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THERMAL-MECHANICAL FATIGUE BEHAVIOUR OF A TITANIUM MATRIX COMPOSITE REINFORCED WITH LONG SiC FIBERS

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SUMMARY

This study investigates the thermal-mechanical fatigue (TMF) behaviour of a titanium matrix composite, SCS6/Ti-6242 aimed to be used in future jet engines by Snecma. The TMF tests conditions under stress control are chosen to simulate the actual loading of the composite part in a compressor disc during engine operation. Observations of fracture surfaces are consistent with a failure controlled by fibre fracture and matrix micro-cracks. A finite element model is made to estimate the stress in the various components based on the Transformation Analysis Model of Dvorak. A complex redistribution occurs under thermal mechanical cycle due to viscoplasticity of Ti-6242 matrix. This is a major input for damage models to predict lifetime under these complex loading conditions.

Keywords: Titanium matrix composites, thermal-mechanical fatigue, damage mechanisms

INTRODUCTION

Titanium based metal matrix composites (MMC) reinforced by unidirectional continuous SiC fibres exhibit higher specific strength and stiffness at medium temperature than monolithic materials such as superalloys. Therefore, they are attractive candidate materials for aircraft engine components such as compressor discs. These SiC-Ti composites can be used as a unidirectional reinforcement in titanium compressor discs. Different component designs are proposed to use maximum benefit of the high strength and stiffness of SiC fibres and of the damage tolerance of titanium alloys. In every case, this technology gives rise to a significant weight gain with respect to conventional components [1].

During operation, stresses are mostly due to centrifugal forces and thermal loading; they are maxima in the loop direction of compressor disc along the fibre axis. Therefore, the fatigue resistance has been investigated using specimens with a volume fraction of unidirectional fibres in the range 0.2 – 0.35 and loaded in the longitudinal direction under isothermal conditions [2,3]. A few authors have studied the fatigue life of SiC-Ti composites under thermal-mechanical fatigue conditions but using simple cycles using out-of-phase or in-phase stress-temperature cycles [2,3]. Our group has a different testing philosophy and thermal–mechanical fatigue (TMF) cycles, which simulate the actual loading in the component, are used instead of simpler cycles. This procedure mostly used for monolithic materials was recently applied to SiC-Ti composites [4].

The purpose of this paper is to report on such an investigation of the behaviour of a SiC-Ti composite considered by Snecma, Safran group, for advanced compressor discs under TMF loading. Results are shown in the low cycle fatigue range, including stress-strain behaviour and fatigue failure. Analysis of these results is attempted using finite element analysis of tested specimens and a constitutive model for the composite.

MATERIALS AND EXPERIMENTAL PROCEDURE

Cylindrical specimens 102 mm long and 3.2 mm in diameter in gage length were prepared by Snecma to simulate a volume element of the MMC reinforcement of compressor disc; specimen geometry is given in Figure 1. The composite material is made from a matrix Ti-6Al-2Sn-4Zr-2Mo-0.1Si (wt %, often referred to as Ti-6242). SCS6 fibres were used 0.140 mm in diameter. An industrial process was used to obtain a fibre impregnated by Ti-6242 alloy which gives rise to a composite wire. These wires are then given a hot isostatically pressing treatment in a Ti-6242 container. The volume fraction achieved in the composite used for specimens was about 0.2. The cylinder so obtained is then carefully machined in the central part. In the gage section, the composite is almost centred and an external layer of Ti alloy of a few 0.1 mm is left around the composite. Specimen section is shown in Figure 2, which illustrates the regular arrangement of fibres achieved in the MMC part. The microstructures of SiC fibres, of the Ti alloy in the composite and of the Ti alloy in the external layer of the specimen are shown in Figure 2.

Axial strain was measured using a high temperature extensometer with a 10 mm gage length, designed in our laboratory. The thermal-mechanical fatigue tests were made using a servo-hydraulic or electro-mechanical machine and a computer, which generates two synchronous temperature and load cycles. The computer is used to record stress, mechanical strain and temperature.

