Investigations on the mechanics and tribology of multilayer graphene nanosheet in TiAl aviation composites

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Abstract
Requirements of low energy consumption and material-volume reduction in the aerospace industry have spurred improvements of mechanical and tribological behaviors of TiAl (TA) alloys. TA-graphene (TAG) has poorer mechanical properties (6.02 ± 0.42 GPa nano-hardness, 150 ± 12.32 GPa elasticity modulus, and 802 ± 21 MPa yield strength) than (6.25 ± 0.52 GPa nano-hardness, 159 ± 14.21 GPa elasticity modulus, and 850 ± 19 MPa yield strength) of TA-graphene-silver (TAGS). Multilayer graphene nanosheets were curled into small loops to resist the applied forces, and helped to improve the mechanical properties of the TAGS. Subsequently, the graphene nanosheets enhanced the tribological performances as observed by the ball-on-disk tribometer. The following factors were primarily responsible for more excellent tribological behaviors (approximately 0.27 friction coefficient, 2.82 × 10⁻⁴ mm³ N⁻¹ m⁻¹ wear rate) of TAGS than those of the TAG: intra-lamellar separation of graphene, graphene-enhanced capacity of wear scar, plastic deformation of silver, the excellent cooperation lubrication of graphene-silver, the low-hardness lubrication film on the grain-refined layer, the well-distributed film grain, and low grain orientation angles.

Keywords
Sliding wear, solid lubricants, electron microscopy, surface analysis

Date received: 7 May 2021; accepted: 30 July 2021

Handling Editor: James Baldwin

Introduction
In recent years, TiAl (TA) alloys have been extensively used for the manufacture of lightweight components in the aerospace industries, such as the turbine blades and turbochargers.¹⁻³ But, the poor tribological and mechanical properties of TA-based components have impeded their applicabilities,⁴,⁵ especially under extreme conditions. Thus, the improvements of friction and wear performances of TA alloys will amplify their industrial applications.

To improve the friction and wear behaviors of these components, most researchers have focused on preparing self-lubricating samples containing silver.⁶⁻⁸ Xu et al.⁹ studied the effect of the migration of silver atoms on the tribological behaviors of materials. They found that the silver atoms in TA-based materials migrated to the wear scars and induced the formation of a silver-rich film, that led to low friction and wear. But, the application of high loads on the silver-rich film resulted in significant peeling and surface cracks, because of the weak bearing capacity of the film.⁷

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In comparison to the silver, multilayer graphene nanosheets were highly reinforced materials, and the nanosheets selected by Xie et al. acted as effective fillers for improving the mechanical and tribological properties of ceramic-based coatings. According to studies by Balog et al. and Kwon et al., graphene improved the mechanical and tribological behaviors of the materials owing to the reduction of the atomic layers. Xu et al. reported that the mechanical and tribological behaviors of TA-based composites were significantly enhanced by graphene. Additionally, the Vicker’s hardness and yield strength obtained by the addition of graphene were considerably higher than those of pure TA alloys. Friction and wear results showed that layer separation of the graphene reduced the friction coefficient and wear rate. Min et al. explored that the substrate coating hardness affected the friction and wear performances of graphene films, and acquired close correlations of tribological properties of graphene films with their coating hardness. Won et al. developed an ultra-thin protection coating for the applied precision components based on excellent mechanical and tribological properties of graphene. The results showed that with continuous increase of sliding cycles, eventual degradation of the graphene coating was well characterized by valid transformation of graphene to an amorphous carbon. Mura et al. reported tribological behaviors of Acrylonitrile Butadiene Styrene (ABS) and PolyCarbonate-Acrylonitrile Butadiene Styrene (PC-ABS) polymers coated with graphene. They found that the graphene coating reduced friction coefficients of the used materials, although the wear strength of the coating was quite weak. To the best of our knowledge, few works have reported on the improvements of mechanical and tribological performances of TA-based composites by the graphene enhancement or the effect of spherical graphene-silver on the tribological behaviors of TA composites.

