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Procedia Engineering 2 (2010) 845–854
Procedia Engineering
www.elsevier.com/locate/procedia

Fatigue 2010

Isothermal and thermomechanical fatigue of titanium alloys

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Received 19 February 2010; revised 10 March 2010; accepted 15 March 2010

Abstract

LCF and TMF tests were conducted on Ti6242 and on the intermetallic TiAl alloy TNB-V2 between 350-650°C and 550-850°C, respectively. A continuous life reduction of Ti6242 was observed with increasing temperature. On contrary, temperature does not have a systematic influence on life for TNB-V2. Life description based on Basquin-Coffin-Manson illustrates the small contribution of plastic strain to fatigue life of TNB-V2. The transition cycle number, which represents the transition from plastic strain to stress controlled fatigue life, was found to be 4 for TNB-V2 at 550°C, while it is 409 for Ti6242. Tests in vacuum demonstrated a strong influence of the environment. TMF tests showed that TNB-V2 is very susceptible to out-of-phase loading.

Keywords: Near-α titanium; γ-titanium aluminide; Basquin-Coffin-Manson relationship; environmental contribution

1. Introduction

Since the advent of turbo engines for airplanes in the 1930s their efficiency has been improved quiet significantly. This development can be attributed to a more sophisticated design of the engine (e.g. increased by-pass-ratio, geared turbo fan) and the development and introduction of advanced engineering materials, which possess better oxidation, creep and fatigue properties. In particular, lightweight materials with superior specific strength properties such as titanium alloys are of prime importance for aerospace applications. The hexagonal packed structure of the α-titanium unit cell yields good creep properties. Alloying this metal with suitable solid solution and precipitation strengtheners has led to the development of the material class of near-α titanium alloys, which is the material of choice for compressor components. During the last two decades considerable optimisation of intermetallic compounds on the basis of titanium aluminides (α_2-Ti_3Al and γ-TiAl) has been achieved [1]. These intermetallic alloys combine high strength and stiffness with low density. This will lead to substantial weight-savings if conventionally-used materials are replaced by titanium aluminides, reducing specific fuel consumption further. In addition, they may extend the temperature field of application of titanium-based alloys from currently 600°C to some 800°C.

This study is devoted to the understanding of deformation behaviour during isothermal low cycle fatigue (LCF) and thermomechanical fatigue (TMF) at service-relevant temperatures of the near-α titanium alloy Ti6242 and the γ-

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doi:10.1016/j.proeng.2010.03.091

based TiAl alloy TNB-V2). Their respective chemical compositions are given in table 1. The microstructure selected, figure 1, represents an optimum compromise between creep and fatigue properties.

Table 1. Chemical composition of Ti6242 and TNB-V2 given in mass-% (atomic-%)

	Ti	Al	Sn	Zr	Mo	Si	Nb	C
Ti6242	bal.	5.9 (10.4)	2.0 (0.8)	3.9 (2.0)	2.0 (1.0)	0.1 (0.2)	---	---
TNB-V2		24.3 (45.0)	---	---	---	---	15.0 (8.0)	0.05 (0.2)

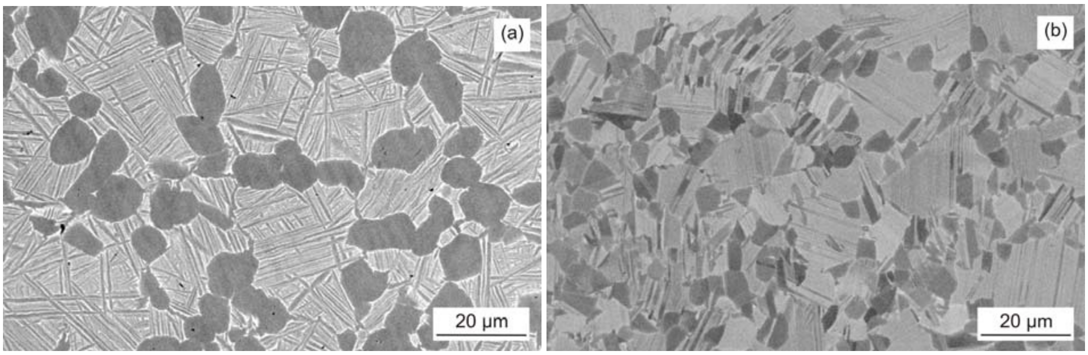

Fig. 1. (a) Duplex microstructure of Ti6242 obtained after 1h recrystallisation at 991°C (i.e. T_β-15°C), followed by 8h stabilization annealing at 595°C; (b) nearly-lamellar microstructure of TNB-V2, obtained after 30min recrystallisation at 1300°C (i.e. T_α-18°C), followed by 6h stabilization annealing at 800°C

