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# Fretting Fatigue Behavior of Ti–6Al–4V and Ti–10V–2Fe–3Al Alloys

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**Abstract**

The effect of fretting on fatigue performance of different microstructures for titanium alloy was studied using a high-frequency push–pull fatigue testing machine. Both plain and fretting fatigue curves were obtained for comparative analysis of the fretting effect on fatigue performance of the different titanium alloy. The result shows that the strength, plain fatigue of Ti6Al4V titanium is lower than those of Ti1023 titanium. But the fretting fatigue of Ti6Al4V titanium is higher under each contact stress. The fatigue source depth of Ti1023 alloy is greater than Ti6Al4V alloy. Hardening of Ti1023 alloy is more serious after fretting. The wear mechanism of two titanium alloys is different, Ti1023 titanium alloy is more sensitive to fretting wear.

**Keywords** Fretting fatigue · Fatigue source · Microhardness · Fretting wear

## 1 Introduction

Ti–10V–2Fe–3Al and Ti–6Al–4V titanium alloys are commonly used in connecting structures of aircraft and engine bearing parts or bolts and gear teeth [1–6]. In these structures, due to vibration load and the role of the structure itself, it is easy to appear fretting fatigue phenomenon, at the same time accompanied by a high frequency alternating load, fretting fatigue damage occurs [4, 7, 8]. Ti1023 has high strength, good fracture toughness, high quenching cross section and low forging temperature. Ti1023 is high strength and high toughness titanium alloy, and Ti6Al4V is medium strength and high toughened titanium alloy. The results of this research group found that the plain fatigue of Ti6Al4V Titanium Alloy is 685 MPa, and the fretting fatigue strength is 271 MPa. The plain fatigue of Ti1023 Titanium Alloy is 836 MPa, and the fretting fatigue strength is 175 MPa. The strength and fatigue performance of Ti1023 were higher than those of Ti6Al4V titanium alloy, but the fretting fatigue properties of Ti1023 titanium alloy under different contact stress were lower than those of Ti6Al4V titanium alloy [9–12]. Many factors might influence fretting fatigue of a titanium alloy: contact pressure, surface condition, slip amplitude, and material structure and property. Considerable research has been conducted for understanding influences of various parameters on fretting fatigue strength [13–25]. In this paper the conditions are the same except the material structure and property. The fretting fatigue properties, fracture morphology, fatigue source depth, depth of hardened layer of Ti1023 and Ti6Al4V titanium alloys and fretting wear are discussed. The comparison between plain fatigue and fretting fatigue properties of the two titanium alloys is made.

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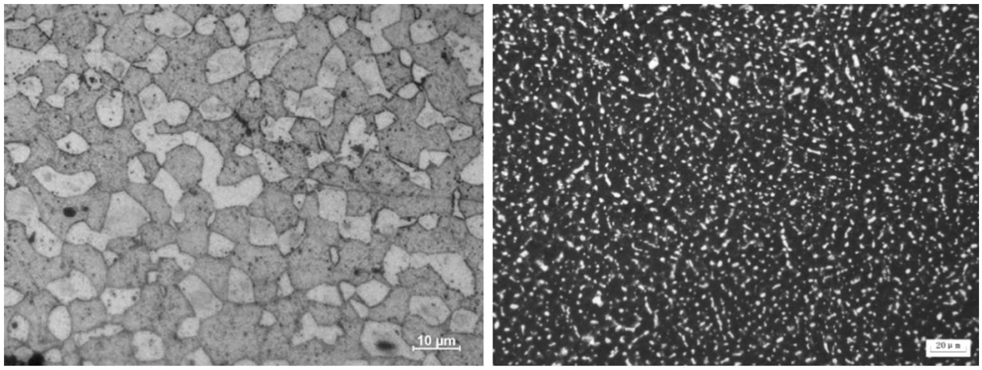
## 2 Materials and Experiments

### 2.1 Materials

Hot-rolled Ti6Al4V and Ti1023 titanium alloy bars were used for fretting fatigue damage study. The treatment process of Ti6Al4V was heating for 2 h at 950 °C, water quenching followed by heating for 6 h at 540 °C, air cooling. The treatment process of Ti1023 was heating for 2 h at 755 °C, water quenching followed by heating for 8 h at 530 °C, air cooling.

