Thermo-mechanical fatigue behavior of Ti-6-22-22 alloy

Z. L. YU, S. X. LI*
Shenyang National Laboratory for Materials Science, Institute of Metal Research, The Chinese Academy of Sciences, Shenyang 110016, People's Republic of China
E-mail: shxli@imr.ac.cn

Y. Y. LIU, J. F. LEI
Titanium Alloy Laboratory, Institute of Metal Research, The Chinese Academy of Sciences, Shenyang 110016, People's Republic of China

Published online: 16 September 2005

Thermo-mechanical fatigue (TMF) results from the simultaneous effects of cyclic variations in load, strain and temperature. Its greater detrimental damage effect has been recognized. TMF may involve mechanical fatigue damage, creep damage and environmental damage, and the fatigue life of materials under TMF test is found to depend in a complex manner on strain ranges, temperature cycles, phase relationships, dwell periods, and frequencies. As TMF tests are time consuming and quite expensive, the life time of components usually is predicted based on isothermal fatigue (IF) data only. This can sometimes lead to nonconservative results, if stress-strain response, crack initiation behavior, or crack growth rate under TMF conditions are different from those under isothermal conditions. It is well known that most often the fatigue life of materials under TMF test is shorter than that under IF test at the maximum temperature of TMF temperature cycle, thus it may take a risk to use IF data to predict TMF behaviors of materials [1–7].

Many studies of TMF behaviors have concerned steels, nickel-base superalloys, or fiber reinforced high temperature titanium alloys. Most conventional titanium alloys do not have a temperature potential high enough, so that TMF loading was of no concern earlier. However, due to the application of high temperature titanium alloy up to 600 °C, the TMF behavior has drawn much attention recently. Ti-6-22-22 alloy is a α-β titanium alloy devised to use at medium temperature [8, 9]. Though its operating temperature is not very high, its operating condition in aircraft involves thermal transients in combination with mechanical strain cycles simultaneously, especially during the aircraft take-off prior to normal flying. It is necessary to investigate the TMF behavior of Ti-6-22-22 alloy.

The α-β titanium alloy Ti-6-22-22 (nominal chemical compositions Ti-6Al-2Sn-2Zr-2Cr-2Mo, in wt. pct) used in this investigation was received in the form of hot forged rod. Before fatigue tests, the alloy was heat treated following the triplex heat treatment schedule: (1) 980 °C for 0.5 h, air cooling; (2) 925 °C for 1 h, air cooling; (3) aging at 540 °C for 8 h and then air cooling. The typical bi-lamellar microstructure was obtained. For the fatigue tests, the specimens with a cylindrical gage length of 18 mm and diameter of 6 mm were machined. The TMF tests, as well as IF tests at the maximum and minimum temperatures of the temperature cycle, were conducted under mechanical strain control, using an MTS810 servohydraulic test system. The cyclic wave forms were triangular for both loading and temperature, and the period was 200 s. The cyclic mechanical strain amplitudes were 1.1, 1.2, 1.5 and 1.8%, and the cyclic temperature range was 200–400 °C. In phase TMF (TMF-IP, i.e. the highest temperature vs. the maximum tensile stress) and out of phase TMF (TMF-OP, i.e. the highest temperature vs. the maximum compressive stress) tests were performed for this alloy. The TMF tests run from 200 to 520 °C as well as corresponding IF tests at the maximum and minimum temperatures of the temperature cycle under a 1.1% mechanical strain amplitude control were also performed. The fractography of the fracture surfaces and metallography of longitudinal sections were analyzed by a SEM-S360 and light microscopy, respectively.

Fig. 1 shows the cyclic strain-life curves of IF tests at 200 °C and 400 °C, and of TMF tests run from

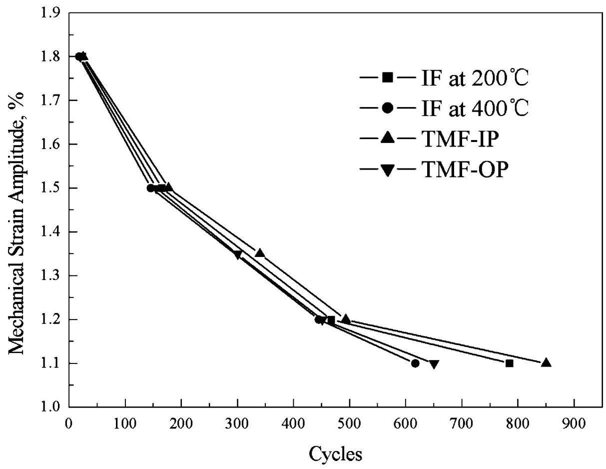

Figure 1 Cyclic strain-life curves of IF at 200 and 400 °C, and of TMF run from 200 to 400 °C.

