Microstructure, mechanical and thermal properties of titanium matrix composites with different reinforcements

Hengpei Pan¹, Liang Ding¹, Yali Xu¹,², Longteng Li¹, Jieming Chen¹, Shuo Wang¹ and Peng Jiang¹,²

1 Luoyang Ship Material Research Institute, Luoyang 471000, People’s Republic of China
2 National New Material Production and Application Demonstration Platforms (Advanced Marine Engineering and High-Tech Ship Materials), Luoyang 471000, People’s Republic of China

* Author to whom any correspondence should be addressed.

E-mail: ylxu_300@163.com

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Abstract

In this study, three titanium matrix composites (TMCs) reinforced with graphite, graphene, and boron carbide (B₄C) were fabricated through powder metallurgical techniques. The morphologies of grains and secondary phases of these TMCs were observed through Optical Micrograph (OM) and Scanning Electron Microscopy (SEM). The results of the mechanical properties of the TMCs showed that B₄C was the most effective in increasing the strength and hardness, while the strengthening effect was comparable between graphite and graphene. The plasticity of the graphene reinforced TMC decreased sharply because of the formation of strip-like agglomerations. The small size, large volume fraction, and uniform distribution of the secondary phases contributed to the enhancement of strength and hardness in boron carbide reinforced TMC. Although the thermal properties of the TMCs were lower than pure titanium in the temperature range of 25 ~ 300 °C, the thermal conductivities of the TMCs were all above 15.6 W m⁻¹ K⁻¹.

1. Introduction

Titanium matrix composites, which were processed through the addition of particles, and fibers to the titanium matrix, usually have excellent mechanical, high-temperature, and wear properties compared with titanium alloys fabricated by conventional routes. Therefore, they have been widely used in the fields of aerospace, chemical industry, and biomedical instruments.

The TMCs can be divided into continuous reinforced TMCs and discontinuous reinforced TMCs due to the different morphologies of the reinforcements. Because of the isotropy, compatibility with hot processing, low cost, and the controllability of properties of the discontinuous TMCs, it has attracted wide attention from researchers all over the world. Up to now, various reinforcements have been used to improve the properties of TMCs, such as Al₂O₃ [1], SiC [2], graphene [3–5], CNTs [6], TiC [7], TiB [8–11], Nb₂O₃ [12], La₂O₃ [13] and so on. Among all the reinforcements mentioned in literature, graphene, TiC and TiB were most widely investigated. Yan [3] used the selective laser melting method to fabricate graphene reinforced Ti-6Al-4V composite and found that the strength, the Elastic Modulus, and the elongation reached 1526MPa, 145GPa, and 1.3%, correspondingly. Cao [5] studied the 0.5 wt% graphene/Ti-6Al-4V composite made through powder metallurgical technique, and the results showed that the yield and ultimate strength increased 20.1% and 12.3%, respectively, compared with pure Ti-6Al-4V titanium alloy, and the elongation remained at 9.4%, which was comparable to pure Ti-6Al-4V titanium alloy. Cao [14] fabricated the 0.3 wt% graphene reinforced TMC through Spark Plasma Sintering (SPS) followed by a hot-rolling and heat treatment process, and he reported that the tensile strength of the composite was as high as 1206 MPa, 46% higher than pure titanium processed under the same condition. Moreover, the area reduction of the fracture surface was 48%, revealing that the composite exhibited excellent plasticity. Due to the low cost, thermal expansion coefficient, good chemical, thermomechanical stability and compatibilities with titanium matrix, TiB and TiC are also widely used as.
reinforcement for titanium and its alloys. Huang [15] investigated the relationship between the volume fraction of TiBw and the mechanical properties, and he believed that the tensile strength firstly increased and then decreased with TiBw addition, whereas the ductility showed a descending trend. Wei [16] has studied the influence of TiC on the mechanical properties of TiC/Ti-6Al-4V composite and the results showed that TiC had improved the strength of the material and at the same time brought a harmful effect on plasticity. The addition of reinforcements could be an effective method to improve the strength of the titanium and its alloys, but the balance between the plasticity and the strength can be a problem affecting its application.

