The Application and Progress of Graphene-Based Composites in the Aerospace Field

Ruojie Xu
Department of Chemical Engineering and Chemistry, Harbin Institute of Technology, Harbin, Heilongjiang Province, 150000, China
2023112871@stu.hit.edu.cn

ABSTRACT

With the rapid development of aerospace technology, it is increasingly difficult for traditional aerospace materials to meet the new requirements of various equipment in the future. Nowadays, people especially need new materials that are reliable, multifunctional and durable, especially to solve the contradiction between the performance of equipment such as “light and short”, “strong and durable”, “good heat dissipation” and “anti-electromagnetic interference”. Because Graphene material has excellent mechanical strength, thermal conductivity and electrical conductivity, it has gradually become a research hotspot of aerospace materials, which makes people see the hope of realizing these contradictory properties at the same time. After analyzing a lot of research, this review summarizes the latest progress in the application of graphene composites in aerospace field. The existing research shows that graphene-based composites can effectively improve the overall properties of materials, and show great potential in multi-functional integration. However, there are still some difficulties, especially in mass production and cost control. Future research should focus on optimizing manufacturing process and improving practical application, so as to provide theoretical support and technical guidance for the new generation of aerospace materials.

Keywords: Graphene-Based Composites; Aerospace Materials; Multifunctional Integration; Thermal and Mechanical Properties; Electromagnetic Shielding.

1. INTRODUCTION

Graphene was first isolated by Andre Geim and Konstantin Novoselov in 2004. They proved that two-dimensional carbon layers with atomic thickness can exist stably, which challenged people’s traditional understanding of low-dimensional systems. This discovery not only stimulates a lot of research on low-dimensional materials, but also provides new opportunities for designing materials with special properties. Because of its unique two-dimensional structure, graphene has a very high specific surface area, superior electrical and thermal conductivity and amazing mechanical strength, which makes it an ideal choice to solve the demanding requirements of aerospace materials. In the aerospace field, materials usually need to meet the requirements of low density, high mechanical strength, high heat dissipation efficiency and reliable electromagnetic shielding performance, and these requirements are often difficult to achieve in a single material. These excellent characteristics rarely appear in common materials at the same time, so graphene has become an ideal choice for multifunctional applications, especially in demanding fields, such as aerospace, because the choice of performance is particularly important in these places [2]. However, although graphene itself is very powerful, there are still many difficulties in directly using the original graphene in the aerospace system. For example, mass production, controllable dispersion, and how to integrate it into the macro structure all limit its practical application. In order to solve these problems, people pay more and more attention to graphene-based composites, that is, adding graphene to different matrices to make the properties stronger and more adjustable. This composite material can meet various requirements of aerospace materials, such as lightweight design, high mechanical strength and stability under extreme conditions. In particular, their high specific strength and multifunctional integration capabilities, such as electrical conductivity, thermal conductivity and electromagnetic shielding, provide unique advantages for structure-function integration [3]. At present, graphene-based composites are shifting from basic research to practical engineering applications in the aerospace field. Their further development depends on the progress of material processing technology, multi-scale structural design and our deeper understanding of their behavior under actual use conditions. In this case, it is very important to systematically summarize the recent progress and remaining challenges to guide future research and promote their practical application.

2. AEROSPACE APPLICATIONS OF GRAPHENE-BASED COMPOSITES

Graphene-based composites have shown great potential in many aerospace fields because they are particularly powerful in machinery and function. In order to better understand their functions in aerospace systems, we can divide their main uses into several aspects, such as making structures stronger, managing heat, conducting electromagnetic shielding, and serving as protective coatings.

2.1 Structural Reinforcement

Graphene-based composites have attracted a lot of attention because of its particularly powerful structural reinforcement ability. Because graphene has super mechanical properties, such as high tensile strength and Young's modulus, it can improve the firmness of composites. When graphene is added to polymer, metal or ceramic materials, it is like a powerful helper, which can help the materials to bear the weight and resist deformation better. Therefore, graphene-based composites have been widely studied in fields that need light and strong materials, such as aerospace engineering.

2.1.1 Fundamental Reinforcement Mechanisms

Graphene has excellent mechanical properties, such as super tensile strength, super high Young's modulus (hardness), and a honeycomb-like structure, which is full of strong carbon-carbon covalent bonds. These characteristics make it particularly capable of carrying heavy loads and difficult to deform, so it is an ideal choice to improve the strength, hardness and impact resistance of composite materials [4,5]. Moreover, molecular dynamics simulation shows that graphene sheets with large size (about 500 nm) and neat arrangement can improve the tensile strength of composites by more than 200% [6]. In addition, graphene's super-large specific surface area and two-dimensional layered structure provide many interface action points, which can strengthen the combination with the matrix, make stress transfer more effective, and prevent crack propagation through crack deflection, bridging and other mechanisms [3,7,8]. For example, when graphene is added to epoxy resin, the tensile strength can be increased by 14.85%, and the fracture toughness can even soar by 155% [8].

