Thermo-mechanical fatigue behavior of the intermetallic gamma-TiAl alloy TNB-V5 with different microstructures

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Abstract. The cyclic deformation and fatigue behavior of the $\gamma$-TiAl alloy TNB-V5 is studied under thermo-mechanical load for the three technically important microstructures Fully-Lamellar (FL), Near-Gamma (NG) and Duplex (DP), respectively. Thus, thermo-mechanical fatigue (TMF) tests were carried out with different temperature-strain cycles, different temperature ranges from 400°C to 800°C and with two different strain ranges. Cyclic deformation curves, stress-strain hysteresis loops and fatigue lives are presented. The type of microstructure shows a surprisingly small influence on the cyclic deformation and fatigue behavior under TMF conditions. For a general life prediction the damage parameter of Smith, Watson and Topper PSWT is well suitable, if the testing and the application temperature ranges, respectively, include temperatures above the ductile-brittle transition temperature (approx. 750°C). If the maximum temperature is below that temperature, the brittle materials’ behavior yields a high scatter of fatigue lives and a low slope of the fatigue life curve and therefore the damage parameter PSWT cannot be applied for the life prediction.

1. Introduction
Alloys on the basis of the intermetallic $\gamma$-TiAl phase are very attractive for modern lightweight high-temperature components, because they combine low density and excellent high-temperature strength [1-6]. Especially 3rd generation $\gamma$-titanium aluminides with 5 - 10 at% Nb (TNB-alloys) show a high potential for applications. Because of the low ductility at temperatures below the ductile-brittle transition (approx. 750°C) [1] and the resulting poor damage tolerance a good knowledge of the cyclic deformation and fatigue behavior is required. Moreover, during start-up and shut-down operations structural components in automotive and aerospace engines can be exposed to cyclic thermal and superimposed cyclic mechanical loadings. This thermo-mechanical fatigue (TMF) load can be decisive for the fatigue life of a component. Up to now only a few studies on the TMF behavior of $\gamma$-TiAl are published. Christ et al. studied the influence of temperature, environment and temperature-strain cycle on the TMF behavior of different $\gamma$-TiAl alloys [1-5]. Brookes et al. studied the TMF behavior of TNB-V5 under multiaxial axial-torsional fatigue [6]. First results of the authors’ group on the TMF behavior of TNB-V5 with Near-Gamma microstructure were recently published elsewhere [7-9].

In the present paper the influence of temperature-strain cycle and temperature range on the cyclic deformation and fatigue behavior of the $\gamma$-TiAl alloy TNB-V5 under thermo-mechanical load is evaluated on three different microstructures, i.e. Near-Gamma (NG), Duplex (DP) and Fully-Lamellar...
TMF tests were carried out with the temperature-strain cycles in-phase (IP), out-of-phase (OP), clockwise diamond (CD) and counter-clockwise diamond (CCD), temperature ranges between 400°C and 800°C and with two different strain ranges.

2. Experimental Details
The investigated alloy TNB-V5 with the nominal composition of Ti-45Al-5Nb-0.2C-0.2B (at-%) was available in three microstructures (Figure 1) designated as a) Near-Gamma b) Duplex and c) Fully-Lamellar, respectively, according to [10].

Figure 1: Near-Gamma (a), Duplex (b) and Fully-Lamellar (c) microstructure of TNB-V5, extrusion direction horizontal, scanning electron microscopy, back-scattered electron contrast.

For TMF tests electrolytically polished, compact cylindrical specimens with a gauge length of 19 mm and a gauge diameter of 6.5 - 7.0 mm were used. The TMF tests were carried out on a servohydraulic testing system under total-strain control mode at constant mechanical strain rates of $5.75 \times 10^{-3}$ s$^{-1}$ to $1.02 \times 10^{-4}$ s$^{-1}$ and at a strain ratio $R = -1$. Two different mechanical strain amplitudes, $\Delta \varepsilon_{\text{mech}}/2 = 5.75 \times 10^{-3}$ and $\Delta \varepsilon_{\text{mech}}/2 = 6.50 \times 10^{-3}$, were applied. Three different temperature ranges were studied, i.e. 400°C - 650°C, 550°C - 800°C and 400°C - 800°C. All tests were performed in laboratory air and match the recommendations of the “Code-of-Practice for Strain-Controlled Thermo-Mechanical Fatigue Testing“ [11]. Four different TMF temperature-strain cycles (in-phase (IP), out-of-phase (OP), clockwise diamond (CD) and counter-clockwise diamond (CCD)) were applied.

