THE EFFECT OF TEMPERATURE AND ENVIRONMENT ON THE FATIGUE BEHAVIOUR OF A THIRD GENERATION γ-TIAL ALLOY

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ABSTRACT

Fatigue tests were performed on a third generation γ-TiAl alloy with duplex microstructure under total strain control at a constant strain rate of $4\cdot10^{-3}s^{-1}$. The total strain amplitude was varied between 0.3% and 0.6% at a strain ratio of R=-1. The tests were performed at temperatures of 550°C, 650°C and 750°C. In order to study the effect of environment, comparative tests at the highest strain amplitude of 0.6% were conducted in vacuum. The fracture surfaces were studied using SEM.

The results of the LCF tests revealed that at the smallest strain amplitude of 0.3% the alloy exhibits the highest fatigue life at all temperatures (>250000 cycles without failure). At the strain amplitude of 0.4% the life was found to increase with increasing temperature. As expected, on further increasing the strain amplitude to higher values of 0.5 and 0.6%, the fatigue life decreased but the drop at 750°C was more drastic. This can by attributed to oxidation induced crack initiation processes which are strongly dependent on strain amplitude. The comparative tests in vacuum at 0.6% displayed an inverse fatigue life behaviour with increasing temperature. The highest N_{vac}/N_{air} ratio was observed for 550°C which was explained based on a superimposed corrosive effect of water vapour and a higher susceptibility to corrosive processes that promoted damage evolution. The fatigue cracks initiated below the surface in this case at the weak spots such as titanium powder particles and coarse γ–grains. A mixed trans- and interlamellar cracking mode was observed under all testing conditions.

1. INTRODUCTION

Intermetallic γ-titanium aluminide based alloys have great potential for application as high temperature structural materials in aerospace and automotive components by virtue of their excellent strength to weight ratio combined with a good creep resistance up to 800°C. Added to this, is their increased oxidation resistance imparted by addition of 2 wt. % Nb [1]. Niobium is known to improve the mechanical properties, especially the ductility and toughness of α_2- and γ-titanium aluminides. It may be mentioned that the density of γ-TiAl based alloy is less than half of the Ni-based superalloys. Furthermore, it should be noted that titanium based intermetallics do not have an inherent tendency to self-ignition "Ti-fire", which is especially important for their use in aircraft engines [2]. The major disadvantage is still admittedly the low ductility at room temperature and the environmental degradation above 700°C [3,4]. Thus, in tensile testing, their elongation at fracture results in the range of 0,5-4% (Fig. 2). In this context not only the composition but also the adjusted microstructure of the alloy plays an important role [5].

2. EXPERIMENTAL

2.1. Material

The material was heat-treated in order to achieve the desired duplex microstructure. The treatment involved the annealing of the alloy at a temperature just below the α-transition temperature for a duration of 45 min followed by furnace cooling at a rate of approximately 5 K/min. The microstructure of the alloy with around 30% volume percent single-phase γ-grains is shown in Fig. 1. As is common with all intermetallics, the γ-TiAl exhibits a Brittle to Ductile Transition Temperature (BDTT) which, for the present material, lies between 650° and 700°C (Fig. 2).