To investigate the enhanced mechanical and tribological behaviors of graphene nanosheets, spark plasma sintering (SPS) and hot-pressed sintering (HPS) were used to prepare the TA, TA-1.5 wt.% graphene (TAG), and TA-spherical graphene-silver (TAGS) (TA-1.5 wt.% graphene-20 wt.% silver). A ball-on-disk tribometer was used, and the friction and wear performances of as-prepared samples sliding against Si₃N₄ balls were tested according to ASTM Standard No. G99-95. The cross-section microstructures and surface morphologies of the wear scars were analyzed using field-emission scanning electron microscopy (FESEM). X-ray diffraction (XRD) was used to characterize the phase components. The mechanical behaviors of TA, TAG, and TAGS were examined using the tensile instrument and nanoindentation tester.

**Material experiments**

**Preparation of spherical graphene-silver**

The powders with nominal mass fraction 93% silver (5–45 μm sizes and 99.92% purities) and 7% graphene nanosheets (0.5–5.0 μm diameters, 0.8–1.2 nm thicknesses, 98.55% purity) were provided by Nanjing XFNANO Materials Tech Co., Ltd., and used to prepare the spherical lubricants. First, the powders were loaded into teflon vials with a diameter of 30 mm and height of 20 mm, and then mixed by vibration milling at a frequency of 55 Hz to form a homogeneous mixture. A flame spray welding instrument was employed to prepare the spherical lubricants. The mixed powders were fed into the combustion nozzle in the argon atmosphere (99.55% purity) at a speed of 2.50 ± 0.25 m s⁻¹ using oxygen. At the nozzle, the oxygen and acetylene were ignited to form a high-temperature atmosphere of almost 1300°C. Subsequently, the molten mixture containing silver and graphene was added to ultrapure water. For rapid cooling, the molten mixture was contracted into a large amount of spherical lubricants. Further, air sieving was employed to obtain the homogenous distribution of the spherical graphene-silver particles; the representative

![Figure 1. Typical FESEM morphologies of graphene (a), silver (b), and graphene-silver mixture (c); EPMA morphology (d) and element distributions (e and f) of spherical graphene-silver.](image-url)
morphology obtained by electron probe microanalysis and elemental distributions of spherical graphene-silver are shown in Figure 1(d) to (f), wherein the silver and graphene were well-distributed in the spherical lubricants.

Preparation of TA base materials

Starting powders (10–35 μm mean sizes, 99.7%–99.90% purities) of commercially available Ti, Al, B, Nb, and Cr were used; the TA matrix powder consisted of Ti, Al, B, Nb, and Cr with nominal compositions (wt.%). of 59.40, 32.80, 2.70, 4.80, and 0.30, respectively. The TA and TAG (TA-1.5 wt.% graphene) were prepared by SPS (D.R. Sinter® SPS3.20) and HPS (KZTY-18-20); spherical graphene-silver was employed to prepare TAGS. Table 1 lists the compositions of the as-prepared samples. Before SPS, the as-obtained powders were mixed by vibration milling at a frequency of 50 Hz and loaded into graphite molds with an inner diameter of 25 mm. After loading, the samples were held for 10–15 min in an argon atmosphere (99.55% purity). The operational parameters for preparing the TA, TAG, and TAGS were: heating rates of 90°C min⁻¹–100°C min⁻¹, sintering temperatures of 950°C–1030°C, and sustaining pressures of 35–40 MPa. The thermodynamic laws reported by Yue et al.,¹⁸ Xu et al.,¹⁹ and Yang et al.²⁰ to explain the in situ synthesis of TA alloys. Table 2 presents the principal reactions and Gibbs free energies (G) of the TA alloys, which indicated that during SPS, the intermediate reactants (Ti₃Al and TiAl₃) were successively converted to form the TA.

Friction and wear tests of as-prepared TA composites

Friction and wear behaviors of the TA, TAG, and TAGS samples were examined according to the ASTM Standard G99-95.¹⁷ The samples were slid against Si₃N₄ balls with a diameter of 6 mm and hardness of 15 GPa, and a HT-1000 ball-on-disk high-temperature tribometer (Zhong Ke Kai Hua Corporation, China) was used for the measurements. With an important reference to the tribological parameters,²¹–²³ a speed of 0.5 m s⁻¹ and the load of 14 N were used for this study. At least three tests under friction and wear were performed at 50%–55% humidity and 25°C–600°C. The coefficients of friction were recorded for 80 min using an HT-1000 computer controlled-system. The TAGS wear rate (W) was calculated by the formula: \( W = V/(FL) \),¹²,²⁴ Herein, L, F, and V are the sliding distance (m), applied load (N), and wear volume (mm³), respectively. Three-dimensional (3D) wear scar profile was measured by a ST400 surface profiler. Subsequently, the wear volume (V) was calculated from the 2D-linear profiles, which were extracted from the 3D profile.