3. Results and Discussion
Figure 2a shows the stress-strain hysteresis loops for the different microstructures (NG, DP and FL) for IP loading as an example within the temperature range 400°C – 800°C with $\Delta \varepsilon_{\text{mech}}/2 = 5.75 \times 10^{-3}$. The Fully-Lamellar microstructure yields slightly higher stresses than the other microstructures. Near-Gamma and Duplex show comparable behaviour with almost identical plastic strain amplitudes which are larger than that of Fully-Lamellar microstructure. In Figure 2b the corresponding cyclic deformation curves are presented. All microstructures show similar characteristics of mean stresses which are compressive in case of IP loading. The microstructures Fully-Lamellar and Duplex offer comparable lifetimes, the microstructure Near-Gamma has the shortest fatigue time. However, it has to be pointed out that there is a surprisingly small influence of the type of microstructure on the cyclic deformation and fatigue behavior under thermo-mechanical loading conditions.

All three microstructures (NG, DP, FL) show a comparable influence of the temperature-strain cycle (IP, OP, CD, CCD) on the cyclic deformation and fatigue behavior. OP loading yields high positive and IP loading high negative mean stresses, whereas in CD and CCD tests significantly smaller positive and negative, respectively, or nearly no mean stresses are observed. The shortest fatigue lives are always found in OP tests, the longest in IP tests. CD and CCD testing yield similar fatigue lives intermediate between those of OP and IP tests, as shown earlier for the Near-Gamma microstructure [7-9].
Comparing the temperature ranges shows that the stress amplitudes and therefore the maximum tensile stresses at 400°C – 650°C are much higher than those at 400°C – 800°C and at 550°C – 800°C. The tests within the temperature range 400°C – 650°C show the smallest numbers of cycles to failure and the tests within the temperature ranges 550°C – 800°C and 400°C – 800°C show significantly higher fatigue lives (not shown in the present paper).

A suitable lifetime prediction for the γ-TiAl alloy TNB-V5 under thermo-mechanical loading can be achieved for the cycles including a maximum temperature of 800°C by using the damage parameter $P_{SWT}$ (equation 1) suggested by Smith, Watson and Topper [12]

$$P_{SWT} = \sqrt{\sigma_{max}^2 \varepsilon_a E}$$  \hspace{1cm} (1)

Here, $\sigma_{max}$ is the maximum tensile stress at half number of cycles to failure $N_f/2$, $\varepsilon_a$ the mechanical strain amplitude ($\Delta$mech/2) and E the Young’s modulus at the temperature of the maximum stress.

In Figure 3a the damage parameter $P_{SWT}$ is plotted in a double-logarithmic diagram vs. the fatigue lives for all tests in the temperature ranges 550°C – 800°C and 400°C – 800°C and in Figure 3b the predicted fatigue lives are compared with the experimentally obtained ones for the temperature ranges including the maximum temperature of 800°C. If the testing and the application temperature ranges, respectively, include temperatures above the ductile-brittle transition temperature (the DBTT is approx. 750°C) the predicted fatigue lives deviate from the experimental fatigue lives in maximum by a factor of 3. If the maximum temperature is below the DBTT, the brittle materials’ behavior yields a high scatter of fatigue lives and a low slope of the $P_{SWT}$ vs. $N_f$ curve, cf. [7-9]. Therefore, this damage parameter cannot be applied for the live prediction.

Figure 3: Damage parameter $P_{SWT}$ vs. fatigue lives (a) and predicted fatigue lives vs. experimentally obtained fatigue lives (b) for all tests in the temperature ranges 550°C – 800°C and 400°C – 800°C.
4. Conclusions

The influence of microstructure, temperature-strain cycle and temperature range on the cyclic deformation and fatigue behavior of the γ-TiAl alloy TNB-V5 under thermo-mechanical load is evaluated. The most important results are:

- The microstructures Fully-Lamellar and Duplex offer comparable lifetimes. The microstructure Near-Gamma has a slightly shorter lifetime. However, there is a surprisingly small influence of the type of microstructure on the cyclic deformation and fatigue behavior under TMF loading conditions.

- All three microstructures (NG, DP, FL) show a comparable influence of the temperature-strain cycle (IP, OP, CD, CCD) on the cyclic deformation and fatigue behavior. The shortest fatigue lives are always observed in OP tests, the longest in IP tests. The fatigue lives correlate with the amount of maximum tensile stress and thus with the mean stresses.

- In accordance to the assumption that the fatigue life is strongly influenced by maximum tensile stress, the tests within the temperature range 400°C – 650°C show the smallest numbers of cycles to failure and the tests within the temperature ranges 550°C – 800°C and 400°C – 800°C show significantly higher fatigue lives.

- For a general life prediction the damage parameter of Smith, Watson and Topper \( P_{SWT} \) is well suitable, if the testing and the application temperature ranges, respectively, include temperatures above the DBTT. If the maximum temperature is below, the brittle materials’ behavior yields a high scatter of fatigue lives and therefore this damage parameter cannot be applied for the life prediction.

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