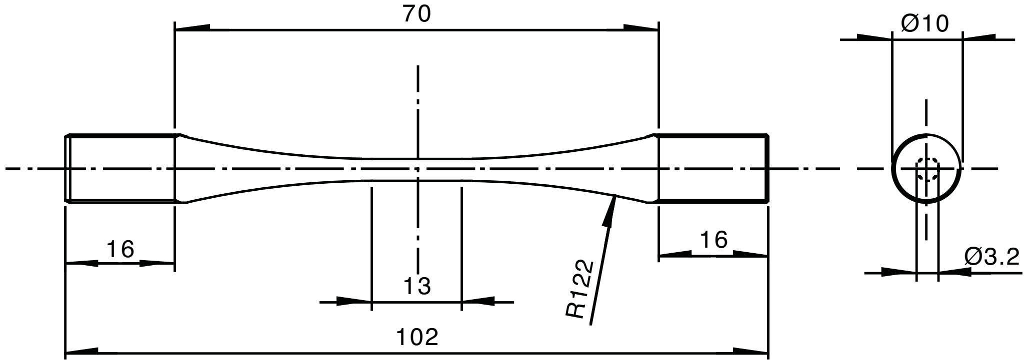
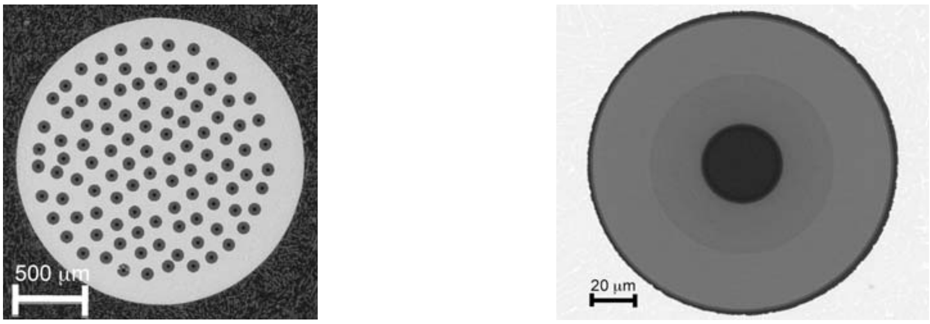
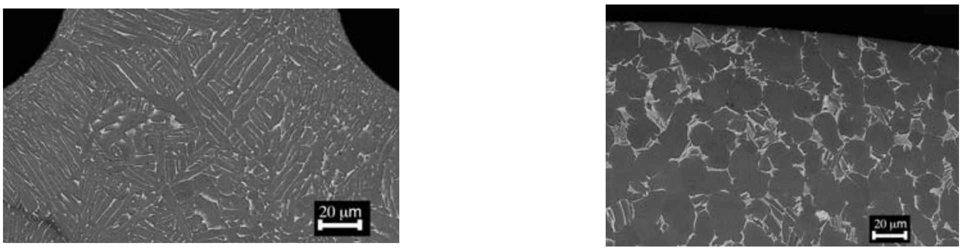


Figure 1. Specimen geometry.



Specimen section SCS6 fibre



Ti alloy in composite Ti alloy in the external layer

Figure 2. Microstructures of different phases of the composite SCS6/Ti-6242.

The thermal-mechanical fatigue cycle was deduced from computations made by Snecma for the MMC part inside the compressor disc, and simulates the loading of the composite part during a flight. The tests are conducted under stress control using a stress ratio R_σ ($R_\sigma=\sigma_{min}/\sigma_{max}$) of zero and a temperature cycle between 100 and 450°C. The cycle period was 270s. The cycle used is shown in Figure 3, for a maximum stress of 1000 MPa. During 20s, specimen is loaded at 100°C. Then temperature is increased at a constant rate 5°C/s from 100°C up to T_{max} = 450°C. Then temperature and stress are hold constant at their maximum value for 90s. Then, the stress is decreased to zero for 40s and with a 20s delay, temperature decreases from 450°C to 100°C. This delay and difference in rates result in a cooling from 350°C to 100°C without load. The shape of the stress-temperature cycle exhibits a very large hysteresis and differs from simple in-phase or out-phase cycles usually investigated (Figure 3).