The microstructure of Ti6Al4V and Ti1023 are shown in Fig. 1. The microstructure of Ti6Al4V Titanium alloy is composed of the equiaxed α, secondary α and β-matrix. The β-matrix is distributed with acicular secondary α phase. The ratio of equiaxed α is 30%, and the average grain size is about 5 μm. The microhardness of Ti6Al4V Titanium alloy




(a) (b)

**Fig. 1** Micrograph of **a** Ti6Al4V and **b** Ti1023 alloy

is 395 HV. The equiaxed α phase is dispersed on the β matrix in Ti-1023 Titanium alloy microstructure. The ratio of equiaxed α is 26%, and the average grain size is about 2.2 μm. The microhardness of Ti-1023 titanium alloy is 365 HV.

## 2.2 Test Equipment, Parameters and Program

Plain fatigue and fretting fatigue tests were carried out using a QBG-100 computer controlled high-frequency tension and compression fatigue testing system manufactured by Changchun Qian bang Test Equipment Co, Ltd. The experiment rig, test specimens and fretting pads are the same as Ref. [11]. The material of fretting pads is the 30CrMnSiA steel, which has the minimum properties of yield strength 835 MPa, tensile strength 1080 MPa, elongation 10%, and reduction of area 45%. The fretting fatigue test rig was calibrated per ASTM E1012-12.

The fretting fatigue test condition and parameters are as follows. The test environment is the atmospheric environment and room temperature. The axial load waveform is a sine wave, plane–plane contact. The stress ratio R is 0.1. The contact pressure varies, F = 3, 5, 7, 10, 20, 45 MPa. These are the average values. The frequency f = 76–85 Hz. For plain fatigue testing, the contact pressure is zero (i.e., not applying contact pressure), and other parameters are the same those used as for fretting fatigue testing. Plain and fretting fatigue testing was in strict accordance with the HB 5287-1996 "Metal Material Axial Loading Fatigue Test Method" and the GB/T24176-2009/ISO 12107-2003 "Metallic Materials—Fatigue Testing—Statistical Planning and Analysis of Data" standards. 8 to 12 specimens were tested for measuring fretting fatigue strength under each contact pressure. 10 MPa was selected as a typical contact pressure. This is the contact pressure when the fretting fatigue strength and the fatigue source depth start to stabilize. Fretting fatigue S–N curve was obtained at this contact pressure only, using 28 specimens, and compared with the plain fatigue S–N curve.

## 2.3 Fatigue Source Depth Measurement and Microhardness Testing

Scanning electron micrographs of fretting fatigue specimens under different contact pressure were obtained, using a same magnification. Measuring from the fatigue specimen surface area as a starting point, to the intersection of the source region and the fatigue propagation as the end, the length of the longest straight line is the depth value H of the fatigue source region. The depth value H of the source region after fatigue fracture at different contact pressure was measured. The typical fatigue source is shown in Fig. 2. Using a HXS-1000 digital electronic smart microhardness measurement machine, the hardness of fretting fatigue fracture surface and wear areas was measured, under a test load of 50 g and loading time of 15 s.

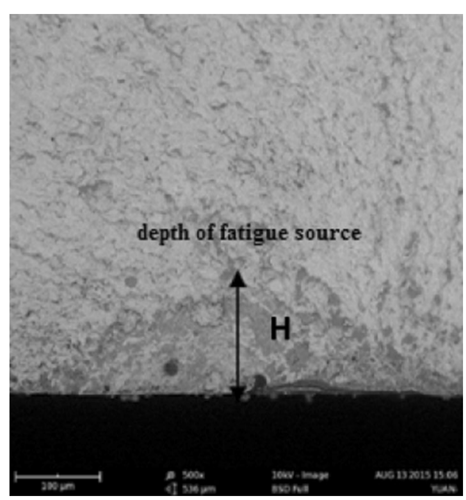



**Fig. 2** Diagram of typical fatigue source

# 3 Results and Discussion

## 3.1 Mechanical Properties, Properties of Plain Fatigue and Fretting Fatigue

Mechanical properties are shown in Table 1. Room strength of Ti1023 is much higher than that of Ti6Al4V, and ductility of Ti1023 is a little higher than that of Ti6Al4V.

