Effects of triple heat treatment on microstructure and the dry sliding wear of TC21 titanium alloy

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Abstract. Triple heat treatment was applied to TC21 titanium (Ti) alloy, and microstructural changes therein were analysed by using an optical microscope (OM). The dry sliding wear properties of TC21 Ti alloy were assessed by conducting “pin-on-disk” friction wear tests under a load of 200 N, at a sliding speed of 0.230 m s⁻¹, for a sliding time of 600 s, at room temperature (25 °C). Using scanning electron microscopy (SEM), morphologies of the worn surface and wear mechanism were analysed. Results show that, by performing solid solution treatment to the β phase region of the TC21Ti alloy, a single-phase β microstructure was obtained. Under this condition, the wear rate is the highest, appearing as abrasive wear and adhesive wear. Through one-time high-temperature aging and low-temperature aging in the α+β phase region, the basket-weave microstructure of TC21 Ti alloy was obtained, with a low wear rate, appearing as abrasive wear and slight oxidation wear in terms of prevailing wear mechanisms.

1. Introduction

Titanium (Ti) alloy is widely used in various industrial applications in aviation and navigation, biomedicine and automobile engineering due to a series of advantages including its low density, high specific strength, good corrosion resistance, and high heat resistance [1-2]. However, the application of Ti alloy in cases subjected to frictional wear is restricted due to its poor wear resistance. At present, scholars have explored the dry sliding frictional wear mechanism of various Ti alloys, e.g., Ti6Al4V and TC4. Results showed that the wear rate of alloys increases with increasing load and sliding speed at normal temperature; in a low-speed state, alloys (including Ti6Al4V and TC4) were mainly subjected to oxidation wear; by contrast, in a high-speed state, the alloys mainly underwent delamination [3-6]. However, with the improvement of technology, the service conditions of Ti alloy have become increasingly complex and onerous: exploring the dry sliding frictional wear properties of Ti alloy may help to improve the wear resistance of Ti alloy and increase its application domain.

As a novel α+β two-phase Ti alloy with damage tolerance, TC21 Ti alloy shows a few advantages including high strength, favourable fracture toughness, and a low rate of crack propagation, so it has been applied in aeronautics and astronautics as an important structural material [7]. However, research into the effect of multiple heat treatments on dry sliding wear properties of TC21 Ti alloy has not yet been reported so triple heat treatment was conducted on TC21 Ti alloy to explore the microstructures of TC21 Ti alloy; furthermore, based on a pin-on-disk contact mode, the dry sliding wear properties of the Ti alloy were investigated.
2. Experimental work

The materials of the test panel were provided by AECC Beijing Institute of Aeronautical Materials, and its key chemical constituents are listed in Table 1. The primary microstructures were typical equiaxial features (Figure 1). To explore the effects of multiple heat treatments on microstructures and dry sliding wear properties of TC21 Ti alloy, three modes of heat treatment are formulated. The specific technological parameters of heat treatment are listed in Table 2, in which AC represents air cooling. After performing heat treatment, metallographic specimens and a friction disk were cut using an electrical discharge machine. The dimensions and shapes of the friction disk and friction pin are shown in Figure 2, in which the friction pin was made of hard alloy steel (YG8). Metallographic observation was conducted by applying a trinocular inverted metallurgical analysis apparatus 11BD-PMS and the hardness was measured by using a TH300 Rockwell hardness tester.

Table 1. Chemical composition of TC21 titanium alloy (ω%)

|   | Al | Mo | Zr | Sn | Nb | Cr | Si | O  | H  | C  | N  | Ti |
|---|----|----|----|----|----|----|----|----|----|----|----|----|
|   | 6.0| 2.85| 2.38| 2.29| 2.24| 1.43| 0.1| 0.07| 0.00| 0.00| 0.1| Other |

Figure 1. The Original structure of TC21 titanium alloy.