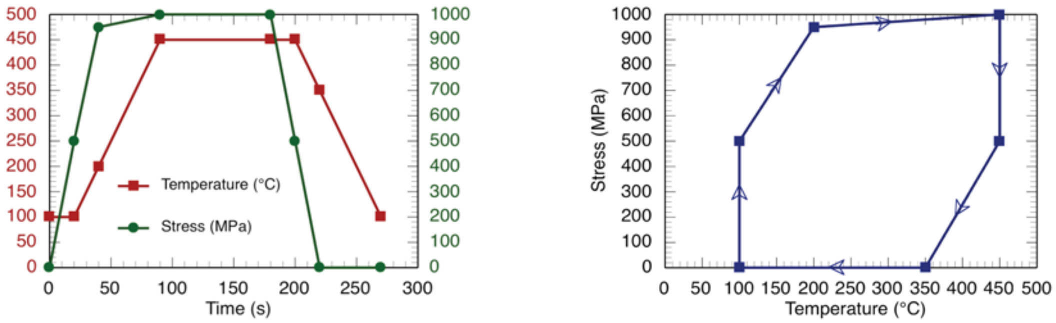


Figure 3. Thermal-mechanical fatigue cycle TMF-90s-450°C.

EXPERIMENTAL RESULTS

The results of the TMF tests on the composite material are shown in Figure 4. Fatigue life defined when specimens are broken shows a very rapid variation, when the maximum stress is decreased from 1000 MPa to 900 MPa. The test at the lowest level was stopped before specimen failure, due to test duration. These TMF tests are compared with usual isothermal tests at 450°C, the maximum temperature of the cycle, carried out by CEAT (under a load ratio of 0.1 and a frequency around 1 Hz).

For the higher maximum stress investigated the fatigue life seems shorter under TMF loading than in the LCF at maximum temperature. On the other hand with decreasing maximum stress, the difference between TMF and LCF tends to disappear for the test conditions used in this investigation, as observed in previous work [4].

The stress-strain behaviour is shown in Figure 5 and 6, for a peak stress at 975 MPa. Figure 5 shows the evolution of the stress versus mechanical strain, and plastic strain respectively for the first and the second TMF cycles. On the first loading, an irreversible strain occurs between 100 °C and 200 °C when applied load increases up to 95% of its maximum. This strain is larger during the final increase of stress when temperature increases from 200 up to 450 °C and stress hold time at 450 °C. A slight hardening is visible during this hold time. A significant plastic strain is so observed at the end of the first cycle. The stress-mechanical strain shows a much smaller hysteresis on the second cycle and plastic strain range becomes very small.

There is a significant ratchetting strain as shown in Figure 6. While the mechanical strain range seems to stabilize rapidly, there is a slow increase of maximum mechanical strain, as well of maximum plastic strain.

