ANLYSIS OF THE THERMO-MECHANICAL FATIGUE BEHAVIOUR OF SiC-FIBRE REINFORCED TITANIUM ALLOY (SCS-6/TI-6242)

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ABSTRACT

Thermomechanical fatigue behaviour of SCS-6/Ti-6242 has been investigated in the scheme of a DLR-BAM co-operation. In this work the experimental results are analysed on the basis of a one-dimensional stress analysis. An important aspect for any type of high temperature testing performed in this investigation (creep at 550°C, isothermal fatigue at 550°C and thermomechanical loading with temperature cycles between 100°C and 550°C) is treated first. This is the stress relaxation of the matrix in the composite, which is predicted on the basis of stress relaxation experiments on the unreinforced alloy. Considering the stress relaxation the stress range for fibres and matrix is determined for the different types of thermomechanical fatigue loading to explain the different damage mechanisms.

1.INTRODUCTION

SiC-fibre reinforced titanium alloys are attractive candidate materials for application in aircraft gas turbines. Depending on the type of titanium alloy the TMC (Titanium Matrix Composite) can be used in the compressor at temperatures up to 550°C. In the last decade the isothermal fatigue behaviour of this material has been investigated at room temperature [*1*] and elevated temperatures [*2, 3*]. It appeared the fatigue behaviour at room temperature can be described following the general concept valid for metal matrix composites [*4*]. The damage mechanisms generally are fibre failure (at high stresses), matrix cracking (at intermediate stresses) and no damage or damage not giving rise to final failure (at low stresses). Fatigue behaviour at elevated temperatures generally also can be described according to this scheme. One important aspect with generally a large influence on damage mechanisms is the relaxation of matrix stresses during fatigue. This causes the matrix stress to cycle under tension-compression, also if the composite stress cycles completely in the positive range [3]. In the final stable situation the matrix cycles according to R = -1, whereas the composite cycles according to R = e.g. 0.1. If the frequency is low, this situation is reached after a small number of cycles. In that case matrix crack formation can be suppressed, which in turn leads to a high endurance limit e.g. for the system SCS-6/Timetal 834 investigated at 600°C [*5*].

Realistic testing of TMC for aircraft gas turbine applications incorporates the variation of temperature as well as load, i.e. thermomechanical loading. For that reason TMC has been tested this way, where temperature and loading can be applied in-phase (maximum load is applied at maximum temperature) or out-of-phase (maximum load is applied at minimum temperature). It has been found that out-of-phase thermomechanical loading generally leads to a stronger reduction of life than in-phase thermomechanical loading [*6-8*]. The stronger reduction in fatigue strength during out-of-phase cycling appears to be controlled by matrix cracking. Failure during in-phase cycling, however tends to be dominated by fibre failure [*7*]. One reason for the small influence of matrix damage to final failure is the result of the small strain range in the matrix [*9*]. Clearly, the high temperature properties (modulus and strength) of the titanium alloy and the high temperature applied play an important role. The strain range e.g. for a TMC with the alloy Timetal 834 at 600°C (Modulus 85 GPa, strength 550 MPa) plays a more important role than making use of the alloy Timetal 21S at 650°C (Modulus 49 GPa, strength 238 MPa [*7*]). It can be expected, that oxidation plays an important role in the

thermo-mechanical fatigue behaviour. Matrix cracking during out-of-phase loading (the strain range in the matrix is large) appeared to take place environment-assisted [*10*]. Apart from the influence of oxidation on matrix crack formation and growth also a deterioration of fibre strength has been found [*10, 11*] as a result of oxidation.

In the present paper the thermomechanical behaviour of unidirectionally reinforced SCS-6/Ti-6242 cycled at R = 0.1 (min. load/max. load = 0.1) and between temperatures of 150°C and 550°C has been analysed. An attempt is made to describe the influence of the different phenomena, e.g. by comparing isothermal fatigue behaviour with thermomechanical fatigue behaviour also making use of the results of creep experiments. This is necessary as in the thermomechanical test programme dwell times at maximum and minimum load are introduced. The material used for the present investigated is processed on the basis of matrix coated fibres. In contradiction to the specimens used in the major part of the investigations quoted in this section [1-3, 6-10] this material has no fibres broken due to specimen preparation and all fibres are covered by the matrix. This prevents initial damage at the surface and oxygen attack of the fibres (as long as there are no surface cracks). Thus a clearer separation of damage mechanisms is possible.