Comparison of fretting fatigue S–N curves of Ti6Al4V and Ti1023 alloy is also shown in Fig. 3a. It can be seen from the graph that the data points on S–N curves of two kinds of titanium alloys also show a tendency of less in ends and more in middle. Different from Ti1023 alloy, the data points on the S–N curve of Ti6Al4V alloy are more scattered; the data points on the S–N curve of Ti6Al4V Titanium alloy distribute above the S–N curve of Ti1023 alloy, fretting fatigue strength of Ti6Al4V is higher than that of Ti1023 alloy. Compare to the plain fatigue S–N curve, the data point distribution on the fretting fatigue S–N curve of both titanium moves right obviously. Different from plain fatigue, there are few data points on fretting fatigue $\sigma_{max}$ versus number of cycles to failure curve between $10^6$ and $10^7$ cycles. Most of all points located in range of $10^5$–$10^6$ cycles. The plain and fretting fatigue properties of Ti6Al4V alloy and Ti1023 alloy are compared and analyzed as shown in Fig. 3b. It can be seen that the strength of both Ti6Al4V alloy and Ti1023 alloy reduce sharply caused by fretting, by as much as 60–80%. The plain fatigue of Ti6Al4V Titanium Alloy is lower than Ti1023 Titanium Alloy, which is consistent with the law of tensile strength of Ti6Al4V alloy is below that of Ti1023 alloy. But its fretting fatigue strength is higher than Ti1023 alloy.

**Table 1** Mechanical properties of Ti6Al4V and Ti1023 at room temperature

| Alloy | $\sigma_b$ (MPa) | $\delta_5$ (%) | $\psi$ (%) | $\sigma_{p0.2}$ (MPa) |
|---|---|---|---|---|
| Ti6Al4V | 895 | 13.3 | 33.5 | 825 |
| Ti1023 | 1123 | 15.3 | 64.4 | 1059 |

## 3.2 Fatigue Fracture Morphology

There is significant different in the morphology of the fretting fatigue source and propagation area of the two titanium alloys. Fatigue source area is flat. The boundary of fatigue source area and propagation area is obvious, and there is no transition zone (Fig. 4).

In propagation area, the cleavage plane of Ti1023 titanium alloy is not obvious, but small cleavage plane of alpha phase is found in Ti6Al4V titanium alloy, the fatigue strip is distributed on the small cleavage plane, and the propagation direction on each small plane is not exactly the same.

In the matrix of Ti1023 titanium alloy, the alpha phase is less and the size is smaller, it has little hindrance to the fatigue crack growth and cannot change the direction of crack propagation. In Ti6Al4V titanium alloy, the size of hexagonal crystals alpha is larger, the fatigue crack is difficult to bypass and can only pass through a certain cleavage surface. The grain orientation of the alpha phase is different, and the sliding system is different, so there is a small angle difference between each other.

