

The Influence of Biomimetic Textures in Synergy with Nanoparticles on the Anti-Friction and Wear Resistance Properties of Titanium Alloys

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Abstract - As a material with excellent properties, titanium alloy is widely used in aerospace, vehicle manufacturing, medical equipment and other industries due to its low density, high strength, and excellent corrosion resistance. However, the non-wear-resistant surface of the titanium alloy makes its application in the drilling environment very difficult.

In order to solve this problem, in this paper, C3N4 nanoparticles were prepared by calcination, C3N4@MoS2 nanoparticles were prepared by hydrothermal method, and titanium alloy (TC4) drill pipe samples with bionic banana leaf texture patterns were processed by laser engraving technology. The MWF-02 friction tester was selected as the main test instrument. Friction and wear tests were conducted under the lubrication of calcium-based bentonite water-based drilling fluid by forming a friction pair with TC4 titanium alloy samples and silicon nitride ceramic balls. The friction coefficient and wear rate were used as evaluation indicators of tribological properties. Through the analysis of the appearance and morphology of the wear scar, the influence of the synergy of bionic texture and nanoparticles on the tribological properties of titanium alloy at 50°C was explored. The conclusions are as follows: (1) After adding C3N4 and C3N4@MoS2 nanoparticles, the friction and wear performance of TC4 titanium alloy drill pipes was effectively improved, among which the improvement effect of C3N4@MoS2 composite particles was better, reducing the average friction coefficient of the original sample by 62.4% and the wear rate by 54.0%. (2) With the introduction of the banana leaf texture, the synergy of nanoparticles and texture further improved the tribological properties of titanium alloy. At 50°C, the average friction coefficient was reduced by 71.6% and the wear rate by 72.3% compared with the original sample.

Keywords: TC4 titanium alloy; C3N4 nanoparticles; biomimetic texture; tribological properties

1. Introduction

In fields such as petroleum exploration, oil extraction and geological drilling, drill pipes are one of the important tools, bearing extreme working conditions including high strength, high temperature and high pressure. Among traditional drill pipe materials, such as steel, there are problems like heavy weight and easy corrosion. In severe cases, the fracture of the drill pipe can lead to accidents [1]. Therefore, better materials need to be proposed as substitutes. Titanium alloy, as a material with excellent properties, meets the strength requirements of drill pipes due to its high strength, low density and excellent corrosion resistance [2]. However, its wear resistance is poor. To improve the wear resistance of titanium alloy drill pipes, appropriate processing techniques need to be selected for treatment.

Hamilton et al. [3] were the first to fabricate micro-scale raised structures on the surface of sealing components using etching technology. Through theoretical and experimental studies, they confirmed that these micro-scale raised structures could achieve fluid dynamic pressure lubrication effects, effectively reducing the friction coefficient. In the past few decades, surface textures have made significant progress in improving the wear resistance of cutting tools [4] and enhancing the anti-wear performance of friction pairs in gear pumps [5]. With the continuous development of bionics and its gradual expansion into the field of friction and wear [6], the microstructures of animal and plant surfaces often possess some unique capabilities [7]. Qin et al. [8] discovered that the wave-like texture structure of bionic shells enhanced the extrusion effect of solid lubricants on both sides of the grooves, promoted the precipitation of lubricants, reduced friction and wear, and decreased surface roughness.

Nanoparticles have a large specific surface area [9] and high activity, and their frictional properties can be enhanced through ball bearing effect, polishing, sintering, self-repairing, tri-body abrasive wear and particle film formation [10]. Yang et al. [11] developed an Al₂O₃/ZnO mixed nanofluid that achieved superior lubrication performance with a lower friction coefficient and better surface quality than pure titanium alloy nanofluids by improving the dispersion stability of ZnO

nanoparticles. Wang et al. [12] conducted experiments and found that the anti-friction performance of BP/TiO₂ was superior to that of a single lubricant additive. This was due to the interaction between BP nanosheets and the worn surface, as well as the repair, polishing and rolling effects of TiO₂ nanoparticles. The synergistic effect of the two particles dominated the anti-friction performance.

In this study, the banyan leaf texture optimized through biomimicry was adopted. The nanoparticles used were C₃N₄@MoS₂. The two were combined to systematically investigate their influence on the friction performance of titanium alloys.