Solid round specimens (gauge diameter: 7 mm) were tested in a servo-hydraulic testing machine under fully-reversed conditions in the temperature range from room temperature to 650°C (Ti6242) and 850°C (TNB-V2). Testes were conducted either in air or vacuum ($p < 3\times10^{-5}$ mbar). The results described herein are limited to results obtained during testing at total strain amplitude of $\Delta\varepsilon/2 = 0.7\%$, further details on the experimental procedure can be found elsewhere [2-3].

2. Results and Discussion

2.1. Isothermal LCF Behavior of Ti6242

Figure 2 shows cyclic deformation curves of Ti6242 at several temperatures. The shape of the curves obviously depends on temperature. At room temperature a continuous softening can be detected. This behaviour may be explained as follows: It is well established that alloys such as Ti6242 contain a certain amount of very fine coherent α_2-Ti_3Al precipitates, their average diameter being in the order of 2 nm [4-5]. In this study, it was only possible to detect the presence of α_2 through superlattice reflections in diffraction patterns. Additional X-ray diffraction (XRD) measurements on the alloy investigated reveal that the amount of coherent α_2-Ti_3Al precepitates is about 4 vol.-%. As the dislocation arrangement is very planar, one can expect that the particles are continuously sheared, thus creating easy slip paths, as has been already suggested by Bania [6].

At 350 and 450°C a slight, though steady increase in stress amplitude can be detected. This indicates processes, which are related to dynamic strain ageing [7]. Solute silicon atoms that interact with dislocations are one reason for this effect [8-10]. At 550°C the regime of saturated stress amplitude is quite pronounced. As TEM observations reveal, dislocations still arrange in a planar fashion at this temperature, indicating that the precipitates are still sheared. However, temperatures are high enough to allow recovery of the precipitates [11]. Finally, at 650°C temperature is high enough to allow for climb processes. Thus the precipitates do not act as obstacles anymore and the dislocation arrangement is preferably homogeneous at this temperature. In addition, existing silicides of the type

(Ti, Zr)$_5$Si$_3$ coarsen [12]. As Zr is removed from the primary α phase into the silicides, the solid solution suffers from an additional loss in strength.

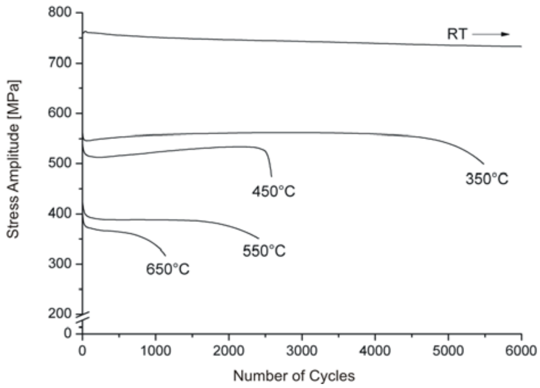

Fig. 2. Stress amplitude vs. number of cycles for Ti6242, $\Delta\varepsilon/2 = 0.7\%$, R = -1 (test at room temperature was stopped after 40,000 cycles)

Figure 3 illustrates fatigue crack formation and dislocation arrangements at low temperatures (i.e. T < 600°C) and at 650°C. At 550°C (and at 350 and 450°C as well, cf. [3]) slip markings are quite abundant and may act as crack initiation sites (figure 3a), while the arrangement of dislocations is rather heterogeneous, figure 3b. However, at 650°C slip bands are absent (figure 3c). This indicates that deformation takes place homogeneously, as is supported by the TEM image shown in figure 3d.

