

# Current Status of Research on Graphene-reinforced Titanium Matrix Composites

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**Abstract:** Graphene, a two-dimensional carbon nanomaterial, has received close attention from researchers since its discovery and is used as a reinforcing material in different composites. In recent years, graphene has been widely used as a reinforcement for metal matrix composites. Compared with the traditional granular fiber reinforcement, graphene has very high strength and modulus, and the enhancement effect is more significant. Titanium matrix composites prepared with graphene as reinforcement have various properties such as excellent mechanical properties, thermal stability and corrosion resistance. However, the agglomeration, uniform distribution, interfacial bonding and structural integrity of graphene in titanium matrix composites are currently still a huge challenge. In order to promote the further improvement of graphene-reinforced titanium matrix composites performance, solving the current technical problems is crucial to realize high performance composites. This review focuses on the preparation of graphene-reinforced titanium matrix composites, the interfacial structure and the reinforcement mechanism. Finally, suggestions for process improvement are made and future trends are summarized.

**Keywords:** Graphene; titanium matrix composite material; interface structure; enhancement mechanism.

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## 1. Introduction

Since the early 1950s, titanium and titanium alloys began to be developed and applied. Due to its excellent physical and chemical properties, such as high specific strength, corrosion resistance and good biocompatibility, it is widely used in aerospace, medical devices, automotive manufacturing and high-end fasteners. For example, the amount of titanium alloy in foreign third-generation fighters accounted for about 20% to 25% of the structural mass of the airframe, and up to 41% in the fifth-generation fighter F-22 [1]. With the continuous development of aerospace equipment and other fields, the comprehensive performance requirements for materials are increasing, and the performance of titanium alloys prepared using traditional process technology has approached or reached the theoretical limit. Graphene, as a two-dimensional carbon nanomaterial, has very high mechanical strength (about 130 GPa), good thermal conductivity (up to 5000 W/m-K), and excellent electrical properties [2-3], has been widely favored by researchers in recent years. Many researchers have incorporated graphene as a reinforcing phase into titanium matrix composites in an attempt to fundamentally improve the comprehensive mechanical properties of titanium alloy fabrications.

Graphene was first added to aluminum matrix composites to enhance their properties [4]. Li et al. [5] synthesized aluminum/graphene composites by powder metallurgy process and found that their tensile and yield strengths were significantly increased. GNPs/Ti are expected to significantly improve the mechanical properties, thermal properties, and wear and corrosion resistance of the material through the synergistic effect between graphene and titanium matrix, thus meeting the demand for high-performance materials in fields such as aviation equipment. GNPs/Ti, as a new type of high-performance material, show a broad application prospect in many fields. However, its development process still faces many challenges, which require researchers to continuously explore and innovate. In this paper, based on the collation of literature, the latest research progress on the preparation,

properties and interfacial structure of GNPs/Ti is reviewed, and an outlook on the future development trend is given.

## 2. Preparation Method of GNPs/Ti Composites

The preparation method of GNPs/Ti aims to homogeneously disperse graphene in titanium matrix to enhance the mechanical, electrical and thermal conductivity properties of the materials. The choice of preparation method directly affects the combination of graphene and titanium, the dispersion of graphene and the final properties of the material. In addition to the traditional methods of powder metallurgy, fusion casting and hot isostatic pressing, as an emerging technology, electrodeposition has also been applied to the preparation of GNPs/Ti in recent years.

### 2.1. Powder metallurgy method

Powder metallurgy is an advanced process used to make titanium matrix composites by homogeneously mixing the powders of the reinforcement and matrix materials, followed by processes such as pressing and sintering, which ultimately results in a dense composite material.

The basic principle of powder metallurgy method is to make the reinforcing phase and matrix phase into powder separately, and prepare the desired metal or non-metal powder by physical or chemical methods, then mix the reinforcing phase powder with the matrix phase powder and compress it under a certain pressure in order to form a preform. Finally, sintering is carried out at temperatures above the melting point of the matrix phase to melt, flow and recrystallize the components in the precast body to form a dense metallurgical bond. Effective control of the organization and properties of the composites can be achieved by adjusting parameters such as the ratio of powders, pressing and sintering conditions [6]. Table 1 lists the preparation methods, processes and properties of titanium matrix composites. Yan et al. [7] successfully prepared GNPs reinforced aluminum alloy nanocomposites by powder metallurgy method, the tensile

and yield strengths of the composites were significantly increased, the yield strength was increased by nearly 50% from 214 MPa to 319 MPa while the tensile strength was increased from 373 MPa to 467 MPa without any decrease in

ductility. Shin et al. [10] who synthesized 0.7 vol% graphene reinforced pure Ti with a compressive yield strength of 1.5 GPa by using powder metallurgy technique and curing by hot pressing at 570 °C and 140 MPa for 1 h.

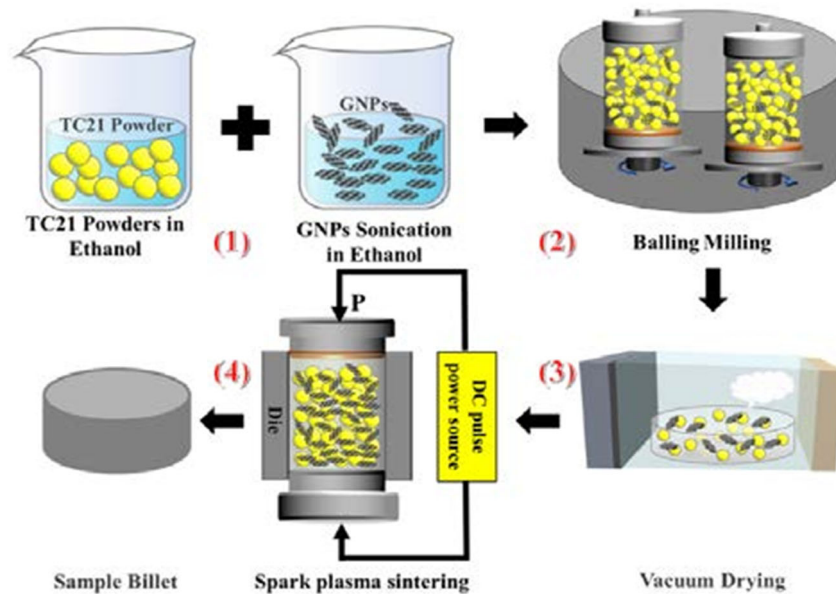
**Table 1.** Table of preparation methods, processes and properties of titanium matrix composites