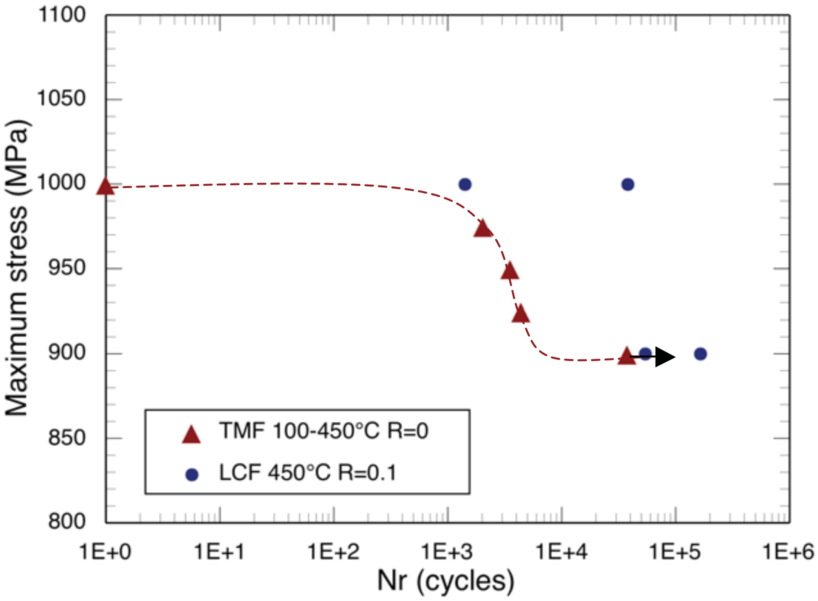


Figure 4. Fatigue life under TMF between 100 and 450°C using cycle depicted in Figure 3 and LCF at 450°C for cylindrical specimens of MMC SCS6/Ti-6242.

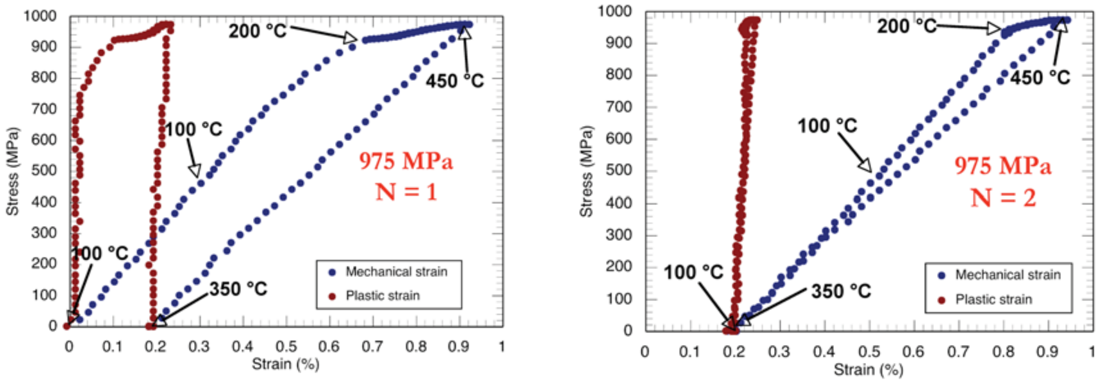


Figure 5. Stress versus mechanical or plastic strain, TMF cycle 100-450°C, σ_{max}=975 MPa, first and second cycles.