* Author to whom all correspondence should be addressed.

0022-2461 © *2005 Springer Science + Business Media, Inc.*
DOI: 10.1007/s10853-005-4554-3

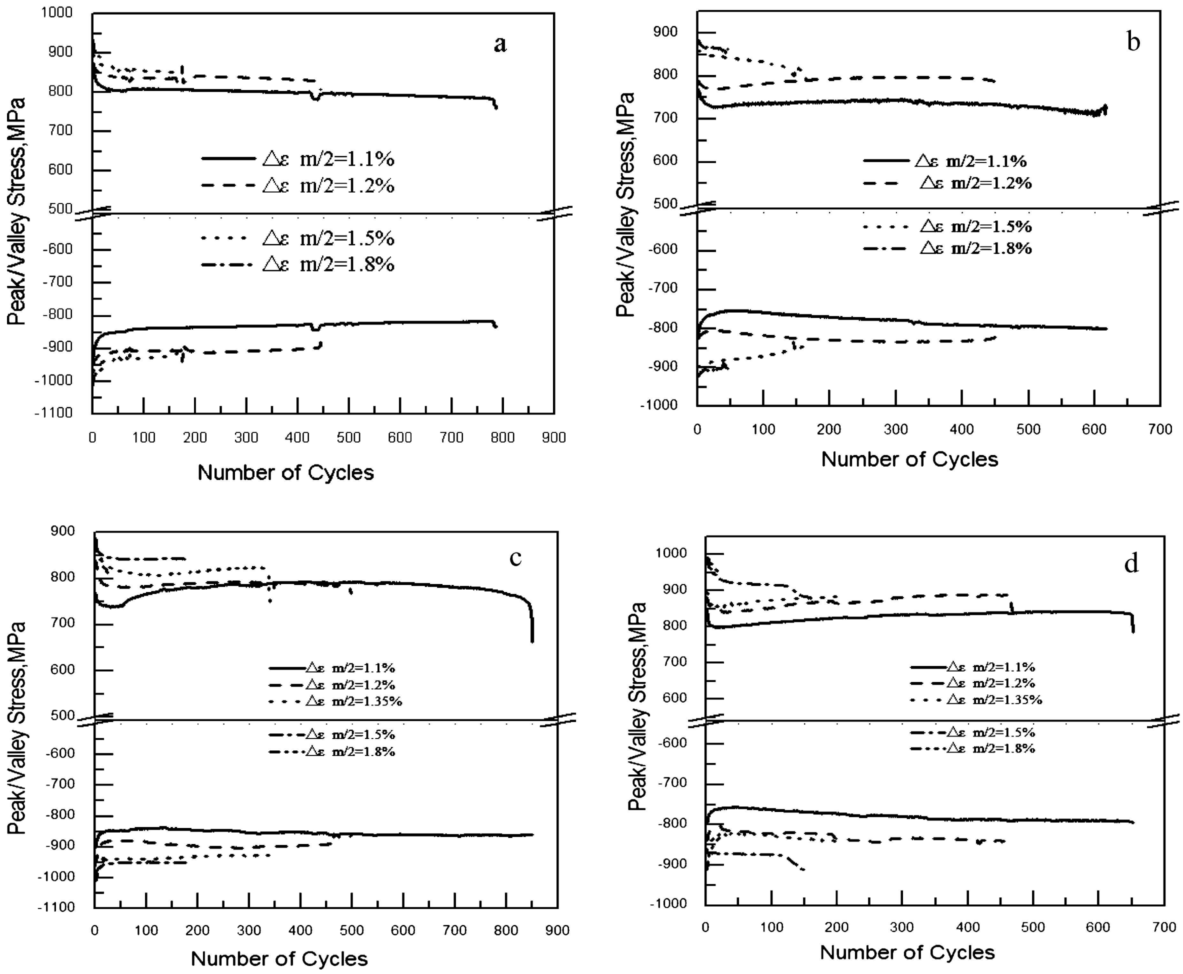

Figure 2 Cyclic stress response curves of IF at 200 and 400 °C, and of TMF run from 200 to 400 °C (a) IF at 200 °C, (b) IF at 400 °C, (c) TMF-IP, (d) TMF-OP.