Results and discussions

Phase compositions of TA-based composites

The principal phases of the TA-based samples were obtained by XRD using Cu-Kα radiation at 30 kV and 40 mA at a scanning rate of 0.01° s⁻¹. A typical XRD pattern of the SPS TA-base samples is shown in Figure 2. Based on the diffraction peak intensities, the TA alloy primarily consisted of γ-TA and α-TA. TA alloy and multilayer graphene nanosheets were observed in

### Table 1. Mechanical and physical performances of as-prepared TA base samples.

| TA base samples | TA (wt.%) | TAG (wt.%) | TAGS (wt.%) |
|----------------|----------|------------|-------------|
| Chemical contents | 59.40 Ti-32.80 Al-2.70 B-4.80 Nb-0.30 Cr | TA-1.5 graphene | TAG-20 silver |
| Material density (g cm⁻³) | 3.95 ± 0.42 | 3.83 ± 0.42 | 4.15 ± 0.45 |
| Nano-hardness (GPa) | 5.95 ± 0.58 | 6.02 ± 0.42 | 6.25 ± 0.52 |
| Elasticity modulus (GPa) | 148 ± 11.34 | 150 ± 12.32 | 159 ± 14.21 |
| Yield strength (MPa) | 750 ± 20 | 802 ± 21 | 850 ± 19 |

### Table 2. Main reactions and Gibbs free energies (G) of synthesizing the TA alloys.

| Reaction formulas | Gibbs free energy (kJ mol⁻¹) |
|------------------|----------------------------|
| Ti + Al → TiAl   | \( \Delta G^0 = -152.91 + 44.44 + 42.72 = -65.75 < 0 \) |
| Ti + 3Al → TiAl₃ | \( \Delta G^0 = -291.06 + (42.72 \times 3) + 44.44 = -118.46 < 0 \) |
| 3Ti + Al → Ti₃Al  | \( \Delta G^0 = -266.5 + (44.44 \times 3) + 42.72 = -90.46 < 0 \) |
| TiAl + 2Ti → Ti₃Al | \( \Delta G^0 = -266.5 + (44.44 \times 2) + 152.91 = -24.71 < 0 \) |
| TiAl + 2Al → TiAl₃ | \( \Delta G^0 = -291.06 + (42.72 \times 2) + 152.91 = -52.71 < 0 \) |
| Ti₃Al + 2Ti → Ti₃Alalogies, which indicated that during SPS, the intermediate reactants (Ti₃Al and TiAl₃) were successively converted to form the TA. |
the TAG samples, and the main TAGS phases were TA, graphene, and silver, slight TiC; the presence of TiC might be well explained by the synthesis reactions in Table 3.

### Mechanical performances of as-prepared samples

At least three measurements were performed to obtain the average densities of the TA-based samples. The densities were estimated according to the ASTM Standard B962-08 and Archimedes’ principle, and the results are listed in Table 1. As seen from the data in Table 1, the use of multilayer graphene resulted in TAG with a density of 3.83 ± 0.42 g cm⁻³, that was less than that of TA (3.95 ± 0.42 g cm⁻³). However, the application of spherical graphene-silver increased the mean density (4.15 ± 0.45 g cm⁻³) of a TAGS, possibly because of the high density of silver (approximately 10.49 g cm⁻³).