2.1.2 Reinforcement Performance in Various Matrix Systems

Graphene can make materials stronger in many different composite materials. However, the degree to which it makes the material strong depends on what kind of material it is added to. In particular, because plastics and metals have different characteristics and are combined with graphene in different ways, the reinforcement effect of graphene in these two materials is also very different. Therefore, we need to discuss the performance of graphene in different materials.

Among all kinds of matrix materials, polymer-based composites have been studied a lot because of their easy processing and wide applications. Adding graphene into polymer matrix can greatly improve the mechanical properties of the material. This improvement mainly depends on the effective load transfer and strong interface between graphene and polymer matrix. Many studies have found that even if only a little graphene is added, the material can be obviously strengthened. For example, Guo et al. found that the strength, fracture toughness (KIC) and steady fracture toughness (KJC) of RGO-SiO2-CNTs/EP nanocomposites increased by 14.85%, 155% and 51.9% respectively when the content of graphene was 0.625 wt% [8]. These results show that proper amount of graphene can greatly enhance the cracking resistance of composites. This improvement of fracture resistance shows that it is more difficult for materials to crack and crack propagation, which is very important for maintaining structural integrity under complex stress conditions. This behavior is attributed to the joint action of layered graphene skeleton, SiO2 _ 2 nano-materials and carbon nanotube bridge-they prevent graphene from stacking and promote crack deflection, thus enhancing the strength and toughness of the material in coordination. In addition, the formation of hybrid network structure further helps stress transfer more effectively inside the composite material.

In order to make the mechanical properties of materials better, we can try to use a mixed network structure instead of just using a filler. In particular, the design of interconnected graphene networks can greatly enhance the overall structural strength of composites. For example, Jin et al. [9] used a method called soft-template-assisted dip-coating to make multi-functional MXene/graphene/polymer composites, forming a three-dimensional interconnected conductive network structure. The schematic diagram of this three-dimensional interconnected MXene/graphene network structure can be seen in Figure 1.

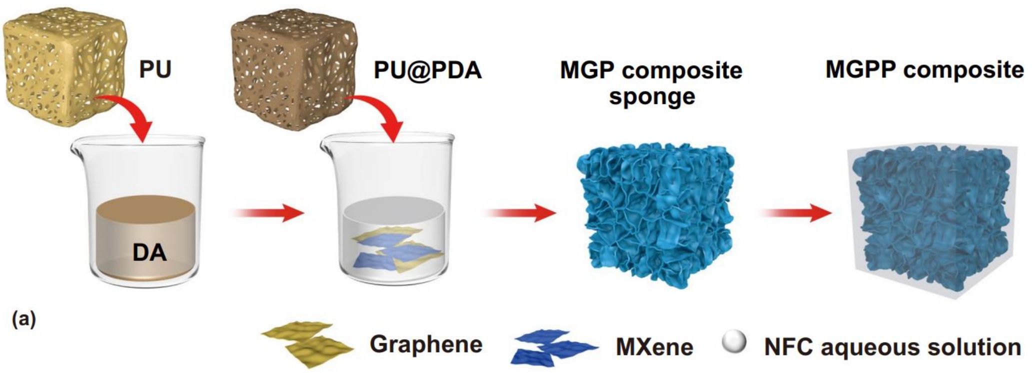

Figure 1. Schematic illustration of the three-dimensional interconnected MXene/graphene network structure in polymer composites, constructed via a soft-template-assisted method [9].

The experimental results show that when the content of MXene and graphene reaches 18.7 wt%, the mechanical properties of this composite are about four times higher than that of pure polymer matrix [9]. This huge improvement shows that the introduction of a continuous interconnected network can effectively improve the efficiency of load transmission and reduce the structural defects inside the material. Moreover, the synergistic effect between graphene, MXene and polymer matrix enhances the interface bonding between them, which is very important to improve the hardness, strength and toughness of the materials at the same time. Such a network structure can also make the stress distribution more uniform and deflect cracks, thus making the composite material more resistant to deformation and failure under external load. In addition, the formation of continuous conductive network also provides an effective path for stress propagation, which further enhances the overall mechanical stability of the material. These results show that structural design is very important for achieving synergistic reinforcement effect in graphene-based composites.

Although polymer-based composites have good processability and portability, their mechanical strength and heat resistance are relatively limited, which limits their use in more harsh environments, especially in the case of high load-bearing and extreme temperature resistance. Compared with polymer systems, metal-based composites can provide significantly higher mechanical strength, thermal stability and structural reliability, making them more suitable for aerospace applications with high pressure and high temperature. However, these advantages are often accompanied by density increase, which will affect the weight loss effect, and the manufacturing process is more complicated, which may limit mass production. Therefore, in the most critical applications of lightweight and flexibility, we usually prefer to choose polymer-based systems; Metal-based systems have more advantages in scenes requiring high structural integrity and durability. This shows their complementary functions, and also urges us to discuss Graphene-based metal composite systems next.