The interest in mechanical properties consisted only a part of the work on TMCs. Researchers were also interested in other properties, especially the wear resistivity [17], fatigue property [18, 19], and creep property [20]. However, the thermal properties of TMCs were less studied according to the authors’ knowledge. There is a growing demand for research on the thermal conductivity of titanium materials because they have been widely used in heat transfer equipment because of their high corrosion resistance. Mevlüt Gürbüz [21] studied the mechanical and thermal properties of graphene/titanium composites containing 0.15, 0.3, 0.45, 0.60 wt% graphene. According to his study, the compressive and tensile strength of 0.15 wt% graphene/titanium composite reached 845 MPa and 613 MPa, respectively, while that for pure titanium was 652 MPa and 413 MPa, seperately. The thermal conductivity and the thermal diffusivity firstly increased and then decreased, reaching the highest at 0.3 wt% graphene. Differently, Yang [22] pointed out that graphene resulted in a degradation of thermal conductivity for the TMCs in the range of 0–0.4 wt% mainly because the addition of graphene led to an increase in grain boundaries and phase boundaries. M Selvakumar [23] proposed a strategy to improve the thermal conductivity of the TMCs by using reinforcements with higher conductivity, such as TiB. The maximum thermal conductivity reported by M Selvakumar [23] was as high as 55.7 W m$^{-1}$K$^{-1}$, however, the volume fraction of TiB reached 40 vol.%, which would deteriorate the mechanical property.

Achieving a balance among the strength, plasticity and thermal conductivity of TMCs is important for the application in heat transfer equipment. However, less attention was paid to this field. In this work, we compared the microstructures, and mechanical and thermal properties of TMCs with three different reinforcements (graphite, graphene and B$_4$C) and investigated the influences of the reinforcements on load transferring and heat transferring processes.

### 2. Materials and experiments

Commercially pure titanium powders with a diameter of 15–53 μm manufactured by the Plasma Rotating Electrode Process (PREP) method were purchased from Avimetal Powder Metallurgy Technology Co., Ltd. in China. The contents of interstitial elements in titanium powder were 0.02% C, 0.022% N, and 0.20% O. Three kinds of reinforcements were utilized to fabricate TMCs, which were graphite, graphene, and B$_4$C. The graphite powders and the high purity graphene plates with a purity of ≥99.9% and ≥99% were provided by Beijing Deke Daojin Science and Technology Co., Ltd. in China. The purity of the B$_4$C powders was ≥99.9% and they were bought from Shanghai Xiangtian Nano Technology Co., Ltd. in China. The three reinforcements were mixed with pure titanium powders with a weight percentage of 0.5 wt%. The mixture of titanium with graphite, graphene, and B$_4$C was labeled as TMC-1, TMC-2, and TMC-3. TMC-0 represented a contrast group without adding any reinforcements. The three types of mixed powders were ball-milled using a planetary ball milling machine. The milling parameters were set as: rotating speed of 200 r min$^{-1}$, the ball to powder ratio of 3:1, and ZrO$_2$ milling balls with diameters of 1–5 mm were used. The total mixture time was 3 h except for a suspension time of 15 min every 30 min continuous rotating to avoid the heating of the powders. Then, the mixed powders as well as the contrast group were compacted into four distinct stainless steel bags of the same size. Afterwards, the samples were consolidated into TMCs via Hot Isotatic Pressing (HIP) at 1050 ℃ for 2 h and the pressure was set as 120 MPa.