The indentation morphology and indentation loading curves of the TA-based composites are shown in Figure 3(a) and (b), respectively. The nanohardness and elasticity modulus of the TA-based samples were obtained by a mechanical apparatus (TI-950, Hysitron, Inc. USA), which are listed in Table 1. The TAG hardness (6.02 ± 0.42 GPa) was higher than that of TA (nearly 5.95 GPa). The spherical graphene-silver in TAGS produced an even higher hardness (6.25 ± 0.52 GPa), that was primarily attributed to the graphene nanosheets curled in the spherical lubricants in TAGS. Three tests were performed, and the mean values of the elasticity modulus of the TA, TAG, and TAGS were estimated to be approximately 148, 150, and 159 GPa, respectively.

Figure 3(c) shows the typical tensile curves of the TA-based composites. The results of the three tests performed on the 1341 instron tester are listed in Table 1; the mean yield strength of a TAG was 802 ± 21 MPa, which was higher than that of TA (750 ± 20 MPa) and lower than that of TAGS (850 ± 19 MPa). Graphene slightly improved the mechanical properties of the TAG, and spherical graphene-silver in the TAGS further enhanced the mechanical performances.

For exploring the enhancement mechanisms of spherical graphene-silver, the TA, TAG, and TAGS were incised to the residual thickness of 1–1.5 mm using the electrospark wire-electrode cutting. Subsequently, the cross-sectional structures were obtained by cooling the fractures. After cooling in liquid nitrogen for 40 min, the incised sample was divided into two parts for the shearing stress test, and the cross-sections were cleaned by ethyl alcohol and analyzed by FESEM. The cross-sectional results of the TA, TAG, and TAGS are shown in Figure 4. The pyknotic microstructure of TA can be observed in Figure 4(a). Figure 4(b) shows that graphene was well-incorporated in TAG and improved the mechanical performance of the TAG, compared to that of TA. The morphology with spherical graphene-silver is shown in Figure 4(c); spherical graphene-silver was well-incorporated within the matrix. The spherical lubricants caused curling of the graphene nanosheets, further improving the mechanical performance of a TAGS. Subsequently, the typical fractured morphology of tensile sample at strain rates of 0.01 s⁻¹ is shown in Figure 4(d). As shown in Figure 4(d), the river microcrack morphologies in the fracture are observed together with the graphene nanosheet and spherical graphene-silver; it indicated that the brittle fractures occurred in the TAGS.

Based on Figure 4, the mechanical performance of TAGS can be further explained by establishing the corresponding mechanisms. Figure 5(a) is the representative hexagonal molecular structure of multilayer graphene. The schematics of the tensile tests of TAGS can be further explained by establishing the corresponding mechanisms.
Figure 3. Typical indentation morphology (a), indentation-loading curves (b), and tensile curves (c) of TA base samples.

Figure 4. Typical cross-sectional structures represented by the FESEM of the TA (a), TAG (b), and TAGS (c) prepared by SPS.
and TAGS are shown in Figure 5(b) and (c), respectively. The graphene nanosheet was parallel to the applied tensile stress, and the weak Van der Waals forces caused an interlamination separation in the multilayered structures, which could be an obstacle in increasing the tensile strength (Figure 5(b)). For the TAG, when the graphene nanosheets were perpendicular to the direction of applied tension, tensile stresses were effectively hindered, resulting in the high strength of approximately 802 MPa. The graphene nanosheets in the spherical lubricants curled into small loops, effectively resisted the tensile force, and caused the tensile strength of TAGS (approximately 850 MPa) to be higher than those of TA and TAG (Figure 5(c)).

Figure 5(d) and (e) show the typical nanoindentation schematics of the TAG and TAGS. The load applied parallel to the multilayer graphene in TAG produced a sliding motion because of the weak Van der Waals forces of multilayer graphene sheets (Figure 5(d)). The graphene nanosheets in TAGS were curled in the spherical graphene-silver. When the loads were applied, the curled graphene resisted graphene slippage via self-volume deformation and caused the TAGS to achieve higher hardness (6.25 ± 0.52 GPa) and modulus (159 ± 16.21 GPa) than those of the TAG.

Friction and wear performances of as-prepared samples

Figure 6(a) shows the schematic of a matching tribopair of an as-prepared sample/Si₃N₄ ball. The 3D profile of a wear scar is shown in the inset of Figure 6(a). Figure 6(b) and (c) show typical histograms of the friction coefficients and wear rates of as-prepared samples at different temperatures. Poorer friction and wear behaviors were obtained for TA than for the TAG, and the low friction coefficient and wear rate were obtained for TAGS. Furthermore, the friction and wear behaviors of TAGS at 450°C were better than those at other temperatures.