For example, Zhao et al. [10] made a graphene reinforced aluminum matrix composite with a specially designed interface structure, and they reported that the tensile strength of this material has been greatly improved. For different functionalized graphene systems, the strength reached 347 6 MPa, 448 8 MPa and 373 MPa, respectively, while that of pure aluminum was only 263 7 MPa, which was equivalent to an increase of 32%, 70% and 42%. At the same time, compared with pure aluminum (4.7%), these composites maintain or even improve their uniform elongation (about 5.0-6.3%), which shows that they have achieved good strong-plastic synergy. The mechanical properties of these graphene reinforced aluminum matrix composites are summarized in Figure 2.

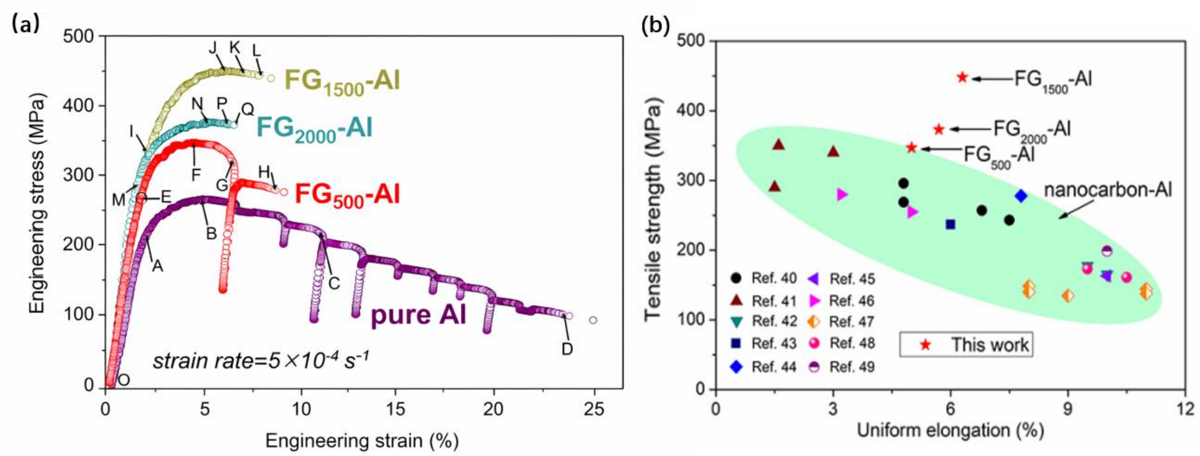

Figure 2. Mechanical performance of graphene-reinforced aluminium composites [10].

(a)Engineering stress-strain curves of pure Al and FG-Al composites. (b)Strength-ductility relationship.

The enhancement effect mainly comes from the bearing function of graphene and the interface interaction between them. This interface acts as an effective barrier to prevent dislocation movement. Quantitative analysis further shows that the enhancement effect caused by interface can reach about 85 MPa at the highest, and the bearing function of graphene also plays an important role according to the degree of functionalization. More importantly, the research shows that the bonding state of the interface plays a key role in the mechanical properties. Specifically, the composites with moderate functionalization show the most balanced performance, because the strong interface is helpful to coordinate deformation, but it limits the reinforcement effect; However, although the weaker interface can better block dislocations, it reduces the efficiency of load transfer.

Generally speaking, graphene-based composites have greatly improved their mechanical properties because of their unique structural design and effective interaction between graphene and the matrix. These improvements mainly rely on the synergy of load transfer, interfacial bonding and microstructural regulation. However, in order to make the performance stable and reliable and suitable for mass production, it is still critical to optimize the interfacial characteristics and dispersion uniformity. Based on these structural advantages, graphene-based composites show great potential in a variety of high-end applications, especially in the harsh environment such as aerospace systems.

2.2 Thermal Management

In addition to mechanical properties, thermal management has become more and more important for advanced materials, especially in the field of aerospace, where equipment often encounters strong heat flow and extreme working environment. Ordinary materials such as polymers and metals are often not good at heat conduction or high temperature resistance, and their heat dissipation ability is not good. Graphene, on the other hand, is a promising choice to improve the heat dissipation capacity of composite materials because of its extremely strong heat conduction and unique two-dimensional structure.

2.2.1 Thermal transport mechanisms

Graphene-based composites, the heat transfer in them is mainly conducted by something called phonon. This is because graphene is naturally very good at heat conduction. The thermal conductivity of single-layer graphene can reach 3100 W/m k [11], and the optimized graphene film can even reach 1781 W/m k [12]. These excellent characteristics come from graphene's unique honeycomb lattice structure and strong chemical bonds inside, which enables phonon to run around efficiently, and also gives the material good anisotropic thermal conductivity, electrical conductivity and mechanical stability [4]. In addition, graphene is ultra-thin and has a large surface area [13], which enables it to form a continuous heat conduction channel in the composite material, so that heat dissipation is particularly effective. Because of these characteristics, composites based on graphene have a very broad prospect in the thermal management of advanced aerospace materials.