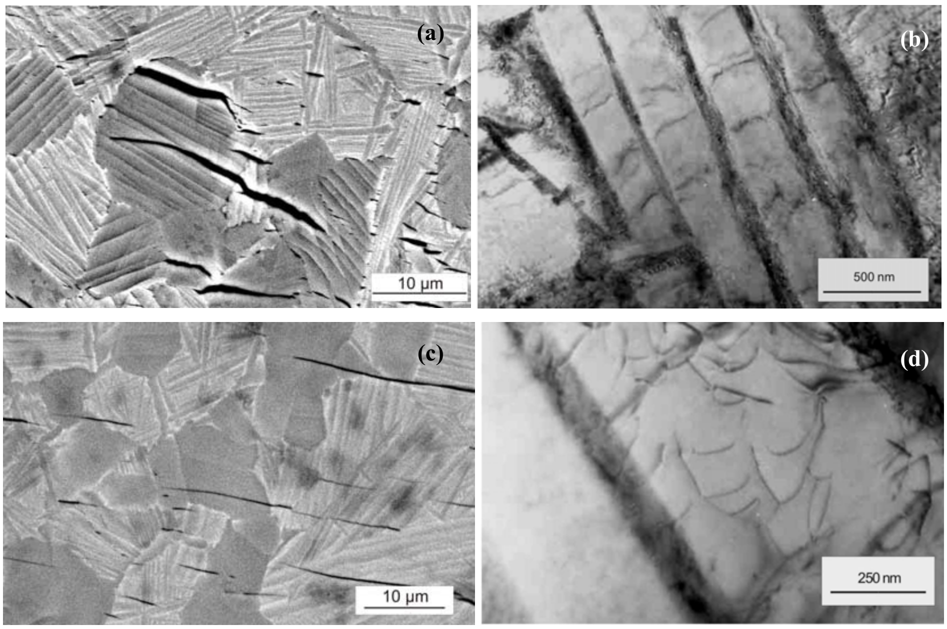

Fig. 3. (a) Fatigue crack formation at 550°C, pronounced slip band markings; (b) heterogeneous dislocation arrangement at temperatures below 600°C; (c) fatigue crack formation at 650°C; (d) more homogeneous dislocation arrangement at 650°C

2.2. Isothermal LCF-Behavior of TNB-V2

Figure 4 illustrates the evolution of stress amplitude during fatigue cycling at several temperatures. A more detailed discussion can be found in [13]. At room temperature one can observe a continuous increase in stress amplitude. It is well known that intermetallics possess only a very limited number of slip systems due to their constitution. It may happen that dislocations operating on these slip systems intersect and lock each other. These newly created dipoles will act as additional glide obstacles. Another reason for the increase in stress amplitude is the high lattice friction of the intermetallic compound. Similar deformation behaviour at room temperature has been reported by [14, 15] for Ti-48Al-2Cr-2Nb.

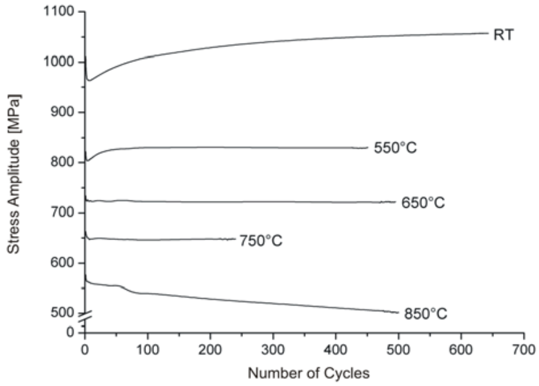

Fig. 4. Stress amplitude vs. number of cycles for TNB-V2, isothermally fatigued in air for various temperatures at $\Delta\varepsilon/2 = 0.7\%$

At 550°C one can again observe a slight hardening, which is more pronounced in the early beginning and then vanishes, though it never disappears completely. This behavior can be attributed to dynamic strain ageing [16]. However, in titanium aluminides this process differs from ordinary alloys. In titanium aluminides dynamic strain ageing is caused by an interaction between dislocations and point defects consisting of vacancies and so-called titanium antisites, i.e. titanium atoms situated in the Al-sublattice. This effect is especially pronounced at an Al-concentration of 45 at.-% [17], as is the case for TNB-V2.