2. Experimental procedure

2.1 Preparation of C₃N₄ nanoparticles

First, dissolve 10g of urea in 30mL of deionized water. Then, dry it in a crucible at 60°C for 8 hours. After that, the white crystalline solid is obtained and transferred to a muffle furnace. It is heated at a heating rate of 15°C/min in a furnace at 550°C for 3 hours. The light yellow solid obtained after the calcination process is C₃N₄.

2.2 Preparation of C₃N₄@MoS₂ Mixed Particles

120 mg ammonium molybdate and 210 mg thiourea were added to 30 mL distilled water and stirred at room temperature for 15 minutes. Then, 30 mg of C₃N₄ was added to the solution, and the suspension was mechanically stirred and transferred to a 50 mL stainless steel high-pressure reactor lined with polytetrafluoroethylene. The reactor was sealed and maintained at 200°C for 24 hours. Subsequently, the high-pressure reactor was naturally cooled to room temperature, and the product was collected by vacuum filtration. The residue was then washed several times with ethanol to remove the impurities. Finally, the product C₃N₄@MoS₂ was dried at 70 °C under vacuum for 24 hours.

2.3 Processing of biomimetic texture patterns

In this study, laser processing technology was employed for the fabrication of texture patterns. Before laser processing, the samples were sequentially polished with 150#, 400#, 800#, and 1200# sandpapers. Then, the samples were placed in anhydrous ethanol for 20 minutes of ultrasonic cleaning. After multiple trials using a laser marking machine as shown in Figure 1, the final setting parameters for the laser marking machine were: marking times 1 (time), processing speed 100 (millimeters/second), processing frequency 30 (KHz), pulse width 1 (microsecond), current 1 (A), opening delay 300 (microseconds), closing delay 150 (microseconds), end delay 300 (microseconds), corner delay 100 (microseconds). To reduce the influence of texture surface density on the tribological properties of micro-textures, the selection of two micro-texture sizes took into account the consistency of texture surface density and the marking and transmission of dimensions during processing. The lateral dimension of the banana leaf texture marked by the laser marking machine was 300 μm. The other texture parameters were fixed values, with a lateral spacing of 0 μm and a longitudinal spacing of 100 μm. As shown in figure 2.

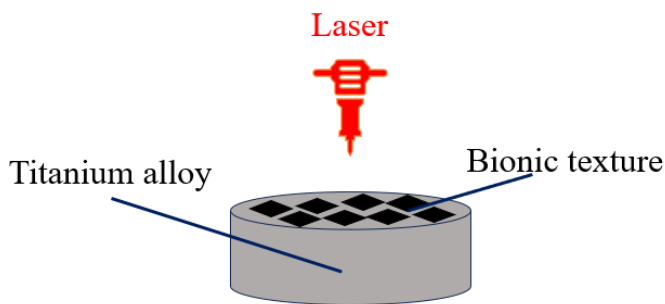


Figure.1 laser marking schematic diagram

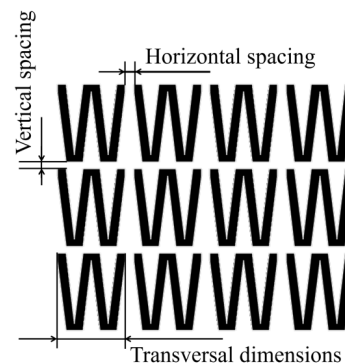


Figure.2 the slightly textured pattern of banana leaf

2.4 Tribological tests

The friction testing machine uses a ball-disc reciprocating friction wear testing machine (MWF-02). The friction pair consists of silicon nitride ceramic balls and TC4 specimens as shown in Figure 3. The frequency of the testing machine is set at 2Hz, the load is set at 30N, and the time is set at 0.5h. The test is conducted under a temperature of 50°C. The specific scheme is as shown in table 1.