ingredient	Preparation process	Sintering process	Yield strength/MPa	Tensile strength/MPa	Elongation/%
GR + TiC + TC4 <sup>[8]</sup>	3D Ball Mill Mixing + SPS Sintering	60 MPa, 900~1050 °C, 5 min	775~916	868~1033	13.2~22.9
0.3wt% GNPs + Ti-3Al-3Zr- 1Mo <sup>[43]</sup>	Ultrasonic Mixing + Mechanical Mixing + Vacuum Drying + SPS Sintering	60 MPa, 1000 °C, 6 min	757	820	21.5
1.2vol.% GNPs + Ti-6Al-4V <sup>[26]</sup>	Planetary ball mill + Hot isostatic sintering + Hot extrusion	150 MPa, 700 °C, 2 h	991	1007	15
0.5wt% GNPs +Ti -6Al-4V	V-mixer mixing + Hot isostatic firing + Forging at 970 °C + Heat treatment	150 MPa, 700 °C, 2 h	1021	1058	9.3
TiB+Ti-6Al-4V	Planetary ball milling + Hot press sintering	1300~1500 °C, 60 min	-	810~900 (Bending strength)	-
5vol.%~12vol.% TiBw+Ti-6Al- 4V <sup>[44]</sup>	Planetary ball milling + Hot press sintering	20MPa, 1200 °C, 60 min	-	-	10~15 (500~700 °C)
0.5wt%~1wt% MWCNTs +Ti <sup>[14]</sup>	High energy ball milling + SPS sintering	50 MPa, 800 °C, 5 min	-	899 (Compression strength)	27
0.5wt% Graphene -Ti	Planetary grinding + Pressing + Microwave sintering	1350 °C, 2 kW, 15 min	-	1595 (Compression strength)	-

Common powder mixing methods mainly use ball milling method and mechanical mixing method, both methods are common and simple alloy powder mixing method. Yue et al. [9] prepared graphene-reinforced copper-based (GO/Cu) composites using ball milling method with a ball milling rate of 400 rpm and a ball-to-material ratio of 10:1 with the addition of 1 wt.% stearic acid as a process control agent. In order to increase the ball milling efficiency and obtain better composites, many researchers use wet ball milling process. Mu [11] et al. mixed and stirred alcohol and titanium powder, after which graphene was added for mixing, the resulting mixture was then ball-milled for 2.5 h at 400 rpm. Lu [12] prepared graphene and Ti-3Al-3Zr-1Mo composites using wet ball milling process and the prepared composites had very few defects.

The molding and sintering process of composite materials is one of the key technologies in the field of materials science, which has a decisive influence on the performance and quality of the final product. Molding sintering processes for composites include discharge plasma sintering (SPS) [12-14],

hot press sintering [15], static isostatic pressure sintering, and microwave sintering [16]. SPS sintering utilizes the instantaneous high temperature and high pressure generated by DC discharge plasma to rapidly heat and densify the powder particles. This type of sintering has the advantages of fast heating speed, short sintering time, and high densities can be realized by low-temperature sintering. During the SPS sintering process, a DC pulse current is applied to the powder samples, and the powder particles produce discharge phenomena and plasma. The high temperature action of the plasma activates the particle surface and causes localized melting, which promotes particle binding. Compression simultaneously promotes particle densification and dense alignment. Yu et al. [17] prepared GNPs/TC21 composites using the “wet ball milling + SPS sintering” process, as shown in Figure 1. It mixed TC21 ball powder with GNPs in alcohol and then used stainless steel ball milling jars for low-energy ball milling, and then the obtained mixed powder was dried, followed by SPS sintering at 1000 °C for 5 min and 45 MPa to form sintered blanks of 50 mm × 14 mm.



**Figure 1.** Flowchart of powder metallurgy preparation of GNPs/TC21 composites [17]

Hot isostatic sintering densifies the powder or billet to be sintered by the combined action of high temperatures and various balanced high-pressure gases. Hot isostatic sintering is capable of obtaining products close to the theoretical density at lower sintering temperatures, which significantly improves the density and properties of the material. et al. [18] produced TiC /Ti-6Al-4V composites by subjecting the composite powders to hot isostatic pressing (HIP) at 900 °C and 950 °C and 100 MPa for 4 hours. Cao et al. [19] subjected the hybrid powder to hot isostatic pressing at 700°C and 150 MPa for 2 h, the composites obtained exhibited significantly improved tensile and yield strengths of 12.3% and 20.1%, respectively, as well as an increase in Young's modulus of 14.6%. Hot isostatic sintering equipment is complex and expensive to manufacture and maintain. At the same time, energy consumption is also higher due to the need for high temperature and high pressure environments, which increases overall production costs. Isostatic pressure sintering using the incompressibility of the liquid medium and the characteristics of the uniform transfer of pressure, in a high-pressure container on the powder or billet for uniform pressure molding, isostatic pressure sintering is not subject to the limitations of the shape of the mold, and is able to prepare complex shapes, large pieces and slender products. Microwave sintering uses the special wavelength band of microwave to couple with the basic fine structure of the material to generate heat, so that the material is heated to the sintering temperature as a whole, so as to achieve densification. Microwave sintering has the advantages of fast heating speed, high energy utilization, high heating efficiency and good uniformity, which is a hot sintering process developed in recent years.

