COMPARING FATIGUE BEHAVIOUR OF TI6242 AND A NOVEL TIAL INTERMETALLIC

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ABSTRACT

In the present study the fatigue behaviour of the commercial near-alpha titanium alloy Ti6242 and the novel gamma-TiAl alloy TNB-V2 was investigated and compared. Ti6242 is the most widely used near-alpha titanium alloy in the high-pressure compressor of civil jet engines. Although near-alpha titanium alloys feature a good mechanical capability up to temperatures of 650°C, which represents the current compressor outlet temperature, the current maximum service temperature is restricted to 540°C because of the potential risk of titanium fire and insufficient oxidation behaviour. Therefore, it is necessary to revert to heavy Ni-base superalloys in the last stages of high-pressure compressors. The latest developed gamma-TiAl alloys like TNB-V2 exhibit superior mechanical properties compared to those of previous generations. The increase in strength, ductility and oxidation resistance is caused by a relatively high content of niobium (5-10 at%). This class of TiAl holds the potential to fill the gap to the design of an all titanium-based compressor, which would reduce weight and thus increase efficiency of jet engines. Therefore it is essential to assess fatigue properties of this novel alloy and compare it to the different behaviour of Ti-based alloys. Isothermal as well as thermomechanical tests were conducted in both, laboratory air and vacuum environment. Tests were conducted in strain control (total and plastic) under symmetric push-pull conditions. Temperature ranged from 350 to 650°C for Ti6242 and from 550 to 850°C for TNB-V2. Investigations covered also the influence of recrystallisation temperature on the microstructure of Ti6242.

Introduction

Since 1950 fuel burn of civil jet engines has been reduced by some 70%. This effect is mainly based on the introduction of advanced engineering materials and concepts leading to better efficiencies. Between 1990 and 2012 it is expected that carbon dioxide emissions per passenger kilometre will be reduced by 64%. Again, this decline bases on the application of new alloys, e.g. organic matrix composites (OMC) for fans or TiAl intermetallics in the compressor or turbine machinery [1].
TiAl intermetallics have come a long way since their beneficial mechanical properties (specific strength, creep resistance) were first discovered and their shortcomings (brittleness, fracture toughness) have been reduced to acceptable limits. The latest developed TNB alloys, containing a high content of niobium (5-10 at%), can be considered as engineering alloys. They have got the potential to fill the gap where conventional near-alpha titanium alloys such as Ti6242 loose their superiority in specific strength (above 650°C) and where nickel base superalloys like IN718 are unfavourable because of their high density (below 850°C). Especially in the final stages of civil jet engine compressors there is a “competition” between titanium and nickel alloys at temperatures around 600°C. Implementation of TiAl intermetallics might be the optimum solution.

Although many investigations on TiAl concentrate on oxidation and creep behaviour, only few studies deal with fatigue behaviour. However, fatigue data has to be assessed to allow failsafe operation.

Materials Studied

Ti6242 was delivered as forging stock from TIMET. Cylindrical specimens were produced via electrical discharge machining (EDM). Subsequently they were heat treated and finally turned with a gauge length of 16mm and a diameter of 8mm. The chemical composition is given in Table 1.

TABLE 1. Chemical Composition of Ti6242 in wt% (at%)

Ti	Al	Sn	Zr	Mo	Si
bal.	5.9 (10.4)	2.0 (0.8)	3.9 (2.0)	2.0 (1.0)	0.1 (0.2)

Heat treatment consisted of two steps, a recrystallisation annealing for one hour and a subsequent stabilisation annealing for eight hours. After both steps specimens were air-cooled. The recrystallisation annealing temperature was chosen with respect to the beta transus temperature (T_β) which lies at 995°C + 15°C according to TIMET. In order to receive a bi-modal microstructure, which is recommended for applications in jet engines [2, 3], containing a primary alpha volume of 30% an annealing temperature of T_β-15°C was chosen for LCF and TMF specimens. The bi-modal microstructure yields a good balance between creep and fatigue properties. In order to define the annealing temperature precisely, the influence of the recrystallisation annealing temperature on the primary alpha volume fraction was varied systematically. Exact recrystallisation temperatures are listed in the paragraph below. All specimens were subsequently annealed at 595°C for eight hours for stabilisation. The microstructure for the LCF and TMF specimens is shown in fig. 1a.