At 650 and 750°C dynamic strain ageing vanishes again and one observes distinct saturation of the stress amplitudes. In this temperature regime deformation is determined by dislocation glide and climb [18]. The test conducted at 850°C reveals a continuous softening. TEM examination of this sample has revealed that the material exhibits a degradation of the lamellar morphology combined with dynamic recrystallisation [13].

Appel [19] has noted that mechanical twinning plays a major and complex role in the plastic deformation and fracture of titanium aluminide alloys. The mechanism apparently compensates for the lack of independent slip systems that can operate simultaneously at a given stress. In γ-TiAl twinning can be supported by alloying with niobium. Crack tip shielding due to mechanical twinning might be a toughening mechanism occurring at the atomic scale, which is able to stabilize fast-growing cracks. Figure 5 shows the formation of twins (indexed T) and pseudo-twins (indexed P), i.e. twins that destroy the ordered L_10-structures of γ-TiAl, in the wake of a fatigue crack.

2.3. Isothermal Fatigue Behavior in Vacuum

In order to characterize the influence of environmental effects on the fatigue performance of the two materials, additional LCF tests were conducted in vacuum. Results of the respective fatigue lives in air and vacuum are given in table 2.

As Peters et al. [20] have shown in oxidation tests on Ti6242 at elevated temperatures, mass gain caused by oxidation becomes noticeable at temperatures exceeding 450°C. In this study it was found that fatigue life at 350°C in vacuum is shorter than in air. At higher temperatures life in vacuum is considerably longer if compared to life in air. The shorter "vacuum life" at 350°C is probably due to the fact that oxidation induced crack closure cannot occur. The lives observed in vacuum at 450 and 550°C result from the absence of oxidation and the fact that the material becomes softer towards higher temperatures, i.e. the decrease in stress amplitude outweighs the increase in plastic strain amplitude. At 650°C life becomes smaller again; the reason for this might be the change in slip mode that has been described in section 2.1. The life in vacuum at 650°C is much longer than in air indicating strong environmental effects.

Microstructural investigations of the fracture surfaces of the specimens fatigued in vacuum have revealed pores inside the material [21]. This observation is in accordance to that made by Hoffmann et al. [22]. The pores probably result from the extended testing times and may eventually lead to a shift of the crack initiation site from the surface to the bulk.

For titanium aluminides, Hotta et al. [23] have found in oxidation tests on an Ti-44Al-7Nb-0.2C fully lamellar alloy that the tensile fracture stress does not show any significant loss up to 800 K (627°C). At higher temperatures environmental embrittlement becomes more apparent. As the alloy in [23] has got a similar chemical composition and microstructure, temperature may influence fatigue life in a similar fashion. Indeed, it was found that at 550°C life in vacuum is shorter than in air; whereas a significant increase is found in the ratio of lives observed in vacuum and air, table 2.

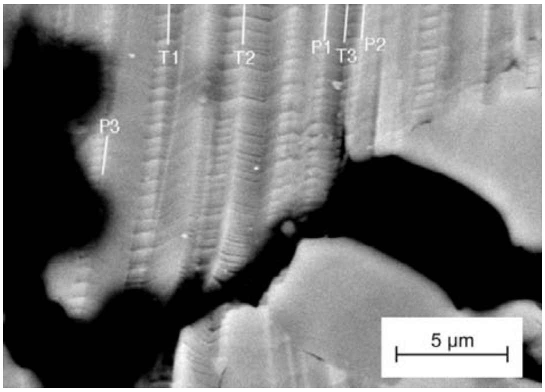

Fig. 5. Formation of twins (T) and pseudo-twins (P) in TNB-V2 formed after LCF at 550°C; (indexing performed by F. Appel)

Table 2. Results of isothermal LCF tests in air and vacuum, $\Delta\varepsilon/2$ = 0.7%, R_ε = -1

Material	Temperature [°C]	$N_{f,\,air}$	$N_{f,\,vac}$	$N_{f,\,vac} / N_{f,\,air}$
Ti6242	350	5483	3699	0.67
	450	2584	3272	1.27
	550	2407	5445	2.26
	650	1135	5098	4.49
TNB-V2	550	452	320	0.71
	650	496	2015	4.06
	750	241	2056	8.53
	850	501	1371	2.73