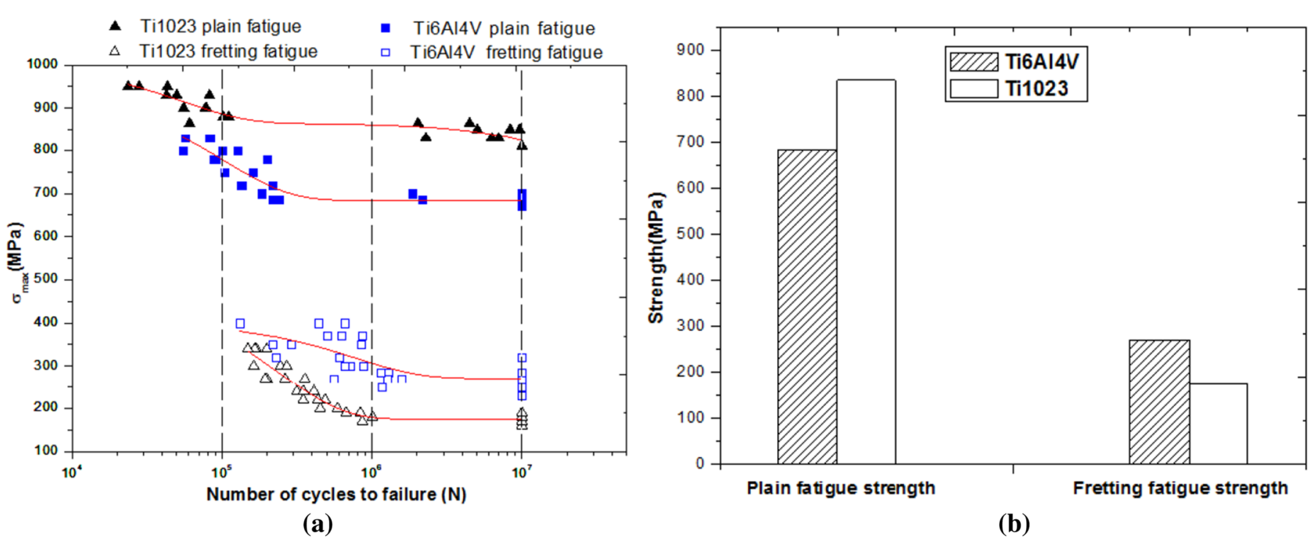



**Fig. 3** Comparison of **a** the plain fatigue and fretting fatigue of Ti6Al4V and Ti1023 and **b** plain fatigue strength and fretting fatigue strength for Ti6Al4V and Ti1023 titanium

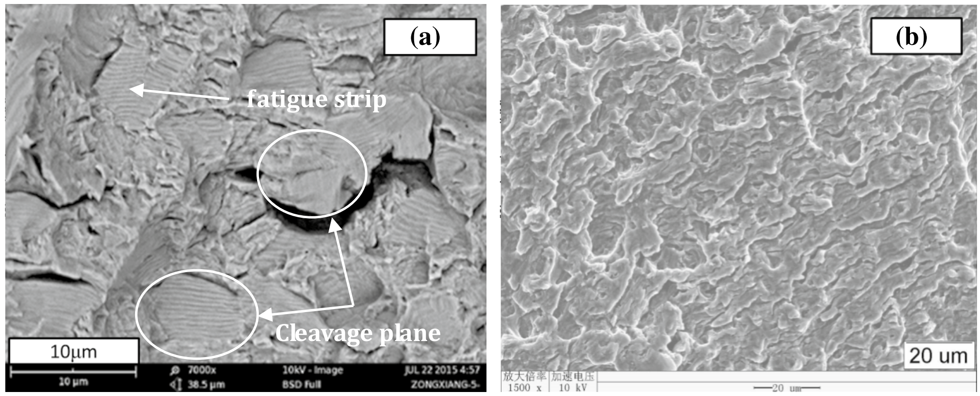



**Fig. 4** SEM micrographs of propagation area of **a** Ti6Al4V and **b** Ti-1023 titanium alloy

### 3.3 Quantitative Analysis of Fatigue Source Area Under Different Contact Stress

Figure 5a shows the relationship between the depth of the fatigue source and the contact stress of Ti6Al4V alloy and Ti1023 alloy under different contact stresses. It can be seen from the graph that the depth of both fretting fatigue source area increases rapidly with the increase of contact stress. The fretting fatigue source depth is maintained at a stable value with the contact stresses is equal or greater than 10 MPa. Under different contact stresses, the fretting fatigue source region of Ti6Al4V alloy is 300 µm at most, and it is always less than that of Ti1023 alloy under any contact stress, this means that for different types of microstructure material, the size of crack will be different when the initial expansion stage transfers to the rapid crack propagation stage. The relationship between the depth of the fatigue source zone and the contact stress of the two kinds of titanium alloys is consistent with the relationship between fretting fatigue strength and contact stress, they are all negatively correlation (Fig. 5b), which proves the universality of this rule in fretting fatigue of titanium alloy.

### 3.4 Microhardness

The microhardness of Ti6Al4V and Ti1023 alloy specimens at different positions was tested. Microhardness depth profiles of fretting fatigue fractured Ti1023 and Ti6Al4V alloy is shown in Fig. 6a. It can be seen that, the microhardness of Ti6Al4V decreases from the surface underneath the fretting area to approximately 200 µm under the surface of the fatigue specimen. And away from the fretting wear zone microhardness is basically fluctuating in a constant level, about 395 HV. The microhardness of Ti1023 decreases from the surface underneath the fretting area to approximately 400 µm under the surface of the fatigue specimen. Away from the fretting area, however, the microhardnesss lightly increases with increasing