The TNB alloys were provided and fully heat-treated by GKSS research centre in Geesthacht, Germany. The chemical composition is given in table 2.

TABLE 2: Chemical Composition of TNB-V2 in wt% (at%)

Ti	Al	Nb	C
bal.	24.3 (45.6)	15.0 (7.8)	0.05 (0.2)

Final heat treatment consisted of recrystallisation annealing at 1300°C for 30 minutes followed by air-cooling and finally stabilisation annealing at 800°C for six hours followed by furnace cooling. The nearly lamellar microstructure of TNB-V2 is depicted in fig. 1b.

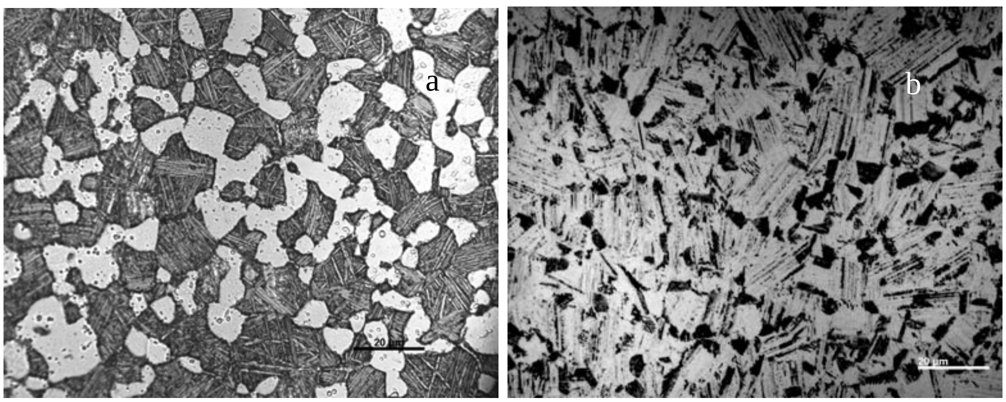

FIGURE 1. a) Microstructure of Ti6242, b) Microstructure of TNB-V2

TNB alloys belong to the 3rd generation of gamma-TiAl. The high amount of Nb (5-10 at%) of the alloys of this 3rd generation enhances the majority of the material properties [4-7]. Nb substitutes Ti atoms and increases the number of slip systems. Carbon is another important alloying element in TNB alloys. Carbon precipitates can impede dislocation glide and can thus yield better creep performance at elevated temperatures [5]. Both, carbon and niobium additions contribute to athermal dislocation mechanisms [5, 6]. The nearly lamellar microstructure shown in fig. 1b is a compromise between acceptable ductility, creep resistance and fracture toughness. TNB-V2 specimens had a 7 mm gauge diameter and gauge length of 14 mm. This small reduction in size as compared to the Ti6242 specimens was done in order to avoid too large forces upon testing.

Experimental

Heat treatment on Ti6242 was conducted on 10mm thick rods of a diameter of 13mm. Specimens were heat treated in the $\alpha+\beta$ phase field at 1000°C, 995°C, 990°C and 985°C, followed by stabilisation annealing at 595°C. Specimens then were embedded, grinded polished and etched with Kroll's solution (2% HF, 2% HNO_3, 96% H_2O). Determination of primary alpha volume was accomplished using a Zeiss optical microscope using a phase analysis programme (Axio Vision Multiphase 3.1). Comparing the results with those of the literature [8-12], a good accordance was received, fig. 2. With the results obtained a beta-transus temperature of 1006°C was determined.