Tensile specimens were cut from the sintered samples after removing the stainless steel bags and were tested using an INSTRON 5985–300 kN test machine at room temperature with a strain rate of 2.5 × 10$^{-4}$ s$^{-1}$. A minimum of 3 repeated samples were used to ensure the reproducibility of the results. The density of the samples ($p$) was characterized using Archimedes methods and the shape of the samples was cubic with a size of 10 × 10 × 10 mm machined through an electrical wire cutting machine followed by grinding of an 800 grit diamond plate. The thermal conductivity, $\lambda$, of the samples was obtained through equation (1) below:

$$\lambda = \alpha \cdot \rho \cdot C_p$$

(1)

Where, $\lambda$ represents the thermal conductivity, $\alpha$ represents the thermal diffusivity, and $C_p$ was the specific heat capacity.
The thermal diffusivity and the specific heat capacity were determined by a laser flash method on a Netzsch LFA 467 machine in the range of 25 °C to 300 °C. The sizes of the samples were 12.7 mm in diameter and 2.0 mm in thickness.

For microstructure observation, the specimens were cut from the sintered samples and were ground and polished to be mirror-like. Then, they were etched with Kroll’s agent (HF: HNO₃: H₂O = 1:3:50, volume ratio) to reveal the grain boundaries. ZEISS Observer Z1.m Optical Microscopy (OM) and Quanta 650 Scanning Electron Microscopy (SEM) were both utilized to compare the microstructure of the TMCs. Besides, the morphologies of the raw powders and the tensile-fractured surfaces were characterized using SEM. TEM was used to reveal the shapes and sizes of graphene plates.

3. Results and discussion

3.1. Characterization of the powders

The morphologies of the raw powders are shown in figure 1. It can be seen that the titanium powders are spherical and with some smaller satellite powders. The surfaces of the titanium powders are overall smooth and with some tiny grooves which were formed during the powder forming process. The graphite powders (shown in figure 1(c)) exhibit as plates, with average thickness of ∼50 nm and diameter of 5–10 μm. Besides, some agglomerates are observed from the inserted picture in figure 1(c). The particle sizes of B₄C powders are relatively homogeneous and are about 50 nm. Graphene plates are in the thickness of 4–20 nm and a flake diameter of 5–10 μm.

3.2. Microstructures of the TMCs

Figure 2 shows the microstructures of the TMCs. From figure 2(a), the grain sizes of TMC-0 were large and in the range of 100–200 μm. As can be seen from figures 2(b)–(d), the grain sizes of the TMC - 1, 2, and 3 all decreased sharply with the addition of reinforcements. Graphite plates and graphene flakes were added to TMC-1 and TMC-2, respectively. In-situ formed TiC can be seen within their microstructures because of the easy reaction between them and the titanium matrix. It can be seen from figures 2(b) and (c) that the dark grey particles belonged to in situ formed TiC and some of them were larger, which were agglomerates of reinforcements due to their non-uniform distribution. Besides, the matrix grain sizes of TMC-1 and TMC-2 were both around 50 μm. For TMC-3 shown in figure 2(d), in situ TiC and TiB were formed and acted as reinforcements [24]. The average matrix grain size of TMC-3 was the smallest, which was about 30 μm. The TiC appeared in granular shape, while the TiB whiskers were like short needles and their sizes were in the range of nanometer to sub-micrometer. Detailed features of the reinforcements in TMC-3 can be further revealed by SEM.
images in figures 3(d) and figure 6. Overall, the microstructure of TMC-3 sample was the most homogeneous and the agglomerates were rarely observed. Moreover, the volume fraction of reinforcements within the TMC-3 sample was relatively larger than that in TMC-1 and TMC-2. Reinforcements usually acted as barriers for grain boundary migration during the sintering process and inhibited grain growth. The larger volume fraction of the reinforcements, the smaller the matrix grain size. That is the main reason for the finer microstructure of TMC-3.