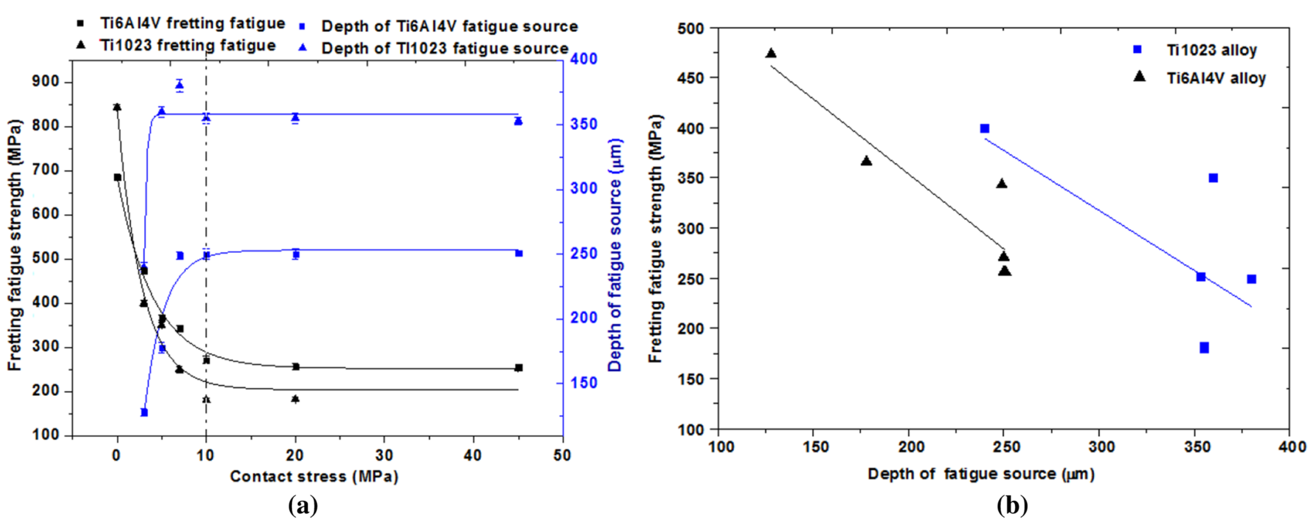



**Fig. 5** Diagram of **a** variation trend of fatigue source depth and fretting fatigue strength of Ti6Al4V and Ti1023 alloy under different contact stress (Kt = 1, R = 0. 1, f = 81–85 Hz) and **b** the correlation between depth fatigue source and fretting fatigue strength

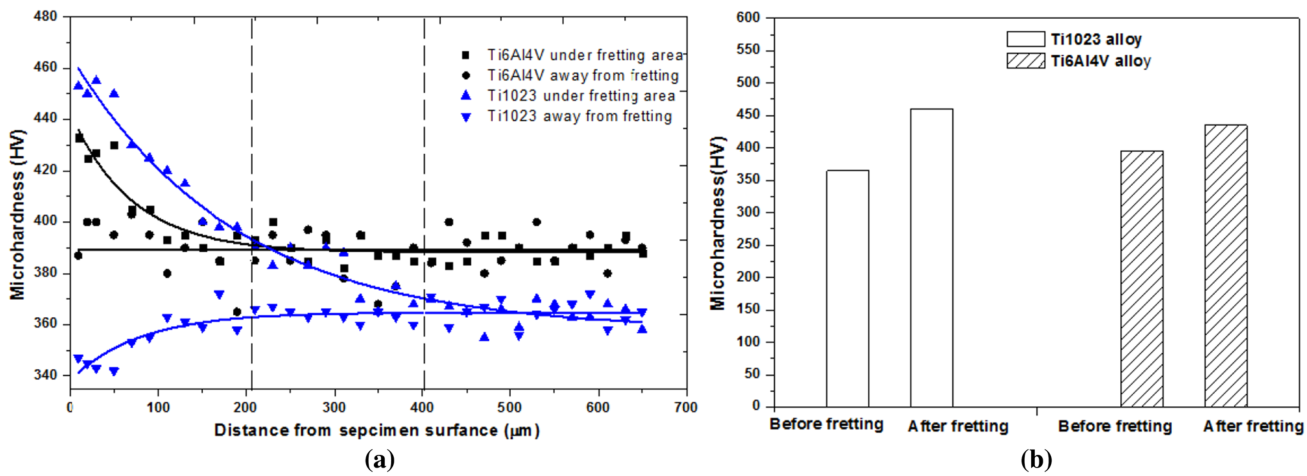



**Fig. 6** The variation of **a** microhardness depth of fretting fatigue fractured Ti-1023 and Ti6Al4V alloy (Kt = 1, R = 0.1, F = 10 MPa) and **b** microhardness of Ti1023 and Ti6Al4V alloy before and after fretting fatigue test

depth from the surface. The stable hardness is reached at approximately 210 mm under the surface of the fatigue specimen. The stable hardness in two types of profiling locations is the same, about 365 HV. The effect of fretting on microhardness of Ti6Al4V and Ti1023 is shown in Fig. 6b. The average microhardness of Ti6Al4V alloy is 395 HV before fretting fatigue test, and reaches 435 HV after fretting fatigue test, and the microhardness increased by 10%. The average microhardness of Ti1023 alloy is 365 HV before fretting fatigue test, and reaches 460 HV after fretting fatigue test, and the microhardness increased by 26%.

