DE GRUYTER OPEN

ADVANCES IN MANUFACTURING SCIENCE AND TECHNOLOGY
Vol. 40, No. 1, 2016
DOI: 10.2478/amst-2016-0006

MICROSTRUCTURAL FACTORS AFFECTING CREEP-FATIGUE BEHAVIOUR OF TWO-PHASE TITANIUM ALLOYS

Waldemar Ziaja

Summary

In the paper the dwell fatigue behaviour of two-phase Ti-6Al-2Mo-2Cr alloy (VT3-1) at elevated temperature was investigated. The reasons of high sensitivity of titanium alloys to dwell periods at high stress level during cyclic loading were summarized. The relations between morphology of the alloy microstructure and the effect of dwell periods at peak stress was established. The microstructure of the alloy was varied by means of changing conditions of heat-treatment. Dwell fatigue tests were carried out at the temperature of 400°C. Relative contributions of cyclic and creep processes to the overall damage were evaluated as a function of stress level.

Keywords: two-phase titanium alloys, creep-fatigue, microstructure

Rola mikrostruktury w procesie pełzania dwufazowych stopów tytanu

Streszczenie

W pracy przedstawiono wyniki badań właściwości dwufazowego stopu tytanu Ti-6Al-2Mo-2Cr (WT3-1) w warunkach pełzania-zmęczenia. Przedstawiono źródła dużej wrażliwości stopów tytanu na okresy przestojów przy wysokim poziomie naprężenia w warunkach obciążenia cyklicznie zmiennego. Określono zależność między morfologią mikrostruktury stopu a wpływem okresów przestojów przy maksymalnym naprężeniu w cyklu obciążenia na trwałość materiału. Mikrostrukturę stopu kształtowano metodami obróbki cieplnej. Próbę zmęczeniową bez i z okresami przestojów przy maksymalnym naprężeniu prowadzono w temperaturze 400°C. Oszacowano względny udział zjawisk towarzyszących zmęczeniu i pełzaniu w procesie niszczenia materiału.

Słowa kluczowe: dwufazowy stop tytanu, pełzanie-zmęczenie, mikrostruktura

1. Introduction

There has been still growing demand for titanium alloys over the last decades. It stems from the combination of their advantageous properties like high specific strength at room and elevated temperature, fracture toughness and corrosion resistance which makes them the important structural material in chemical, energy and aerospace industries [1-3]. These properties accompanied by biocompatibility of titanium are also the reasons for growing number of applications in biotechnology [4].

Address: Waldemar ZIAJA, PhD Eng., Rzeszow University of Technology, Department of Materials Science, W. Pola 2, 35-959 Rzeszów, phone: (+48, 17) 865-11-23, e-mail: wziaja@prz.edu.pl

In the case of discs and blades in compressor section of the turbine aero engines near-α and two-phase α+β alloys are predominantly used, for which maximum operational temperature reaches about 650 and 450°C respectively. In this kind of applications fatigue and creep strength criteria at room and elevated temperature are of primary importance in the material selection process [5]. Operation of cyclic loads at elevated temperature leads to synergetic effect of fatigue and creep phenomena leading to increase in damage accumulation rate [6].

Titanium and its alloys are prone to development of large time dependent strains even for stresses significantly lower than yield strength and temperature below 0,25 Tm. It some cases transient creep strains were observed at room temperature both in CP titanium and titanium alloys [7-9]. This phenomenon is disadvantageous in the case of elements operating under dwell fatigue conditions when it can lead to premature failure. Sensitivity of titanium alloys to dwell periods at peak stresses was reported both for room and elevated temperature fatigue regime [10-12].

Mechanical properties of titanium alloys can be optimized by control of the morphological parameters of microstructure like the size, shape and distribution of the grains of various phases, texture, structure and strength of grain boundaries and others. Fatigue and creep properties of two-phase titanium alloys show strong dependence on microstructure, especially morphology of the α and β phases which is usually developed in the processes of hot working and heat treatment. Important issue is the extent to which the microstructure of two-phase titanium alloys affects the creep-fatigue interaction. According to several studies aligned alpha microstructure formed by slow cooling from above β transus temperature is particularly susceptible to dwell sensitive fatigue due to propagation of small cracks through the alpha phase [13-15].