To understand the effect of wear scars on the tribological behaviors at 450°C, the microcosmic morphologies of the wear scars were analyzed using FESEM (Figure 7). A small plow and isolated island-like layers appeared on the TA wear scars, indicating that plowing was the primary wear mechanism (Figure 7(a)). As shown in Figure 7(b), a big plow and graphene sheets were observed on the TAG wear scars, indicating a severe plowing mechanism. Figure 7(c) shows the high amounts of silver and graphene on the TAGS wear scar, implying that the primary TAGS wear mechanism was plastic deformation.

Figure 8(a) shows the typical lubrication schematics of multilayer graphene. The weak Van der Waals forces in the multilayered structures caused intra-lamellar separation in the graphene nanosheets, which reduced the frictional resistance during wear and preserved the wear scars to be not destroyed. Furthermore, TAG featured smaller friction coefficients and wear rates than TA. Figure 8(b) shows the typical lubrication schematic of spherical graphene-silver in the TAGS; during wear, intra-lamellar separation of the graphene improved the plastic deformation of silver and increased the bearing capacity of wear scar, that reduced the friction coefficients and wear rates. Additionally, wrapping the
Figure 6. Typical schematic of a matching sample/Si$_3$N$_4$ tribopair (a), the friction coefficients (b), and wear rates (c) of as-prepared samples at different temperatures.

Figure 7. Typical microcosmic morphologies obtained by a FESEM of the wear scars of TA (a), TAG (b), and TAGS (c).
Figure 8. The lubrication schematics of multilayer graphene in TAG (a) and TAGS (b).

Figure 9. Typical FESEM cross-section morphology (a), 3D-texture structure (b), and cross-section hardness (d) of the wear scars; an amplified morphology in a rectangle C of Figure 9(a) (c).

graphene in silver to prevent oxidation facilitated excellent cooperation during the lubrication of graphene and silver and produced better friction and wear behaviors for TAGS than for the TAG.

Figure 9(a) shows the FESEM cross-section morphology of the TAGS wear scar. The observed stratification structure mainly composed of a lubrication film, grain-refined layer, and a layer of the TA-based material, which were marked as layers E, F, and G, respectively. Spherical graphene-silver was observed in the lubrication film. During wear, spherical lubricants were enriched on the wear scars and rolled in a lubrication film to significantly reduce the frictional resistance and material loss, resulting in small friction coefficients and wear rates.

The profiler stylus of the ST400 instrument was moved across a wear scar at the scanning rate of 20 mm s$^{-1}$ to represent a 100 μm × 100 μm rectangle at a scanning step of 0.1 μm. The three-dimensional texture of the surface structure of a lubrication film is shown in Figure 9(b). The excellent deformation of silver repaired the wear scars and caused them to acquire small height parameters: arithmetical mean height: $S_a$ (0.18 μm), root mean square height: $S_q$ (0.37 μm), height distribution kurtosis: $S_{ku}$ (4.25), and Skewness of height distribution: $S_{sk}$ (0.51). Thus, the wear scars
of TAGS were smooth. Figure 9(c) shows the incorporation morphology of the lubrication film above the grain-refined layer. The layered nanohardness of the TAGS was obtained by an indentation test, based on a nano-mechanical apparatus. As shown in Figure 9(d), hardness values of the layers were approximately 1.45 ± 0.23, 7.23 ± 0.73, and 5.95 ± 0.42 GPa for the lubrication film, grain-refined layer, and the TA-based material, respectively. As discussed by Li and Xu, the appearance of a low-hardness layer (lubrication film) above the high-hardness grain-refined layer (5.95 ± 0.58 GPa) facilitated the excellent friction and wear performance.