Detailed microstructures of TMC-1, 2, and 3 were revealed by SEM and the compositions of the secondary phases were characterized by EDS shown in figure 3. It can be verified by EDS results of point A and B in figures 3(a) and (b) that the granular particles in TMC-1 and TMC-2 were TiC-rich areas. Figure 3(c) was the magnified image for the red square area in figure 3(b) and TiC was observed locating at the grain boundaries as thin strips with lengths of 10–20 μm except for as granular particles and agglomerates shown in figure 2(c). Some of these strips even connected with each other to form longer wavy lines with sizes larger than the graphene.
diameters, as could be seen from figure 3(b). The reason for the appearance of thin TiC strips was that the morphology of graphene was thin plates and they were pushed to aggregate at grain boundaries due to grain growth and then the in situ reaction of graphene and Ti matrix consumed them and resulted in the formation of TiC-rich strips. Similar phenomenon of TiC strips was reported by Lu [25], who believed that TiC inclined to grow along a certain crystal plane of the Ti matrix. The composition of the strip in Figure 3(c) was further revealed by EDS, confirming that the strips were mainly TiC-rich areas. The relatively lower C content of point C compared with point A and B was maybe because the EDS detection width was larger than the thickness of the TiC strip so that signals from the matrix were simultaneously collected, leading to the lower fraction of C element. For TMC-3, there were two kinds of secondary phases: particle TiC and short whisker TiB. The distinct shapes of TiB and TiC resulted from their crystal structures [26]. TiC belonged to FCC lattice structure, and the growth speeds in different directions were the same. Therefore, they usually exhibited as granular particles. Whereas TiB was B27 structure, and the growth along [010] was faster than that along with other directions, leading to the formation of whiskers. The sizes of whisker TiB were in the sizes of nanometers and submicrometer, and they were located not only at grain boundaries but also inside Ti matrix grains. On the contrary, the TiC particles were relatively larger with sizes of 1–5 μm and appeared mostly at grain boundaries. Besides, the volume fraction of TiB was larger than that of TiC. According to the reaction between Ti matrix and B₄C : B₄C + 5Ti = 4TiB + TiC. There would be four times of TiB formation accompanied by one TiC formation, which explained the larger volume fraction of TiB in TMC-3.

Figure 4 shows the morphology of a cluster in the TMC-1 specimen, from which one could see the core–shell structure of the agglomerate. From detailed image reveling the edge of the core–shell structure figure 4(b)), one could deduce that the core of the agglomerate was graphite with layered features and the shell was composed of TiC. Similar phenomenon was observed by Li [27]. The mechanism of the formation of core–shell TiC@GNPs structure was explained by Lu [25], who proposed that the out layer of the graphene firstly reacted in situ with adjacent Ti matrix and they formed TiC nanolayers which formed a shielding effect for the inner graphene and thus resulting in the core–shell structure. Although we added graphite in TMC-1, the mechanisms were similar. The raw graphite powders consisted of some agglomerates (see figure 1(c)) and some of these were not sufficiently broken down in the ball-milling process, so they were left in the sintering process. The out layer of the graphite firstly diffused into and reacted with the surrounding Ti matrix to form TiC and this prevented the reaction of the graphite in the center. As a result, the core–shell structure formed.

Similarly, agglomerates were observed in the TMC-2 specimen in figures 5(a) and (b). Figure 5(b) shows the magnified image of the area indicated by the red square in figure 5(a) and the results showed that the agglomerates in TMC-2 belonged to core–shell structure, which was similar to that in TMC-1. Since the morphologies of graphite and graphene were both thin plates, and the mechanisms of the formation of core–shell agglomerations was the same as discussed before. Except for the core–shell structure, figure 5(a) displayed agglomerates accumulated as strips indicated by white arrows and the agglomerates strips were discontinuous. Since the thickness of graphene was thinner than graphite, they were easier to accumulate at grain boundaries and move along with grain growth and finally terminated when the obstacle was large enough to stop the grain boundary. Therefore, the smaller agglomerates tended to align to inhibit grain growth, which explains the formation of these strip-like agglomerates.

Figure 6 shows the microstructure of the TMC-3 sample. The microstructure was homogeneous and agglomerates were rarely seen. A large amount of TiB short fibers was in the sizes of nanometer and
submicrometer, and only a few TiB whiskers were about 5–10 μm. TiB and TiC mainly located at grain boundaries and some of them were seen inside the titanium matrix grains.