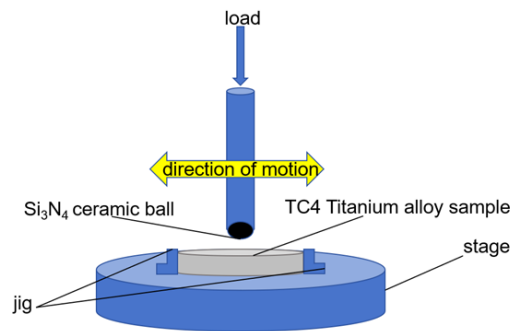


Figure.3 schematic diagram of friction pair

Table.1 test plan

Groups	Lubrication Conditions
control group	clay water-based liquid
experimental Group 1	mass fraction 2.5% C3N4 with clay water-based liquid
experimental Group 2	mass fraction 2.5% C3N4@MoS2 with clay water-based liquid
experimental Group 3	mass fraction 2.5% C3N4@MoS2 added banana leaf with clay water-based liquid

Specific method for preparing water-based liquid: Add the nanoparticles to the calcium-based bentonite and mix them together. Control the mass of the mixture to be 5g, and add 100ml of ultra-pure water to it to obtain the mixed solution. Place the mixed solution in a mechanical ultrasonic cleaning machine and ultrasonically disperse it for 30 minutes to ensure that the particles are evenly dispersed in the solution and to prevent particle aggregation and deposition.

3.Results and discussion

3.1 Friction coefficient and wear rate analysis

The original data in Figures 4 and 5 are from the reciprocating friction and wear testing machine (MWF-02). They were drawn by the means of the Origin drawing software. As can be seen from Figures 4 and 5, the introduction of C3N4 nanoparticles can effectively reduce the friction coefficient of the friction pair. In Figure 4, it can be observed that the three curves with the addition of nanoparticles are all below the original sample. Among them, the curves with C3N4@MoS2 particles added and those in synergy with the banana leaf texture are located at the bottom and gradually approach 0.34 after a stable trend. As shown in Figure 5, the corresponding average friction coefficients of the original sample, the sample with C3N4 added, the sample with C3N4@MoS2 particles added, the sample with C3N4@MoS2 particles added in synergy with the banana leaf texture are: 1.09, 0.75, 0.41, 0.36 respectively. The friction coefficients with nanoparticles added are all lower than that of the original sample, indicating that the addition of nanoparticles has improved the wear resistance of the titanium alloy sample. The improvement effect increases successively. Among them, the improvement effect of adding C3N4@MoS2 mixed particles and in synergy with the banana leaf texture is the best.

As shown in Figure 6, the original wear rate without adding nanoparticles was $54 \times 10^{-6} \text{ mm}^3/(\text{N} \cdot \text{m})$, and the wear rate after adding C3N4 nanoparticles was even lower; among them, the wear rate of the particles C3N4@MoS2 was $25 \times 10^{-6} \text{ mm}^3/(\text{N} \cdot \text{m})$, which was less than $44 \times 10^{-6} \text{ mm}^3/(\text{N} \cdot \text{m})$ of the particles C3N4, and after the synergistic effect with the banana leaf texture, the wear rate was even lower at $14 \times 10^{-6} \text{ mm}^3/(\text{N} \cdot \text{m})$. This indicates that there is a good synergistic effect between

the nanoparticles C3N4@MoS2 and the micro-texture, and their combined action can further reduce the wear of the titanium alloy.

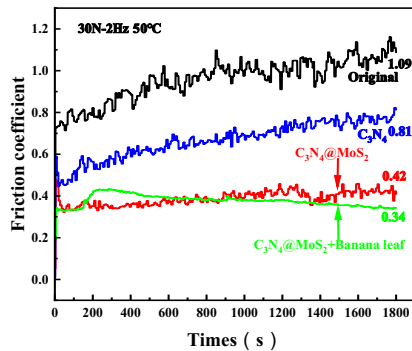


Figure.4 comparison of instantaneous friction coefficients in four groups of tests