2.4. Thermomechanical Fatigue Behavior of TNB-V2

TMF is found in many areas of engines. The example given in figure 6 illustrates the influence of TMF loading conditions on a hollow turbine blade. At the outside surface compressive stresses arise during operation at high temperature as expansion is constrained because of the cooler interior, i.e. maximum temperature and minimum load coincide and vice versa. This is referred to as "out-of-phase" TMF (OP-TMF). The opposite relationship between temperature and load can be found at the inside surface, where contraction of the material is impeded because of the hotter outside, i.e. maximum (local) temperature and maximum load are in-phase (IP-TMF). Because of changing material properties at different temperatures the hysteresis loops are shifted either to tensile mean stresses (OP condition) or compressive mean stresses (IP condition).

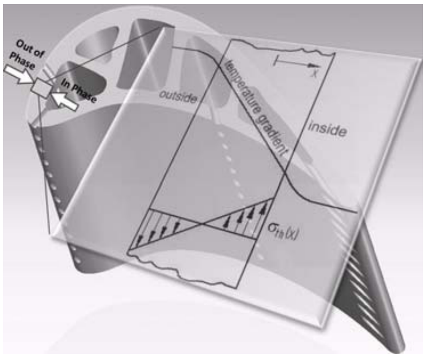

Fig. 6. Illustration of thermomechanical loading conditions in a turbine blade

Figure 7 indicates that there is a tremendous effect of mean stress on life during TMF testing. The example displayed represents peak and valley stresses during cyclic loading at $\Delta\varepsilon/2 = 0.7$ % and $\Delta T = 650\text{-}850°C$ of TNB-V2. During in-phase loading, the asymmetry in absolute values of peak and valley stresses leads to a continuous build-up of compressive mean stresses, having a beneficial influence on life (at half life maximum and mean stress of the IP-test depicted in figure 7 were $\sigma_{max} = +175$ *MPa* and $\sigma_{mean} = -265$ *MPa*, resp.). Under OP loading, however, tensile mean stresses are imposed on the material, which lead to sudden failure ($\sigma_{max} = +835$ *MPa* and $\sigma_{mean} = +220$ *MPa*). In addition, environmental attack is strongly promoted in OP-mode. In the example given in figure 7, fracture occurred already after 16 cycles. When the OP-test is conducted in vacuum a pronounced increase in life can be observed (thin lines). Thus, not only maximum and mean stress but also the environment exhibits a strong influence on fatigue life. Table 3 summarizes the TMF number of cycles until failure observed using a temperature interval of $\Delta T = 200°C$. IP life data fall within the scatter bands observed for isothermal LCF, an observation that holds true for near-α titanium alloys as well [1, 24]. A more detailed description of the TMF-behaviour of TNB-V2 is given in [2] and similar results on the TMF behavior of various TiAl alloys can be found elsewhere [25-27].

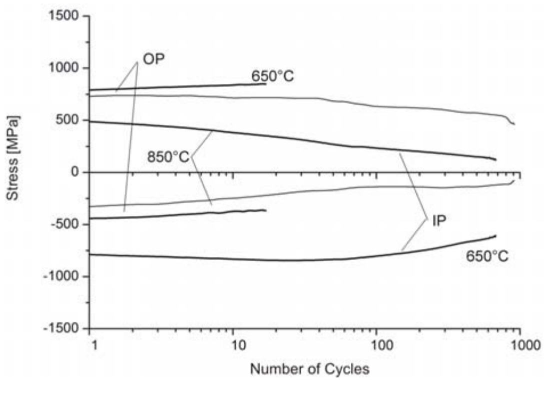

Fig. 7. Development of minimum and maximum stresses vs. number of cycles under OP and IP TMF conditions in air (bold lines) and vacuum

Table 3. Thermomechanical fatigue lives of TNB-V2 in temperature intervals of ΔT = 200°C

Temperature interval	550-750°C	650-850°C
IP_{air}	515 cycles	676 cycles
OP_{air}	16 cycles	17 cycles
OP_{vacuum}	180 cycles	911 cycles