2.2.2 Thermal performance in different composite systems

The thermal conductivity of a material made of graphene depends mainly on what it is mixed with and what its internal structure is like. Generally speaking, whether it is plastic or metal, as long as graphene is added, they can become better at heat conduction and heat dissipation. However, how much better it can be depends on whether graphene is evenly dispersed, whether it is well combined with other materials, and whether it can form a series of heat conduction paths. Therefore, we should compare graphene composites made of different materials, so as to understand how the properties of the materials themselves affect the heat conduction effect.

In polymer matrix composites, adding graphene can greatly improve the thermal conductivity, because it can form an interconnected heat conduction network. Because the thermal conductivity of polymer itself is very poor (usually lower than 1 W m k), adding high thermal conductivity filler like graphene can greatly improve the heat transfer performance. For example, a kind of polyurethane composite material with graphene nanosheets and liquid metal has a vertical thermal conductivity of 18.69 W m k and a horizontal thermal conductivity of 8.05 W m k, which is much stronger than ordinary polymer materials [14]. The thermal conductivity of this graphene-based polymer composite under different structures is shown in Figure 3.

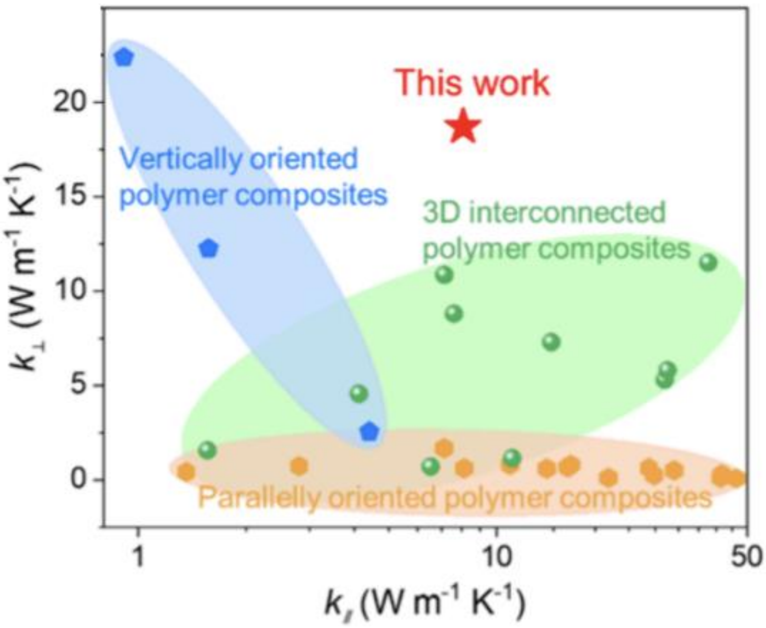

Figure 3. Thermal conductivity of graphene-based polymer composites with different structural configurations [14].

This improvement is mainly due to the formation of an efficient heat conduction path, in which graphene nanosheets is the main heat carrier, and the liquid metal component further connects the adjacent fillers, reducing phonon scattering and enhancing the continuity of heat transfer. At the same time, Supra molecular interfacial interactions promote better dispersion of fillers and stronger interface coupling, which helps to reduce thermal boundary resistance and make phonons transmit more effectively in composites. In addition to the improvement of thermal conductivity, this composite also shows excellent extensibility (maximum strain of 1050%) and photo-thermal conversion efficiency as high as 84%, which shows that Graphene-based polymer composites can achieve both mechanical compliance and multifunctional thermal management capability [14].

Although the materials made of polymer can make their thermal conductivity stronger by joining the connected graphene network, their overall heat dissipation ability is limited by the characteristics of polymer itself, especially in the case of extremely large heat and high requirements for temperature stability. In contrast, the materials based on metal have better thermal conductivity. The addition of graphene can further improve the heat transfer efficiency, and through structural design and interface treatment, heat can be conducted in a specific direction. These characteristics make metal-based composites especially suitable for occasions that need rapid heat dissipation and efficient thermal management. Therefore, polymer-based materials are more suitable for thermal management applications that require light and soft materials, while metal-based materials are more suitable for environments that require high thermal conductivity and strong structure. Because of this, we will discuss the metal composite system based on graphene next.

In the composite material made of metal, we add graphene not only to make it better in heat transfer, but also to control the heat transfer route through special design. Compared with plastic materials, metal itself can transfer heat faster, so graphene can play an advantage in it, such as helping heat transfer in a specific direction or improving the effect of contact surface. For example, there is a kind of copper composite reinforced by graphene film, and its thermal conductivity in a certain direction is as high as 820 W m k, which is much stronger than ordinary graphene/ copper composite (usually less than 500 W m k) and almost twice that of pure copper [15]. As shown in Figure 4, neatly arranged graphene films can form a continuous path in copper, allowing heat to pass smoothly.