## 2.2. Fusion casting method

Fusion casting is an important method in the processing of composite materials and is particularly suitable for the preparation of titanium matrix composites. By melting at high temperatures, the reinforcement and metal matrix materials are mixed well and then poured into molds to form composite products with specific shapes and properties by utilizing the solidification characteristics of the metal. Fusion casting process is simple, superior performance, through the

reasonable dosage and process control, the composite products prepared by fusion casting method can have excellent mechanical properties and corrosion resistance. Zeng Songyan [20] of Harbin Institute of Technology prepared Ti-25Al-0.5C alloy by arc melting under high purity argon atmosphere, and the XRD results showed the presence of Ti<sub>3</sub>Al and Ti<sub>3</sub>AlC phases in Ti-25Al-0.5C alloy. Soboyejo [21-22] prepared the reinforcing material TiBw by induction melting method and used it to prepare titanium matrix composites. Meanwhile, the tensile properties of the heat-treated titanium matrix composites were significantly improved.

Melt casting technology has many advantages, but also many disadvantages. For example, due to the high reactivity of the titanium alloy base material and reinforcement in the liquid phase, the low humidity during the melting and casting process leads to a non-uniform distribution of the reinforcement in the matrix, this may have an impact on the quality and performance of the final composite product. Zhang et al. [23] prepared TiC /Ti-6Al and (TiC+TiB)/Ti-6Al composites using the melt casting method.

## 2.3. Electrodeposition

Electrodeposition is a method of preparing composite materials by depositing metal ions or molecules on the surface of an electrode using electrochemical principles. Through electrochemical reaction, ions or molecules of different materials are mixed into the electrolyte, and then the electrode is immersed in the electrolyte, and a certain voltage and current are applied so that these ions or molecules are deposited on the surface of the electrode to form a composite material. Ge et al. [24] used electrodeposition method to obtain nickel-coated graphene nano- (Ni-GNFs) by dispersing functionalized GNPs in nickel sulphate solution, adding hydrazine hydrate as a reducing agent, and reacting under ultrasonic and mechanical stirring for 2 h at 343 K as shown in Figure 2. The electroplated nickel layer effectively improved the dispersion of GNPs in the titanium matrix and controlled the interfacial reaction between GNPs and the titanium matrix. Ni-GNFs/Ti composites exhibit excellent mechanical properties and have potential as high-performance engineering materials. Szeptycka [25] prepared

nickel-graphene composite coatings by electrochemical deposition in watt-type nickel plating solutions containing different concentrations of graphene. The nickel-graphene composite coating showed higher corrosion resistance compared to the pure nickel coating. In particular, the corrosion rate of the composite coating was seven times slower than that of the pure nickel coating when the graphene

concentration in the plating solution was 1 g/dm<sup>3</sup>, and the corrosion rate was reduced by 85.84%. Although the electrodeposition method has many advantages in the preparation of composites, it still faces some challenges, such as small preparation thickness, difficult to control the structure of composites, and easy to produce bubbles during the preparation process.

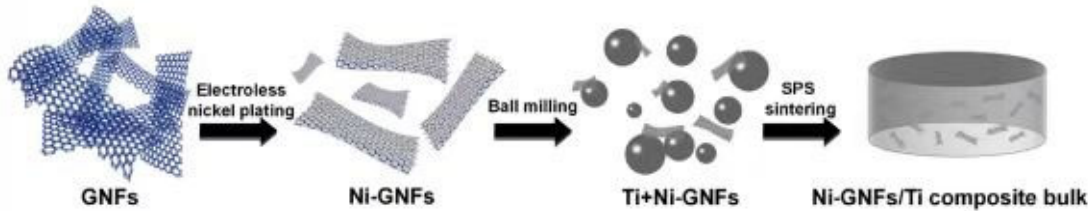


Figure 2. The preparation process of Ni-GNFs/Ti composites has been [24]

### 3. Effect of Graphene on The Properties of Titanium Matrix Composites

The addition of graphene as a reinforcing phase to titanium matrix composites improves the composite properties to varying degrees. The size, distribution and morphology of graphene, as well as the microstructure of the matrix microstructure, have extremely important effects on the properties of titanium matrix composites.

#### 3.1. Mechanical properties

Graphene can significantly enhance the tensile and yield strength of titanium matrix composites with its excellent mechanical properties, especially high strength and high modulus. Cao et al. [26] produced GNFs/TC4 composites with an increase in the modulus of elasticity from 114 to 122 GPa, a tensile strength of 1007 MPa, and a yield strength of 991 MPa, which is significantly higher than that of pure titanium alloys, with a slight decrease in the total elongation from 17% to 15%, but still exhibiting significant toughness. Otte [27] proposed the use of aerosolized spherical pure titanium (CP-Ti) powder mixed with hexagonal boron nitride (BN) nanopowder in a certain ratio to prepare TiB nanowhisker-reinforced titanium matrix composites with excellent mechanical properties and good biocompatibility, and the hardness of the resulting composites was significantly increased, up to 10.48 GPa, and the elastic modulus exceeded 165 GPa.