2. MATERIALS AND EXPERIMENTS

Specimens for thermomechanical, isothermal and creep testing are produced at DLR with the aid of fibres coated with the Ti-6242 alloy. The fibres are coated in a magnetron sputtering device. A coating thickness of 41-49 µm is applied to arrive at a fibre volume fraction of V_f = 0.40-0.35. In a second step coated fibres are cut at the required length and stacked into a tube of Ti-6242 alloy. A lid on top and bottom of the tube is vacuum welded and in a final processing step the preform is hipped at 950°C and 190 MPa. Specimens with the dimensions as given in Figure 1 are milled out of the consolidated tubes. A cross section of such a specimen, also given in Figure 1 shows the regular distribution of the ~ 190 fibres with an outer ring of ~ 0.2 mm near the specimen surface which is unreinforced. As outlined in the introduction in contradiction with the fibre/foil/fibre technique all fibres are undamaged during specimen preparation and completely embedded in the matrix.

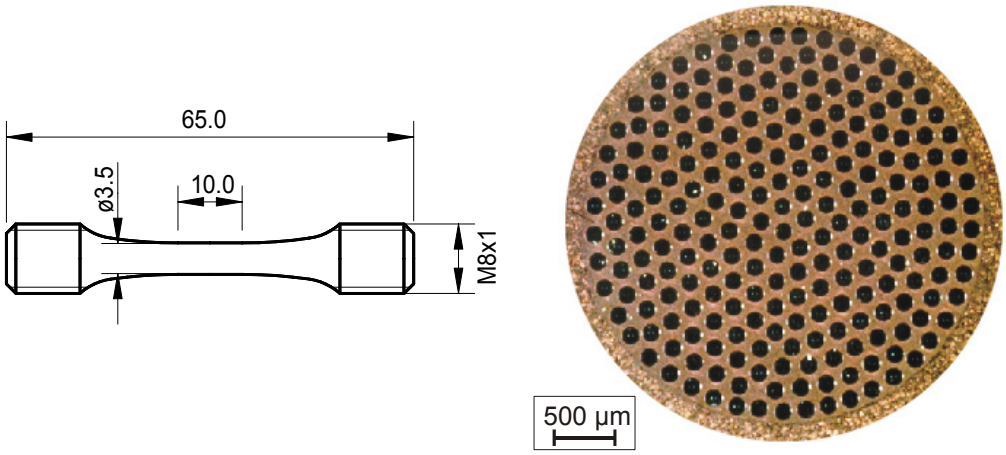

Fig. 1: Specimen dimensions (in mm, left) and cross section of a typical specimen (right)

Experiments are performed to determine the (short time) creep behaviour at 550°C and the fatigue properties at room temperature and 550°C. Further the thermomechanical behaviour is determined by cycling the temperature between 550°C and 100°C and the load at a stress ratio of R_σ=0.1 ($\sigma_{min}/\sigma_{max}$ = 0.1). During the cooling cycle the specimen is not actively cooled, which is the reason for selecting 100°C for the minimum temperature. The stress ratio for the

isothermal and thermomechanical experiments measures also R_σ=0.1. Figure 2 illustrates the shape of in-phase and out-of-phase thermomechanical cycles. Dwell times of 2 min at maximum and minimum load (and temperature respectively) and heating and cooling rates of 5°C/s give rise to a duration of 7 minutes for each cycle. The specimens are heated with the aid of a conduction heating device. A coil around the gauge section of the specimen allows to fix a high temperature extensometer to measure the extension during the different experiments. A complete overview of the registered data in the different experiment will be published elsewhere.