Fatigue tests were carried out on a MTS servohydraulic test system. Ti6242 specimens were tested in the temperature range of 350-650°C. LCF tests were carried out, both, in total ($\Delta\varepsilon_t/2$=0.7%) and plastic ($\Delta\varepsilon_p/2$=0.2%) strain control applying a triangular command signal. Temperature was measured and controlled using a calibrated thermocouple attached to the centre of the gauge length. Elevated temperatures were generated using induction heating. Fracture surface was examined using SEM. LCF tests were conducted with the MTS programme Advanced Cyclic Fatigue, which enables to control the tests with peak/valley values for both, total and plastic strain amplitude.
In-phase (IP) and out-of-phase (OP) TMF tests were controlled with MTS Multi Purpose Testware. Control signal for TMF tests was plastic strain at a constant amplitude ($\Delta\varepsilon_p/2$=0.2%) and a temperature interval ΔT=650-350°C. TMF tests were always started at the mean temperature and at zero strain. In IP tests the peak and valley values of both, plastic strain and

temperature coincide, whereas in OP tests there is a 180° phase shift, i.e. the peak plastic strain coincides with the valley temperature and vice versa, fig. 3.

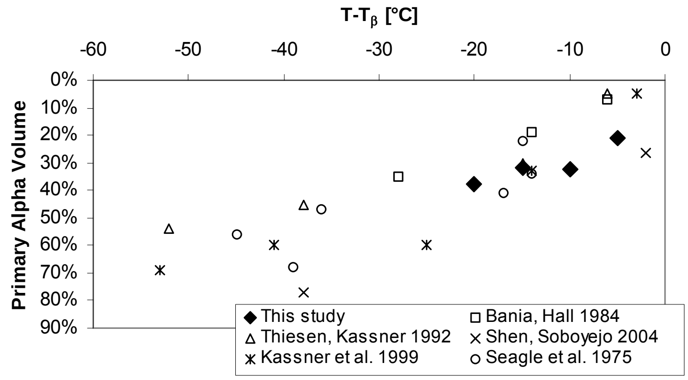

FIGURE 2. Primary alpha volume of Ti6242 versus difference to beta-transus temperature (T_β=1006°C)

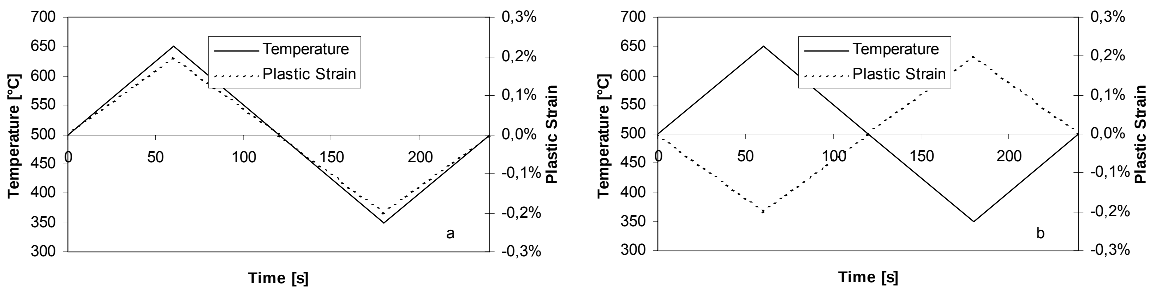

FIGURE 3. Command Signals for TMF tests on Ti6242, a) in-phase, b) out-of-phase

The plastic strain, which cannot be measured directly, was calculated continuously from the total strain ε_t and the stress σ according to the following equation, which was incorporated into the programme:

$$\varepsilon_p = \varepsilon_t - \frac{\sigma}{E(T)} - \varepsilon_{th} \tag{1}$$

where

$E(T)$ = temperature dependent Young's modulus
ε_{th} = thermal expansion

In order to provide ε_{th} during the TMF cycle, the coefficient of thermal expansion was measured by running a thermal cycle at zero load prior to each TMF test. The Young's modulus was described by a linear function of temperature and was adapted during testing, in order to ascertain that the elastic parts of the of the plastic strain hysteresis loop are parallel to the stress axis. An example of the accuracy achieved is given in fig. 4.