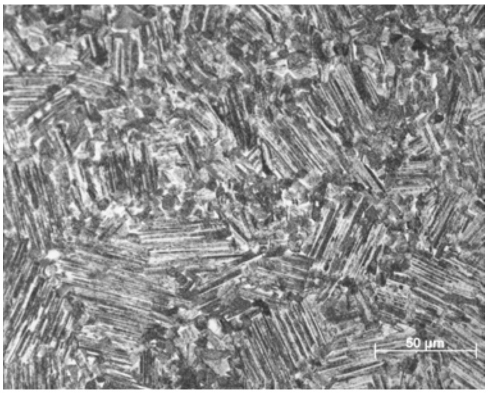


Fig. 1: Adjusted duplex micrstructure with approximately 30% of γ-grains

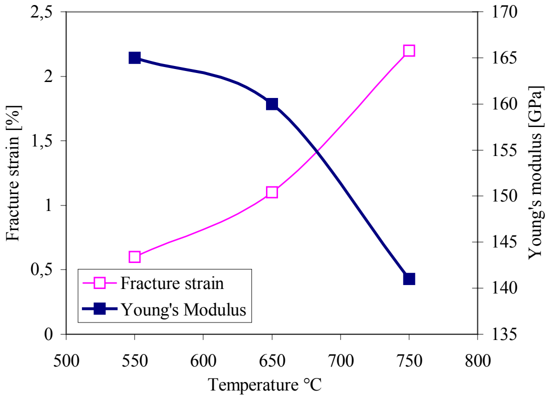


Fig. 2: Tensile properties within the BDTT regime

2.2. *Testing procedure*

The fatigue tests were conducted on solid specimens with a gauge length of 14 mm and a gauge diameter of 7 mm. Since the material is known to be very sensitive to surface irregularities like small notches, turning grooves and probably hardness gradients from machining, the specimens were given an electrochemical polish after the initial mechanical polish. All the tests were performed using a servohydraulic testing system under fully reversed, total axial strain control mode at a constant strain rate of 4×10^{-3} s^{-1}. Tests were carried out at different strain amplitudes in the range of ±0.3% to ±0.6% at temperatures of 550, 650 and 750°C. A high-frequency induction heater was employed for heating the specimens, and temperature gradients within the gauge length were limited to below 5°C. A ribbon-type thermocouple, attached to the test piece by means of a ceramic glue, was used for measuring and controlling the temperature. The fracture surfaces were examined using Philip XL30 SEM.

In order to study the effect of environment, companion tests at the highest strain amplitude of ±0.6% were performed in vacuum environment. The quality of the vacuum that could be attained, varied between 1×10^{-5} and 3.2×10^{-5} hPa.

3. RESULTS

3.1. *Cyclic stress-strain response and fatigue life*

Fig. 3 shows the half-life hysteresis loops and the corresponding cyclic stress response curves obtained from the LCF tests at various strain amplitudes for the alloy at 550°C. The tests conducted at the smallest strain amplitude of ±0.3% resulted in a negligible plastic deformation and yielded long fatigue lives. Because of the prolonged test durations, these tests had to be terminated at 250000 cycles. Other investigators [6,7] have reported lives of less than 10^5 cycles for the earlier versions of titanium aluminide intermetallics even at strain amplitudes of below ±0.3%. With increasing strain amplitude, the hysteresis loops were seen to open up gradually and at $\varepsilon_{tot}/2$ = ±0.6% a plastic strain range of 0.2% was obtained. A noteworthy feature was that the cyclic stress at $\varepsilon_{tot}/2$ = ±0.4% reaches the same level as that at ±0.5% and the stiffness of the specimen according to the hysteresis loops seems to be higher for ±0.4% test than for other specimens. The difference in the stress response can be attributed to the lamellar orientation in the specimen [8] which is preferentially orientated at ϕ=90° to the stress axis. Umakoshi [9] analysed the flow stress anisotropy due to lamellar orientation by considering different structural parameters of the lamellar morphology. The evaluation revealed that the α_2/γ interfaces provide the highest barrier strength when compared with γ/γ interfaces or domain boundaries. The barrier strength of the α_2 lamellae apparently depends on their orientation with respect to the loading axis. This has been referred to the glide anisotropy of the α_2-phase by considering the Schmid factor for prismatic slip. As the lamellae have orientations of ϕ=90°, no prismatic slip could occurs and the pyramidal slip requires very high shear stresses [10,11]. The α_2 lamellae provide the highest glide resistance in this orientation.

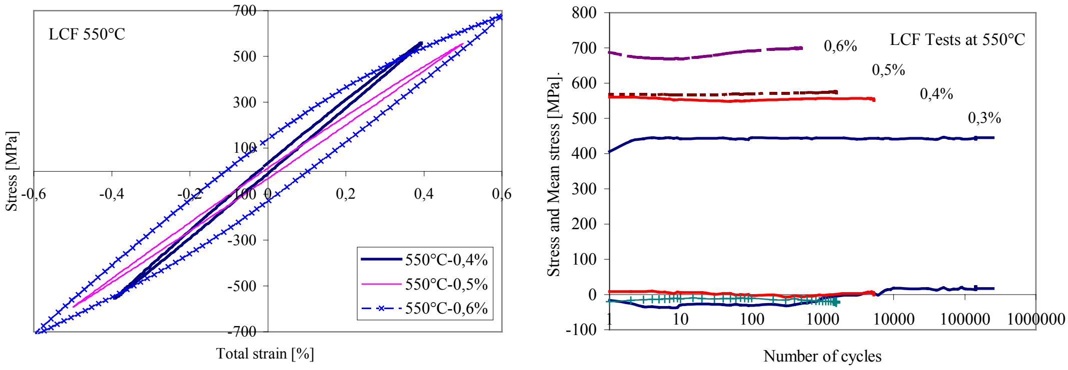


Fig. 3: Half-life hysteresis loops and cyclic stress response curves at different strain amplitudes at 550°C