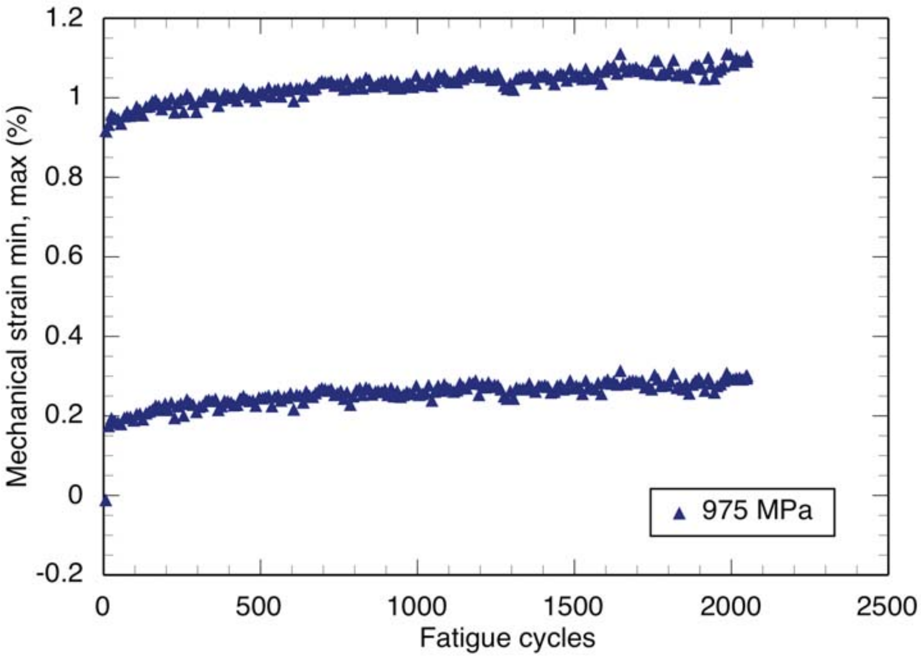


Figure 6. Maximum and minimum mechanical strain as a function of TMF cycles.

Fracture surfaces of broken TMF specimens have been observed under scanning electron microscopy. Figure 7 shows a typical fracture surface with the overall view of specimen section and details of the fracture surface. A fairly planar area corresponds to the initiation and propagation of short cracks. Figure 7 illustrates matrix cracks around fibres near the interface between composite and external titanium layer. Fatigue striations are observed in these areas and fibres are broken near the fracture plane. Final fracture area is more irregular and shows dimples typical of ductile fracture of the matrix as well as extensive pull out of fibres.

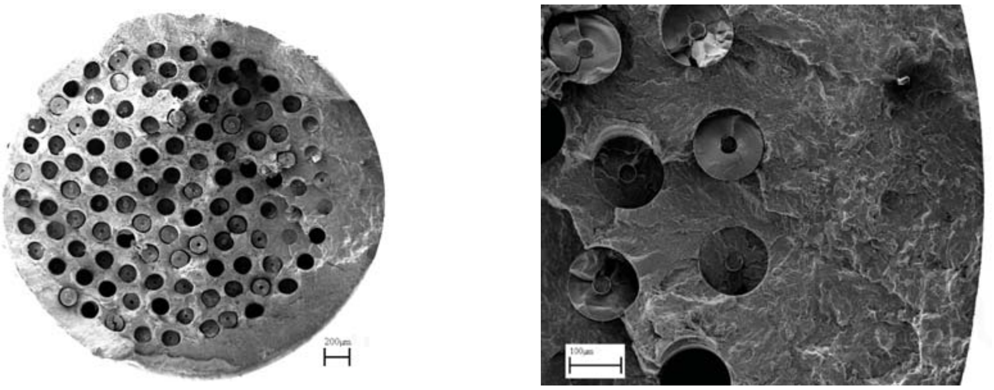


Figure 7. Fracture surfaces: TMF Cycle-100-450°C, σ_{max} = 975 MPa, N_r = 2044 cycles

DISCUSSION

Damage mechanisms in SiC-Ti composites are very complex to analyse under thermal-mechanical loading. In the low cycle fatigue regime at high temperature, as well as under simple in-phase or out-of-phase, most authors [2-5] have concluded that in the high stress range fatigue fracture of the MMC is controlled by fibre fracture events, whereas in the medium stress range matrix cracks can contribute significantly to fatigue damage. Legrand et al [5] have proposed a Monte-Carlo model of fatigue life using different damage mechanisms and a local analysis of stress transfer from one fibre fracture event on its first neighbours. Interface degradation mechanisms can play a major role in controlling the overall damage kinetics. At this stage such a model has not been used to the present experiments. The observations of specimens tested under TMF show that fibre fracture is still a major factor in the range of lifetimes investigated.