### 3.3. Mechanical properties and strengthening mechanism

Figure 7 illustrates the engineering Stress-Strain curves of the four TMCs, and figure 8 draws the yield strength, ultimate strength, and elongation of the TMCs. The results showed that all three reinforcements had induced a strengthening effect. It could be deduced that TMC-3 had the highest strength, with yield strength and ultimate strength reaching 550 MPa and 656 MPa, individually, increased by 103% and 82%, respectively, compared with the TMC-0. The strength increments of TMC-1 and TMC-2 were similar. The yield strength of TMC-1 and TMC-2 increased by 140 MPa and 157 MPa, separately, and the ultimate strength increased by 127 MPa and 136 MPa, correspondingly.

There were several strengthening mechanisms for TMCs, including grain refinement strengthening, thermal mismatch strengthening, load-transfer strengthening, in situ formed TiC strengthening, and Orowan strengthening. As could be seen from the microstructures in figures 2 and 3, the grain sizes of TMC-1, 2, and 3 were smaller than that of TMC-0, meaning that the grain refinement effect should be one reason for strengthening. The thermal mismatch effect was often caused by the huge difference between Ti matrix and the in situ formed secondary phases, which usually appeared after quenching [28]. Since the thermal expansion coefficients of TiB, TiC and Ti were close and the material did not go through a large temperature change, this effect should be neglected. The Orowan strengthening mechanism referred to the inhibition of dislocation movement in the way of the dislocation loop, which was more significant for smaller secondary phases. As for
TMC-1 and TMC-2, the scale of TiC was so large that the Orowan effect could be omitted. While for TMC-3, which had many TiB with sizes of nanometer or micrometer inside the matrix Ti grains (see figure 6), the Orowan effect contributed greatly to the strengthening. Therefore, the major strengthening mechanism for TMC-1 and TMC-2 should be grain refinement strengthening, load transfer strengthening, and in situ formed TiC (secondary phase) strengthening, and Orowan strengthening should be a plus for TMC-3.

The grain refinement effect could be calculated through the Hall-Petch equation:

\[ \sigma = \sigma_0 + k d^{(-0.5)} \]

Where, \( \sigma_0 \) and \( k \) are constant, \( d \) represents the grain size of the Ti matrix without reinforcements.

The strength improvement \( \Delta \sigma \) caused by reinforcements could be depicted as the following equation:

\[ \Delta \sigma = k (d_1^{(-0.5)} - d_0^{(-0.5)}) \]

Where \( d_1 \) was the grain size after adding reinforcements, and \( d_0 \) represents the grain size of the Ti matrix without reinforcements. For titanium alloys, \( k \) was 0.4 MPa·\( \mu \)m\(^{0.5} \) [29]. The grain sizes TMC-0 \( \sim 3 \) could be measured through metallurgical graphs, which were \( \sim 200 \) \( \mu \)m, 50 \( \mu \)m, 50 \( \mu \)m, and 30 \( \mu \)m, separately. Through calculation, the strength improvement of TMC-1, 2, and 3 induced by grain refinement effect should be 28.3 MPa, 28.3 MPa, and 44.7 MPa, respectively. As a result, the grain refinement strengthening had a limited effect on the total strengthening. This result is consistent with the conclusions drawn by Huang [30].

The strengthening effect of TMC-3 almost doubled compared with the TMC-1 and 2. Two reasons were responsible for this result. On one hand, the Orowan strengthening contributed to the strength increment of
TMC-3. On the other hand, the higher volume proportion of TiB and the higher Elastic Modulus of TiB than TiC contributed to the strengthening. Because the TiC and TiB were both generated from the reaction of Ti matrix and reinforcements, the interfacial bonding of them with Ti would both be strong, so the load transferring should be close. However, more and finer TiB whiskers were generated, facilitating the secondary phase strengthening. Further, the Elastic Modulus of TiB was 550 GPa, while that for TiC was 440 GPa \[31\], indicating that the load-bearing capacity of TiB could be higher than TiC. The above-mentioned reasons contributed together to the strength increment of TMC-3.