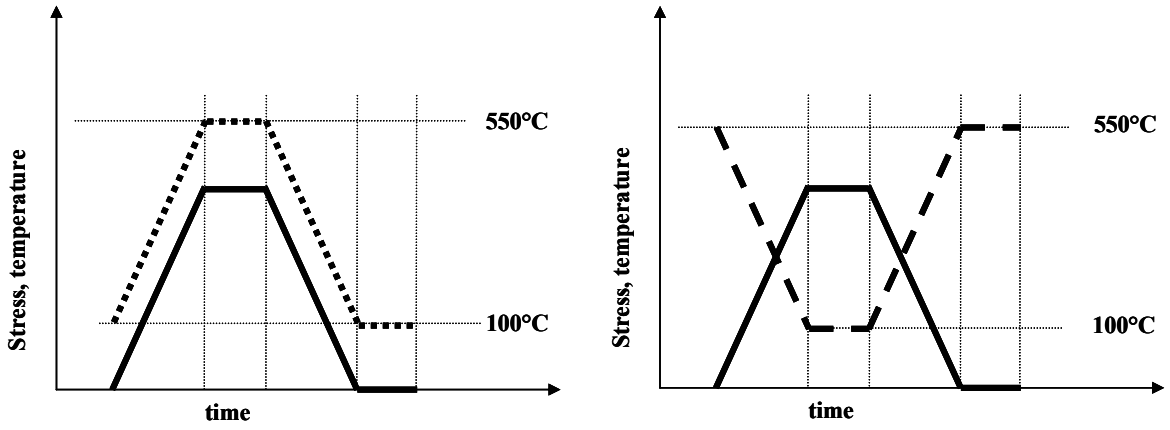

Fig.2: Thermomechanical loading conditions, left: in-phase right: out-of-phase.

In order to be able to analyse the influence of creep of the matrix under the different loading conditions the creep behaviour of the unreinforced matrix has been investigated in a separate test programme at 550°C. As the condition of creep of the matrix in the TMC more closely follows a relaxation process rather than a creep process the unreinforced specimens with dimensions as given in Figure 1 are investigated under a constant applied strain. In these experiments first the specimen is heated to a temperature of 550°C and after reaching the stable temperature distribution a mechanical strain of 0.6 % is applied. At reaching this amount of strain machine control is shifted to strain control maintaining the applied strain under a reducing load. The dependence of the load during the relaxation process is registered as a function of the time up to a maximum of 100 h.

3. RESULTS AND DISCUSSION

3.1 Isothermal and thermomechanical test results

The complete test results for the thermomechanical and isothermal fatigue experiments are given in Figure 3. A first evaluation of the experimental data has been performed recently [*12*] and a more extensive evaluation of these experiments considering crack growth data from extensive studies of fracture surfaces and evaluation of data of extensometer recordings will follow. The isothermal fatigue data at room temperature and 550°C for the presently investigated SCS-6/Ti-6242 closely resemble the fatigue data of SCS-6/Timetal 834 tested at room temperature and 600°C [*5*]. The Wöhler curves for the two temperatures intersect at a maximum stress level of 1400 MPa. The endurance limit at room temperature approaches 600-700 MPa, whereas at 550°C it is close to 900 MPa. The strong drop in fatigue strength at room temperature is mainly driven by the formation of matrix cracks (as found for the system SCS-6/Timetal 834 [*5*]) as a result of the large stress range of the matrix during cycling. Fatigue at 550°C appears to be less matrix crack sensitive.

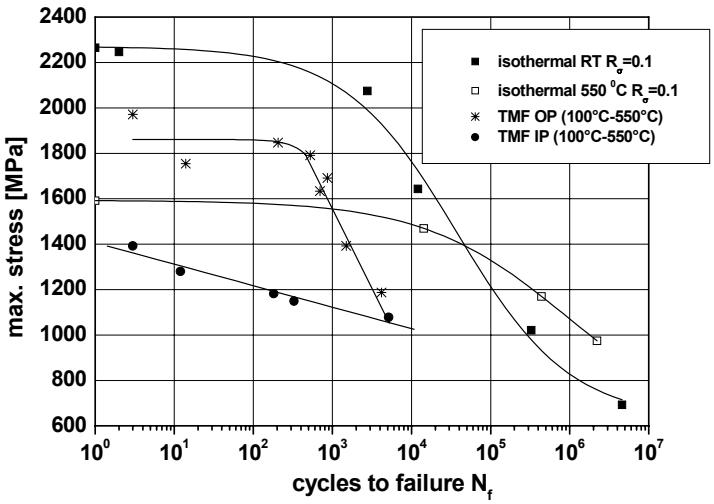

Fig. 3: Isothermal and thermomechanical fatigue life for SCS-6/Ti-6242 (V_f=0.35).