Table 2. Heat treatment process parameters of TC21 titanium alloy

| The specimen number | Heat treatment system |
|--------------------|-----------------------|
| a                  | 980℃/0.5h AC         |
| b                  | 980℃/0.5h AC+880℃/4h AC |
| c                  | 980℃/0.5h AC+880℃/4h AC+580℃/4h AC |

Figure 2. The friction disk and friction pin
The friction–wear test was carried out on a MMUD-10B high-temperature friction–wear tester for end faces controlled by a microcomputer. The test was conducted under an external environment with an air atmosphere, with the following test parameters: a load of 200 N, a sliding time of 600 s, a sliding speed of 0.230 m s\(^{-1}\), and an ambient temperature of 25 °C (room temperature). Before the test, surfaces of the friction disk and pin were polished by using metallographical sand paper, with surface roughness \(R_a \leq 0.1 \mu m\). Before and after the friction–wear test, the specimens were cleaned by using acetone; moreover, the masses of the specimens before and after wear were separately measured on an FA1004N electronic scale and the wear rate was calculated according to Equation (1) \(^{[8]}\):

\[
r = \frac{\Delta m}{L \cdot F}
\]

where, \(\Delta m\), \(L\), and \(F\) refer to the wear loss (g) of mass, sliding distance (m), and load (N), respectively.

The worn surface was observed and analysed by applying an FEI INSPECT F50 SEM.

3. Results and analysis

3.1 Effects of triple heat treatment on microstructures and hardness

TC21 Ti alloy was subjected to solid solution treatment at 980 °C, held for 0.5 h, and then air cooled. It can be found that the primary equiaxial \(\alpha\) phase nearly disappeared and single-phase equiaxial \(\beta\) grains appeared, in which there was a small number of fine \(\alpha\) phases, as shown in Figure 3(a). The second aging heat treatment was carried out at 880 °C, followed by air cooling after being kept for 4 h. In this case, many fine lamellar microstructures of \(\alpha\) phases were precipitated from \(\beta\) grains, as shown in Figure 3(b), thus forming typical basket-weave microstructures. Afterwards, the third aging heat treatment was conducted at 580 °C, followed by heat preservation for 4 h and air cooling. Under these conditions, the lamellar microstructures of \(\alpha\) phases precipitated from \(\beta\) grains grew slightly and still appeared as basket-weave features (Figure 3(c)). It can be seen from Figure 4 that, with increasing cycles of heat treatment, the Rockwell hardness of each specimen increased. The reason for this was that, after conducting solid solution treatment in the \(\beta\) phase region, \(\alpha\) phases were nearly completely transformed into \(\beta\) phases. During high-temperature aging treatment, many fine lamellar microstructures of these \(\alpha\) phases were precipitated from \(\beta\) grains, having a certain strengthening effect. As a result, the hardness was increased. After being subjected to three low-temperature aging treatments, the microstructures of TC21 Ti alloy were changed slightly so that the hardness increased, albeit slightly.

![Figure 3. Microstructure of TC21 titanium alloy after triple heat treatment](image-url)
3.2 Effects of triple heat treatments on friction coefficient and wear rate

Dry friction tests were conducted under a load of 200 N and sliding for 600 s at a sliding speed of 0.230 m s⁻¹. Under three heat treatments, the friction coefficients and wear rates of disk-shaped specimens of TC21 Ti alloy are separately shown in Figures 5 and 6. As shown in Figure 5, during dry friction in air, the changes in friction coefficients of the specimens under single, double, and triple heat treatments with time were similar, and all underwent significant fluctuations. Under the same friction conditions, the friction coefficient of the specimens gradually increased with increasing cycles of treatment. It can be seen from Figure 6 that under the same friction conditions, the wear rate of a specimen subjected to high-temperature solid solution treatment at 980 °C was about $3.9 \times 10^{-5}$ g N⁻¹·m⁻¹; the wear rate of specimen b undergoing secondary aging treatment at 880 °C was reduced to $2.76 \times 10^{-5}$ g N⁻¹·m⁻¹; the wear rate of specimen c subjected to tertiary aging treatment at 580 °C was further decreased to about $2.7 \times 10^{-5}$ g N⁻¹·m⁻¹. It can be seen that double heat treatment exhibited the most significant effect on the friction properties. The reason was that after double aging treatment, many fine lamellar microstructures of $\alpha$ phases were precipitated from $\beta$ grains, thus showing a certain strengthening effect. Moreover, this was also related to the changed wear mechanism.
3.3 Effects of triple heat treatments on wear surface morphologies