2.5. Comparison of Both Alloys and Fatigue Life Estimation

One interesting observation made is that the influence of temperature on fatigue life of TNB-V2 is not as clear as in the case for Ti6242. Figure 8 depicts the testing temperature versus the number of cycles until failure for both alloys in air. In the case of Ti6242 a slow and monotonic decrease of life occurs with rising temperature. For 550 and 650°C fatigue life data exists of both alloys can be compared. It becomes obvious that even at 650°C life of Ti6242 is still about twice as large as of TNB-V2; a similar factor is observed for tests in vacuum at 650°C, cf. table 2.

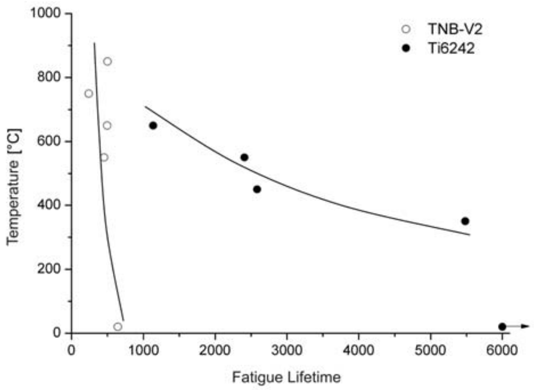

Fig. 8. Temperature versus fatigue life for Ti6242 and TNB-V2 under identical testing conditions ($\Delta\varepsilon/2$ = 0.7%), room temperature test of Ti6242 was stopped after 40,000 cycles

The experimental results of tests under various strain amplitudes at 550°C form the basis for a fatigue life description model based on the Basquin-Coffin-Manson law

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f}{E}\left(2N_f\right)^{-a} + \varepsilon_f\left(2N_f\right)^{-b} \quad (1)$$

where $\Delta\varepsilon/2$, $\Delta\varepsilon_e/2$ and $\Delta\varepsilon_p/2$ are total, elastic and plastic strain amplitude, respectively, σ_f and a are fatigue strength coefficient and exponent, respectively, E is elastic modulus, N_f is number of cycles until failure, ε_f and b are fatigue ductility coefficient and exponent, respectively.

In order to describe the fatigue life as a function of the strain amplitude applied, the parameters of the Coffin-Manson and Basquin equations have been calculated. The values are given in table 4, a comprehensive discussion can be found in [21].

Table 4. Basquin-Coffin-Manson parameters of Ti6242 and TNB-V2

Material	Temperature [°C]	σ_f [MPa]	E [GPa]	a	ε_f	b
	350	2687.0	97	0.171	103.514	1.275
Ti6242	450	2626.5	91	0.187	649.531	1.532
	550	1695.5	84	0.162	1.080	0.756
TNB-V2	550	1424.8	146	0.101	0.026	0.527

The predictive capability of the values calculated can be estimated by plotting the calculated fatigue life data is plotted versus the observed lives. For Ti6242 it can be seen that the calculated lives correspond nicely to the experimental values and form a narrow scatter band, representing a maximum deviation of a factor of 1.5, figure 9a. In the case of TNB-V2, a scatter band with a factor of 4 is necessary to envelop all test results, figure 9b.

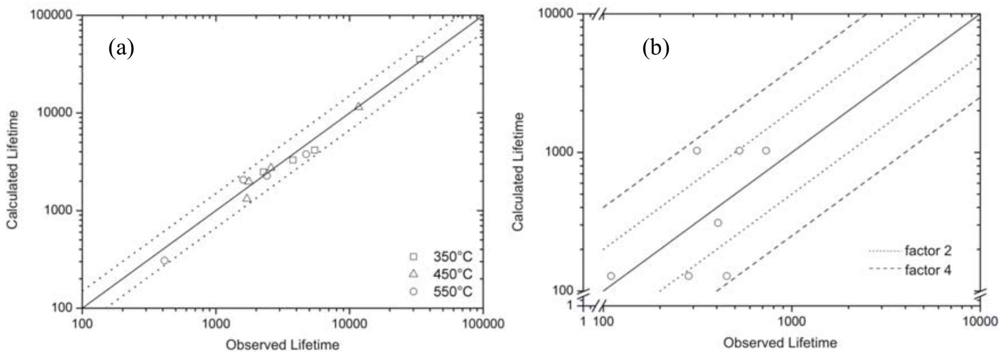

Fig. 9. Calculated LCF lives vs. observed values; (a) Ti6242 – all results fall within a scatter band of 1.5; (b) TNB-V2 – data points taken at 550°C