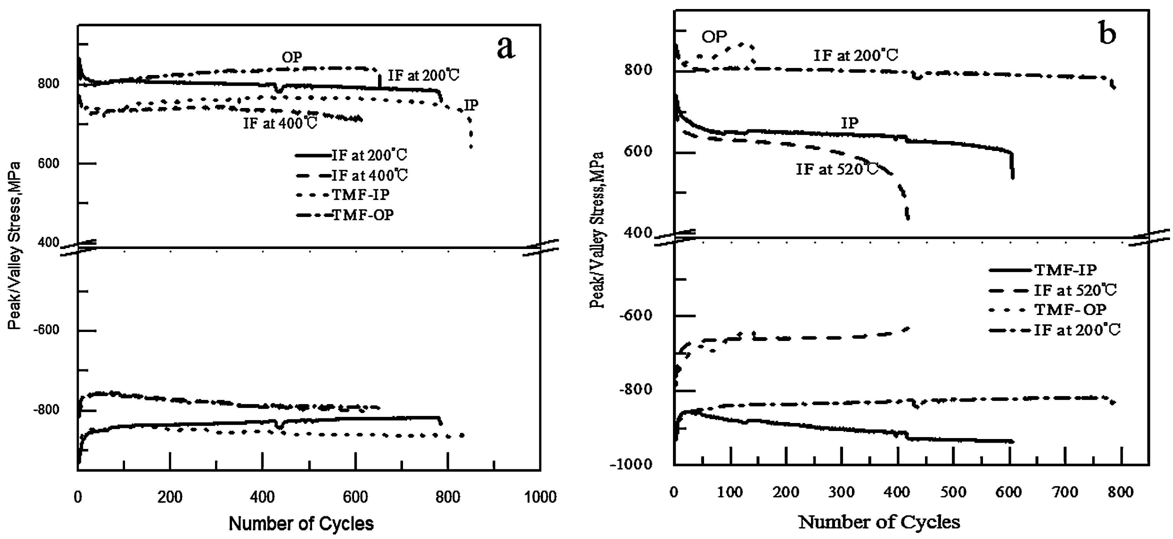

Figure 3 Cyclic stress response curves of Ti-6-22-22 for (a) IF at 200 and 400 °C, and TMF run from 200 to 400 °C, (b) IF at 200 and 520 °C, and TMF run from 200 to 520 °C under a mechanical strain amplitude of 1.1%.

200 to 400 °C under different strain amplitudes control. At all strain amplitudes tested, the fatigue lives (N_f) of Ti-6-22-22 for IF tests at 200 °C are greater than that at 400 °C, this indicates that the fatigue life decreases with increasing temperature. At all strain amplitudes applied, the fatigue lives, N_f, of TMF-IP are greater than those of TMF-OP, which indicates that the phase relationship affects fatigue life obviously. For each strain amplitude applied, the fatigue lives are different depending on the specific testing conditions. We can see that the maximum fatigue life for this alloy can be achieved by TMF-IP test, and in contrast, the minimum fatigue life can be achieved by IF test at 400 °C. For example, at strain amplitude of 1.1%, the maximum fatigue life is 870 cycles obtained by TMF IP test, while the minimum fatigue life is 620 cycles obtained by IF

