improves the anti-corrosion performance of graphene composite coating (Cui et al., 2019). The following figure illustrates the dispersion of graphene and the extension of the permeation path of the corrosive material.

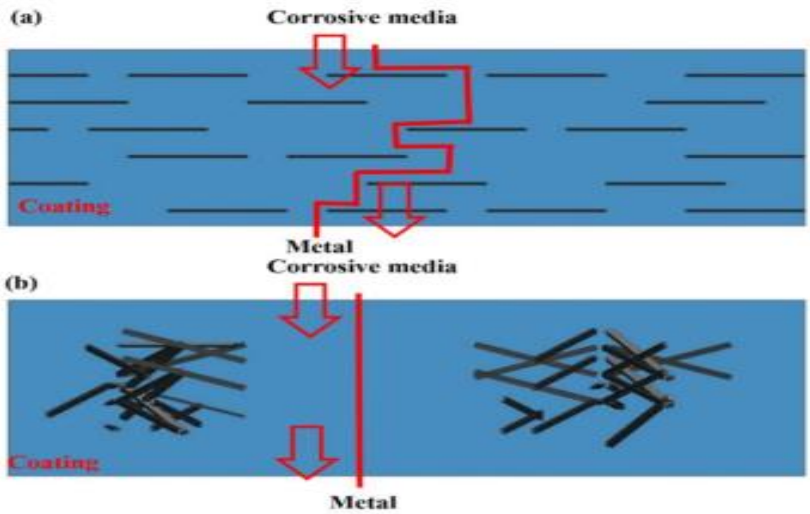

Figure 9. (a) Well-dispersed graphene creates an extended permeation path for corrosive substances, enhancing protection; (b) Poorly dispersed graphene results in a shorter permeation path, reducing its effectiveness (Cui et al., 2019)

Because of its large specific surface area, high conductivity, excellent anti-oxidation ability, stable thermal properties, and strong mechanical characteristics, graphene is regarded as a promising additive. The self-healing behavior of graphene has also been reported, and cracks of 0.3-0.5nm have also been self-healed by molecular dynamics simulations. Figure 9 demonstrates the various defects and self-healing ability of graphene sheets. This result is the foundation for the development of self-healing materials, and graphene plays an important role in self-healing polymer/graphene nanocomposite materials (Idumah et al., 2020; VijayaSekhar et al., 2016).

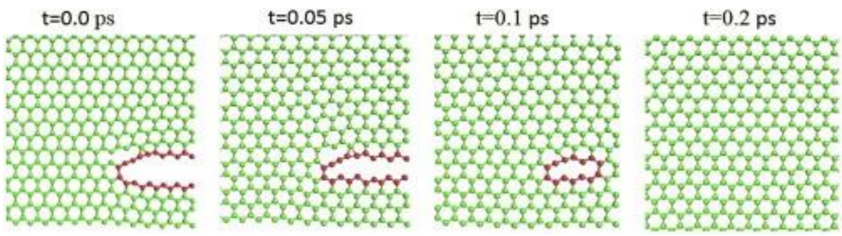

Figure 10. Different stages in the self-healing process of the original graphene sheet (VijayaSekhar et al., 2016)

The carbon atoms in the defect region are energetically unstable and exhibit unsaturated dangling bonds at $t = 0ps$. The remaining attraction between nearby atoms results from a negative bond energy if the crack length is less than or equal to 0.5nm. The carbon atoms start to reorganize at $t = 0.1ps$. Additionally, at $t = 0.2ps$, the structure is fully repaired (Vijaya Sekhar et al., 2016). Self-healing graphene/polymer composites have been considered, and in some cases, graphene can play an active role in the self-healing process due to its photothermal energy conversion ability. In this case, graphene acts as an energy absorber to convert radiation or sunlight into thermal energy quickly and efficiently to promote the mutual diffusion of polymer chains across the damaged interface (Du et al., 2018).