Figure 7 shows morphologies of the worn surface of the disk-shaped specimens of TC21 Ti alloy under a load of 200 N, after a sliding time of 600 s at a sliding speed of 0.230 m s\(^{-1}\). According to the technological parameters for heat treatment listed in Table 2, the ploughed and viscous masses were uniformly distributed on the worn surface of the specimens subjected to single heat treatment along the sliding direction (Figure 7(a)). This indicated that TC21 Ti alloy was mainly subjected to abrasive wear and adhesive wear. As for specimens b and c undergoing double and triple heat treatments, fine, shallow furrows were uniformly distributed on their worn surfaces along the sliding direction, with narrow scratches. The number of furrows slightly reduced compared with the specimens subjected to single heat treatment (Figure 7(b)). This revealed that wear mainly appeared as abrasive wear induced by a micro-ploughing effect of micro-bulges on frictional pairs, also showing slight oxide formation therewith \[6\]. The effect of such an oxidation wear mechanism increased to lead to the reduction in overall wear. This implied that the change in wear mechanism was one of reasons causing the change of wear rate, which also explained the conclusion reached from inspection of the data in Figure 6.

![Surface morphology of TC21 titanium alloy after triple heat treatment](image)

Figure 7. Surface morphology of TC21 titanium alloy after triple heat treatment

4. Conclusion

As for specimen a of the TC21 Ti alloy subjected to solid solution treatment at 980 °C for 0.5 h and air cooling treatment in the \(\beta\) region, the primary equiaxial \(\alpha\) phases almost completely disappeared to retain single-phase equiaxial \(\beta\) grains. For specimen b subjected to another high-temperature aging treatment at 880 °C for 4 h and then air cooling besides the first treatment, and specimen c undergoing another low-temperature aging treatment at 580 °C for 4 h and then air cooling treatment in addition to the above two treatments, basket-weave microstructures appeared. The hardness increased slightly with increasing number of treatment cycles.

Under a load of 200 N, dry friction tests were conducted at a sliding speed of 0.230 m s\(^{-1}\) for 600 s. Upon application of three heat treatments, the friction coefficients of the disk-shaped specimens of TC21 Ti alloy all increased, while the wear rate decreased with increasing number of treatment cycles.

In terms of wear mechanism, specimen a was mainly subjected to abrasive wear and adhesive wear; specimens b and c mainly underwent abrasive wear and oxidation wear.

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References

[1] Kangmin Chen, Qiuyang Zhang, Xinxing Li, et al. Dry Sliding Wear Behavior of TC11 Alloy/GCr15 Steel Tribo-pair, J. Rare Metal Materials and Engineering, 44(2015)6:1531-1535.

[2] Chao Zhen, Shicheng Wei, Yi Liang, et al. Dry Friction Wearing Characteristics of Titanium Materials, J. Equipment Environmental Engineering, 15(2018)4:44-50.

[3] Haifeng Lu, Qiang Miao, Wenping Liang, et al. Effect of Different Temperatures on Tribological Properties of TC4-DT Alloy, J. Journal of Nanjing University of Aeronautics & Astronautics, 48(2016)1:29-33.

[4] Baoguo Yuan, Chengguo Wang, Shengquan Wei, et al. Wear Property of Ti6Al4V Alloy with Different Hydrogen Contents, J. Rare Metal Materials and Engineering, 43(2014)2:399-402.

[5] Lan Wang, Shuqi Wang, Kangmin Chen, et al. A Comparison on the Wear Performance of TC4 and TC11 Alloys, J. Tribology, 35 (2015)2:214-220.

[6] Qiuyang Zhang, Hongyan Ding, Guanghong Zhou, et al. Role of Fe2O3 in Dry Sliding Wear of A Titanium alloy and Formation of Tribo-Layers, J. Rare Metal Materials and Engineering, 48(2019)1:159-163.

[7] Weiping Fang, Lun Chen, Yaowu Shi, et al. Research Development and Application of Damage Tolerance Titanium Alloy, J. Journal of Materials Engineering, 38(2010) 9: 95-98.

[8] Junxi Zhang, Baiming Chen, Xiangbin Yi, et al. Tribological Properties of Vanadis 4 Extra Steel at Dry Sliding Condition, J. Transactions of Materials and Heat Treatment, 38(2017)4:185-192.