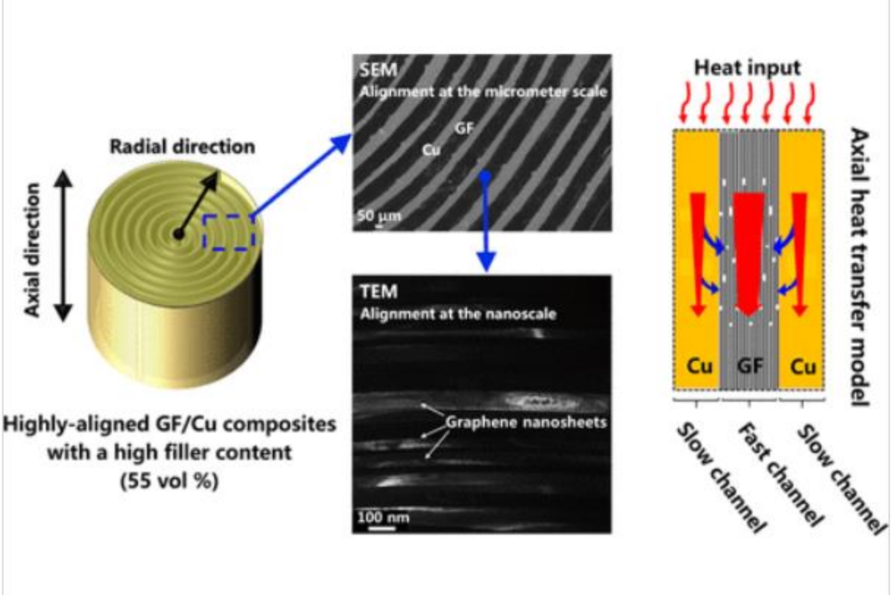

Figure 4. Structural alignment and heat conduction pathways in graphene film/Cu composites [15].

This remarkable performance is mainly due to the spiral layered graphene structure, which can form a highly ordered heat conduction channel. In addition, interface modification such as Zr alloying enhances the connection between interfaces and reduces the thermal boundary resistance, so that phonons can pass through the interface between graphene and metal more smoothly. These results tell us that in metallic materials, the directional arrangement of structures and interface design are extremely important for achieving high thermal conductivity.

Generally speaking, graphene-based composites have great potential in thermal management, because they have high thermal conductivity, and they can also build efficient thermal conduction networks in different matrix systems. Their thermal performance is improved mainly by forming interconnected or highly oriented thermal pathways and optimizing interface characteristics, which can reduce thermal boundary resistance and help phonon transport. In particular, the thermal behavior of these composites depends largely on the properties of the matrix: polymer-based systems mainly benefit from the formation of networks, while metal-based systems can further utilize structural orientation and interface engineering to achieve better thermal conductivity. These characteristics make graphene-based composites very promising in advanced thermal management applications, especially in aerospace systems, because there is a great need for efficient heat dissipation and structural adaptability.

2.3 Electrical and EMI Shielding

In addition to strengthening mechanical properties and thermal management, electrical conductivity and electromagnetic interference (EMI) shielding performance are becoming more and more important for advanced functional materials, especially in aerospace and electronic systems. The rapid development of high-frequency and high-power equipment makes people more and more worried about electromagnetic pollution and signal interference, because these will seriously affect the reliability and stability of electronic components. Graphene has been widely studied as an effective filler to enhance the conductivity and EMI shielding performance of composites because of its good conductivity, high carrier mobility and unique two-dimensional structure.

2.3.1 Electrical conduction and EMI shielding mechanisms

The conductivity and electromagnetic interference (EMI) shielding effect of composites based on graphene mainly depend on the movement of electrons, because the carriers in graphene run very fast and are easy to conduct electricity. In suspended graphene, the Hall mobility of carriers can reach 10,000-13,000 cm V s [16], which makes the charge transfer very efficient. In composite materials, graphene can further improve the conductivity and EMI shielding performance because of its large specific surface area and rich surface functional groups, which can help to form conductive paths and produce interfacial polarization [17]. In addition, graphene can be transformed into a 3D conductive network or a directional layered structure through self-assembly or directional arrangement, which can greatly improve the efficiency of electron transmission. For example, the conductivity of graphene films assembled by electrostatic repulsion can reach 1.285× 10 s m [18], which shows that structural design is really effective in optimizing electrical properties. These characteristics lay a solid foundation for graphene-based composites to be used in high-performance electrical and EMI shielding materials.