In fretting wear zone, grain slipping, elongation and fracture increase the hardness near the surface. The hardness of both titanium alloys extends to a certain depth, the hardening depth of Ti1023 alloy is greater than that of Ti6Al4V. The hardening depth of Ti6Al4V alloy is about 210 µm, and the hardening depth of Ti1023 alloy is about 400 µm. Away from the fretting area, the microhardness of Ti6Al4V titanium alloy is basically maintained at the same level, while the Ti1023 alloy has a certain depth softened layer. Possibly the fatigue softening effect caused by the alternating cyclic load is more serious on the surface of the Ti1023 fatigue specimen [26–28], and the Ti6Al4V alloy does not appear cyclic softening phenomenon. Compared with Ti6Al4V alloy, the fretting is more serious to the hardening of Ti1023 alloy, and the fatigue crack is more prone to initiation; In addition, the hardening depth of Ti1023 alloy is deeper, the fatigue crack can reach critical crack length more quickly. Under the combined action, fretting fatigue strength of Ti1023 alloy is lower than that of Ti6Al4V alloy.

### 3.5 Fretting Wear

Figure 7a shows the edge of Ti6Al4V fretting area is grinding mark parallel to the fretting direction. It is caused by adhesive wear and abrasion. In the middle part of the fretting zone, It is full of grinding pits formed from delamination of debris, because the fretting pairs are always in contact state, and the center part of fretting scar was damaged by abrasive wear. The appearance of the grinding pit not only aggravates the damage of fretting fatigue, but also the fatigue crack is more easily sprout from the pit [29–31]. Morphology of fretting fatigue area of Ti1023 alloy is shown in Fig. 7b, The adhesion of Ti10V2Fe3Al in fretting damage is not obvious, In fretting area, It's mainly splintering and delamination of surface layer, and fish-scale pits formed. Delamination is the main mechanism of the fretting damage of Ti10V2Fe3Al alloy [32], the crack sprouted in the delamination area with serious stress concentration.

## 4 Conclusion

(1) The mechanical strength and plain fatigue strength of Ti1023 is higher than those of Ti6Al4V alloy, but fretting fatigue strength of Ti1023 under each contact stress is lower than that of Ti6Al4V alloy. With the increase of contact stress, the depth of fretting fatigue source area of both alloy increases rapidly, and when the contact stress increases to 10 MPa, the depth of fretting fatigue source is maintained at a stable value, the fatigue source depth of Ti1023 alloy is greater than that of Ti6Al4V alloy under each contact stress.