Although the inclusion of reinforcements had led to an increase in strength, the elongations of all TMCs were all reduced (figure 8(b)). Among all the three TMCs, the elongation loss of TMC-2 was the most and it fell to only 22% of that before graphene addition. The elongation of TMC-1 and TMC-2 decreased by \(~\)25% and \(~\)60% compared with the TMC-0. The strength increments of TMC-1 and TMC-2 were close, while the plasticity changes of the two were different. From the fracture surfaces of TMC-2 shown in figure 9, one can find that the fracture surfaces of TMC-2 were mainly quasi-cleavage. The TiC-rich strips were observed and indicated by the red curves in figure 9(b). EDS results of points 1 and 2 confirmed that they belonged to a core–shell structure with TiC particles surrounding residual graphene plates. Moreover, secondary cracks were observed inside the TiC strips, indicating that the crack would propagate easily in these areas and that would be harmful to plasticity. Li [27] proposed that porosity formed between the layered structure graphite caused by weak bonding of the graphite interlayer easily due to the mismatch in thermal expansion of Ti matrix and unreacted graphite, which was the major reason for mechanical property’s degradation. Some of the cracks were observed to propagate through the middle of strip-like TiC-rich areas (indicated by the red curve in figure 9(c)), and the fracture exhibited to be brittle. For TMC-2, since there were many strip-like TiC-rich areas that were inherited from the previously accumulated graphene plates, in situ TiC particles mainly formed at both sides of the graphene plates and consumed graphene. When the thickness of the graphene plates was above a critical value, the combination strength between TiC particles on both sides would be relatively low, which acted as weak regions for crack initiation and propagation. Thus, lower energy would be consumed when passing through these regions and the crack propagating speed was faster, leading to a brittle fracture, and finally a reduction in plasticity.

Figure 10 illustrates the fracture surfaces of TMC-3, and it shows a typical ductile fracture. From detailed analysis in figure 10(b), small TiB whisker pull-out and long TiB fibers fracturing were observed, revealing that they played an important role in the load-bearing and contributed to the strengthening effect. Because TiB
whiskers distributed discontinuously and kept good interfacial strength with the Ti matrix, the plasticity was maintained to a large extent.

Figure 11 shows the Vicker hardness results of the four TMCs and the trend kept the same with that of strength. The hardness of TMC-1 and TMC-2 both increased by about 50% comparing TMC-0, and that of TMC-3 increased by ∼80%. The difference in hardness was related to the type, proportion, and size of the secondary phases, and the reasons were explained in the previous strength section.

3.4. Thermal properties

The thermal diffusivity and specific heat capacity of TMCs are shown in figure 12, the densities of the TMCs are listed in table 1. Thermal conductivities were calculated according to equation (1), and the results are shown in figure 13. It is worth noting that the thermal diffusivities kept decreasing with the increase of temperature for all the TMCs. Among all the four specimens, TMC-0 dropped the most, to almost 2/3 at temperature 300 °C compared with that at 25 °C, while TMC-3 dropped relatively slower. The specific heat capacity increased slightly with temperature, and the differences among distinct TMCs were small because the content of the reinforcements was only 0.5 wt% and they contributed little to the change in specific heat capacity. The results in table 1 showed that the densities of TMC-1 ∼ 3 were close to that of TMC-0, reaching almost full density and the differences were because of the existence of few residual pores. So the density difference was not an important factor influencing the thermal conductivity among the three TMCs. Thermal conductivity follows a similar trend to thermal diffusivity. TMC-0 had the highest thermal conductivity and TMC-1 ∼ 3 all decreased to some extent.