Usually, with the appropriate increase of graphene content,

the enhancement effect becomes more and more significant, but care should be taken to avoid the performance degradation caused by over-addition. Yang et al. [28] prepared titanium matrix composites with different graphene contents by powder metallurgy method, first, the compressive strength of the composites increased dramatically with the increase of graphene content, from 1345 MPa for pure titanium to 1595 MPa for 0.3 wt% graphene-titanium composites, and then decreased slightly at a graphene content of 0.4 wt%. This is attributed to fine-crystal reinforcement, the reinforcing effect of graphene, and the agglomeration effect of graphene at the pores. Gürbüz et al. [29] studied the effects of different graphene nanoplatelet (GNPs) contents (0.15, 0.30, 0.45, 0.60 wt%) on the performance of titanium-based composite materials, and the changes in compressive and tensile strength are shown in Figure 3. The 0.15 wt% GNPs significantly increased the compressive and tensile strengths of the titanium matrix composites to 845 MPa and 613 MPa, respectively, which were 30% and 50% higher compared to pure titanium. The mechanical properties of the composites decreased with further increase in the content of GNPs, which was attributed to the agglomeration and sliding effects of GNPs. When the graphene content is too high, it may lead to agglomeration of graphene, which not only destroys the homogeneous distribution of graphene in the matrix, but also introduces defects and stress concentration points, which reduces the strength and hardness of the composite. In order to obtain the best mechanical properties, it is necessary to rationally control the content of graphene and optimize the preparation process and parameters of the composites.

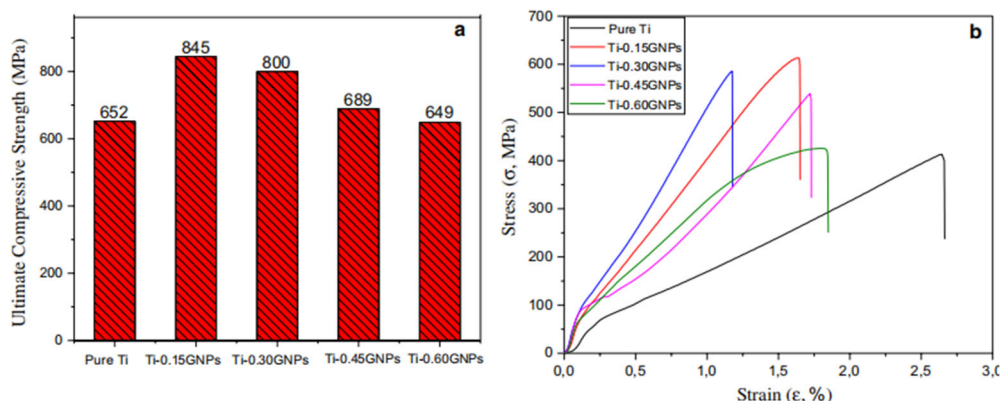


Figure 3. Effect of different GNPs content (mass fraction) on titanium matrix composites [29](a) ultimate compressive strength; (b) ultimate tensile strength.

### 3.2. Electrical and thermal conductivity

The electrical and thermal conductivity of GNPs/Ti were significantly improved. The resistivity of the GNPs/ Ti composites was tested using a KDY-1 four-probe tester from Guangzhou Kunde Technology Co. and the results are shown in Table 2. Chen [30] suggested that the factors affecting the conductivity of GNPs/Ti are mainly the dispersion of graphene and the interfacial bonding between graphene and titanium matrix. Uniform dispersion of graphene in the titanium matrix is critical to ensure good electrical

conductivity, and good interfacial bonding ensures effective electron transfer from the titanium matrix to the graphene, thereby improving overall electrical conductivity.

In modern industrial development, titanium matrix composites also need to fulfill high thermal conductivity requirements. Zhang et al. [31] successfully prepared dense GNS/Ti composites with uniformly distributed GNPs using ball milling method and hot press sintering technique, and the thermal conductivity of the composites was significantly enhanced.

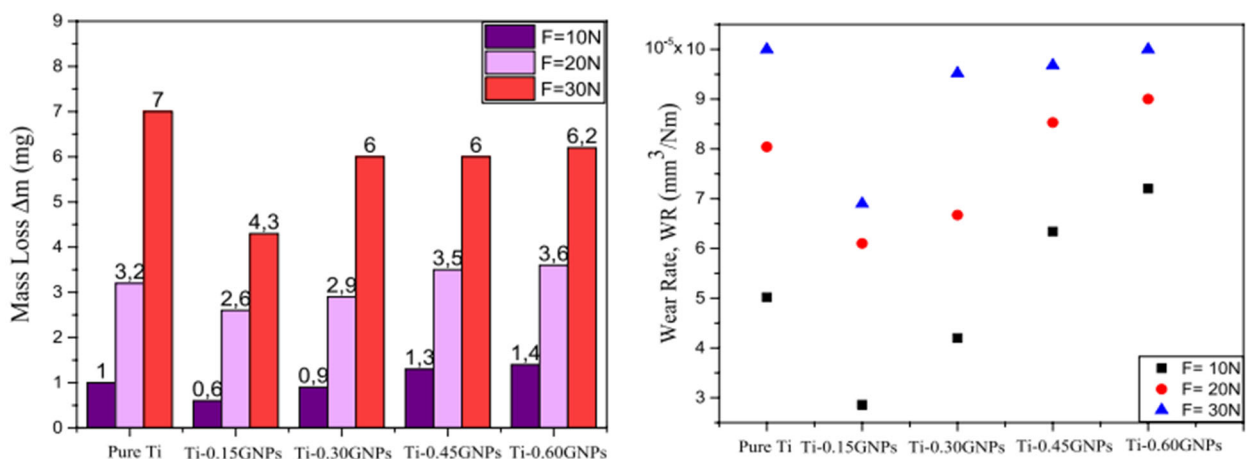
**Table 2.** Electrical resistivity/conductivity and grain size of GNP/Ti composites with different graphene contents

w(GNPs)/%	$\rho/(\Omega \cdot \text{cm})$	$\sigma/(\text{S} \cdot \text{m}^{-1})$	粒径/ $\mu\text{m}$
0	631	158	92
0.1	532	188	68
0.2	426	235	55
0.3	306	326	46
0.4	231	432	50
0.5	281	352	52

### 3.3. Friction resistance

In high-end manufacturing fields such as aerospace, automotive industry, power metallurgy, etc., the wear resistance of materials is required to be extremely high. Hu et al [32] prepared composite coatings of graphene oxide reinforced titanium with different contents by powder metallurgical method, and the experimental results showed that the friction factor of the composite coatings changed with the increase of graphene oxide content and reached the minimum value at graphene content of 2.5%. Experimentally, it was found that the mass loss and wear rate of GNPs/Ti increased as expected with the increase of loading in wear tests for titanium matrix composites prepared by Güler et al.

