Effect of Rare Earth Element Content on High Cycle Fatigue Property of Titanium Alloys

Zeng Liying, Hong Quan, Mao Xiaonan, Qi Yunlian, Zhao Yongqing
Northwest Institute for Nonferrous Metal Research, Xi’an 710016, China

E-mail: ZENG-ly@163.com

Abstract: High cycle fatigue (HCF) properties for high temperature titanium alloys without and with different content of rare earth element Y have been tested at ambient temperature at a frequency of 100Hz or so and a load ratio R of 0.1, and the effect of Y on fatigue fracture behavior was also analyzed. The results indicated that the HCF strength for the alloys increases with the increment of rare earth element content, and the strength of the two alloys with Y are lower than that of the alloy without Y. Compared with the alloy without Y, the strength for the two alloys with Y decreases 11.2% and 17.4%, respectively. The particle size for rare earth oxide dispersely precipitated from the matrix alloy varies from several hundred nanometer to several micrometer. The crack initiations for the alloys are related to the fracture of rare earth oxide particles.

Introduction
Rare earth elements (RE) are either solutioned in high temperature titanium alloys or existed as RE2O3, RExMy [1, 2]. When RE is added to the alloy, oxygen can be easily captured to form RE2O3 for an internal oxidation role, which can reduce oxygen content in the matrix alloy and improve its mechanical properties. The thermal expansion coefficients of RE2O3 particles dispersely precipitated are different from those of the matrix Ti alloys. So, dislocation loops are easy to form near RE2O3 particles when the alloy is cooled, which would strengthen the matrix alloy, resulting in the enhancement of the instantaneous strength and creep strength at high temperature. Rare earth element Y play a beneficial role in refining grains, increasing fatigue properties and improving thermal stability, as shown in reference 2.

Ti-600 alloy, a near-α high temperature Ti alloy added with rare earth element Y, can be used as a candidate material for high temperature parts of advanced engines at 600°C [3,4]. Previous studies showed that rare earth oxide Y2O3 particles with grain size less than 1µm were formed between oxygen and Y in Ti-600 alloy. The addition of Y can refine the grain size sharply and improve the plasticity and thermal stability for the alloy [2]. At the same time, the internal oxidation of rare earth Y can reduce the oxygen sensitivity of the matrix alloy, and the rare earth oxide can hinder the grain growth and refine the grains of the matrix alloy obviously. So, the alloy has good thermal strength and thermal stability, favorite tensile strength, creep resistance and high temperature durability.

The key components of an aero-engine, such as compressor disk, are subjected to high temperature, high pressure and low cyclic stress during service, and most of failure modes are fatigue failure. Therefore, fatigue properties should be studied in detail. At present, few reports can be found for the fatigue properties of high temperature alloy, especially the effect of rare earth element Y on the fatigue properties [4]. The high cycle fatigue properties at room temperature for high temperature Ti alloys
smooth specimens with different contents of rare earth Y are investigated in this paper, and the effect of rare earth element Y on the fatigue fracture behavior of the alloy is also analyzed.

1. Experimental materials and procedures
High temperature Ti alloy ingots of diameter 440mm without Y and with different Y content were produced by electrode consumption vacuum arc furnace for three times, the nominal composition for the matrix alloy is Ti-6Al-2.8Sn-4Zr-0.5Mo-0.4Si. The alloys were forged at 1100 °C from the starting diameter to 90mm square cross-section bars. Then diameter 32mm bars were conventionally forged. The forgings were eventually rolled to diameter 18mm bars at the temperatures below 950 °C. The fatigue samples were cut from the bars and were solutioned at 1020 °C for 1 h, air cooling, then aged at 650 °C for 8 h, air cooling.

Smooth axial fatigue tests were carried out on the fatigue specimens of 5mm gauge diameter using a QBG-100 high cycle fatigue tester at a frequency of 100Hz or so with a load ratio R of 0.1, and the maximum fatigue cycle is 10^7 times.

JSM 6460 scanning electron microscopy (SEM) was used to observe the morphology for the fatigue testing samples. Thin foils of 0.3mm for TEM observations were prepared from longitudinal sections of fatigued specimens. They were mechanically thinned on papers with grades 600 and 1200 to a thickness about 45μm, then electrolytically thinned to electron transparency with a solution composed of 6% perchloric acid, 20% butylglycol, and 70% methanol at -30°C. Microstructures were observed on JEM 200CX transmission electron microscopy (TEM).