Figure 10 shows the electron backscatter diffraction (EBSD) patterns of the wear scar cross-sections of a TAGS. Figure 10(a) shows multiple submicron grains in the lubrication film, and Figure 10(b) shows the well-distributed strain on the lubrication film. As shown in Figure 10(c), silver atoms appeared primarily in the blue regions, whereas the white regions were occupied by graphene. The orientation pattern of the grain distributions in the lubrication film is shown in Figure 10(d). The EBSD pattern with the misorientation angles distributed at the scanning line D in Figure 10(d) is shown in Figure 10(e). The above figures revealed that multilayer graphene nanosheet, which was tightly wrapped by silver during wear, redistributed the film strain and orientated the angles. Hence, the film grain was well-distributed with the low orientation angles, producing excellent friction and wear behaviors in TAGS.

As the sliding time increased from 0 to 80 min, spherical graphene-silver was squeezed out of TAGS and enriched on the wear scars. Following sliding wear, the graphene and silver were redistributed to form a lubrication film under the effect of frictional force. Large amounts of silver caused plastic deformation on the wear scar, and that was cooperated with the graphene to achieve improved deformation and layer separation. Consequently, the lubrication film of a TAGS showed excellent properties during dry wear, which resulted in small friction coefficients and wear rates.

Conclusions

This paper investigated the enhancements of mechanical and tribological properties of multilayer graphene nanosheets in TA composites. The following conclusions were drawn:

1. For a TAG, graphene nanosheets that were parallel to the applied tension caused interlaminar separation in the multilayered nanosheets, while the graphene sheets perpendicular to the applied tension effectively hindered stresses and produced a high strength of approximately 802 MPa.
In the TAGS, the graphene nanosheets curled into small loops and resisted the tensile force, causing the tensile strength of TAGS to be higher than that of the TAG. Furthermore, the graphene slippage was resisted in the TAGS, and resulted in the enhanced hardness and modulus.

During wear, the intra-lamellar separation of the graphene improved the silver deformation and increased the bearing capacity of the wear scars; this reduced the friction coefficients and wear rates of TAG than the TA.

Multilayer graphene was wrapped by the silver to facilitate excellent cooperation during the lubrication of graphene and silver; consequently, the TAGS exhibited better friction and wear behaviors than the TAG.

In the TAGS, the low-hardness lubrication film appeared on the high-hardness grain-refinement layer, that facilitated excellent tribological performances. The film grain produced the uniform distribution and low orientation angle, which improved the tribological behaviors.

**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.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work is supported by China Postdoctoral Science Foundation (2019M662484), Henan Postdoctoral Foundation and Postdoctoral Foundation of Anyang Institute of Technology (BHJ2019006), Foundation of Henan Educational Committee (19A460011), Doctoral Start-Up Funding of Anyang Institute of Technology (BS2018005), The Project for Science and Technology Plan of Henan Province (192102210010), Tribology Science Fund of State Key Laboratory of Tribology (SKLTKF18B09), Provencial College Students Innovation and Entrepreneurship Training Program of Henan Province (S202011330001), Sichuan Provincial Key Lab of Process Equipment and Control (GK201901). Authors are also appreciative to Nanjing XFNANO Materials Tech Co., Ltd for their kind assistance.

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**References**

1. Won S, Jang JW, Choi HJ, et al. A graphene meta-interface for enhancing the stretchability of brittle oxide layers. *Nanoscale* 2016; 8: 4961–4969.

2. Idowu A, Boesl B and Agarwal A. 3D graphene foam-reinforced polymer composites – a review. *Carbon N Y* 2018; 135: 52–71.

3. Geim AK and Novoselov KS. The rise of graphene. *Nat Mater* 2007; 6: 183–191.

4. Wang L and Duan F. Nanoscale wear mechanisms of few-layer graphene sheets induced by interfacial adhesion. *Tribol Int* 2018; 123: 266–272.

5. Vasić B, Matković A, Ralević U, et al. Nanoscale wear of graphene and wear protection by graphene. *Carbon N Y* 2017; 120: 137–144.

6. Xu Z, Zhang Q, Huang X, et al. An approximate model for the migration of solid lubricant on metal matrix self-lubricating composites. *Tribol Int* 2016; 93: 104–114.

7. Li X, Yang K, Ma H, et al. The analysis of the self-lubricating behavior and local failure mechanism of silver-rich solid film. *Ind Lubrication Tribol* 2018; 70: 1560–1568.

