Study on tribological properties of new TiAl based self-lubricating alloys

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Abstract. The alloys are based on Ti-45Al-5Nb, Added different contents of TiC, Y₂O₃ and 62% BaF₂-38%CaF₂ to prepared new TiAl-based self-lubricating Alloys with excellent mechanical properties, excellent tribological properties and light weight. Investigated flexural strengths, fracture toughness, hardness, and densities of different compositions TiAl based self-lubricating alloys, as well as the friction and wear characteristics at 600°C. The results show that the mechanical properties, tribological properties and physics of the new TiAl-based alloys are better with 5% TiC, 0.25% Y₂O₃, and 13% (62% BaF₂-38%CaF₂). The wear mechanism of the alloys is adhesive wear.

1. Introduction

TiAl-based alloys with high relative strength, low density, good mechanical properties and flame retardancy under high temperature condition. They are considered as the most promising new generation of high-temperature resistant materials with wide applications in aerospace, automotive and so on[1-3]. However, the insufficient tribological properties at high temperatures severely restrict the applications of TiAl-based alloys. So, it is great significance to study and improve the friction and wear properties of TiAl alloys under high temperature[4-5].

Added proper amount of solid lubricants in Ti-Al alloys can effectively improve the tribological properties. It was found that the eutectic solid lubricants 62%BaF₂-38%CaF₂ (hereinafter referred to as BC) has good anti-friction above 600°C. Added solid lubricants, the physical and mechanical properties of alloys have been reduced to varying degrees, which have great impact on its carrying capacity. But added some hard particles in TiAl alloys can effectively improve the mechanical properties. TiC, Al₂O₃, SiC, etc. are often added in alloys. Among these hard materials, TiC particles have good compatibility and great strengthening with the TiAl alloys[6]. Refinement grains can also effectively improve the mechanical and tribological properties for alloys. The rare earth elements with special structure which make they have special mechanical properties. Added a trace amount of rare earth elements can effectively refine grains size and improve the microstructures of the TiAl alloys[7]. The study found that the mechanical properties of Y₂O₃ are the most stable[8], the TiAl alloys added micron-sized Y₂O₃ are better than those which with the same amount of Y.

Therefore, in this study, Ti-45Al-5Nb as the matrix, added different amounts of Y₂O₃/TiC/BC to prepare new TiAl-based alloys with excellent mechanical properties, good wear resistances and self-lubricating properties. Study the mechanical and tribological properties of these alloys.
2. Alloys preparation

The raw materials used in experiments were Ti powders, Al powders, Nb powders, TiC powders, Y$_2$O$_3$ powders, BaF$_2$ powders, and CaF$_2$ powders. Among them, the purities of Ti, Al, Nb, BaF$_2$, CaF$_2$ are higher than 99.5%, the average particle sizes are less than 325 mesh; the purities of TiC and Y$_2$O$_3$ are 99.99%, and the average particle sizes are less than 50nm.

To Ti45Al5Nb matrix added different levels of TiC/Y$_2$O$_3$/BC, the percentages of different materials as shown in table 1. Here, using orthogonal experiment to match material compositions. The weighed powders were placed in a ball mill barrel, 200 r/min and ball milled for 4 h in argo. Then put those powders into the graphite mold, cold pressure molding under 30MPa for 1 min. Finally, the new TiAl-based self-lubricating alloys were prepared by vacuum hot-press sintering. The sintering process parameters are shown in table 2.

### Table 1. Compositions of TiC/Y$_2$O$_3$/BC.

| Level | Y$_2$O$_3$ (wt%) | TiC (wt%) | BC (wt%) |
|-------|-----------------|-----------|----------|
| A     | 0               | 0         | 7        |
| B     | 0.25            | 2.5       | 10       |
| C     | 0.5             | 5         | 13       |
| D     | 0.75            | 7.5       | 15       |

### Table 2. Sintering process parameters.

| Temperature/℃ | Pressure/Mpa | Time/min |
|---------------|--------------|----------|
| 1200          | 30           | 30       |

3. Experimental results and discussion

3.1. Physical and mechanical properties of the samples

The bending strength, fracture toughness, actual density, and hardness test results of each component alloys are shown in table 3.