One of the possible reasons of dwell sensitivity of titanium alloys is stress redistribution between relatively week and strong grains in the alloy which occurs in the case of rate dependence of the material, even at temperatures considered low for creep. Weak grains are these with basal plane at an angle to the tensile axis and strong areas include those in which the basal planes are perpendicular to the tensile axis. The slip on weak grains piles up at the boundary with a neighboring strong grain. The pile-up generates the required combination of shear and tensile stresses on the unfavorably oriented basal plane, which induces facet formation in alliance with the applied principal stress [13]. The magnitude of the induced stress is proportional to the length of the dislocation pile-up and hence the grain size. The alloys in which the primary β-phase grains are broken up by heat treatment are usually less dwell sensitive. Cleavage or quasi-cleavage facets are typical features of the fracture surface of alpha-beta titanium alloys in the creep-fatigue regime. The facets typically have a basal plane orientation [16, 17].

2. Experimental

The material studied was two-phase titanium alloy Ti-6Al-2Mo-2Cr, developed in Russia and known under the designation VT3-1, having following chemical composition (wt.%): Al – 6.2, Mo – 1.96, Cr – 2.07, Fe – 0.12, C – 0.08, Ti – balance. This is martensitic $\alpha+\beta$ alloy which is characterized by high strength at room and elevated temperature and high fracture toughness. As a result of careful selection of heat treatment conditions high creep resistance of the alloy can also be obtained at the temperature up to 450°C [2, 18]. The alloy was delivered in the form of rolled bars, 16 mm in diameter in mill-annealed condition. In order to determine the influence of basic morphological features of the microstructure on the high temperature properties of the alloy two distinct schemes of heat treatment process were applied.

As a result of annealing at the temperature above β transus (1000°C) followed by controlled cooling at the rate of 0.06°C s^{-1} typical lamellar microstructure was developed, consisting of α-phase plates layered with β-phase (Fig. 1a). Annealing at the temperature in $\alpha+\beta\rightarrow\beta$ phase transformation range (930°C) followed by air cooling led to formation of globular morphology of stable α and β phases (Fig. 1b).

Microstructure of the alloy was examined using light microscope Nikon Epiphot 3 equipped with DS-1 camera. Average values of selected quantitative parameters of the microstructure were determined using image analysis software Aphelion v.2.3. For the lamellar microstructure diameter of primary β-phase grains (d_β), diameter of the colonies of α-phase lamellae (d_c) and thickness of α lamellae (t_α) were measured while for globular microstructure grain size (d_α) and volume fraction (V_α) of α phase were determined.

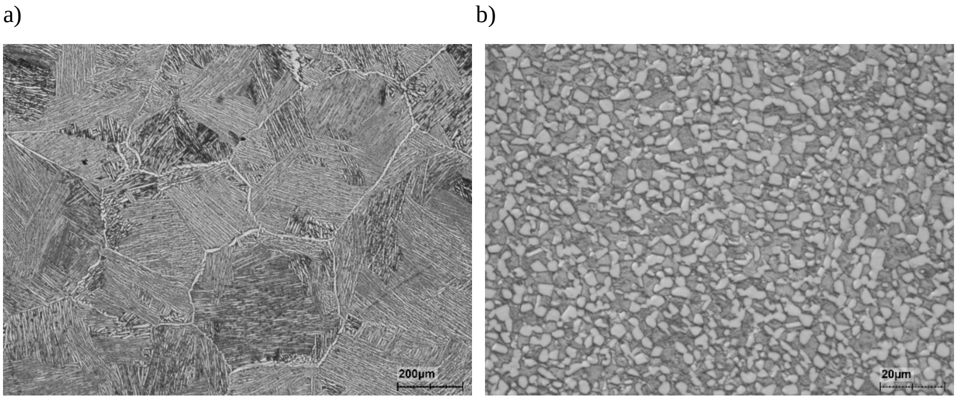

Fig. 1. Microstructure of two-phase Ti-6Al-2Mo-2Cr alloy: lamellar (a), globular (b)

In order to define cyclic stress ranges in fatigue tests static tensile tests were carried out at the temperature of 400°C using round specimens 6 mm in diameter on universal machine Instron 5982 at the constant strain rate of 0.005 s^{-1}. The strain was measured during the test by extensometer with 1µm resolution.