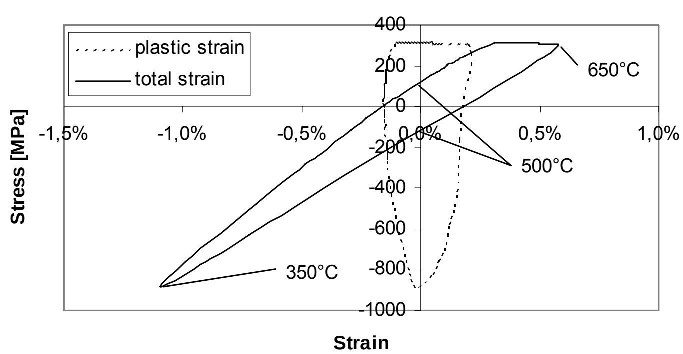

FIGURE 4. Plastic and total hysteresis loops of an in-phase TMF test on Ti6242 at half-life under plastic strain control ($\Delta\varepsilon_p/2$ = 0.2%)

In the case of TNB-V2 a ribbon type thermocouple was attached and fixed with a ceramic paste. LCF tests were carried out under total strain control ($\Delta\varepsilon_t/2$ = 0.7%) at temperatures between 550 and 850°C.

Results and Discussion

Since near-alpha titanium alloys are mostly investigated with regard to creep properties, only little information about their fatigue behaviour at elevated temperatures is accessible [13-17]. Results obtained on Ti6242 tested under total strain control at a strain amplitude of 0.7% between 350 and 650°C are illustrated in fig. 5.

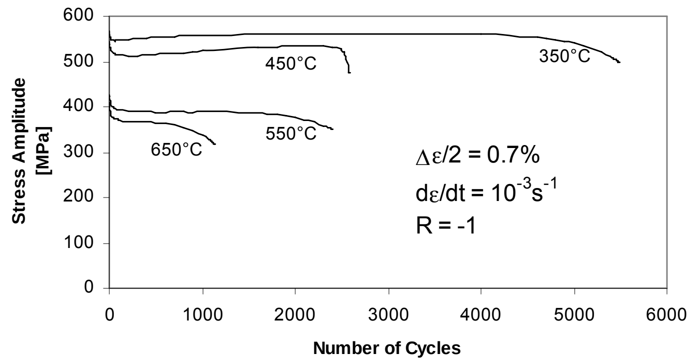

FIGURE 5. Stress amplitude vs. number of cycles of Ti6242 at elevated temperatures

It can clearly be seen from fig. 5 that at all temperatures the material shows softening in the beginning, which is followed by cyclic saturation until a fatal fatigue crack starts growing. The larger the temperature the more pronounced is the initial cyclic softening. While increasing temperature fatigue lifetime becomes less, despite the significant reduction in stress amplitude. This behaviour is probably due to strong environmental effects. An additional test conducted at room temperature is not represented in fig. 5 since it did not fail after some 40,000 cycles. The observed emerging saturation stress amplitude at ambient temperatures under total strain amplitude control ($\Delta\varepsilon/2$ = 0.7%) was smaller than the static yield strength ($\Delta\sigma/2$ = 750 MPa compared to $R_{p0.2} \approx$ 900 MPa, according to the manufacturer). LCF tests on Ti6242 in vacuum are just underway. However, a first test conducted at 650°C revealed qualitatively the same cyclic stress-strain behaviour, i.e. a slight softening in the beginning, followed by saturation and finally a drop in stress amplitude as the fatigue crack has passed its critical threshold. The fatigue lifetime of the specimen tested in vacuum was 5,089 cycles, thus it lasted almost five times longer than the specimen tested in laboratory air. This result can be considered as a strong indicator for environmental effects. A slight increase in the stress amplitude of the vacuum test (415 MPa compared to 360 MPa) is probably due to an increase in strain rate in order to keep the vacuum test in suitable time (strain rate for vacuum tests is ten times larger than the one for air tests).