With an increase of the test temperature to 650°C - which is very close to the BDTT - the plastic strain range increased and the stress response decreased in comparison with that at 550°C (Fig. 4). The plastic strain range for the test at $\varepsilon_{tot}/2 = \pm0.3\%$ remained very low and the test was terminated without failure after 250000 cycles. It is to be noted that at $\varepsilon_{tot}/2 = \pm0.5\%$, the cyclic stress response is very close to that at ±0.6%. This could also be related to an unfavourable orientation of the lamellae to the loading direction [8] as described above.

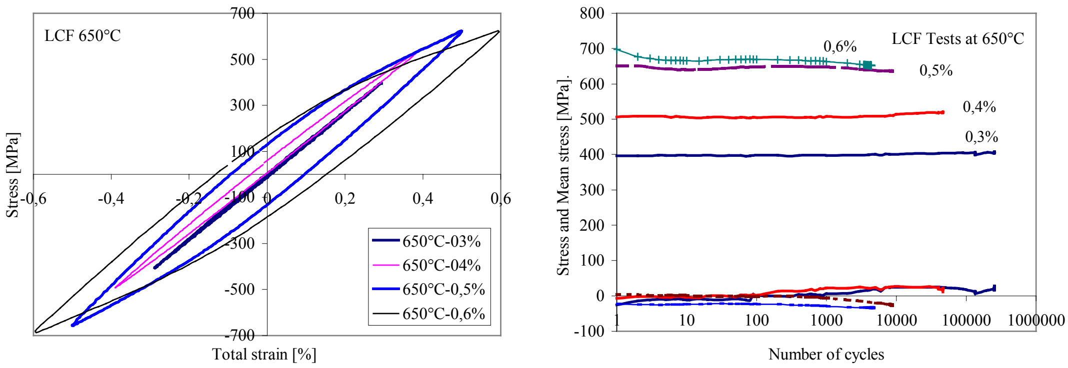


Fig. 4: Half-life hysteresis loops and cyclic stress response curves at different strain amplitudes at 650°C

The results pertaining to the tests at 750°C are illustrated in Fig.5. As can be seen, at the strain amplitude of ±0.3%, the plastic deformation remains negligible leading to high fatigue life of greater than 250000 cycles. A significant plastic strain develops at $\varepsilon_{tot}/2 = \pm0.4\%$ at this temperature due to the strong decrease in the Young´s modulus beyond 650°C. At $\varepsilon_{tot}/2 = \pm0.6\%$, a plastic strain range of nearly 0.4% was noticed. These values are comparable with those reported for Waspaloy [12] at 650°C. Referring to the cyclic stress response curve (Fig. 5), it can be seen that with the progress of cycling, the material slightly softens due to the occurrence of thermally driven microstructural changes that take place at higher temperatures. At lower temperatures of below 650°C, the deformation in the two-phase γ-TiAl alloy takes place mainly in the γ-phase due to the high yield strength of the α_2-phase [8,5,13]. At high temperatures, the formation of deformation twins, dynamic recrystallization and recovery processes may occur [14, 15]. In the Nb-alloyed materials the dynamic recrystalization processes are unlikely to occur, because of the higher activation energy [15], and therefore recovery processes as a result of dislocation climbing at higher temperatures are assumed to operate. To clarify the reasons for these phenomena, further microstructural investigations are necessary.