2.3.2 Electrical and EMI shielding performance in different composite systems

In the composite material made of plastic, adding graphene can establish a continuous conductive network, which makes the material's conductivity and anti-electromagnetic interference (EMI) ability particularly strong. As Figure 5a shows, the conductivity of graphene/ polymer nanosheets increases obviously with the increase of graphene content, which indicates that an effective charge transport channel is formed in the composite. Accordingly, these materials show strong EMI shielding performance, and the shielding effect reaches about 60 dB (Figure 5b) when it is only 33 microns thick, which shows that it can effectively weaken electromagnetic waves in a wide frequency range [19]. The shielding effect is greatly influenced by structural parameters. As shown in Figure 5c, the shielding effect increases with the increase of thickness, which indicates that absorption plays a major role in the overall shielding performance. In addition, the absolute shielding effectiveness is closely related to the graphene content (Figure 5d), and the highest shielding effectiveness can reach about 3× 10 dB cm g, which is one of the highest values reported in nonmetallic materials [19].

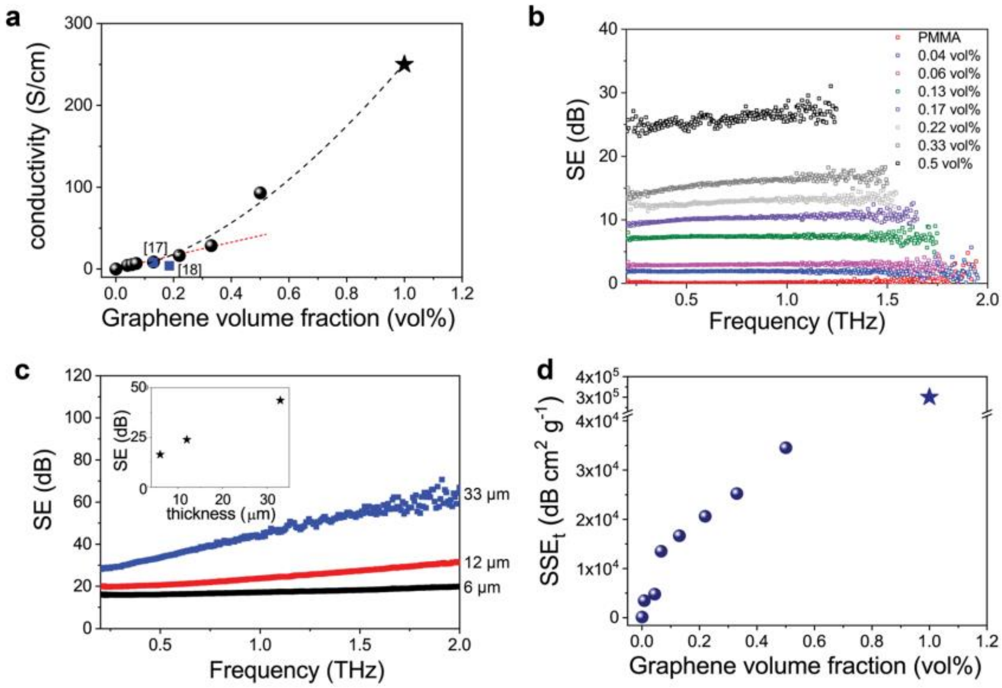

Figure 5. Electrical conductivity and EMI shielding performance of graphene/polymer nanolaminates [19].

(a)Electrical conductivity as a function of graphene content. (b)Shielding effectiveness versus frequency. (c)Shielding effectiveness as a function of thickness. (d)Absolute shielding effectiveness versus graphene content.

This excellent performance mainly comes from a special structure of continuous graphene, which can make electrons run faster and reduce the problems caused by discontinuous graphene fillers. In this structure, the EMI shielding effect is the result of reflection, absorption and internal multiple reflections, which are closely related to the arrangement of conductive networks and layers.

Although materials made of polymers can achieve good conductive and electromagnetic shielding effects by making light conductive layers and laminated structures, they are usually not strong enough and their structures are not stable, especially when they need to be used for a long time or bear weight. In contrast, metal materials can provide a stronger and more conductive framework, so that graphene can form a continuous three-dimensional network, which can not only better block electromagnetic waves, but also maintain the strong characteristics of the material. These characteristics make metal materials more suitable for use in complex electromagnetic environments with good electromagnetic shielding effect and strong structure. Therefore, polymer materials have more advantages in applications that require light and soft electromagnetic shielding, while metal materials perform better in scenes that require high shielding efficiency and strong mechanical properties, which naturally leads to what we will discuss next-graphene-based metal composites.

In the composite materials made of metal, graphene is not only used to improve the conductivity, but also to build a solid 3D conductive frame. This can not only effectively block the EMI shielding, but also keep the material firm. Compared with materials made of plastic, the metal base itself conducts electricity better and bears pressure more, which can combine firmness with functionality. For example, when the thickness of AZ91D composite reinforced with graphene skeleton is 3 mm, the EMI shielding effect reaches 76.7 dB, while the compressive strength is 276 MPa and the tensile strength is 231 MPa [20]. Such a powerful performance may be due to the formation of a continuous three-dimensional graphene network, which makes electronic transmission smoother and can better absorb electromagnetic waves. After the molten metal permeates into the graphene skeleton, the interface bonding is stronger and the structure is more stable, so this material can effectively shield electromagnetic waves (EMI shielding) and is particularly strong. These results show that in metal materials, three-dimensional structural design and interface engineering are particularly important for creating multifunctional materials that can adapt to harsh environments.