In the above tests, there are several test results for each sample. In order to analysis these results, quantify different indicators by comprehensive scores. Weighted by importance of different test results, the weights about bending strength: fracture toughness: hardness: the density are 3:3:2:2. Respectively, the comprehensive score is:

\[
\text{Comprehensive score} = 3 \times \text{flexural strength} + 3 \times \text{fracture toughness} + 2 \times \text{hardness} + 2 \times \text{density}
\]

According to the table 3, the largest range is factor B, factor C is second and factor A is last. So it can be seen that the degree of influence about the physical and mechanical properties were TiC, BC, Y$_2$O$_3$ in descending order. When B3C3A2 that 5% TiC, 13% BC, 0.25%Y$_2$O$_3$, the alloy is better. However, this alloy was not included in the above-mentioned 16 components. It is necessary to prepare this, which is numbered as 17, and compared with the above-mentioned 16 groups of samples.

According to the test results, the flexural strength, fracture toughness, hardness and density of No. 17 TiAl-based self-lubricating alloy is 522MPa, 13MPa/m$^{1/2}$, 530HV, and 4.1g/cm$^3$. The Comprehensive score is 2682.89. As shown in figure1, No. 17 has the highest score, so No. 17 has the better comprehensive mechanical properties.
Table 3. Test results of samples.

| Factors | 1 A | 2 B | 3 C | Various indicators experimental results | comprehensive score |
|---------|-----|-----|-----|------------------------------------------|---------------------|
| Level   |     |     |     | Flexural strength (MPa) | Fracture toughness (MPa m$^{1/2}$) | Density (g/cm$^3$) | Hardness (HV) |     |
| 1       | 1   | 1   | 1   | 427 | 10.3 | 3.978 | 436.07 | 2191.99 |
| 2       | 1   | 2   | 2   | 475 | 11.6 | 3.921 | 498.13 | 2463.90 |
| 3       | 1   | 3   | 3   | 493 | 12.1 | 3.910 | 509   | 2541.12 |
| 4       | 2   | 4   | 4   | 461 | 11.2 | 3.833 | 458.3  | 2340.87 |
| 5       | 2   | 1   | 2   | 452.5 | 11.7 | 3.931 | 465.9  | 2332.26 |
| 6       | 2   | 2   | 1   | 464 | 11.4 | 4.025 | 492.25 | 2418.75 |
| 7       | 2   | 3   | 4   | 506 | 13.5 | 3.968 | 471.55 | 2509.54 |
| 8       | 2   | 4   | 3   | 523 | 14.2 | 3.926 | 482.23 | 2583.90 |
| 9       | 3   | 1   | 3   | 470 | 12.2 | 3.903 | 428.18 | 2310.76 |
| 10      | 3   | 2   | 4   | 454 | 14.6 | 3.959 | 457.33 | 2328.37 |
| 11      | 3   | 3   | 1   | 514 | 11.2 | 3.993 | 528.4  | 2640.39 |
| 12      | 3   | 4   | 2   | 444 | 10.6 | 3.967 | 547.55 | 2466.83 |
| 13      | 4   | 1   | 4   | 387 | 10.8 | 3.897 | 467.9  | 2136.99 |
| 14      | 4   | 2   | 3   | 490 | 12.2 | 3.964 | 430.9  | 2376.33 |
| 15      | 4   | 3   | 2   | 457 | 10.4 | 3.917 | 484.83 | 2379.69 |
| 16      | 4   | 4   | 1   | 458 | 12.5 | 3.927 | 542.06 | 2503.47 |
| K1      | 9537.88 | 8972.01 | 9754.61 |
| K2      | 9844.45 | 9587.35 | 9642.69 |
| K3      | 9746.34 | 10070.74 | 9812.11 |
| K4      | 9396.49 | 9895.08 | 9315.76 |
| k1      | 2384.47 | 2243.00 | 2438.65 |
| k2      | 2461.11 | 2396.83 | 2410.67 |
| k3      | 2436.57 | 2517.68 | 2453.03 |
| k4      | 2349.12 | 2473.77 | 2328.94 |
| Range   | 111.99 | 274.68 | 124.0  |
| Excellent solution | A2 | B3 | C3 |

Figure 1. 17 samples comprehensive scores.