Before running into a local analysis of stress redistribution during damage development, it is necessary to estimate the overall stress redistribution during thermal cycling and thermal-mechanical fatigue occurring in the tested specimen, between external un-reinforced matrix and composite and within the composite between fibres and composite matrix. On the one side, expansion coefficient mismatch between SiC fibres and Ti-6242 matrix promotes the building of internal stress. On the other side, titanium alloys can show extensive viscoplasticity in the higher temperature investigated so that they will creep under stress which gives rise to progressive reloading of the fibres.

Constitutive equations for the MMC

The constitutive behaviour of the composite is estimated using an homogeneous equivalent medium using the Transformation Field Analysis, so called TFA, proposed by Dvorak [6,7]. A macroscopic law is obtained from a multi-scale approach using appropriate constitutive equations for MMC constituents, fibres and matrix. The TFA approach uses a representative volume element; this volume element is divided in N sub-volumes and mechanical fields are supposed uniform in each sub-volume. For elastic behaviour linear, relations hold between local microscopic fields and macroscopic mechanical fields. When local behaviour deviates from elasticity, additional terms need to be introduced and Dvorak has considered non-linear behaviour due to plastic or thermal strains as eigenstrain.

The local stress and strain field (σ_r, ε_r) in a sub volume V_r is related to macroscopic stress and strain field (Σ, E) through the following equations:

$$\sigma_r = B_r : \Sigma - \sum_{s=1}^{N} F_{rs} : L_s : (\varepsilon_s^p + \varepsilon_s^{th}) \tag{1}$$

$$\varepsilon_r = A_r : \mathrm{E} + \sum_{s=1}^{N} D_{rs} : (\varepsilon_s^p + \varepsilon_s^{th}) \tag{2}$$

where B_r and A_r are fourth order localisation tensors for stress and strain, L_s is stiffness tensor of sub-volume V_s , $\varepsilon_s^{in} = \varepsilon_s^p + \varepsilon_s^{th}$ is the inelastic strain sum of plastic and thermal strain uniform in the sub-volume V_s , F_{rs} et D_{rs} are transformation influence tensors that describe the influence of inelastic strain of sub-volume V_s on sub-volume V_r . The homogenisation step is made using a volume average of local fields for stress and strains, according to:

$$\Sigma = \sum_{r=1}^{N} \upsilon_r \sigma_r \tag{3}$$

$$\mathrm{E} = \sum_{r=1}^{N} \upsilon_r \varepsilon_r \tag{4}$$

where υ_r is the volume fraction of sub-volume V_r in the representative volume element. This model has been applied to the present SiC-Ti MMC. The SCS6 fibre has a thermo-elastic behaviour and transverse isotropic elasticity is used, as identified in previous work (S. Kruch).

Alloy Ti-6242 has a visco-plastic constitutive law that is considered as isotropic. A Chaboche type unified viscoplastic law has been identified from several studies [6,7] (and using parameters given by S. Kruch). This law combines an isotropic hardening and two non-linear kinematic hardening terms used to describe both monotonic behaviour as well as cyclic tests. The equations used are listed below:

Strain partition

$$\varepsilon = \varepsilon_e + \varepsilon_{vp}$$

$$\text{where } \varepsilon_e = S : \sigma + \alpha (T - T_0)$$

Yield function

$$f = J_2(\sigma - X) - R - \sigma_y(T)$$

$$J_2(\sigma - X) = \sqrt{\frac{3}{2}(s - \sigma) : (s - \sigma)}$$

$$s = \sigma - \frac{1}{3} tr(\sigma) I$$

Viscoplastic flow rule

$$\dot{\varepsilon}^{vp} = \frac{3}{2} \left\langle \frac{f}{k(T)} \right\rangle^{n(T)} \frac{s - \sigma}{J_2(\sigma - X)}$$

Isotropic hardening

$$R = Q(T)(1 - \exp(-bp))$$

Kinematic hardening

$$X = X_1 + X_2$$

$$\dot{X}_i = \gamma_\infty \left(\frac{2}{3} C_i \dot{\varepsilon}^{vp} - X_i \dot{p}\right)$$

Cumulative plastic strain rate

$$\dot{p} = \sqrt{\frac{2}{3} \dot{\varepsilon}^{vp} : \dot{\varepsilon}^{vp}}$$

Application to composite specimens loaded under TMF

The Finite Element model is shown in Figure 8 for a quarter of specimen section. Computation has been done under 2.5 D generalised plane strains. Boundary conditions used are displacement $U_1 = 0$ for $x = 0$ and displacement $U_2 = 0$ for $y = 0$ (symmetry conditions).