Based upon the Basquin and Coffin-Manson parameters obtained, strain versus life curves for both alloys at 550°C can be drawn, figure 10. It becomes evident that the amount of plastic strain amplitude in case of the intermetallic alloy is very small. The transition life (i.e. the number of cycles to fatigue where plastic and elastic strain are identical) at 550°C was found to be just 4 for TNB-V2, while it is 409 for Ti6242. As the slope of the strain amplitude versus fatigue life in the case of TNB-V2 is very flat, small deviations in strain amplitude will have a large influence of fatigue life. This may explain the enormous scattering of lives shown in figure 9b.

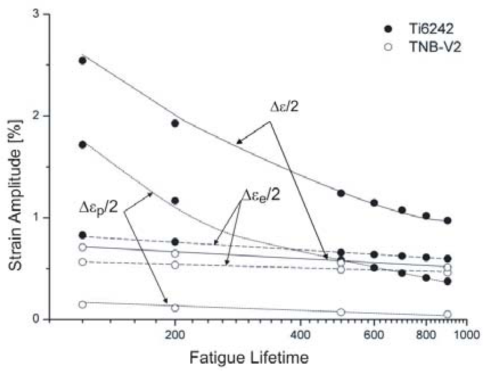

Fig. 10. Strain versus fatigue life curves of Ti6242 and TNB-V2 at 550°C

3. Summary and Conclusions

Both alloys investigated, Ti6242 and TNB-V2, exhibit different slip mechanisms at different temperatures, having a visible influence of the stress amplitude under strain-controlled fatigue conditions. This behavior is summarized in table 5.

Vacuum tests have clearly demonstrated the damaging contribution of air to fatigue life. For Ti6242 the negative influence of air on the fatigue performance becomes apparent at 450°C, whereas for TNB-V2 this temperature lies at about 650°C. The materials' properties are even more severely affected by a combination of air and tensile mean stresses, which occurs during TMF-OP.

A simple fatigue life description based on the equations of Basquin and Coffin-Manson is suitable for Ti6242 over a wide range of temperature. A reduction in life at higher temperatures is mainly caused by increased oxidation. When the homologous temperature exceeds 0.4, creep will contribute to a further loss in fatigue life. The predicted isothermal fatigue lives were found to agree to the experimental data within a scatter band of 1.5. However, due to the small plastic strain amplitude involved in the low cycle fatigue of TNB-V2, the Coffin-Manson law is not suitable. In this alloy the crack propagation phase is always very small as compared to the crack initiation phase. This may explain the scatter in fatigue life.

Table 5. Temperature-dependent dislocation slip behavior of Ti6242 and TNB-V2 during strain-controlled LCF, in addition the change in stress amplitude during cycling is given (increasing stress amplitude: "+"; decreasing: "–"; constant: "=")

Temperature interval	Ti6242	$\Delta\sigma/2$	TNB-V2	$\Delta\sigma/2$
RT	cutting of coherent precipitates (Ti_3Al)	–	dislocation locking caused by dense arrangement of strong obstacles, high lattice friction	+
I	350/450°C: dynamic strain ageing, interaction between solute Si atoms and dislocations	+	550°C: dynamic strain ageing, interaction between Ti_{Al} antisites and dislocations	+/=
II	550°C: precipitates may recover	=	650/750°C: dislocation climb	=
III	650°C: cross slip and climb, coarsening of incoherent precipitates	–	850°C: degradation of lamellar microstructure	–

Acknowledgments

Financial support of this work by Deutsche Forschungsgemeinschaft is gratefully acknowledged. The authors would also like to thank their project partner for providing the material and performing complementary investigations (Dr. F. Appel and his research group, GKSS Research Centre, Geesthacht, Germany).

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