3.2. Samples fracture analysis
Figure 2(a) is a micrograph of the fracture surface of No.7, figure 2(b) is a microscopic topography of
the fracture surface of No.8 and figure 2(c) is a microscopic topography of the fracture surface of No.17. From figures 2(a)(b)(c), the fractures of the three alloys are very flat and these are typically brittle fractures. Figure 2(c) shows some strip morphologies at the fracture, which is typical transgranular cleavage fracture. This fracture means the alloys have good mechanical properties, especially the fracture toughness.

**Figure 2.** No.7, No.8, No.17 samples microcosmic fracture morphology.

3.3. The friction coefficient and wear rate of the samples

Under the conditions of 600°C, spindle speed 100r/min and load 100N, 17 groups of new TiAl-based self-lubricating alloys tested the changes about friction coefficient and wear rate. The test time is 60min.

Figure 3 shows the changes of friction coefficients and wear rates of 17 samples. It can be seen that the friction coefficients are between 0.28~0.44, the wear rates are between 0.27×10⁻⁴mm⁻¹N⁻¹m⁻¹~0.38×10⁻⁴mm⁻¹N⁻¹m⁻¹. It is difficult to see the rule in figure 3, so further data processing is required.

**Figure 3.** The change of friction coefficient and wear rate of 17 samples.

The 17 samples were divided into 4 groups based on the content of the self-lubricants, as shown in figures 4(a)(b)(c)(d). Figure 4(a) is the curves of the friction coefficients and the wear rates about samples at 7% BC, figure 4(b) is the curves of the friction coefficients and the wear rates about samples at 10% BC, figure 4(c) is the curves of the friction coefficients and the wear rates about samples at 13% BC, figure 4(d) is the curves of the friction coefficients and the wear rates about samples at 15% BC.

The samples numbers in figure 4(a) are 1,6,11 and 16, the friction coefficients are between 0.36~0.44, and the wear rates are between 0.32×10⁻⁴mm⁻¹N⁻¹m⁻¹~0.36×10⁻⁴mm⁻¹N⁻¹m⁻¹, but No. 16 the wear rate has some decreased. With the hard particles TiC increased at certain extent the wear resistance has some effectively improved. Figure 4(b) are 2,5,12,15, the friction coefficients between 0.34~0.36, and the wear rates between 0.31×10⁻⁴mm⁻¹N⁻¹m⁻¹~0.33×10⁻⁴mm⁻¹N⁻¹m⁻¹. Figure 4(c) are
3, 8, 9, 14, 17, the friction coefficients between 0.305~0.344, the wear rates between 0.28×10^{-4} \text{mm}^3 \text{N}^{-1} \text{m}^{-1} ~0.3×10^{-4} \text{mm}^3 \text{N}^{-1} \text{m}^{-1}. Figure 4(d) are 4, 7, 10, 13, the friction coefficients between 0.29~0.34, and the wear rates between 0.27×10^{-4} \text{mm}^3 \text{N}^{-1} \text{m}^{-1} ~0.29×10^{-4} \text{mm}^3 \text{N}^{-1} \text{m}^{-1}. As the solid lubricants increase, the friction coefficients and wear rates of the alloys continue to decrease. Among them, the best friction and wear performance is No. 13, and the friction coefficient and the wear rate is 0.29 and 0.285×10^{-4} \text{mm}^3 \text{N}^{-1} \text{m}^{-1}, but its mechanical ability is so poor. The friction coefficient is 0.32 and the wear rate is 0.283×10^{-4} \text{mm}^3 \text{N}^{-1} \text{m}^{-1} about No. 17 with the better mechanical properties, which has better tribological properties than the other 16 specimens.

![Figure 4](image)

**Figure 4 (a)(b)(c)(d).** Curves of friction coefficients and wear rates of samples with different contents of solid lubricants.