In addition to LCF tests under total strain control, also the LCF behaviour of Ti6242 under plastic strain control ($\Delta\varepsilon_p/2$ = 0.2%) was investigated. As shown in fig. 6 the plastic strain amplitude at room temperature leads to a finite LCF life. It is also obvious that the material is softening throughout fatigue lifetime at room temperature. At 350°C and 450°C the material reaches the state of saturation immediately, whereas at 650°C a softening was detected. This material behaviour is in excellent accordance with the one observed for IMI 834 [13].

The slight hardening at 350 and 450°C during the test was also reported earlier [13]. Fatigue lifetime of the tests at 350 and 450°C in fig. 6 is smaller than shown in fig. 5, whereas at 650°C almost identical fatigue lifetimes were established. The reason for this is that the evolving plastic strain amplitude of the tests represented in fig. 5 at test temperatures below 650°C is smaller than the applied plastic strain amplitude of the tests shown in fig. 6. At 650°C a total strain amplitude of $\Delta\varepsilon/2$ = 0.7% roughly corresponds to a plastic strain amplitude of $\Delta\varepsilon_p/2$ = 0.2%.

TMF tests on Ti6242 in the range of 650°C to 350°C had to be conducted in plastic strain control, since in total strain control material hardening was observed, which exceeded the capacity of the load cell. The results obtained from the TMF tests on Ti6242 are given in fig. 7.

Upon IP loading the material is continuously hardening throughout lifetime, leading to compressive mean stresses. The comparison of peak stress at 650°C of the IP-TMF cycle with the stress amplitude in fig.6 shows that both, magnitude and slope, are in good accordance. However, comparing the stress-strain-response at 350°C in figs. 6 and 7 it becomes obvious that the continuous hardening in the OP-TMF test is much more pronounced. From fig. 7 it can also be seen that an OP loading is by far more detrimental than an IP loading. This type of material behaviour is classified as “type O behaviour”, according to [18], where the environmental influence at peak temperatures is the limiting factor for a component’s fatigue lifetime. Fatigue lifetime of the IP-TMF test is similar to the lifetime observed at 650°C under isothermal conditions.

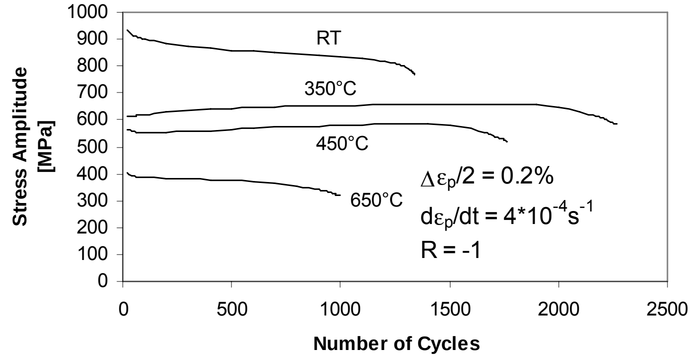

FIGURE 6. Stress amplitude vs. number of cycles of Ti6242 under plastic strain control

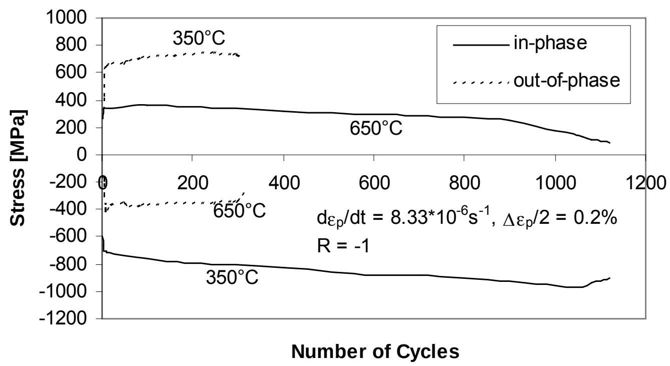

FIGURE 7. Peak and valley stresses of TMF tests on Ti6242

LCF tests on the gamma-TiAl alloy TNB-V2 were carried out under total strain amplitude control ($\Delta\varepsilon/2$ = 0.7%). Previous investigations [19-21] did not apply such large amplitudes. Tests were conducted at temperatures between 550°C and 850°C. The cyclic stress behaviour for various temperatures is shown in fig. 8.