The thermomechanical (TMF) fatigue curves show in comparison with the isothermal fatigue curve the same phenomenon. They also intersect, but at a lower stress level of ~ 1050 MPa. Again this is caused by a strong reduction in fatigue strength for the out-of-phase type of loading (TMF OP) which appears to show a strong sensitivity to matrix crack formation and growth (see section 3.5).

3.2 Analysis of stress relaxation in the unreinforced alloy

Results of the stress relaxation experiments on the unreinforced Ti-6242 alloy are indicated in Figure 4. It shows for two specimens the development of the applied load under a constant applied strain of 0.6 %. After ~ 100 h the initial stress of more than 500 MPa drops to

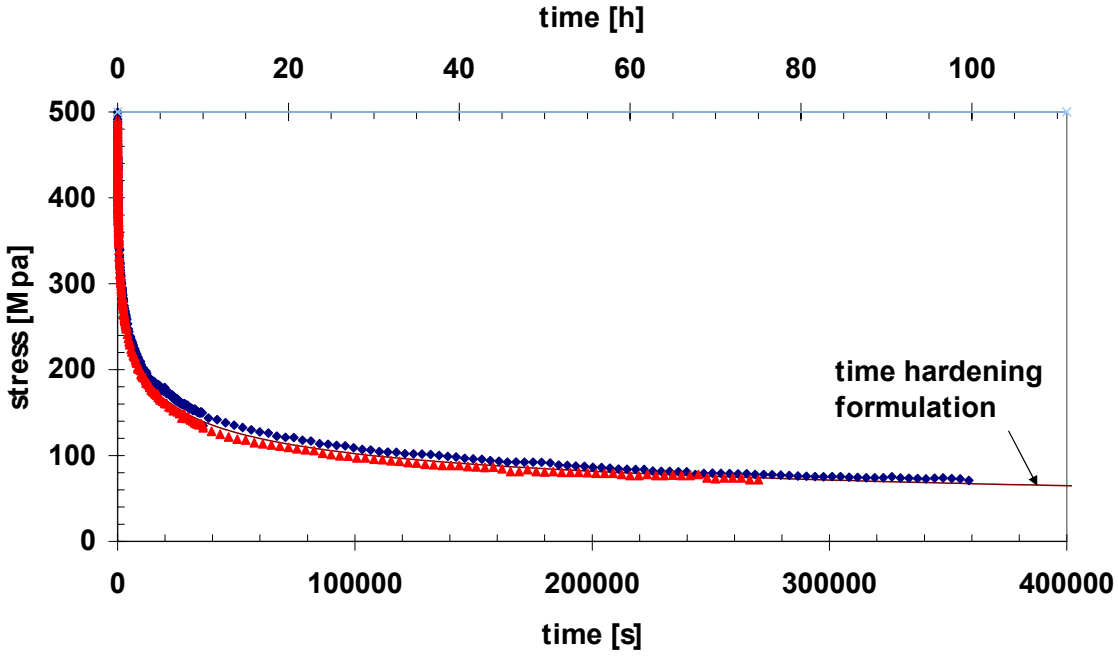

Fig. 4: Stress relaxation experiments on unreinforced Ti-6242 at 550°C (2 specimens)

~70 MPa. The stress relaxation due to primary and secondary creep can be described with the aid of the Bailey-Norton equation:

$$\varepsilon_{m,c} = A \cdot \sigma_m{}^{\alpha} \cdot t^{\beta} \qquad (1)$$

showing the influence of time t (with exponent β) and stress (with exponent α) [*14*]. Relaxation of the stress can be calculated by numerical integration of:

$$\dot{\varepsilon}_m = E_m \cdot \dot{\varepsilon}_{m,c} \text{ with } \dot{\varepsilon}_{m,c} = A \cdot \beta \cdot \sigma_m^{\alpha} \cdot t^{\beta-1} \qquad (2)$$

The values of the constants A, β and α are determined by fitting the calculated dependence of the stress σ to the measured one as given in Figure 4. For the fine grained Ti-6242 (grain size 0.5-1μm) these constants measure A = 1.104 x 10^{-10}, α= 2.266 and β = 0.463. Creep generally strongly depends on the grain size. The influence of different grain size on the relaxation behaviour of Ti-6242 has been published elsewhere [*13*]. Stress relaxation calculated on the basis of the determined constants A, α and β and the time hardening rule [*14*] also indicated in Figure 4 shows a good correlation wit the measured data.