Graphene has the power to reinforce and maintain the integrity of the composite material surface at high temperatures, thus slowing down the thermal deformation of the structure (Nine et al., 2015). Graphene can withstand very high temperatures of 2126^0C. Graphene also acts as a general additive with other additives such as Bromine, Chlorine, Phosphorus, inorganic compounds, and melamine. They combine with polymers to form graphene/polymer composite coatings to improve fire resistance. Graphene is used to reduce the amount of other additives because most of the additives are toxic and affect humans and the environment (Nine et al., 2015). Graphene is a nanocomposite flame retardant in a polymer matrix that can easily improve the smoke barrier properties of composite materials through the "winding path" effect of the layered impermeable graphene structure. Figure 11 illustrates the mechanism of fire hazard reduction that has been explained.

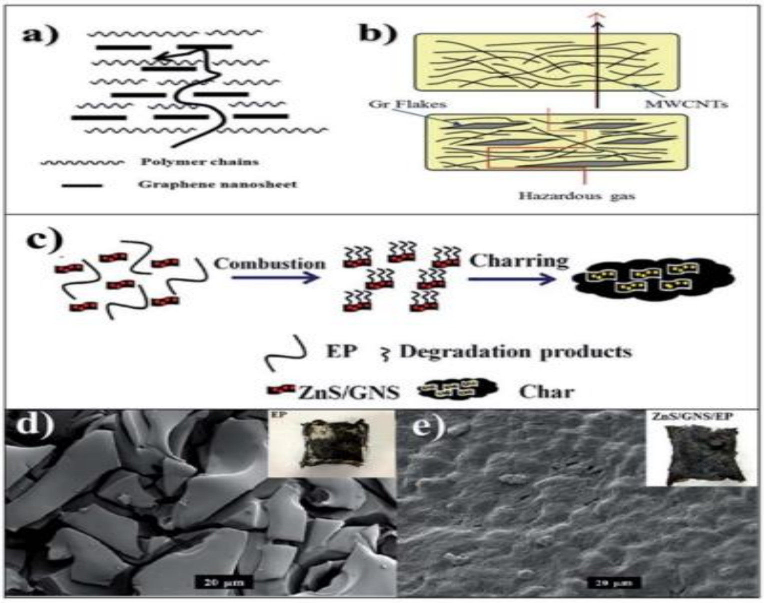

Figure 11. Mechanism of fire hazard reduction. a) Graphene in polymer exhibits tortuous path improving smoke containment; b) combination of Graphene and MWCNT in polymer creates optimal barrier; c) combination of Graphene and ZnS in polymer to form dense carbon; d) SEM surface morphology of epoxy carbon residue; e) ZnS/G/epoxy carbon residue (Nine et al., 2015)

3.3. Comparison of graphene with metal oxides mixed in coating composition

The development of coatings has undergone significant changes in the composition of the blends with the desire to find materials with optimal properties, more and more new blends are being studied, including graphene or nano-sized metal oxide particles that provide special corrosion resistance when present in the composition of the coating (Ezzeddin et al., 2024). Each blend has its own outstanding properties, they play a certain role in the composition of the coating, they can be combined to overcome each other's disadvantages to create a coating that completely meets certain needs (Zhang et al., 2020). Below is a comparison table of the corrosion resistance and some other properties of these two materials.

TABLE 3. Comparison between graphene and Zinc oxide in terms of corrosion resistance and some other properties in coatings

Properties	Graphene	Zinc oxide	Literature Reference
Corrosion resistance	Graphene creates an effective physical barrier, preventing the penetration of water and ions that cause corrosion.	ZnO acts as a semiconductor, providing cathodic protection and preventing corrosion.	(Tong et al., 2013; Javadi et al.,2019; Ezzeddin et al., 2024)
Mechanical strength	Very high, helps to increase the durability of the coating	Enhances adhesion and strength of coating	(Vu et al., 2023; Zhang et al.,2020)
UV resistance	No natural UV protection, but combines with other materials to improve	Has the ability to absorb UV rays and protect the paint layer from the effects of sunlight.	(Vu et al., 2023; Xia et al., 2013; Ezzeddin et al., 2024)
Antibacterial ability	Nonatural antibacterial properties	Has antibacterial properties, preventing the growth of bacteria and mold	(Alimardani et al., 2019; Kumar et al., 2019; Panda et al., 2018)
Application	Often used in high-end coatings requiring high strength and corrosion resistance	Suitable for more economical coatings, especially in environments requiring UV protection and antibacterial properties	(Vu et al., 2023; Xia et al., 2013; Alimardani et al., 2019)