Since the addition of reinforcements induced more grain boundaries, phase boundaries, and pores, which would increase the heat resistances [22, 32], the thermal conductivities of TMC-1 ∼ 3 were smaller than...
TMC-0. Even though the in situ formed TiC in TMC-1 and TMC-2 were generated from different carbon sources, i.e., graphite and graphene, the thermal conductivities of the two were close. From the microstructures shown in figures 2 and 3, one could see that the sizes, the distribution, and the volume fractions of the TiC and the agglomerates within the two specimens were almost the same, meaning that the interfacial heat dissipation and the heat loss should be similar. Thus, the thermal conductivities of the two specimens were nearly the identical. TMC-3 differed from TMC-1 and TMC-2 in the following aspects: volume fraction, size, and distribution of in situ formed secondary phases and matrix grain size. On one hand, finer matrix grains TMC-3 meant more grain boundaries, which caused an increase in thermal resistance. On the other hand, there were more in situ formed TiB than TMC-1 and 2, and many TiB whiskers existed not only at the grain boundaries but also inside the matrix grains. Smaller size of the reinforcements meant more reinforcements and that led to more interfaces. The increased interfaces between TiB and Ti matrix acted as barriers for heat transfer. Phonon was the main heat carrier and their mean free path was the key factor influencing thermal diffusivity \([21]\). The higher density of secondary phases decreased the mean free path of phonons, leading to a decrease in thermal diffusivity and finally the thermal conductivity. It is worth noting that the thermal diffusivity of TMC-3 decreased slower than other TMCs, with the increase of temperature. That could be explained by the higher TiB thermal conductivities.

**Figure 12.** (a) Thermal Diffusivity and (b) Specific heat capacity of TMCs in the temperature range of 25 °C ~ 300 °C.

**Figure 13.** Thermal conductivity of TMCs in the temperature range of 25 °C ~ 300 °C.

**Table 1.** Densities of TMCs.

| Specimen | TMC-0 | TMC-1 | TMC-2 | TMC-3 |
|----------|-------|-------|-------|-------|
| Density /g·cm\(^{-3}\) | 4.52  | 4.51  | 4.51  | 4.51  |
diffusivity than Ti [23] and they compensated for the thermal diffusivity decrease to some extent. The enhancement of thermal diffusivity of TiB to the Titanium matrix composites was reported by Selvakumar [23].

In summary, the increase of grain boundaries and phase boundaries caused by the inclusion of reinforcements increased the thermal resistance of TMCs and resulted in the reduction of thermal conductivity.

4. Conclusions

Titanium matrix composites reinforced with graphite, graphene and B4C were fabricated through ball milling and the following HIP sintering. The microstructure, mechanical, and thermal properties of the composites were evaluated. The main conclusions are as follows:

(1) The addition of reinforcements led to a decrease in matrix grain size, and B4C was the most effective in refining the grains because of the smaller size and larger volume fraction of in situ formed TiB and TiC.

(2) Three reinforcements all resulted in an increase of strength, hardness, and a decrease of plasticity. The effects of graphite and graphene were similar and they led to ∼50% and ∼35% increase in yield strength and ultimate strength, respectively. The hardness of the graphite and graphene reinforced composites were both ∼50% higher than the unreinforced pure titanium. Due to the finer and larger amount of in situ TiB in B4C reinforced composite, the yield strength and the ultimate strength increased to 550MPa and 636MPa, respectively, which almost doubled the strength of pure titanium fabricated under the same condition. The sharp decrease in the plasticity of graphene reinforced TMC-2 was due to the strip-like TiC agglomerates at grain boundaries.

(3) The main strengthening mechanisms for graphite and graphene reinforced composites were load-transfer strengthening and in situ formed secondary phase strengthening and grain refinement strengthening, while an extra Orowan strengthening effect should be taken into account for B4C reinforced composite.

(4) Thermal conductivities of the three TMCs were lower than that of pure titanium owing to the inclusion of more grain boundaries, phase boundaries, and pores. Among the three TMCs, the B4C reinforced TMC exhibited the lowest thermal diffusivity and thermal conductivity, mainly because the matrix grain size was the smallest and the TiB existed both at grain boundaries and inside grains, which reduced the mean free path of phonons. However, the thermal diffusivity and conductivity at 300 °C were comparable for the TMCs and pure titanium.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ORCID iDs

Yali Xu https://orcid.org/0000-0001-6610-8936

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