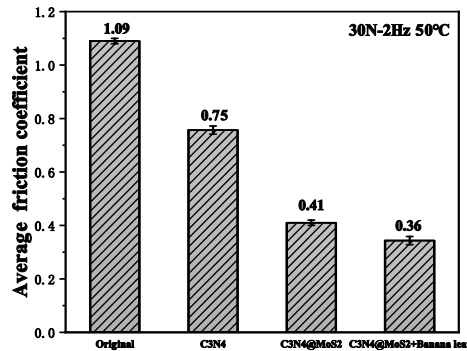


Figure.5 comparison of average friction coefficients in four groups of tests

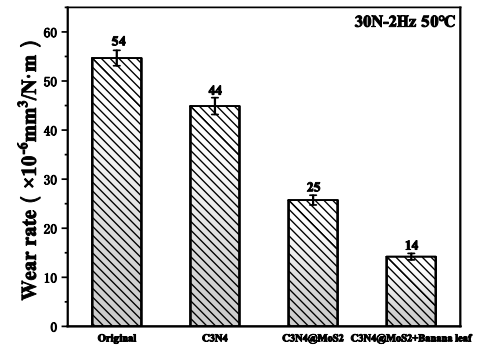


Figure.6 comparison of wear rate in four groups of tests

3.2 Analysis of wear mechanism

Figure 7 shows the comparison chart of wear profiles for the four groups of tests which is shot by the spectral confocal two-dimensional profile measurement instrument (VS-TA2). In the Figure 7, it can be seen that the wear depth and width of the group with added nanoparticles are both smaller than those without added nanoparticles. Among them, the wear profile with C3N4@MoS2 particles added and in synergy with the banana leaf texture is the shallowest and narrowest. The one with C3N4@MoS2 added comes second, and the one with a single nanoparticle C3N4 is the worst. Similarly, in the Figure 8, the depth of the wear marks can be more intuitively observed, which also provides support for the analysis in Figures 4 and 6, where the test groups with C3N4@MoS2 mixed particles in synergy with the texture have the best improvement effect on the wear reduction and wear resistance of the titanium alloy.

Figure 9 shows the morphological images of the wear marks captured under light microscopy (SM-5000) and electron microscopy (KYKY-EM6X00) for four sets of experiments. In the Figure 9 (a), the original wear surface morphology and a local magnified view are presented. It is observed that numerous grooves appear along the sliding direction, accompanied by a small amount of debris and adhesion, resulting in severe wear of the sample. The wear mechanism mainly manifests as abrasive wear and adhesive wear. In the Figure 9 (b), it can be observed that the wear scar surface presents a distinct undulating morphology and ploughing cutting characteristics. At this time, the amount of abrasive debris decreases and the wear slows down, indicating that the addition of C3N4 nanoparticles forms a small amount of lubricating film, which plays a lubricating role. In the Figure 9 (c), it can be observed that the wear scar surface shows a significant large-scale peeling phenomenon. After peeling, a relatively smooth area appears, reducing the roughness of the sample surface and forming a large amount of lubricating film, further reducing the wear. In the Figure 9 (d), it can be observed that the texture has not been completely worn away, indicating that the texture has fully exerted its effect. There are not obvious grooves and furrows on the surface, and the overall appearance is relatively smooth. It is hypothesized that the synergistic effect of the formed lubricating film and the grooved texture on the surface leads to a further improvement in the tribological properties of the titanium alloy surface [13].

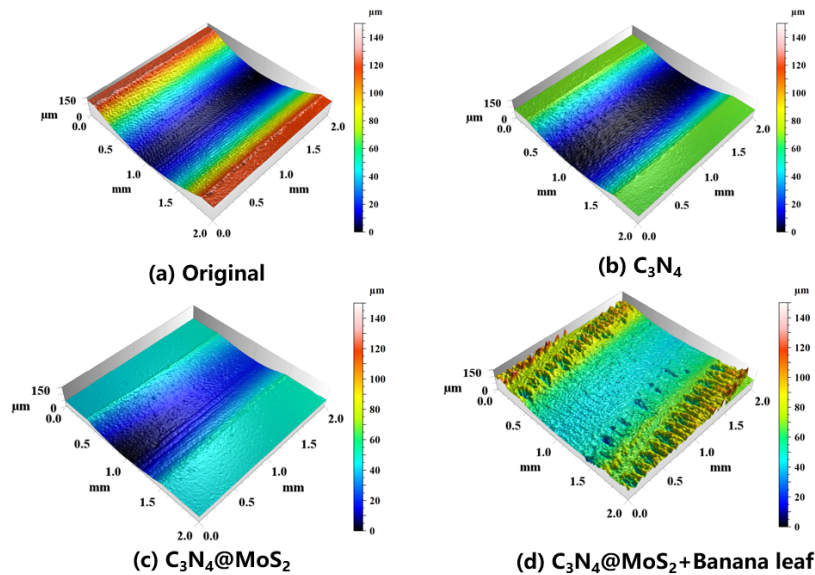


Figure.7 comparison of 3D wear profile in four groups of tests: (a)Original (b)C3N4 (c)C3N4@MoS2 (d)C3N4@MoS2+Banana leaf