No definite conclusions regarding fatigue lifetime vs. temperature can be drawn from fig. 8. Some authors [19-21] previously argued that fatigue lifetime is increasing with rising temperature until the material has reached the ductile to brittle transition temperature (DBTT, approx. 830°C according to [5]). Above DBTT a decrease was observed. This reverse temperature-lifetime relationship was only observed at very small strain amplitudes (maximum of $\Delta\varepsilon/2$ = 0.3%). Below 850°C the material reaches a state of saturation immediately, at 850°C a continuous softening is present, which indicates that this temperature is above DBTT.
One explanation for fatigue lifetime vs. temperature behaviour might be that oxidation induced degradation below 750°C does not deteriorate the mechanical properties and that above 750°C the increase in ductility allows similar fatigue lifetimes despite increasing oxidation.

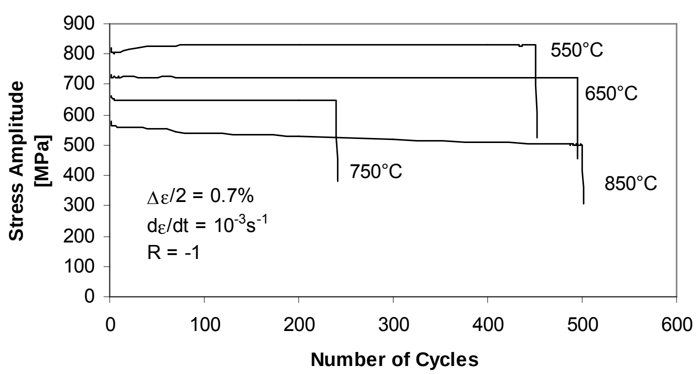

FIGURE 8. Stress amplitude vs. number of cycles of TNB-V2

Comparing stress amplitude for both materials, Ti6242 and TNB-V2, it is very evident that, at constant total strain amplitude, the gamma-TiAl alloy is superior by a factor of two at 550°C and 650°C to the near-alpha titanium alloy, fig 9.

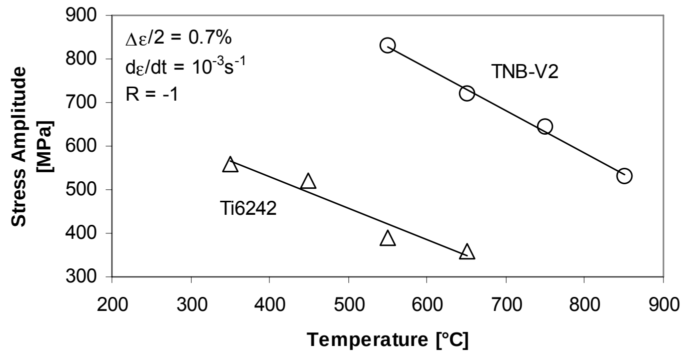

FIGURE 9. Comparison of stress vs. temperature of TNB-V2 and Ti6242

Since engineering components for compressor applications are exposed to smaller strain amplitudes than those used in the isothermal tests, TNB-V2 alloys offer the potential for the implementation in next-generation jet engines. Fig. 10 illustrates the development of plastic strain amplitude vs. temperature for both materials.