3.3 Analysis of matrix stress relaxation in TMC

At elevated temperature during different types of mechanical loading the stress in the matrix of TMC relaxes. As the matrix relaxes a transition of stress from the matrix to the fibres occurs, which is accompanied by an additional strain in the TMC. The influence of the relaxing stress in the titanium is analysed with a one-dimensional stress analysis. Under an applied mechanical strain ε, which is assumed to be identical in fibre and matrix, the axial stress in the components follows from [*15*] :

$$\sigma_f = \frac{\varepsilon_{m,pl} + \left(\alpha_m - \alpha_f\right) \cdot \Delta T}{\frac{1}{E_f} + \frac{V_f}{\left(1 - V_f\right) \cdot E_m}} + \varepsilon \cdot E_f \quad \text{and} \quad \sigma_m = -\frac{V_f}{\left(1 - V_f\right)} \cdot \frac{\varepsilon_{m,pl} + \left(\alpha_m - \alpha_f\right) \cdot \Delta T}{\frac{1}{E_f} + \frac{V_f}{\left(1 - V_f\right) \cdot E_m}} + \varepsilon \cdot E_m \qquad (3)$$

In these equations the thermal stress at 550°C test temperature as a result of the different coefficients of thermal expansion is considered (α_f = 4.21 x 10^{-6} m/m/°C, α_m = 10,47 x 10^{-6} m/m/°C), where ΔT = -200°C (a stress free temperature of 750°C is assumed). Further at 550°C the moduli of fibres and matrix are given by: E_f=380GPa E_m=87.2GPa. The time dependent plastic deformation of the matrix is considered with the parameter $\varepsilon_{m,pl}$. This follows from the integration of equation (2). With the aid of a computer programme based on equation (1) to (3) stress relaxation in the matrix and stress increase in the fibres is calculated numerically for different loading conditions.

3.4 Matrix stress relaxation in TMC during creep

As an example for the stress development in fibres and matrix of TMC a stress calculation for a creep experiment at an applied stress of 1100 MPa has been performed. Creep tests are done at 550°C on specimens loaded in the range of 1400 to 1100 MPa up to times of 100 h. The specimen tested at the lowest stress failed after 77.8 h. Figure 5 presents the calculated stress development in fibre and matrix up to the failure time of 77.8 h. Further the elongation during

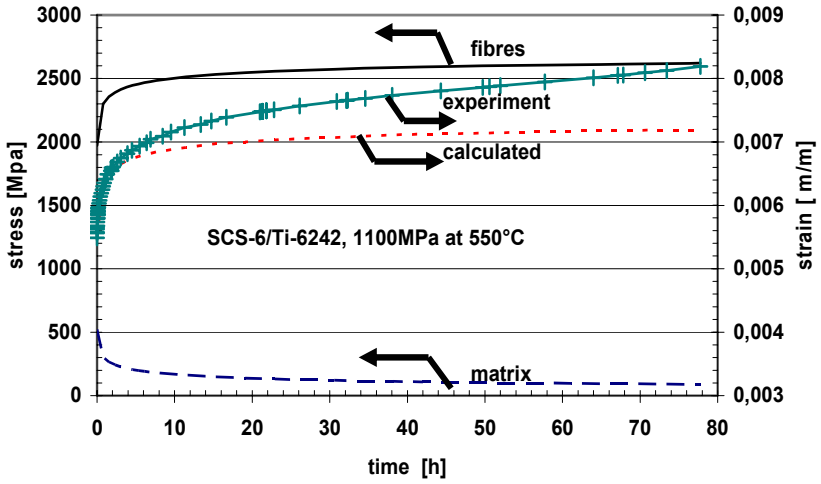

Fig. 5: Calculated and measured strain, and calculated stress development in the fibres and matrix during a creep test at 1100MPa at 550°C (V_f=0.38)