8. Li X, Liang J, Shi T, et al. Tribological behaviors of vacuum hot-pressed ceramic composites with enhanced cyclic oxidation and corrosion resistance. *Ceram Int* 2020; 46: 12911–12920.

9. Xie Y, Li H, Zhang C, et al. Graphene-reinforced calcium silicate coatings for load-bearing implants. *Biomed Mater* 2014; 9: 025009.

10. Balog R, Jørgensen B, Nilsson L, et al. Bandgap opening in graphene induced by patterned hydrogen adsorption. *Nat Mater* 2010; 9: 315–319.

11. Kwon S, Ko JH, Jeon KJ, et al. Enhanced nanoscale friction on fluorinated graphene. *Nano Lett* 2012; 12: 6043–6048.

12. Xu ZS, Shi XS, Zhai WZ, et al. Preparation and tribological properties of TiAl matrix composites reinforced by multilayer graphene. *Carbon N Y* 2014; 67: 168–177.

13. Min Y, Penkov OV, Khadem M, et al. Effects of molybdenum-based substrate coatings on tribological performance of graphene films. *Carbon N Y* 2021; 176: 488–499.

14. Won MS, Penkov OV and Kim DE. Durability and degradation mechanism of graphene coatings deposited on Cu substrates under dry contact sliding. *Carbon N Y* 2013; 54: 472–481.

15. Mura A, Adamo F, Wang H, et al. Investigation about tribological behavior of ABS and PC-ABS polymers coated with graphene. *Tribol Int* 2019; 134: 335–340.

16. Zhai W, Srikanth N, Kong LB, et al. Carbon nanomaterials in tribology. *Carbon N Y* 2017; 119: 150–171.

17. ASTM Standards G99-95. Standard test method for wear testing with a pin-on-disk apparatus. West Conshohocken, PA: ASTM International, 1995.

18. Yue YL, Wu HT, Wu B, et al. Thermodynamic and dynamics analysis on the combustion synthesis of TiAl intermetallic. *J Univ Jinan* 2005; 19: 106–109. (in chinese).

19. Xu Y, Peng Y, Dearn KD, et al. Synergistic lubricating behaviors of graphene and MoS2 dispersed in esterified bio-oil for steel/steel contact. *Wear* 2015; 342-343: 297–309.

20. Yang K, Shi X, Zou J, et al. The study of the preparation and tribological behavior of TiAl matrix composites containing 1 wt% multi-walled carbon nanotubes. *RSC Adv* 2016; 6: 29334–29341.

21. Yang K, Ma Y, Ma H, et al. Investigation of tribological and mechanical performances of Ti-based self-lubricating composites containing SnAgCu and Al2O3. *Adv Eng Mater* 2021; 23: 1–11.
22. Yang K, Ma H, Ma M, et al. The experiment research and engineering verification on the synergistic lubrication properties of silver and multiwalled carbon nanotubes. Adv Mech Eng 2019; 11: 1–12.

23. Yang K, Ma H, Li X, et al.; Q. He. The analysis in In Situ preparation, mechanics, and tribology of TiAl-SnAgCu/Graphene composites. Adv Eng Mater 2018; 20: 1–8.

24. Zhang P, Lu W, Liu X, et al. Torsional fretting wear behavior of CuNiAl against 42CrMo4 under flat on flat contact. Wear 2017; 380-381: 6–14.

25. ASTM B962-08. Standard test methods for density of compacted or sintered powder metallurgy (PM) products using Archimedes’ principle. West Conshohocken, PA: ASTM International, 2008.

26. Zhai W, Lu W, Zhang P, et al. Microstructure, mechanical and tribological properties of nickel-aluminium bronze alloys developed via gas-atomization and spark plasma sintering. Mater Sci Eng A 2017; 707: 325–336.

27. Yang K, Shi X, Zhai W, et al. Tribological behavior of TiAl matrix self-lubricating composites reinforced by multilayer graphene. RSC Adv 2015; 5: 44618–44625.

28. Li X and Xu J. Coordinating influence of multilayer graphene and spherical SnAgCu for improving tribological properties of a 20CrMnTi material. RSC Adv 2018; 8: 14129–14137.