The stress controlled fatigue and dwell-fatigue tests were carried out at the temperature of 400°C on Instron 8801 servohydraulic testing machine, in tensile mode at the load ratio $R = 0.1$. Smooth, cylindrical specimens with initial diameter of 6 mm were tested. Loading and unloading ramp was realised at the constant time of 4.5 s (in both cases). Holding time at peak stress equal to 1 and 120 s was applied in fatigue and dwell fatigue tests respectively (Fig. 2).

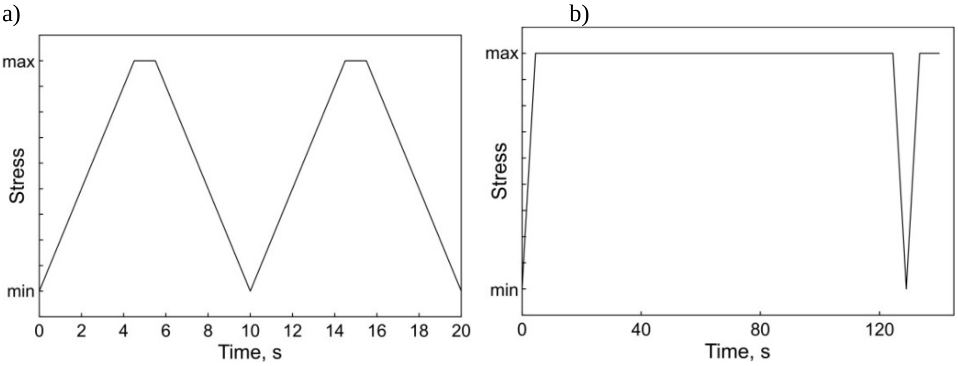

Fig. 2. Loading waveforms applied in fatigue (a) and dwell-fatigue (b) tests

3. Results and discussion

As a result of the annealing above β-transus significant grain growth of primary β-phase took place ($d_\beta = 430$ μm). During slow, controlled cooling α-phase was formed in the primary β-phase grains in the shape of parallel lamellae of the average thickness $t_\alpha = 2.1$ μm arranged in colonies having average diameter $d_c = 48$ μm.

For the globular microstructure obtained by air cooling from the temperature in $\alpha+\beta \rightarrow \beta$ phase transformation range insignificant grain growth was noticed comparing to initial state of the alloy, and the average values of stereological parameters of α-phase were equal $d_\alpha = 3.5$ μm, $V_\alpha = 62\%$.

Two variants of the alloy tested showed important differences in the low-cycle fatigue behaviour with respect to their sensitivity to dwell loading. In the case of the alloy with globular microstructure dwell periods only slightly reduced the life compared to the cyclic data. This reduction is more evident at relatively high stresses (Fig. 3a). The alloy with lamellar microstructure showed more pronounced dwell effect at all values of cyclic stress amplitude (Fig. 3b). This different dwell sensitivity is more clearly noticeable when the dwell fatigue data are plotted against normalized stress value (the maximum applied cyclic stress divided by tensile strength) to allow for relative differences in tensile strength of the two variants of the alloy (Fig. 4). It was found that fatigue life data for lamellar and globular microstructure superimpose when plotted against normalized stress.