creep is calculated and compared with the measured strain increase (on the secondary axis). The measured strain increase exceeds the calculated one after 2-3 h creeping time with an absolute difference of ~ 0.1 % at failure. The difference between measured and calculated creep strain is probably the result of breaking fibres. The contribution of breaking fibres to an additional creep strain is not considered in the calculation. Other investigations [*16, 17*] have shown, that fibre failure is the major mechanism contributing to creep failure. The fibre stress in Figure 5 hardly exceeds 2600 MPa and appears thus to be rather low to explain fibre failure. In a recent work however it has been shown that fibres fail under a lower stress under constant load conditions at higher temperatures [*17*]. In the quoted literature growth of fibre defects has been made responsible for this.

3.5 Analysis of thermomechanical loading

Insight in the damage mechanisms for the two types of thermomechanical loading can be expected from investigations of the fracture surfaces and the development of stresses in the fibres and matrix. The evaluation of the fracture surfaces and other metallographic investigations have not yet been completed. It can however be expected, that as for the creep experiments at 550°C - during in-phase thermomechanical loading - statistically distributed fibre failures dominate the damage process. One aspect which promotes fibre failure is the relaxation of stress in the matrix. The influence of stress relaxation during in-phase thermomechanical loading for the first four cycles is given in Figure 6. The stress in the matrix relaxes from originally 530 MPa to 400 MPa at the end of the fourth cycle. Simultaneously the fibre stress increases from 2032 MPa to 2380 MPa (not indicated in Figure 7) and the calculated strain increases. The latter increase is however less strong than measured in an experiment.

Characteristic for the specimens thermomechanically loaded in out-of-phase condition is the sensitivity to matrix crack formation and growth. This is visible from the fracture surface of a specimen loaded up to a maximum stress of 1700 MPa that failed after 850 cycles (Figure 7). The fatigue cracks formed during high temperature fatigue are striking due to the colouring effect of oxidation [5]. Figure 7 shows that a (coloured) surface crack completely surrounds the specimens. The crack penetrates the outer unreinforced rim and locally it crosses the first row of fibres. Crack formation and growth is enhanced by the effect of oxidation which mainly takes place during the 2 min dwell time at 550°C (and 170 MPa stress). The effect of oxidation on life becomes more critical as soon as a matrix crack touches the fibres. Oxidation

of the fibre has shown to severely reduce its strength. Oxidation in air e.g. for 4 h at 600°C reduced the characteristic strength from 4610 MPa (for untreated fibres) to 3001 MPa [11].

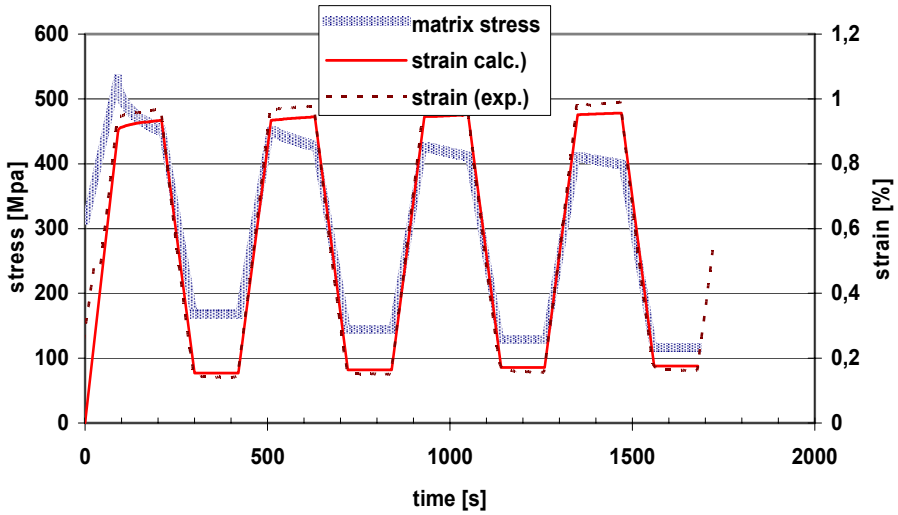

Fig. 6: Stress (calculated) in the matrix and strain (calculated and measured) development during the first 4 in-phase thermomechanical cycles (composite stress 1100-110MPa, temperature 550°C-100°C).