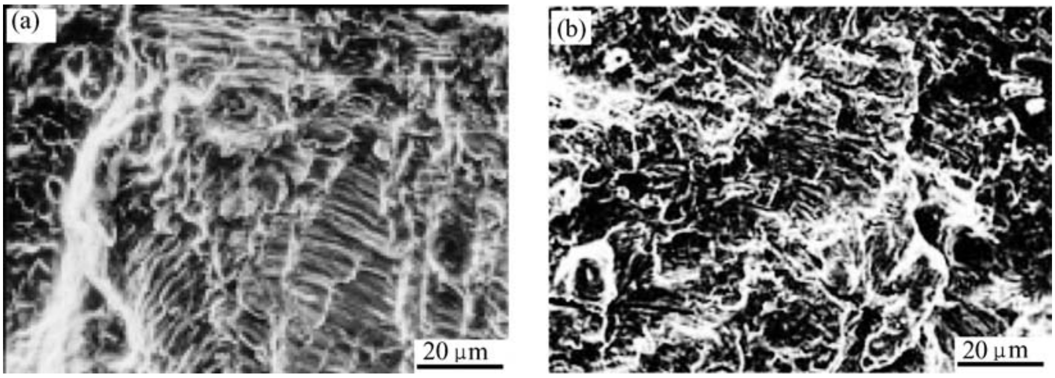

Figure 4 SEM fractography of IF specimens (a) at 400 °C and (b) at 520 °C.

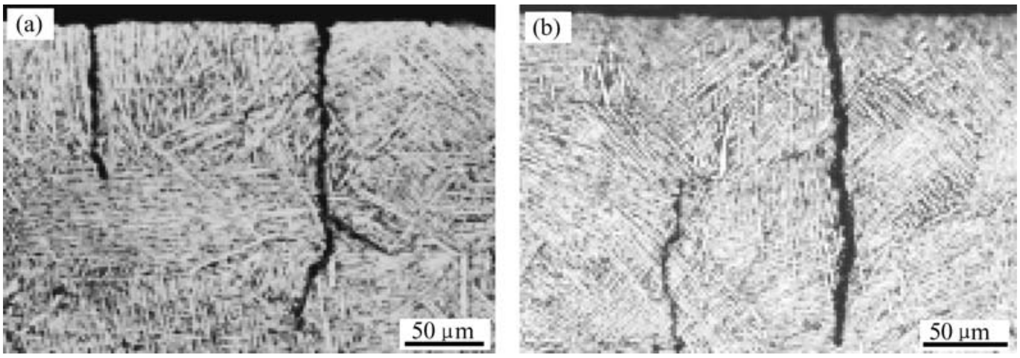

Figure 5 Metallography of longitudinal section of IF specimens (a) at 400 °C and (b) 520 °C.

test at 400 °C. This effect becomes more obvious when the mechanical strain amplitude decreases (see Fig. 1).

The maximum fatigue lives N_f achieved for Ti-6-22-22 by TMF IP test can be explained as follows. It is known for Ti-6Al-4V alloy, which is similar to Ti-6-22-22 alloy, that the deformation mechanism transition from planar slip to wavy slip occurs at about 300 °C. The deformation is more homogeneous after transition, and N_f for IF test at 300 °C is the greatest both in air and in vacuum. Below 300 °C N_f will decrease due to severe localized plastic deformation caused by planar slip [10], and above 300 °C an N_f decrease may be due to increased mobility of wavy slip dislocations and hence enhanced severe localized plastic deformation again at higher temperatures. At the same time the environmental effects at high temperature should be taken into account. Because of varying temperature for TMF-IP, the low temperature dislocation structure is different from the high temperature dislocation structure, and the low temperature dislocation structure interacts with the high temperature dislocations during every cycle [11], leading to a final dislocation structure similar to the structure at the mean temperature of temperature cycle, which is similar to the dislocation structure of Ti-6Al-4V at 300 °C. Therefore the N_f of Ti-6-22-22 for TMF-IP test is the greatest among the four testing conditions.

Fig. 2 shows the cyclic stress response curves of IF and TMF, which were obtained from the maximum tensile stress and compressive stress of every cyclic hysteresis loop. All the curves under different fatigue testing conditions are characterized with cyclic stress softening drastically at the first 10 cycles. For example, Fig. 1(a) shows that at strain amplitude of 1.1% (solid line) the maximum tensile stress varies from about 850 to 800 MPa within the first 30 cycles for IF test at 200 °C. When the mechanical strain amplitudes are smaller, say 1.1%, after initial cyclic softening at the first 10 cycles, the slight cyclic hardening and then cyclic stress saturation stage can be observed as shown in Fig. 2(a) to (c). However, when the mechanical strain amplitude is as large as 1.8%, the cyclic stress softening occurs during entire test for all fatigue tests.