The thermal mechanical needs a fairly complex history to be accounted for. First of all the processing conditions are taken into account since they have a strong influence on residual stresses which are very important in MMCs. A cooling is thus imposed from an initial temperature to have the initial residual stress state. Then as in the experimental procedure the specimen is submitted to 10 thermal cycles without load to allow stabilisation of thermal transients in the specimen. Then 10 thermal mechanical fatigue cycles have been imposed used the TMF cycle defined in Figure 3 (Figure 9).

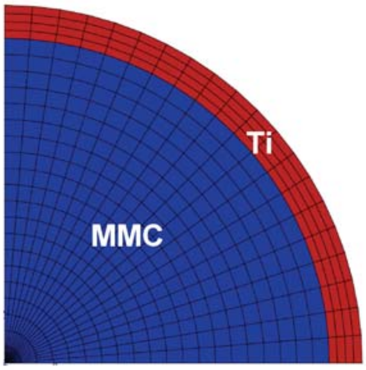


Figure 8. Finite element mesh used to model MMC specimen

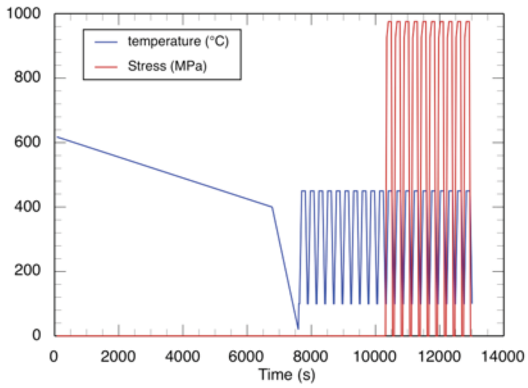


Figure 9. Thermal and mechanical loading sequence used in simulation

Figure 10 shows the computed stress-mechanical strain loops obtained by the FE model and the comparison with experimental results for a TMF cycle with a maximum stress of 975 MPa. The elastic domain is well described but the FE model tends to overestimate the inelastic strain at the first loading cycle and at the second one.

The average stress in the composite core tends to increase and the average stress in the external layer of Ti-6242 tends to relax due to alloy visco-plasticity during the TMF cycle as shown in Figure 11. The effect of the relaxation of the matrix is very significant in the first TMF cycles. Figure 12 displays the same evolution of stress between the fibres and the matrix within the composite core of the specimens. It is worth noting that the initial compressive stress in the fibres is relaxed in the first TMF cycle under load and the average residual stress tends to be tensile at minimum temperature of the TMF cycle (100°C).

Progressive stress relaxation in the matrix, due to viscoplasticity, is the source of severe load transfer on fibres in the first cycle. However the load transfer is a long period phenomenon, which needs to compute more numerous cycles to be properly estimated. This gives an explanation of the significant ratchetting strain that is experimentally observed in TMF experiments as in a creep test.