### 3.4. Samples wear mechanism

Figure 5(a) is the No. 7 sample SEM image of surface abrasion, figure 5(b) is the No. 8 sample SEM image of surface abrasion, and Figure 5(c) is the No.17 sample SEM image of surface abrasion. It can be seen from figures 5(a)(b)(c), the wear patterns of the samples are adhesive wear. The figure 5(a)(b) show that there are some pits like a,b on the wear surface, and accompanied with some trace furrows. The reason is that as the temperature continues to rise in the wear surface, the solid lubricants BC expand and were pushed out. Under the continuous action of the abrasive parts, cracks appear at the position where the solid lubricants were extruded on the surface, forming fatigue and falling off, finally generating pits. Figure 5(c) shows the wear surface is relatively flat and there are no defects. Figure 6 is No.17 Wear Surface EDS, there are lots of Ba and Ca appear on the wear surface. This proves that No. 17 sample has excellent tribological properties and good self-lubricating properties on its friction surface.
Figures 7(a)(b)(c)(d) show the friction and wear processes of the samples. Figure 7(a) is the schematic diagram of the new TiAl self-lubricating alloy materials. TiC, Y$_2$O$_3$ and BC are randomly and uniformly distributed in the matrix. In the initial stages of friction and wear, solid lubricants do not function, when a portion of hard particles TiC are distributed on the wear surface, as shown in figure 7(b), the friction coefficient fluctuates slightly and rises. But with the progress of friction and wear, the temperature keeps rising, solid lubricants BC were expand and extruded onto the wear surface as shown in figure (c). With the continuous rotation of the abrasive parts, the solid lubricants will spread evenly to the friction surface and as the solid lubricant continuously extruded, the complete lubricating film will be formed as shown in figure 7(d). At this time, the influence of the hard particles on the friction coefficient will be reduced, and the friction coefficient and wear rate will be decrease and tend to be stable.
Figure 7. Lubrication mechanism of TiAl-based self-lubricating materials.

4. Conclusions
It was found that the new TiAl-based self-lubricating alloy with 5% TiC, 0.25% Y₂O₃, and 13% (62% BaF₂-38%CaF₂), the flexural strength, fracture toughness, hardness, and density were 522 MPa, 13 MPa m¹/₂, 530 HV, 4.1 g/cm³. At 600°C, 100N, 100r/min and dry friction, the friction coefficient is 0.32, the wear rate is 0.283×10⁻⁴ mm³/N·m. Compared with other TiAl-based self-lubricating alloy materials, it has superior comprehensive performance.

With the increase of solid lubricant 62%BaF₂-38%CaF₂, the friction coefficient and wear rate have gradually decrease. The wear patterns of new TiAl-based alloys wear are adhesive wear. It shows that the alloys have stable and complete lubricating film on the friction surface at 13% BC, and they have good tribological properties.

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References
[1] Bewlay B P, Nag S, Suzuki A and Weimer M J 2016 TiAl alloys in commercial aircraft engines High Temperature Technology (Materials at High Temperatures vol 33) pp 549-559
[2] Clemens H and Mayer S 2013 Design, processing, microstructure, and applications of advanced intermetallic TiAl alloys Adv. Eng. Mater vol 15 pp 191–215
[3] Liss K D, Funakoshi K I, Dippenaar R, Higo Y J, Shiro A, Reid M, Suzuki H, Shobu T and Akita K C 2016 Hydrostatic compression behavior and high-pressure stabilized β-phase in γ-based titanium aluminate intermetallics Metals (Metallurgy vol 6) p165
[4] Cheng J, Yang J, Zhang X H, Zhong H, Ma J Q, Li F, Fu L C, Bi Q L and Li J S 2012 High temperature tribological behavior of a Ti-46Al-2Cr-2Nb intermetallics Intermetallics vol 31(4) pp 120-126
[5] Rakesh K G and Suresh K R N 2017 Evaluation of friction and wear characteristics of electrostatic solid lubricant at different sliding conditions Surface & Coatings Technology vol 332 pp 341-350
[6] Nathan M and Ahearn J S 1993 Nanometre-scale chemical compatibility of TiAl with Al₂O₃, TiB₂ and TiC Materials Science Letters vol 12(20) pp1622-1624
[7] Ma X Z, Shen J and Jia J. 2001 Microstructure evolution of rare earth rich phase for rapidly-solidified TiAl based alloys Materials Science Letters pp 2013-2015
[8] Gao M, Cui R J, Ma L M, Zhang H R and Tang X X 2011 Physical erosion of yttria crucibles in Ti–54Al alloy casting process Materials Processing Technology vol 211(12) pp 2004-2011