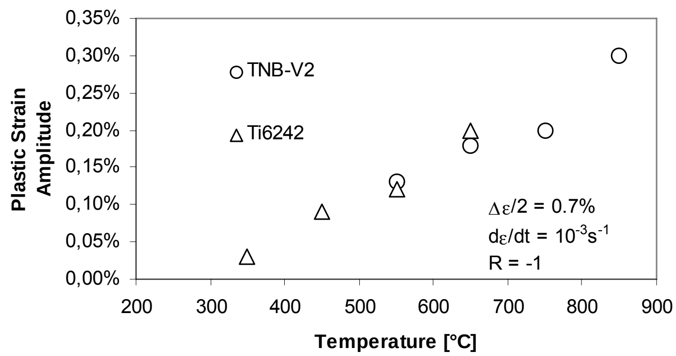

FIGURE 10. Plastic Strain amplitude vs. temperature for Ti6242 and TNB-V2

The values observed at 550 and 650°C for both alloys are almost identical. The increase in plastic strain for Ti6242 is linear, whereas for TNB-V2, there is only a slight increase between 650°C and 750°C followed by a steep increase between 750 and 850°C. This can be interpreted in terms of the transition from brittle to ductile behaviour.
Comparing stress response and fatigue lifetime of Ti6242 and TNB-V2 at 550 and 650°C directly to each other, fig. 11, it is obvious that the stress amplitude ratio ($\sigma_{TiAl}/\sigma_{Ti}$) remains almost constant, whereas the fatigue lifetime ratio ($N_{f,\ TiAl}/N_{f,\ Ti}$) almost doubles. Nevertheless this lifetime ratio remains far below 1.

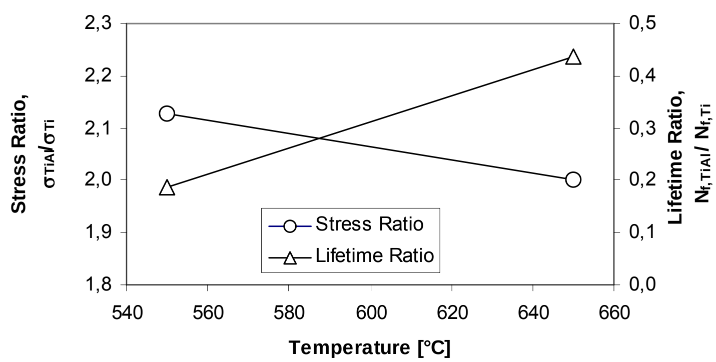

FIGURE 11. Stress and lifetime ratios of TNB-V2 vs. Ti6242

Examination of isothermal fracture surfaces revealed that in Ti6242 fatigue cracks always originated from the surface of the specimen. Fracture morphology between 350°C and 650°C does not change. Cracks mainly propagate along the transformed-β lamellae, since these allow relatively long slip paths. The fatigue cracks observed are of transgranular nature in the temperature regime investigated. Fig. 12a gives a representation of the fracture surfaces observed. No significant differences in the fracture surfaces of isothermal and thermomechanical fatigue tests were observed. Also no differences between IP and OP testing appeared. Fig. 12b shows the fracture surface of the OP test.

In contrast, the fatigue crack nucleation in case of TNB-V2 is not trivial. Since gamma-TiAl alloys exhibit a relatively low fracture toughness, especially at temperatures below DBTT, fatigue cracks may form within the specimen, as has been observed previously [22]. In the case of the isothermal test at 550°C the crack initiation site could not be detected. The jagged fracture surface of this test is shown in fig. 12c. At temperatures between 650 and 850°C the fatigue crack nucleated at the specimen's surface. However, it is difficult to say whether the specimen failed instantaneously once the fatal flaw had emerged or whether there was any crack propagation prior to failure. Fig. 12d (LCF test at 650°C) exhibits some features, which might be interpreted as striations, but cannot be distinguished from broken lamellar colonies. Similar morphologies were observed at 750 and 850°C.