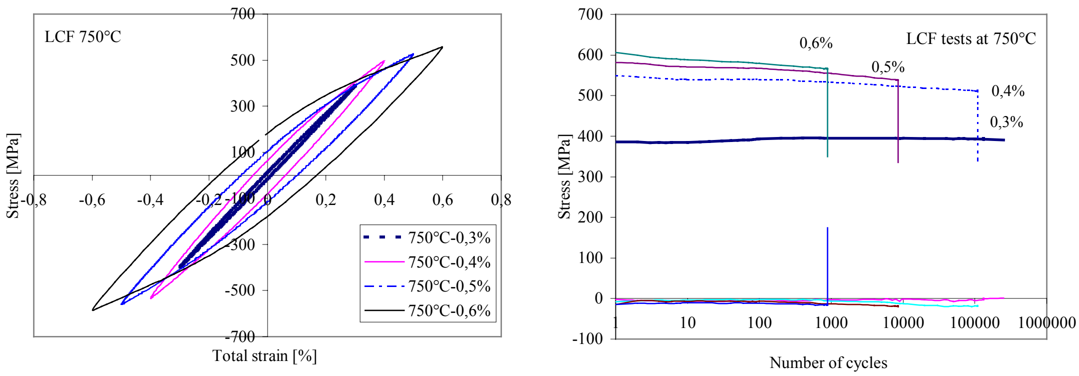


Fig. 5: Half-life hysteresis loops and cyclic stress response curves at different strain amplitudes at 750°C

In Figure 6, the fatigue life as a function of temperature at different strain amplitudes is plotted. It can be noticed that at $\varepsilon_{tot}/2 = \pm 0.4\%$, the life increases with increasing temperature. This behaviour was also observed by Christ et al. [7] in tests at $\varepsilon_{tot}/2 = \pm 0.28\%$. Because of the opposite behaviour in vacuum, the authors attributed the lower fatigue life at lower temperatures to the superimposed corrosive effects of water vapour and a higher susceptibility to corrosive processes that

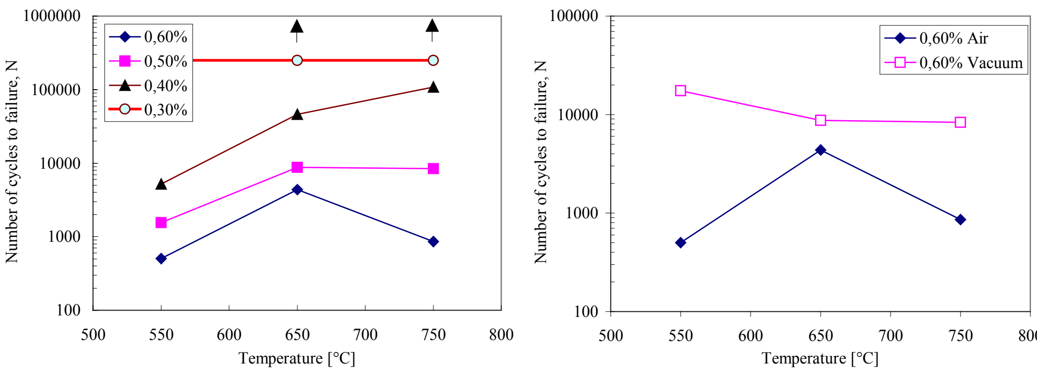


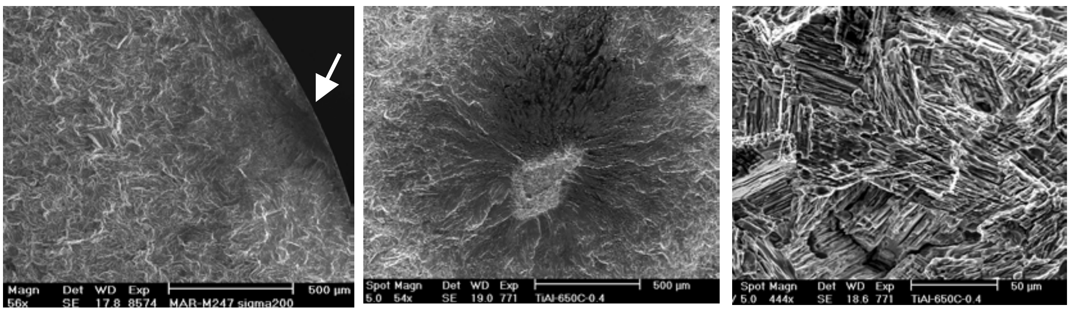
Fig. 6: Relationships among fatigue life, temperature and total strain amplitude in air and vacuum

promote crack initiation and propagation. However, considering the life data at $\varepsilon_{tot}/2 = \pm 0.5\%$, it can be seen that fatigue life at 750°C is nearly the same as that at 650°C. With further increase of the strain amplitude to ±0.6%, the life at 750°C is even lower than that at 650°C. Because below the BDTT the fatigue life increases with temperature for all strain amplitudes, the similar fatigue damage mechanisms can be assumed at these temperatures. Above 650°C a strong oxidation effect, which obviously depends on the applied plastic strain range, may explain the sharp reduction in life with increasing temperature.