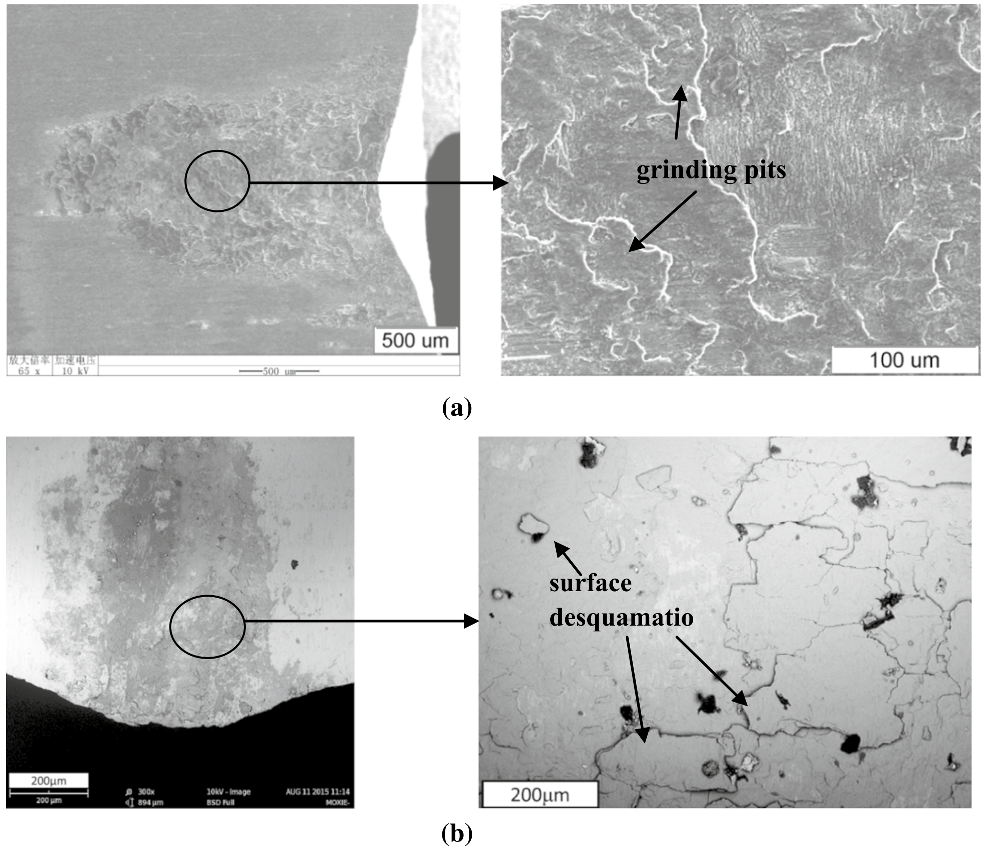



**Fig. 7** Morphology of fretting fatigue area of **a** Ti6Al4V alloy and **b** Ti1023 alloy

(2) The contact stress and fretting effect cause serious hardening of the titanium alloy surface. The hardening depth of Ti1023 alloy is greater than that of Ti6Al4V alloy. The damage mechanism of Ti6Al4V fretting fatigue was adhering wear and abrasion, and the damage mechanism of Ti1023 fretting fatigue was delamination fatigue. Ti-1023 titanium alloy is more sensitive to fretting wear.

(3) The structure, mechanical properties and plain fatigue are material properties; fretting fatigue represents the service life. The microstructure and mechanical properties of Ti1023 alloy have reached the better match, but the service life is not the best. So fretting fatigue is a very important indicator to predict and improve the service life.

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## Compliance with Ethical Standards

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

1. C. Leyens, M. Peters (eds.), *Titanium and Titanium Alloys: Fundamentals and Applications* (Wiley-VCH, Weinheim, 2003)
2. G. Lutjering, J.C. Williams, *Titanium*, 2nd edn. (Springer, New York, 2007)
3. B. Oberwinkler, M. Riedler, W. Eichlseder, Importance of local microstructure for damage tolerant light weight design of Ti–6Al–4V forgings. Int. J. Fatigue **32**, 808–814 (2010)
4. H. Knobbe, P. Koster, H. Christ, C. Fritzen, M. Riedler, Initiation and propagation of short fatigue cracks in forged Ti–6Al–4V. Procedia Eng. **2**, 931–940 (2010)
5. A. Drechsler, T. Dorr, L. Wagner, Mechanical surface treatments on Ti–10V–2Fe–3Al for improved fatigue resistance. Mater. Sci. Eng. A **243**(1–2), 217–220 (1998)
6. S.K. Jha, K.S. Ravichandran, High-cycle fatigue resistance in beta-titanium alloys. JOM J. Min. Met. Mater. Soc. **53**(3), 30–35 (2000)
7. R.A. Antoniou, T.C. Radtke, Mechanisms of fretting-fatigue of titanium alloys. Mater. Sci. Eng. A **237**(2), 229–240 (1997)