Because the obvious oxidation of titanium alloys occurs above 500 °C [12], the environmental effects on N_f should be slight for IF tests at 200 and 400 °C and TMF tests run from 200 to 400 °C, even if it cannot be neglected entirely. In the temperature range of 200–520 °C, the effects of oxidation are more detrimental for Ti-6-22-22 alloy. To investigate this effect, the IF tests at 200 and 520 °C, and TMF tests run from 200 to 520 °C under a constant mechanical strain amplitude of 1.1% control were conducted, and the cyclic stress response curves are shown in Fig. 3(b). For comparison, the cyclic stress response curves for IF tests at 200 and 400 °C, and for TMF tests run from 200 to 400 °C under a constant mechanical strain amplitude of 1.1% control were shown in Fig. 3(a). It shows that the fatigue life of Ti-6-22-22 for TMF-OP run from 200 to 520 °C (about 150 cycles, see Fig. 3(b)) is much lower than that run from 200 to 400 °C (about 670 cycles, see Fig. 3(a)), and it is also lower than that for IF test at 520 °C (about 400 cycles, see Fig. 3(b)). It is well known that TMF-OP is in tensile stress at minimum temperature, the obvious oxidation at maximum temperature causes the plasticity loss at lower temperature, thus the N_f for TMF-OP test decreases drastically.

SEM fractography and longitudinal section metallography indicate that the fatigue cracks initiate at the specimen surface by multiple sources, then propagate transgranularly into the matrix of the alloy (see Figs 4 and 5). The fatigue cracks are basically caused by machining trances on the specimen surface. The fatigue cracks grow either parallel or perpendicular to the α/β interfaces. Similar to the Ti alloy of IMI834, the extensive metallographic examination has indicated that the conventional creep damage, i.e., void formation, is negligible in all fatigue tests. There is nearly no difference among the metallographies of specimens under different testing conditions.

In summary, for Ti-6-22-22 alloy, the detrimental effects of TMF run from 200 to 400 °C are not obvious, in other words, the alloy is suitable for service in this temperature range. However, when the maximum cyclic temperature increases to 520 °C, the effect of oxidation on fatigue life is substantial, leading to the fatigue life for TMF-OP tests much lower, and the detrimental effects for TMF tests are more pronounced than those for IF test at the maximum temperature of TMF temperature cycle.

Acknowledgments
This work was financially supported by Fundamental Research Project of China (G19990650).

References

1. S. TAIRA, ASTM STP 520, ASTM Philadephia (1973) 80.
2. R. W. NEU and H. SEHITOGLU, *Metall. Trans.* **A20** (1989) 1755.
3. L. LAWSON, M. E. FINE and D. JEANNOTE, *ibid.* **A22** (1991) 1059.
4. R. ZAUTER, H. J. CHRIST and H. MUGHRABI, *ibid.* **A25** (1994) 401.
5. P. POTOZKY, H. J. MAIER and H. J. CHRIST, *ibid.* **A29** (1998) 2995.
6. H. J. MAIER, R. G. PETERUK and H. J. CHRIST, *ibid.* **A31** (2000) 431.
7. Y. C. WANG, S. X. LI, L. ZHOU, S. H. AI, F. LIU, H. ZHANG, and Z. G. WANG, *Philo. Mag.* **84** (2004) 3335
8. X. D. ZHANG, J. M. K. WIEZOREK, W. A. BAESLACK, D. J. EVANS and H. L. FRASER, *Acta. Metall.* **46** (1998) 4485.
9. Z. L. YU, S. X. LI, Y. Y. LIU, Q. Y. ZHANG, J. F. LEI and Z. X. MU, *Mater. Sci. Eng.* **A383** (2004) 283.
10. J. MENDEZ, in: P.A. BLENKSHOP, W. J. EVANS, H. M. FLOWER (eds), *Titanium'95 Science and Technology* (The Institute of Materials, London, 1996) p. 285.
11. V. S. BHATTACHAR and D. C. STOUFFER, *Trans. ASME* **115** (1993) 358.
12. S. LESTERLIN, C. SARRAZIN-BAUDOUX and J. PETIT, *Scr. Mater.* **34** (1996) 651.

Received 9 February 2004
and accepted 16 February 2005