[29]. Figure 4 a, b shows the lowest mass loss ( $\Delta m = 0.6 \text{ mg}$ ) and wear rate ( $\text{WR} = 286 \times 10^{-5} \text{ mm}^3/\text{Nm}$ ) of Ti-0.15GNPs At 10 N loading, the Ti-0.15GNPs composite exhibits the lowest mass loss (0.6 mg) and wear rate ( $\text{WR} = 286 \times 10^{-5} \text{ mm}^3/\text{Nm}$ ). As the content of GNPs increases, the wear rate deteriorates. SEM analysis after the wear test showed that the Ti-0.15GNPs composites with low GNPs content had more uniform particle distribution and better wear surfaces, Figure 5 shows the SEM micrographs of the wear surfaces. During the friction experiments, some of the graphene undergoes interlayer separation and spreads out on the wear marks, which hinders the direct contact between the grinding ball and the composite material, and contributes to the reduction of the coefficient of friction [33].



**Figure 4.** Mass loss (a) wear rate (b) variation of Ti-GNPs composites [29]

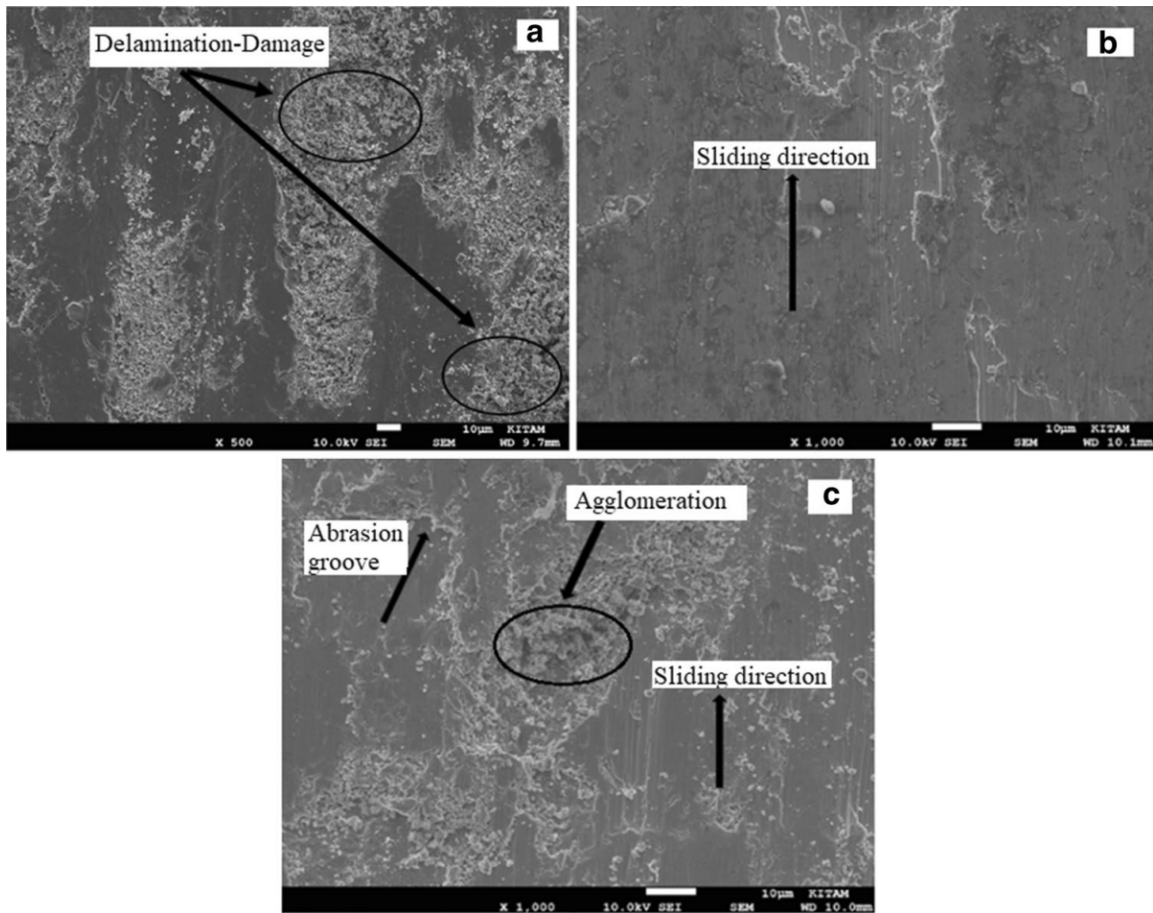


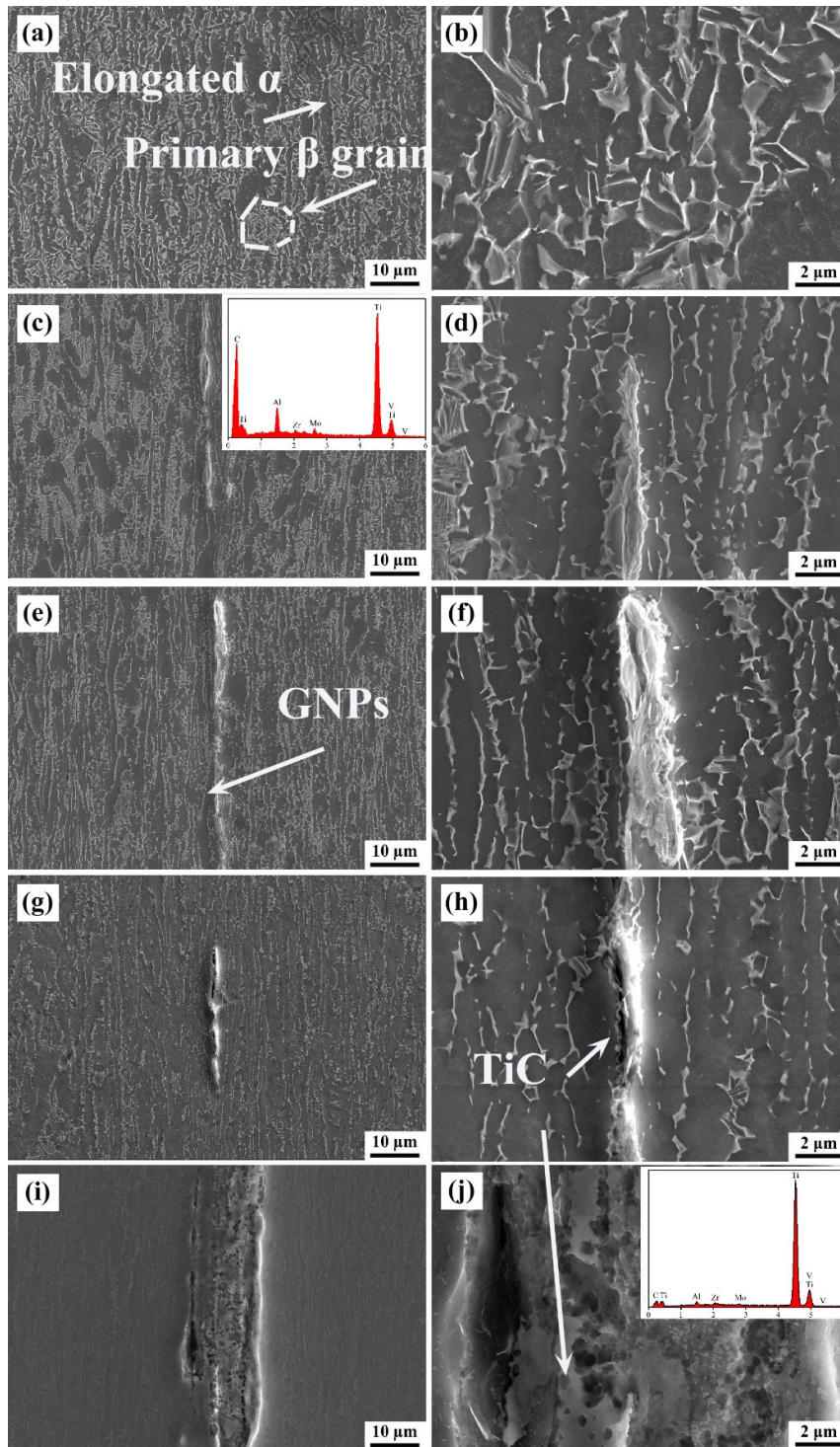
Figure 5. SEM micrographs of worn surfaces [29]: pure Ti (a), Ti-0.15 GNPs (b), Ti-0.60 GNPs (c)

#### 4. Interfacial Bonding of Graphene in Titanium Matrix Composites

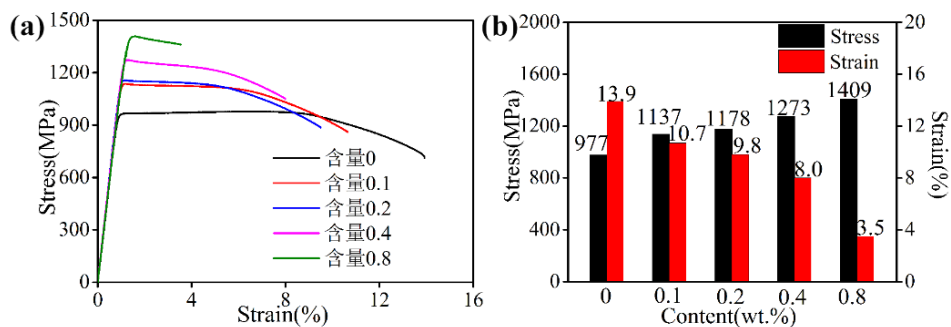
In the high-temperature environment, GNPs/Ti composites are prone to severe interfacial reactions in thermal deformation, and in-situ self-generated TiC particles-reinforced titanium matrix composites [34-35]. Discontinuous reinforced titanium matrix composites reinforced with carbon nanomaterials prepared by Melendez et al. [36] using powder treatment and hot compression molding, it was found that heat treatment leads to an increase in the TiC phase area and this composite has high hardness and strength, but poor plasticity (toughness). Shin [10] prepared titanium matrix composites using a powder metallurgical method at a temperature of about 500°C and in a high pressure environment, the GNPs are bonded to the titanium substrate through Ti-C ionic bonds and van der Waals weak bonds, and not much interfacial reaction occurs between them, composites are susceptible to interface detachment under loading conditions due to weak interfacial bond strength. It can be concluded that TiC is reinforced as the second phase, and if the content of TiC phase in the interface of GNPs/Ti composites is too low, it will lead to insufficient interfacial bonding, which will not be able to

significantly enhance the material properties; However, the excessive generation of TiC phase can damage the original structure of GNPs, weaken the plasticity (toughness) of the composites, and may lead to brittle failure of the materials. Therefore, the key is how to accurately cover GNPs with the right amount of TiC layer to optimise the overall performance of composites.