8. D.L. Anton, M.J. Lutian, L.H. Favrow, D. Logan, B. Annigeri, The effects of contact stress and slip distance on fretting fatigue damage in Ti–6Al–4V/17–4PH contacts, in *Symposium on Fretting Fatigue: Current Technology and Practices, Salt Lake City,* 1998, ASTM International, West Conshohocken, 2000, pp. 119–140
9. T. Hattori, V.T. Kien, M. Yamashita, Fretting fatigue life estimations based on fretting mechanisms. Tribol. Int. **44**(11), 1389–1393 (2011)
10. X. Li, S. Wang, Z. Wang, P. Li, Q.J. Wang, Location of the first yield point and wear mechanism in torsional fretting. Tribol. Int. **66**, 265–273 (2013)
11. Z.Y. Li, X.L. Liu, G.Q. Wu, W. Sha, Observation of fretting fatigue cracks of Ti6Al4V titanium alloy. Mater. Sci. Eng. A **707**, 51–57 (2017)
12. G.Q. Wu, Z. Li, W. Sha et al., Effect of fretting on fatigue performance of Ti-1023 titanium alloy. Wear **309**(1–2), 74–81 (2014)
13. S. Mall, S.A. Namjoshi, W.J. Porter, Effects of microstructure on fretting crack initiation behavior of Ti–6Al–4V. Mater. Sci. Eng A **383**, 334–340 (2004)
14. O. Jin, S. Mall, Effect of independent pad displacement on fretting fatigue behavior of Ti–6Al–4V. Wear **253**(5–6), 585–596 (2002)
15. J. Takeda, M. Niinomi, T. Akahori, Gunawarman effect of microstructure on fretting fatigue and sliding wear of highly workable titanium alloy Ti–4.5Al–3V–2Mo–2Fe. Int. J. Fatigue **26**(9), 1003–1015 (2004)
16. G.H. Majzoobi, K. Azadikhah, J. Nemati, The effect of deep rolling and shot peening on fretting fatigue resistance of Aluminum -7075-T6. Mater. Sci. Eng. A **516**(1–2), 235–247 (2009)
17. H. Lee, S. Mall, Fretting fatigue behavior of Ti–6Al–4V under seawater environment. Mater. Sci. Eng. A **403**(1–2), 281–289 (2005)
18. T.E. Matikas, E.B. Shell, P.D. Nicolaou, Proc. SPIE **3585**, 2–10 (1999)
19. P.J. Golden, M.J. Shepard, Life prediction of fretting fatigue with advanced surface treatments. Mater. Sci. Eng. A **468–470**, 15–22 (2007)
20. O.J. McCarthy, J.P. McGarry, S.B. Leen, Microstructure-sensitive prediction and experimental validation of fretting fatigue. Wear **305**(1–2), 100–114 (2013)
21. J. Vázquez, C. Navarro, J. Domínguez, Analysis of the effect of a textured surface on fretting fatigue. Wear **305**(1–2), 23–35 (2013)
22. J.J. Madge, S.B. Leen, I.R. McColl, P.H. Shipway, Contact-evolution based prediction of fretting fatigue life: effect of slip amplitude. Wear **262**(9–10), 1159–1170 (2007)
23. J.J. Madge, S.B. Leen, P.H. Shipway, The critical role of fretting wear in the analysis of fretting fatigue. Wear **263**(1–6), 542–551 (2007)
24. J.J. Madge, S.B. Leen, P.H. Shipway, A combined wear and crack nucleation –propagation methodology for fretting fatigue prediction. Int. J. Fatigue **30**(9), 1509–1528 (2008)
25. Y. Berthier, C. Colombie, L. Vinenet, Fretting wear and their effects on fretting fatigue. Tribology **110**, 517 (1988)
26. D. Ye, Mater. Chem. Phys. **93**, 495–503 (2005)
27. D. Ye, Z. Wang, An approach to investigate pre-nucleation fatigue damage of cyclically loaded metals using Vicker microhardness test. Int. J. Fatigue **23**(1), 85–91 (2001)
28. A. Hutson, H. Lee, S. Mall, Effect of dissimilar metal on fretting fatigue behavior of Ti–6Al–4V. Tribol. Int. **39**(10), 1187–1196 (2006)
29. R. Bertolini, S. Bruschi, A. Bordin, Fretting corrosion behavior of additive manufactured and cryogenic-machined Ti6Al4V for biomedical applications. Adv. Eng. Mater. **19**(6), 15006–15029 (2017)
30. Z. Wei, M. Wang, Study on fretting fatigue behavior of TC4 titanium alloy. Rare Met. Mater. Eng. **35**, 7 (2006)
31. Z. Wei, M. Wang, L. Li, Fretting fatigue damage behavior of TC4 alloy. Mater. Mech. Eng. **30**, 1 (2006)
32. S. Wang, B. Ye, Fretting damage and fatigue of high strength titanium alloy. J. Beijing Univ. Aeronaut. Astronaut. No. 4 (1990)