On the other hand, environmental factors such as temperature, humidity, light, and chemical environment affect polymer/graphene materials and polymer/metal oxide materials completely differently. For example, under the influence of heat, well-dispersed graphene helps improve the heat resistance of polymers (Ajorloo et al., 2019), while metal oxides such as TiO_2 or ZnO are thermally stable but easily react with catalysts, causing polymer decomposition, reducing the life of the coating (Wang et al., 2019). This reaction can lead to significant performance issues in coatings, necessitating careful selection of materials based on the intended application. Understanding these interactions is crucial for optimizing the durability and functionality of polymer-based composites in various environmental conditions.

3.4. Current research trends on coating materials

One of the most promising advancements in smart materials is self-healing graphene/polymer composites (Idumah et al., 2020). Despite the rapid progress in this field, several challenges remain, particularly in practical applications. In graphene/conducting polymer composites, mechanical strength and electrical conductivity often exhibit a trade-off (Cui et al.,2019). While increasing the graphene content enhances electrical conductivity, excessive graphene can compromise mechanical strength. In self-healing graphene-based composites, the difficulty is striking a balance between electrical conductivity and high mechanical strength. To enhance polymer-graphene compatibility, graphene typically undergoes modifications (Cui et al.,2019). However, these modifications may diminish some of graphene's inherent properties. The key challenge is to improve the compatibility of polymers with graphene while preserving as much of graphene's intrinsic characteristics as possible within composite materials. Furthermore, achieving a combination of desired properties in a single material remains difficult due to structural incompatibility between certain polymers.

Graphene also offers numerous potential applications, including flexible transparent electrodes, sensors, and electronic components (Dutta et al., 2024). While defect-free graphene is ideal for various applications, current fabrication techniques are yet to be perfected. Additionally, scaling up graphene-based materials while maintaining acceptable strength presents another challenge.

The surface morphology of graphene coatings significantly influences the properties and quality of composite materials, warranting further study (Zhang et al., 2021). To optimize polymer/graphene-based composite materials, controlling the orientation and dispersion of graphene during processing is essential. The method of dispersing graphene is still under research and development because the difficulty faced is the choice of surfactant that must be suitable for graphene parameters, such as surface tension, solubility, electrostatic attraction, and bonding between surfactant molecules and graphene. The biggest limitation is that the surfactant affects the application's effectiveness (Perumal et al., 2021). This calls for the development of advanced processing techniques.

In the realm of coating applications, the choice of coating methods plays a crucial role in determining the properties and morphology of the final material (Yadav et al., 2025). Advancing fabrication and processing technologies for graphene-based coatings is necessary to response industrial standards and address current challenges, particularly within the coating industry.

4. Conclusion

In short, the common graphene fabrication methods showed on and blending techniques into composite coating materials as additives to optimize the anti-corrosion, fire-retardant, and antibacterial properties of recently developed materials. Graphene in polymers exhibits a tortuous path that enhances smoke-blocking ability. Additionally, the combination of graphene and multi-walled carbon nanotubes in polymers creates an optimal barrier, while the integration of graphene and ZnS in polymers forms dense carbon structures that reduce fire risks in composite materials.

The role of graphene is analyzed, evaluated, and compared with its ability to combine with other types of metal oxide materials such as TiO_2 and ZnO in polymer composite materials. Notably, the dispersion method of graphene in the coating matrix plays a crucial role. The surface of pure graphene lacks functional groups, which causes it to easily aggregate and prevents effective dispersion in composite coatings, leading to diminished anti-corrosion properties. Therefore, improving the dispersion process is essential to optimizing the performance of coating materials.

The integration of graphene into coating formulations shows great promise in enhancing the performance of protective coatings for metal structures. Future research should focus on refining these methods and exploring innovative applications to fully harness the benefits of graphene in the paint industry. This exploration could lead to the development of coatings that not only provide superior protection against corrosion but also enhance the overall durability and functionality of metal surfaces. By leveraging the unique properties of graphene, researchers have the potential to revolutionize the paint industry and create more sustainable and efficient protective solutions.

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