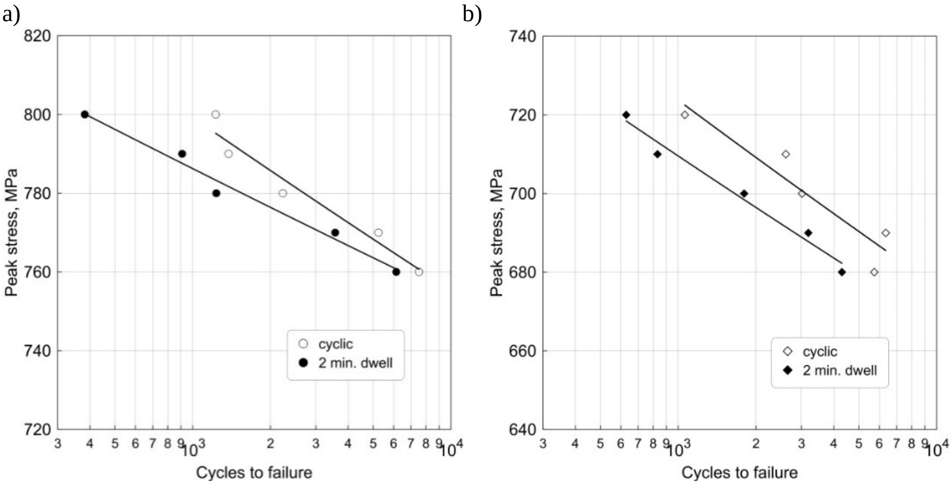

Fig. 3. Fatigue life of Ti-6Al-2Mo-2Cr alloy at 400°C: a) globular, b) lamellar microstructure

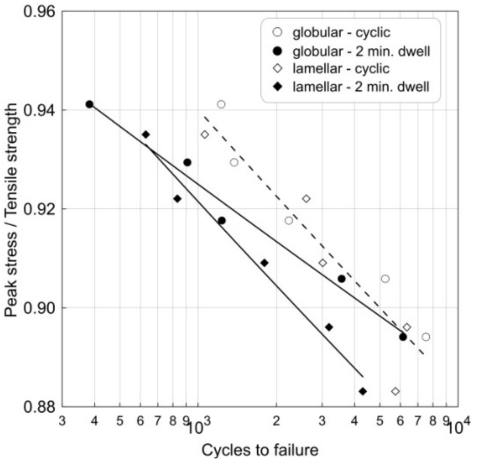

Fig. 4. Fatigue life of Ti-6Al-2Mo-2Cr alloy at 400°C against normalised stress

Some evidences suggest that in the case of dwell fatigue test creep was the dominant mode of failure leading to life reduction. Fracture surfaces appearance was similar to that obtained in creep tests. Cracks were found to initiate internally which is characteristic of creep failure as opposed to fatigue cracks which usually initiate at the surface.

In the case of specimens tested with load dwells quasi-cleavage facets were identified on the fracture surfaces. They are more likely to nucleate in cycles with stress hold rather than strain hold due to the effect of load shedding, when the stresses redistribute from soft, creeping grains to the hard grains to maintain force equilibrium. The facets were found predominantly in samples of the alloy with lamellar microstructure (Fig. 5). Although the thickness of the individual α-phase lamellae is comparable with grain size of globular α–phase, the factor facilitating the facets formation is the common crystallographic orientation of α-lamellae within the colonies as the facets nucleate along basal planes orientated approximately perpendicularly to the loading direction.

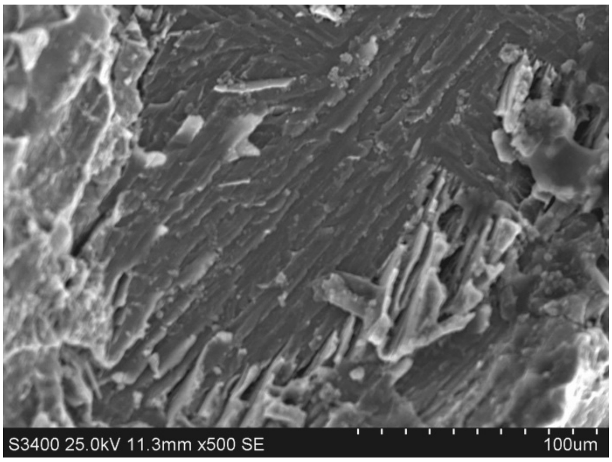

Fig. 5. Fracture surface of Ti-6Al-2Mo-2Cr alloy with lamellar microstructure after dwell fatigue test – quasi-cleavage facets

4. Conclusions

Two-phase titanium alloy Ti-6Al-2Mo-2Cr with lamellar and globular microstructure was examined in low-cycle and dwell fatigue tests at 400°C. On the basis of the analysis of the test results following findings were formulated:

- Fatigue life data for lamellar and globular microstructure superimposed when plotted against normalized cyclic stress, showing no significant dependence on the microstructure.
- Dwell periods (120 s) in cyclic loading resulted in significant decrease in fatigue life of the alloy.
- The alloy with lamellar microstructure showed higher sensitivity to dwell periods especially for lower range of applied stress.