Generally speaking, graphene composites can greatly improve the conductivity and EMI shielding performance in different material systems. The shielding effect mainly depends on the formation of conductive network, interfacial polarization and multiple attenuation mechanisms, such as reflection, absorption and internal scattering. In particular, the properties of these composites depend largely on the matrix type and structural design. The advantages of polymer-based system are lightweight structure and efficient conductive path, while metal-based system uses three-dimensional structural frame and strong interface coupling to achieve better mechanical strength and shielding performance. These characteristics make graphene composites particularly promising in the advanced aerospace field, because there is a great need for lightweight, high-strength and multifunctional materials.

In order to compare the performance characteristics and application potential of different graphene composite systems more clearly, we summarized them in Table 1.

Table 1. Comparison of polymer-based and metal-based graphene composites for aerospace applications.

Composite system	Core advantages	Core limitations	Suitable aerospace scenarios
Polymer-based graphene composites	Lightweight, good processability, flexible structural design, effective reinforcement and EMI shielding through conductive networks	Relatively limited thermal stability and mechanical strength under extreme conditions	Lightweight structural components, flexible thermal management materials, EMI shielding layers
Metal-based graphene composites	High mechanical strength, good thermal stability, excellent thermal conductivity and EMI shielding performance	Higher density, more complex fabrication process, more difficult interface control	High-load-bearing structures, high-temperature components, rapid heat dissipation systems, robust EMI shielding structures

3. CONCLUSION

Generally speaking, graphene composites have become very powerful multifunctional materials because of their excellent mechanical properties, thermal conductivity and electrical conductivity. Adding graphene to different materials can improve the strength, heat conduction and electromagnetic interference (EMI) shielding effect of these materials, so they are particularly popular in the demanding aerospace field. The improvement of these properties mainly depends on several key factors, such as effective load transfer, the formation of interconnected or oriented conductive networks, and the optimization of interface interaction. It is particularly noteworthy that the structural design of graphene in composite materials, such as layered structure and three-dimensional framework, plays a key role in realizing the synergistic performance of multiple functions. In addition, as summarized in Table 1, polymer-based and metal-based graphene composites have their own advantages in weight, mechanical properties, thermal management and electrical functions, indicating that they have unique application potential in different aerospace scenes. Despite these advances, there are still many challenges to make graphene evenly dispersed, control interface characteristics, expand production scale and maintain stable performance. In the future, if advanced manufacturing technology and multi-scale design strategy can be combined, the potential of graphene composites can be better brought into play and they can be more widely used in the next-generation aerospace system.