2. Results and discussions

2.1. Fatigue limit of Ti-600 alloy with different rare earth element
Table 1 shows the fatigue properties of smooth specimens for the alloys with different Y contents and the matrix alloy. From Table 1, it can be seen that after 10^7 cycles of fatigue, the conditional fatigue strength limits of the alloy containing 0.1wt. % Y and 0.2wt. % Y and the matrix alloys are 537 MPa, 500 MPa and 605 MPa, respectively. Compared with the matrix alloy, the fatigue limit of the alloy decreases with rare earth element Y, and decreases by 11.2% and 17.4% respectively with the addition of 0.1wt. % Y and 0.2wt. % Y. At the same time, the higher the rare earth content, the lower the fatigue limit for the alloy.

| The alloy with 0.2wt%Y | The alloy with 0.1wt%Y | The matrix alloy |
|-----------------------|-----------------------|-----------------|
| Stress, MPa | Cycles | Stress, MPa | Cycles | Stress, MPa | Cycles |
| 480 | >1x10^7 | 520 | >1x10^7 | 580 | >1x10^7 |
| | >1x10^7 | | >1x10^7 | | >1x10^7 |
| | >1x10^7 | | >1x10^7 | | >1x10^7 |
| 500 | >1x10^7 | 540 | 6.65x10^6 | 605 | >1x10^7 |
| | 4.54x10^6 | 6.08x10^6 | 8.48x10^6 |
| Fatigue limit: 500MPa | Fatigue limit: 537MPa | Fatigue limit: 605MPa |

2.2. Effect of rare earth oxide on fatigue property for Ti-600 alloy
There are different opinions on the effect of rare earth second phase on fatigue crack initiation. Whether rare earth oxide particles can initiate fatigue crack initiation is also debatable. Some researchers believe that it is not easy to form micro-cracks near the rare earth phase [5,6], and fatigue cracks originated from
particles poor with Mo, rich with Si and Fe, but not from particles containing rare earth Gd [7]. Gd was considered to be beneficial to fatigue properties, and the average cycle times of IMI829 alloy with 0.2wt%Gd were about 40% higher than that of matrix alloy [5,6]. Debonding or pre-cracking of rare earth phase particles in high temperature titanium alloys with rare earth Nd will not initiate cracks, low cycle fatigue cracks originate in matrix alloys. The existence of rare earth phase makes the crack propagation path zigzag [5]. However, the low cycle fatigue crack originates from the rare earth oxide particles in the near-α type titanium alloy with rare earth Er, and its fatigue life is lower than that of the matrix alloy [5].

Figure 1 shows the morphology of rare earth phase in the alloy with 0.1wt%Y. It can be seen that the ellipsoidal rare earth phase precipitates at any position of the alloy, its size varies largely, and its distribution is also uneven. The long axis of large rare earth phases can reach several or even tens of microns, while which of small ones is only about 0.2 μm.

![Figure 1](image1.png)

**Figure 1.** Morphologies of rare earth particles in the alloy with 0.1wt%Y fatigued at 500MPa with the stress ratio of 0.1 and the cycle of 9.53×10^5

Under fatigue loading, dislocations in high temperature Ti alloy slip and grow. When dislocations gather at grain boundaries, phase boundaries or other obstacles, stress concentration accumulates to a certain extent, small cracks will occur. For the alloy with 0.1wt%Y, cracks can be easily formed on the weakest cleavage plane in rare earth phase, as shown in Fig. 2. From the figure, it can be seen that most of the fatigue cracks originate from the larger rare earth phase, not the smaller ones, which is mainly caused by the local stress concentration around the larger rare earth phase [4].

During the process of fatigue fracture, the persistent slip band (PSB) can be formed due to the local plastic flow in the alloy. The dislocation density in PSB is much higher than that in other places, and it is the channel of dislocation movement [8]. After the formation of PSB, a large amount of plastic deformation can be accumulated in the slip band. Dislocation movement would be blocked and dislocation congestion would be formed after meeting with rare earth phase. Then rare earth phase and the matrix would separate and would become the location of crack initiation, and intergranular crack would be found macroscopically. The higher the content of rare earth phase, the higher the probability of fatigue crack initiation (surface crack and corner crack), the more the number of fatigue crack, the earlier the initiation time, and the lower the fatigue life of the alloy. This is consistent with the data shown in Table 1. In conclusion, the fatigue crack initiation life of specimens with rare earth phase is lower than that of specimens without rare earth phase, and the more rare earth phase content, the more cracks under lower load. This indicates that the crack initiation is directly related to the rare earth phase.
3. Conclusions
In this paper, high cycle axial fatigue properties for Ti alloy smooth specimens without and with different rare earth contents at the stress ratio of 0.1 are studied at room temperature. The effect of rare earth elements on the fatigue fracture behavior of the alloys is also analyzed. The following conclusions can be drawn:

(1) After $10^7$ cycles of fatigue, the conditional fatigue strength limits of the alloy with 0.1wt.% Y and 0.2wt.% Y and the matrix alloy are 537 MPa, 500 MPa and 605 MPa, respectively. The fatigue limit of the alloy decreases with the addition of rare earth element Y, and the higher the content of rare earth, the lower the fatigue limit of the alloy.

(2) The size of rare earth oxide particles varies greatly, and its ellipsoid axis size is several hundred nanometers or even several microns. The crack initiation of the alloys is related to the fracture of rare earth phase particles.

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