- Fatigue fracture surfaces had mixed character. The areas of ductile type fracture were separated by facets characteristic for quasi-cleavage fracture. Secondary cracks were also observed which is characteristic for fatigue cracking of titanium alloys.
- Facets formation was facilitated in the alloy with microstructure consisting of aligned α-lamellae sharing common crystallographic orientation. This resulted in more pronounced dwell sensitivity of that variant of the alloy.
- The voids and wedge cracks were not observed on fracture surfaces after dwell fatigue test indicating that dislocation creep mechanism was a dominant mode of deformation at dwell periods.

References

[1] C. LEYENS, M. PETERS (eds): Titanium and Titanium Alloys. Wiley-VCH GmbH & Co. KGaA, Weinheim 2003.

[2] G. LÜTJERING, J.C. WILLIAMS: Titanium. Springer, Berlin Heidelberg 2007

[3] R.R. BOYER, R.D. BRIGGS: The use of β titanium alloys in the aerospace industry. *Journal of Materials Engineering and Performance*, **14**(2005), 681-685.

[4] A.M. KHORASANI et al.: Titanium in biomedical applications – properties and fabrication: a review. *Journal of Biomaterials and Tissue Engineering*, **5**(2015), 593-619.

[5] J.S. HEWITT et al.: Titanium alloy developments for aeroengine fan systems. *Materials Science and Technology*, **30**(2014), 1919-1925.

[6] T. GOSWAMI: Low cycle fatigue – dwell effects and damage mechanisms. *International Journal of Fatigue*, **21**(1999), 55-76.

[7] M.F. SAVAGE, T. NEERAJ, M.J. MILLS: Observations of room-temperature creep recovery in titanium alloys. *Metallurgical and Materials Transactions*, **33A**(2002), 891-898.

[8] J. PENG et al.: The temperature and stress dependent primary creep of CP-Ti at low and intermediate temperature. *Materials Science & Engineering*, **A611**(2014), 123-135.

[9] W.J. HARRISON, M.T. WHITTAKER, R.J. LANCASTER: A model for time dependent strain accumulation and damage at low temperatures in Ti-6Al-4V. *Materials Science & Engineering*, **A574**(2013), 130-136.

[10] P. LEFRANC et al.: Nucleation of cracks from shear-induced cavities in an α/β titanium alloy in fatigue, room-temperature creep and dwell-fatigue. *Acta Materialia*, **56**(2008), 4450-4457.

[11] M.R. BACHE et al.: Crack growth in the creep-fatigue regime under constrained loading of thin sheet combustor alloys. *International Journal of Fatigue*, **42**(2012), 82-87.

[12] J. KUMAR, S.G.S. RAMAN, V. KUMAR: Creep-fatigue interactions in Ti-6Al-4V alloy at ambient temperature. *Trans Indian Inst Met*, **69**(2016)2, 349-352.

[13] M.R. BACHE: A review of dwell sensitive fatigue in titanium alloys: the role of microstructure, texture and operating conditions. *International Journal of Fatigue*, **25**(2003), 1079-1087.

[14] W. SHEN, A.B.O. SOBOYEJO, W.O. SOBOYEJO: Microstructural effects on fatigue and dwell fatigue crack growth in α/β Ti-6Al-2Sn-4Zr-2Mo-0.1Si. *Metallurgical and Materials Transactions*, **35A**(2004), 163-187.

[15] W.J. EVANS: Time dependent effects in fatigue of titanium and nickel alloys. *Fatigue Fract Engng Mater Struct,* **27**(2004), 543-557.

[16] F.P.E. DUNNE, D. RUGG: On the mechanisms of fatigue facet nucleation in titanium alloys. *Fatigue Fract Engng Mater Struct*, **31**(2008), 949-958.

[17] S. ANKEM et al.: Mechanical properties of alloys consisting of two ductile phases. *Progress in Materials Science,* **51**(2006), 632-709.

[18] G. LÜTJERING: Influence of processing on microstructure and mechanical properties of (α+β) titanium alloys. *Materials Science & Engineering*, **A243**(1998), 32-45.

Received in February 2016