In Figure 6 the fatigue lives in air and vacuum are plotted versus the test temperature for a total strain amplitude of ±0.6%. It can be seen that fatigue life in vacuum decreased with increasing temperature as reported in [7]. However, the high N_{vac}/N_{air} ratio (>100) as found in reference [7] could not be observed because of the fatigue-dominated damage occurring at higher plastic strain range that developed at $\varepsilon_{tot}/2=\pm 0.6\%$ and an apparently better oxidation resistance of the material.

3.2. *Fracture surface observation*

Regarding the fracture surfaces two types of crack initiation and propagation were detected. Most of the fatigue cracks were formed on the surface of the specimens, as seen in Fig.7a. However, some sub-surface initiation was also noticed, Fig.7b. EDAX analysis revealed that such cracks originated from large titanium powder particles that formed during the sintering and processing of the alloy. The crack initiation inside the material occurred at temperatures below DBTT for lower strain amplitude of ≤±0.4%. At 650°C, the area of fatigue crack propagation before rupture reaches a diameter of 1mm. At 750°C the crack initiation occurred on the surface and the final crack depth was found to be about 350~400 µm for all the tests. The crack width varied from 0.7 to 1.2 mm and on the edge of the specimens, a narrow, highly oxidized layer was observed (as indicated by arrow). In the stage of rupture, the cracks propagate in trans- and interlamellar mode depending on the lamellar orientation with respect to the loading axis (Fig.7c).



a) 750°C b) 650°C c) 650°C

Figure 7: Crack initiation sites and fracture mode on fracture surface of ±0.4% test at various temperatures

3.3. *Discussion*

Recina [6] reported strong scatter in the results of low cycle fatigue tests with increasing fraction of lamellae in the γ-TiAl alloys. The LCF studies reported here, also showed that the values of Young's modulus, the stress response, and the plastic deformation behaviour as well as the fatigue life data can deviate enormously even under identical test conditions. The parameters that may influence the microstructure and hence the LCF behaviour are manifold even for a given chemical composition. Particularly the orientation and arrangement of the lamellae, the percentage of γ-gains, the size of the lamellae colonies and the colony spacing influence the deformation behaviour strongly [5,8] and thus affect fatigue life.

Generally, the obtained results on Nb-modified alloy reveal better tensile properties, stiffness and fatigue life under total strain control as compared to predecessor alloys. The increased oxidation resistance may also contribute to a better fatigue properties at high temperatures due to the slowing down of oxidation-induced crack initiation processes. The reinforcement with Nb as reported by [15] leads to higher activation energy and thus to increased thermal stability and creep resistance. Nevertheless the disadvantage of lower ductility of third generation γ-TiAl can't be hidden or avoided.

4. SUMMARY

In the present work, the low cycle fatigue behaviour of a third generation γ-TiAl alloy with duplex microstructure was investigated. The results revealed that fatigue life depends strongly on the applied strain amplitude. The alloy yielded fatigue lives of greater than 250000 at the smallest strain amplitude of ±0.3%. With increasing strain amplitude, the life decreased gradually but the decrease was drastic at 750°C due to oxidation effects which seem to be promoted by high plastic strain amplitudes. With decreasing temperature saturation stress amplitude increases and fatigue life in air environment decreases at low total strain amplitudes. The combined effect of corrosion by water vapour and high corrosive sensitivity in the brittle state was made responsible for this tendencies. In vacuum, the alloy displayed strongly improved fatigue life. The fatigue cracks initiated either inside or on the surface of the specimens. Weak spots such as titanium powder particles and coarse γ–grain were found to be vulnerable sites for crack initiation. A mixed trans- and interlamellar crack propagation mode was observed.

5. REFERENCES

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