REFERENCES

[1] Novoselov, K., Geim, A., Morozov, S., Jiang, D., Zhang, Y., Dubonos, S., Grigorieva, I., & Firsov, A. (2004). Electric field effect in atomically thin carbon films. Science, 306(5696), 666–669. https://doi.org/10.1126/science.1102896
[2] Ostermann, M., Bilotto, P., Kadlec, M., Schodl, J., Duchoslav, J., Stöger-Pollach, M., Lieberzeit, P., & Valtiner, M. (2023). l-Ascorbic Acid Treatment of Electrochemical Graphene Nanosheets: Reduction Optimization and Application for De-Icing, Water Uptake Prevention, and Corrosion Resistance. ACS Appl Mater Interfaces, 15(18), 22471-22484. https://doi.org/10.1021/acsami.2c22854
[3] Du, J., Fu, G., Xu, X., Elshahawy, A. M., & Guan, C. (2023). 3D Printed Graphene-Based Metamaterials: Guesting Multi-Functionality in One Gain. Small, 19(19), e2207833. https://doi.org/10.1002/smll.202207833
[4] Wu, Y., An, C., Guo, Y., Zong, Y., Jiang, N., Zheng, Q., & Yu, Z. Z. (2024). Highly Aligned Graphene Aerogels for Multifunctional Composites. Nanomicro Lett, 16(1), 118. https://doi.org/10.1007/s40820-024-01357-w
[5] Zhou, T., & Cheng, Q. (2021). Chemical Strategies for Making Strong Graphene Materials. Angew Chem Int Ed Engl, 60(34), 18397–18410. https://doi.org/10.1002/anie.202102761
[6] Suter, J. L., Vassaux, M., & Coveney, P. V. (2023). Large-Scale Molecular Dynamics Elucidates the Mechanics of Reinforcement in Graphene-Based Composites. Adv Mater, 35(35), e2302237. https://doi.org/10.1002/adma.202302237
[7] Chen, K., Tang, X., Jia, B., Chao, C., Wei, Y., Hou, J., Dong, L., Deng, X., Xiao, T. H., Goda, K., & Guo, L. (2022). Graphene oxide bulk material reinforced by heterophase platelets with multiscale interface crosslinking. Nat Mater, 21(10), 1121-1129. https://doi.org/10.1038/s41563-022-01292-4
[8] Guo, D., Huang, X., Mu, Z., Yao, Z., Niu, S., Han, Z., & Ren, L. (2026). Strength-Toughness Synergistic Epoxy Nanocomposites Coupling a Layered Graphene Framework and Nanomodified Interfaces. Nano Lett, 26(10), 3485–3494. https://doi.org/10.1021/acs.nanolett.5c06497
[9] Jin, L., Cao, W., Wang, P., Song, N., & Ding, P. (2022). Interconnected MXene/Graphene Network Constructed by Soft Template for Multi-Performance Improvement of Polymer Composites. Nanomicro Lett, 14(1), 133. https://doi.org/10.1007/s40820-022-00877-7
[10] Zhao, L., Lee, T., Ryu, S., Oshima, Y., Guo, Q., & Zhang, D. (2021). Mechanical Robustness of Metal Nanocomposites Rendered by Graphene Functionalization. Nano Lett, 21(13), 5706–5713. https://doi.org/10.1021/acs.nanolett.1c01438
[11] Li, J., Zheng, J., Zhai, L., Liu, P., Qing, F., Li, X., Chen, D., Xu, Z., Wang, H., & Zhu, H. (2026). Layer-Dependent Thermal Conductivity of Graphene toward Thermal Management Applications. ACS Appl Mater Interfaces, 18(7), 11764-11773. https://doi.org/10.1021/acsami.5c24572
[12] Zheng, H., He, P., Yang, S., Lu, Y., Guo, N., Li, Y., Wang, G., & Ding, G. (2025). Achieving Ultra-High Heat Flux Transfer in Graphene Films via Tunable Gas Escape Channels. Adv Sci (Weinh), 12(1), e2410913. https://doi.org/10.1002/advs.202410913
[13] Shi, Z., Ge, Y., Yun, Q., & Zhang, H. (2022). Two-Dimensional Nanomaterial-Templated Composites. Acc Chem Res, 55(24), 3581–3593. https://doi.org/10.1021/acs.accounts.2c00579
[14] He, X., He, Q., Liu, Z., & Yao, Y. (2025). Noncovalent Soft Composites with Superior Thermal Conductivity and Photothermal Efficiency for Advanced Thermal Management. Nano Lett, 25(19), 7933-7942. https://doi.org/10.1021/acs.nanolett.5c01391
[15] Chang, G., Wang, L., Zhang, Y., Li, X., Chen, K., Kan, D., Zhang, W., Zhang, S., Dong, L., Li, L., Bai, X., Zhang, H., & Huo, W. (2022). Superior Thermal Conductivity of Graphene Film/Cu-Zr Alloy Composites for Thermal Management Applications. ACS Appl Mater Interfaces, 14(50), 56156-56168. https://doi.org/10.1021/acsami.2c18101
[16] Li, H., Chen, H., Pang, B., Zhang, J., Luo, B., Silva, S. R. P., Wang, Y. C., Zhao, S., Shearing, P. R., Robinson, J. B., & Novoselov, K. S. (2025). Van-der-Waals-forces-modulated graphene-P-phenyl-graphene carbon allotropes. Nat

Commun, 16(1), 10011. https://doi.org/10.1038/s41467-025-64971-1
[17] Zarepour, A., Ahmadi, S., Rabiee, N., Zarrabi, A., & Iravani, S. (2023). Self-Healing MXene- and Graphene-Based Composites: Properties and Applications. Nanomicro Lett, 15(1), 100. https://doi.org/10.1007/s40820-023-01074-w
[18] Qian, W., Fu, H., Sun, Y., Wang, Z., Wu, H., Kou, Z., Li, B. W., He, D., & Nan, C. W. (2022). Scalable Assembly of High-Quality Graphene Films via Electrostatic-Repulsion Aligning. Adv Mater, 34(50), e2206101. https://doi.org/10.1002/adma.202206101
[19] Pavlou, C., Pastore Carbone, M. G., Manikas, A. C., Trakakis, G., Koral, C., Papari, G., Andreone, A., & Galiotis, C. (2021). Effective EMI shielding behaviour of thin graphene/PMMA nanolaminates in the THz range. Nat Commun, 12(1), 4655. https://doi.org/10.1038/s41467-021-24970-4
[20] Ma, Y., Guo, L., Cao, Y., & Qi, L. (2026). Increased electromagnetic interference shielding and load bearing with a three-dimensional pristine graphene@pyrocarbon skeleton in AZ91D. Nat Commun, 17(1), 1544. https://doi.org/10.1038/s41467-025-68266-3