Hou Jiabin [37], Harbin Institute of Technology, prepared titanium matrix composites with different GNPs content by the pre-dispersion process of “low energy ball milling + mechanical stirring + vacuum filtration”, jacket sintering and hot extrusion process, the contents of GNPs were 0 wt.%, 0.1 wt.%, 0.2 wt.%, 0.4 wt.%, and 0.8 wt.%, respectively. Figure 6 shows the longitudinal microstructure of the composites with different GNPs contents. During the sintering process, with the increase of GNPs content, the amount of C atoms in GNPs diffusion into the Ti matrix also increased, resulting in a gradual increase in the concentration of C atoms in the Ti matrix. The  $\alpha$ -phase content of the tissues increases with the content of GNPs, and the opposite is true for the  $\beta$ -transformed tissues. Figure 7 shows the room temperature tensile properties of the composites with different GNPs contents. From the experiments, this shows that the addition of GNPs has a strengthening effect on the composites and the elongation decreases as the strengthening effect increases.



**Figure 6.** Longitudinal SEM low and high magnification maps of composites with different GNPs contents [37]  
 (a,b) 0wt.%, (c,d) 0.1wt.%, (e,f) 0.2wt.%, (g,h) 0.4wt.%, (i,j) 0.8wt.%



**Figure 7.** Room temperature mechanical properties of composites with different GNPs contents [37]  
 (a) Stress-strain curves, (b) Statistical plots of mechanical properties

## 5. Strengthening Mechanism of Graphene in Titanium Matrix Composites

The strengthening mechanism of graphene in titanium matrix composites is a complex and multifactorial process, which mainly includes dislocation strengthening, fine grain strengthening, Orowan strengthening and load transfer strengthening. For example, graphene nanosheets dispersed in titanium matrix composites can maintain the Weiss microstructure while refining the matrix grains, effectively hindering the dislocation motion and thus improving the mechanical properties of the composites. However, with the increase of GNPs, the severe accumulation of dislocations and overproduction of TiC tend to lead to the deterioration of the ductility of titanium matrix composites. Therefore, by studying the strengthening mechanism of graphene in titanium matrix composites, it can provide an in-depth understanding of the interaction between graphene and titanium matrix, and thus optimize the preparation process. Such as adjusting the ball milling parameters, sintering temperature and time, etc., which is of great significance to enhance the material properties and broaden the application areas.

### 5.1. Load Transfer Reinforcement Mechanism

Among the reported studies on titanium-based graphene composites, most of them show that graphene reinforces the composites mainly through a load transfer strengthening mechanism. Load transfer strengthening mechanisms are an important form of material strengthening that ensures uniform and efficient load transfer from one component to another by optimizing the interfacial connections between components in a composite or structural material[38]. This mechanism requires a high-strength interfacial bond between the reinforcement and the matrix, so that when the force is applied, the load can be smoothly transferred along the interface, so that the reinforcement can give full play to its load-bearing capacity, thereby enhancing the overall strength and toughness of the material.

Song et al. [39] introduced graphene oxide (GO) nanosheets as reinforcement and prepared GO/TC4 composites using SPS technique. Through the shear lag model prediction and the computational analysis of dislocation density, dislocation reinforcement and strong load transfer are the main factors of composite strength enhancement, this was attributed to the improved interfacial binding between GO and TC4 matrix. Mu [42] prepared MLG/Ti composites by three steps of ball milling and mixing, discharge plasma sintering (SPS) and hot rolling, and the tensile strength of MLG/Ti composites increased significantly with the increase of hot rolling temperature, in particular, the tensile strength of 0.2 wt% MLG/Ti reached 1045 MPa after hot rolling at 1223 K, which is about twice that of pure titanium. It was found that the formation of the TiC layer significantly improved the interfacial bonding between the MLG and the Ti matrix, allowing for a more efficient transfer of loads from the matrix to the MLG, thereby enhancing the overall strength of the composite. Lu et al. [43] prepared 0.05 % (mass fraction) GNPs/Ti-3Al-3Zr-1Mo (CT20) composites, under experimental conditions of 1000 °C and 60 MPa pressure, the yield strength and ultimate tensile strength of composites are significantly improved, the yield strength and

ultimate tensile strength of 0.3 wt% GNPs/CT20 composites increased by 27% and 34%, respectively, over pure CT20. It was found that the TiC@GNPs strip structure was formed at the junction of titanium matrix and graphene during sintering, as shown in Figure 8. This special structure can absorb a large amount of energy during tensile deformation, inhibit crack extension, and further improve the mechanical properties of GNPs/CT20 composites through an effective load transfer effect from the matrix to the TiC layer and then to the GNPs.

Because graphene has very high strength and modulus, it is able to effectively carry and transfer loads when it forms a good interfacial bond with the titanium substrate. In addition, the uniform dispersion and special morphology (e.g., folds, curls, etc.) of the graphene sheet layers also contribute to the load transfer efficiency. Experimental studies have shown that the strength and toughness of GNPs/Ti can be significantly improved by optimizing the preparation process and interface design to achieve better overall performance.

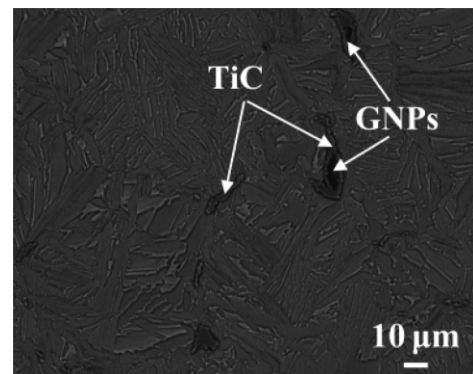


Figure 8. SEM image of TiC@GNPs formed in situ [43]

### 5.2. Microcrystalline Peening

Fine grain strengthening is a technique that significantly increases the strength of a material by refining the grain size within the material. When the grain size is reduced to the micron or nanometer level, the number of grain boundaries increases and the dislocation motion is more impeded, leading to an increase in the yield stress of the material and realizing the strengthening effect. This strengthening mechanism is widely used in the processing and treatment of metals, alloys and other materials to improve their mechanical properties and resistance to deformation.