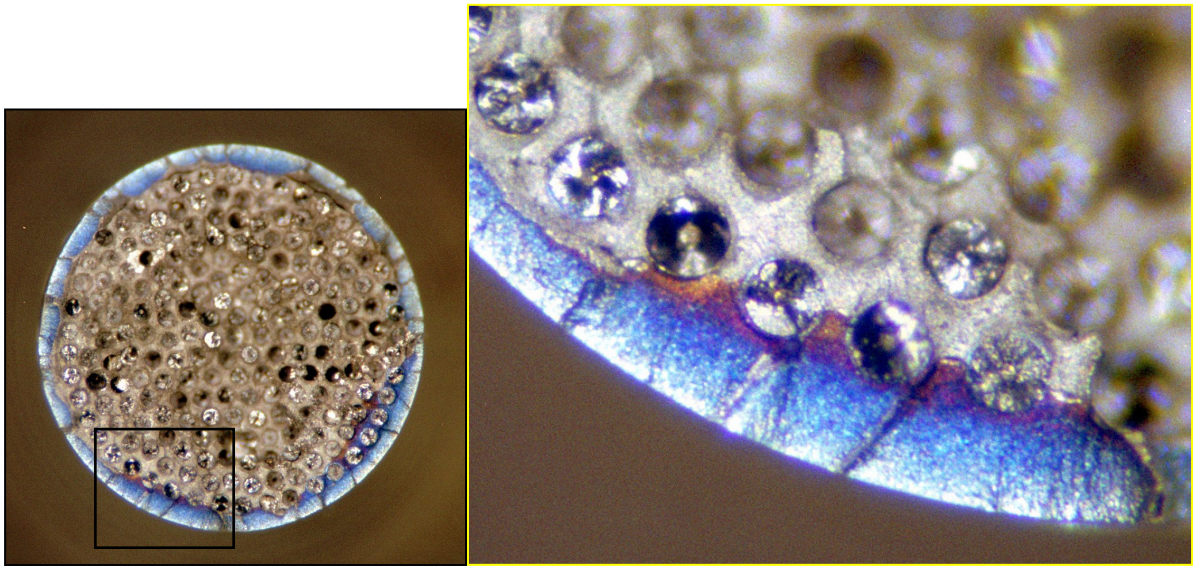

Fig. 7: Fracture surface with circumferential matrix fatigue crack of specimen thermomechanically out-of-phase cycled at 1700-170 MPa and 100°C-550°C (right: magnification of indicated area in left)

For that reason the strong drop in thermomechanical fatigue strength (out-of-phase) for more than 500 cycles is strongly influenced by the oxidation attack on the fibres. It is clear (as discussed in the introduction) that the large stress range of the matrix contributes much to the formation of matrix crack. The one-dimensional analysis of stress for the present experimental results (σ_{max} = 1700 MPa) shows that in the first cycle the yield point of the matrix is clearly exceeded. Making use of the properties of Ti-6242 at room temperature (the properties at 100°C are not determined) the matrix yields at a composite stress of 1317 MPa and the matrix stress at σ_c = 1700 MPa is 1150 MPa. On unloading to σ_c = 170 MPa (and heating to 550°C) the matrix stress is reduced to a compressive stress of -136 MPa (neglecting the relaxation process at 100°C during the 2 min dwell). Under such high stress range adhanced by oxidation clearly matrix cracks are initiated under a small number of cycles.

4. CONCLUSIONS

Relaxation of matrix stresses plays an important role during testing of TMC at elevated temperature (creep, isothermal and thermomechanical fatigue tests). This causes the matrix stress to reduce and simultaneously the fibre stress to increase. The increasing fibre stress tends to increase the occurrence of statistically distributed fibre failures during creep and in-phase thermo mechanical fatigue testing (especially if dwell periods at maximum temperature and load are introduced). During thermomechanical out-of-phase experiments the matrix stress range is large (with maximum stress at minimum temperature) leading to early initiation and growth of cracks (due to embrittlement of the titanium at the surface). When matrix surface cracks penetrate the fibre reinforced area oxidation of the fibres gives rise to a strong decrease of thermomechanical strength.

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