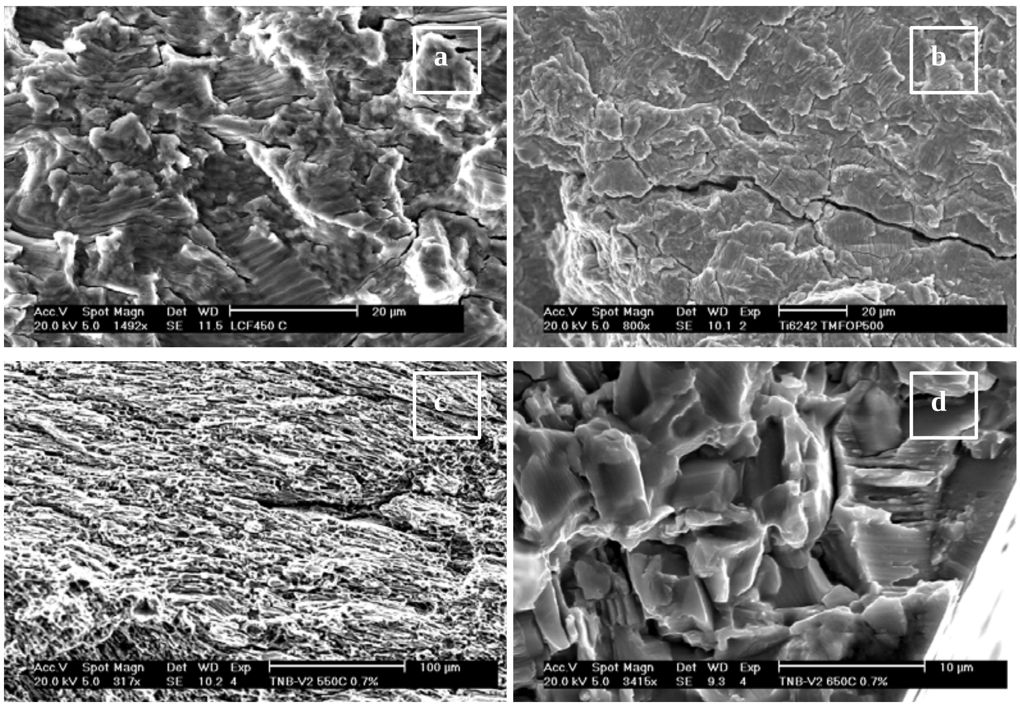

FIGURE 12. Fracture surfaces. a) isothermal test on Ti6242 at 450°C, $\Delta\varepsilon_p/2$ = 0.2%; b) OP-TMF test on Ti6242, 650-350°C, $\Delta\varepsilon_p/2$ = 0.2%; c) isothermal test on TNB-V2, 550°C, $\Delta\varepsilon/2$ = 0.7%; d) isothermal test on TNB-V2, 650°C, $\Delta\varepsilon/2$ = 0.7%

Conclusions

LCF tests at elevated temperatures were performed on a near-alpha titanium alloy (Ti6242) and a gamma titanium aluminide intermetallic (TNB-V2). Comparative testing conditions have revealed that strength of TNB-V2 in the temperature regime investigated is superior to Ti6242. At the same time TNB-V2 shows inferior fatigue lifetime, although the TiAl intermetallic reaches almost 50% of lifetime at 650°C compared to Ti6242. This has to be considered as a remarkable result as TiAl alloys are usually not exposed to such high strain amplitudes applied in the study presented. The increase in plastic strain amplitude for Ti6242 is rather linear, whereas for TNB-V2 a certain threshold could be observed between 750 and 850°C, probably marking the ductile to brittle transition temperature regime. At the test temperatures below 850°C TNB-V2 exhibited a pronounced state of saturation throughout fatigue lifetime, at 850°C, however, a steady softening was observed, which can again be interpreted that at 850°C the material is in the ductile regime. These results are in accordance with the statement that a high niobium content shifts the ductile to brittle transition temperature to higher temperatures.

Investigations on LCF and TMF behaviour of Ti6242 under plastic strain control were supposed to determine whether it is possible to predict TMF behaviour on the basis of isothermal investigations. Results have shown that the hardening, which occurs in the OP test at 350°C, was not predicted by the corresponding isothermal test. Thus, a lifetime prediction model for TMF simply based on LCF tests for Ti6242 cannot be recommended. IP and OP tests show similar fracture surfaces, however an OP loading is more harmful (the IP test lasted almost four times longer than the OP test). At peak temperature (650°C) oxygen can diffuse rapidly and easily along the lamellae into the material where it forms an embrittled subsurface layer. Due to the oxygen induced damage at 650°C in OP testing, flaws can easily emerge along the embrittled lamellae. This will ultimately lead to fatal fatigue crack growth.

It is the incentive of this on-going research project to develop a protective coating for both materials and apply it successfully under fatigue conditions.

Acknowledgments

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