Composites prepared by Zhou et al [40] by adding trace amounts of multilayer graphene to Ti-47Al-2Cr-4Nb-0.3W alloy showed a significant increase in flexural and compressive strengths, when the graphene content was increased to 0.8 at.%, the flexural strength reached almost 1000 MPa, the compressive strength increased to  $2347 \pm 12$  MPa, and the coefficient of friction was reduced from about 0.6 to 0.4, a reduction of about 1/3. It was found that the average grain size of TiAl alloys decreased significantly with increasing graphene content, when the graphene content was increased to 0.8 at.%, the average grain size decreased from  $14.8 \pm 1.4 \mu\text{m}$  to  $8.2 \pm 0.8 \mu\text{m}$ , and the enhancement of the mechanical properties was mainly attributed to the fine grain strengthening. The yield strength and grain size of composites generally follow the Hall-Petch formula [41], i.e.,  $\sigma_c = \sigma_0 + k_d d^{-1/2}$ , where:  $\sigma_0$  denotes the friction stress;  $k_d$  denotes the Hall-Petch slope; and  $d$  denotes the grain size, it can be seen from the equation that reducing the grain size improves the strength of the composite.

### 5.3. Other Enhancements

In addition to the above two types of strengthening, dislocation strengthening enhances the strength of a material by introducing dislocations (i.e., localized irregularities in the arrangement of crystal atoms) into the crystalline material. Dislocations, as a defect in the crystal, can effectively hinder the slip of crystal atoms and increase the deformation resistance of the material, thus making it more difficult for the material to undergo plastic deformation when it is subjected to external forces, and thus enhancing the overall strength of the material. Orowan strengthening mechanism, a type of strengthening in which second-phase particles in the metal matrix impede dislocation motion. When the dislocations move in front of the particles, the dislocations can only go around the particles due to the high strength of the particles that cannot deform, resulting in the growth of the dislocation line and increasing the stress of the dislocations moving, thus realizing the strengthening of the material. This mechanism can effectively regulate the strength and hardness of a material by controlling the size and distribution of the second phase particles in the material.

Song et al. [39] used multilayer graphene (MLG) reinforced titanium matrix composites. The hardness, indentation yield strength and shear strength of this composite were improved compared to pure titanium samples, the modulus of elasticity and hardness of the 0.5 wt% MLG/Ti composites were increased by about 6.4% and 71.4%, respectively. It was hypothesized that during the cooling process, a high density of dislocations would be generated near the MLG due to the mismatch in the coefficient of thermal expansion between the MLG and the titanium, thus increasing the strength of the composite. MLG, as hard particles, can impede dislocation motion and form dislocation rings, thereby increasing the strength of the composite. It suggests that the main strengthening mechanisms of the composite are dislocation strengthening and Orowan strengthening.

## 6. Conclusions and Outlook

Although the research on GNPs/Ti has made some progress, it has not yet constructed a complete research and application system, and further in-depth explorations are still needed to promote its technological development and industrialization application process. At present, in the process of preparing high-performance GNPs/Ti, there are still many challenges and difficulties to be solved.

(1) Optimization of preparation techniques: development of advanced processes to improve graphene dispersion and interfacial bonding.

In the future development, the preparation technology of GNPs/Ti will pay more attention to improving the dispersion and interfacial bonding of graphene in titanium matrix. This will be the key to achieve the optimization of material properties.

Decentralization enhancement: Through the development of new dispersants, optimization of ultrasonic treatment conditions and the use of more advanced mixing techniques, such as mechanical alloying and high-energy ball milling, the dispersion of graphene in the titanium matrix can be effectively improved to avoid the phenomenon of agglomeration, which ensures that graphene can give full play to its enhancement effect.

Interface bonding is enhanced: Interfacial bonding is an

important factor in determining the properties of composites. Future research will explore the introduction of functional groups or coatings on the graphene surface through surface modification, chemical vapor deposition (CVD) and other methods, Enhances its interfacial bonding with the titanium matrix. In addition, the effect of different heat treatment processes on interfacial bonding can be investigated to further optimize the properties of the composites.

(2) Multi-functional composite materials: Develop multi-functional composite materials with excellent mechanical properties, electrical conductivity, thermal conductivity and corrosion resistance.

By precisely controlling the content, distribution and orientation of graphene, the strength and toughness of composites can be further optimized to meet the needs of different application scenarios. Moreover, graphene, as an excellent conductive material, can be introduced into the titanium matrix to significantly improve the conductivity of the composite material, making it potentially applicable in electromagnetic shielding, sensors and other fields. The high thermal conductivity of graphene makes its composites promising in the field of thermal management. By adjusting the addition amount and structure of graphene, composite materials with excellent thermal conductivity can be prepared to meet the heat dissipation needs of high-power electronic devices. Finally, through the barrier effect of graphene and its protective effect on the titanium matrix, the corrosion resistance of its composites can be significantly improved and the service life of the materials can be extended, especially for applications in harsh environments.

(3) Expansion and industrialization of applications: promote the large-scale production and application of GNPs/Ti

In order to realize the wide application of graphene reinforced titanium matrix composites, it is necessary to solve the existing bottlenecks, such as cost and stability, and to promote their large-scale production and application. By optimizing the preparation process, improving the production efficiency and realizing the large-scale supply of raw materials, the cost of composite materials can be effectively reduced, making them more competitive in the market. With the continuous optimization of preparation technology and performance, GNPs/Ti will show a wide range of application prospects in many fields such as aerospace, automotive, electronics, medical, etc. Especially in the high-end manufacturing fields with demanding material performance requirements, the composite material is expected to play an important role. The government, enterprises and research institutions should strengthen cooperation and jointly promote the industrialization of GNPs/Ti Through the establishment of a perfect industrial chain, the strengthening of personnel training and technological innovation, we will accelerate the commercial application of this composite material and contribute to the socio-economic development.

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