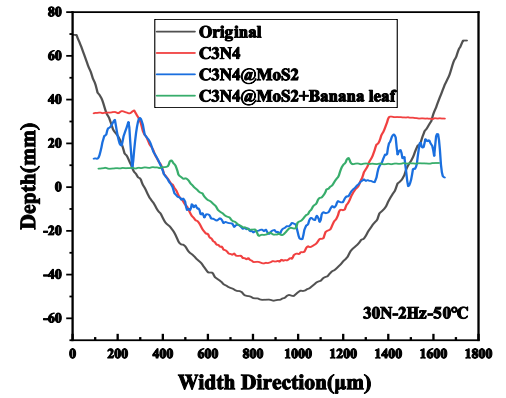


Figure.8 comparison of 2D wear profiles

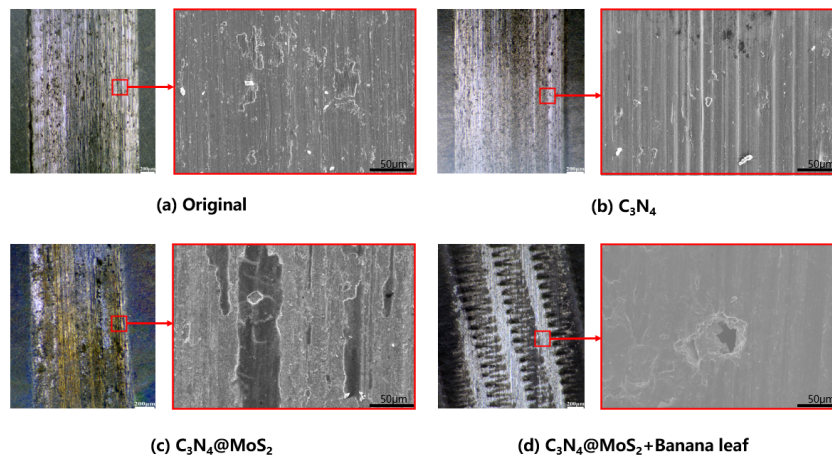


Figure.9 wear tracks in four groups of tests: (a)Original (b)C3N4 (c)C3N4@MoS2 (d)C3N4@MoS2+Banana leaf Left: optical microscope image of the morphology Right: SEM image of the morphology

Conclusion

This paper explores the influence of biomimetic textured nano-particles on the tribological properties of titanium alloy at 50°C, explains the effects of different nano-particles and their synergy with the texture on the wear reduction and wear resistance of TC4 titanium alloy, and reveals the mechanism of the influence of the synergy of nano-particles and texture on the tribological behavior of TC4 titanium alloy. Based on the research in this paper, the following conclusions are drawn:

- (1) The wear mechanism of the original sample (without adding nanoparticles) was abrasive wear and adhesive wear. After adding C3N4 nanoparticles, a small amount of lubricating film was formed, which prevented direct contact between the friction pair and effectively improved the friction and wear performance of the TC4 titanium drill rod.

After adding the C3N4@MoS2 composite particles, a large amount of lubricating film was formed. The layered structure of MoS2 enhanced its pressure-bearing capacity [14], resulting in a 62.4% decrease in the average friction coefficient and a 54.0% decrease in the wear rate of the original sample, further improving the friction and wear performance of the TC4 titanium drill rod.

- (2) With the introduction of the banana leaf texture, a large number of lubricating films were formed by C3N4@MoS2 nanoparticles. The concave texture could store the abrasive debris, accelerating the film formation process. The synergistic effect further improved the frictional properties of the titanium alloy. At 50°C, the average friction coefficient of the modified sample was reduced by 71.6% compared to the original sample, and the wear rate decreased by 72.3%. This significantly enhanced the friction reduction and wear resistance of the TC4 titanium alloy drill pipe.

The research is based on the Natural Science Foundation Project of Sichuan Province ‘Research on the Tribological Properties of Titanium Alloys Modified by Texture-Synergistic Nanoparticles (2023NSFSC0871)’, Sichuan Province College Students' Innovation and Entrepreneurship Training Program Project ‘Research and Development of Texture-Synergistic Nanoparticle Modified Wear-resistant Titanium Alloy Surface(S202410623045)’.

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