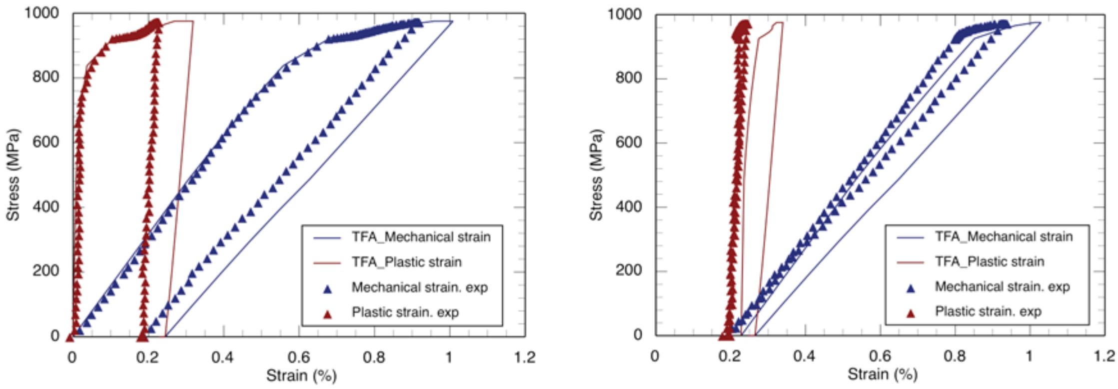


Figure 10. Stress-mechanical and stress-plastic strain loops at cycle 1 and 2. σ_{max}= 975 MPa, TMF cycle-90s-450°C.

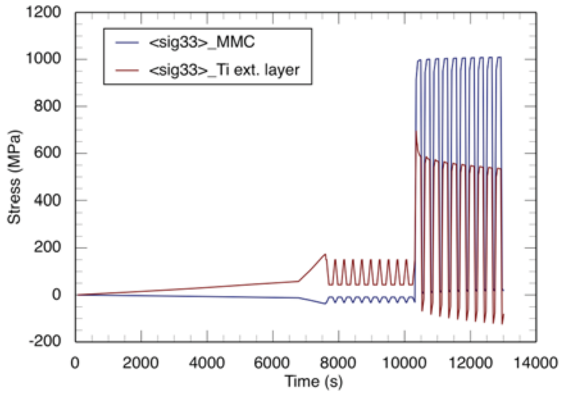


Figure 11. Evolution of average stress in MMC core and external layer of Titanium, σ_{max}= 975 MPa.

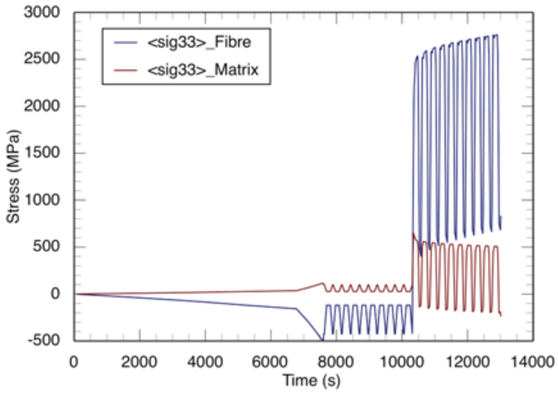


Figure 12. Evolution of average stress in fibres and titanium matrix in the MMC core, σ_{max}= 975 MPa.

CONCLUSIONS

The fatigue life of SiC-Ti6242 composite material has been investigated under a thermal-mechanical fatigue cycle representative of the actual loading of the composite core in a compressor disc under stress controlled conditions.

The thermal mechanical fatigue life tends to be shorter than isothermal LCF life at maximum temperature (450°C) while they seem to be similar at lower stresses. Observations of fracture surfaces support the fact that fibre fracture is still the dominant failure mechanism in the low cycle fatigue range under thermal mechanical fatigue.

A finite element model based on the constitutive model of Transformation Strain Analysis proposed by Dvorak was used to estimate the local stress in composite and external layer of Ti alloy as well as the average stress in fibres and matrix in composite core of specimens. Viscoplasticity in Ti-6242 plays a major role in load redistribution from matrix to fibres with increasing number of cycles.

However a large number of cycles needs to be computed to better assess the ratchetting occurring under thermal mechanical fatigue. This is the primary ingredient to be used in a life prediction model and in physically based damage models under work.

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