

# Assessment of failure mechanisms of aero engine TMC rotor disks at high rates of strain

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## Abstract

This paper reports the results of analytical and experimental investigations for the characterization of continuous fiber SiC/Ti composite structures under static, monotonic increasing highspeed and cyclic loading to failure.

In overspeed burst spin tests with altogether 3 titanium matrix composite (TMC) bladed ings (blings) it is demonstrated that with all influences of the bling manufacturing process a burst strain close to 0.9% is achievable and reproducible. 1.0% strain to failure is the well known mean value fracture strain for flat laboratory TMC specimens with an almost perfect fiber alignment. In highspeed 4 point bending tests of TMC specimens and in impact tests on cantilever TMC plates strain levels above 10% ( - far beyond the brittle fiber cracking - ) are achieved in the monolithic titanium areas of the structure without any crack detection in the titanium. Finally with fatigue tests of TMC hourglass specimens it is demonstrated that residual prestraining substantially improves the HCF strength of TMC at ambient temperature.

## 1 Introduction

MTU Aero Engines is being investigating the feasibility of silicon carbide fiber reinforced titanium (SiC/Ti) blades and rings for application in military jet engine low pressure compressor blisks. Compared to state of the art integrally bladed rotor disks (blisk), made of solid monolithic titanium, significant weight savings are predicted without compromising overspeed burst capability or low and high cycle fatigue. For the characterization of the high strength material properties of SiC/Ti MTU Aero Engines is cooperating with specialized material research institutes such as the German Aerospace Center (DLR),

Cologne, and the Institute of Materials and Impact Engineering (LWM) within the Technical University of Chemnitz, Germany.

To make use of the high stiffness and strength properties of SiC reinforced titanium in aero engine applications, the scatter from manufacturing process in the ultimate strain to failure of TMC rings and the damage behaviour of the ductile titanium matrix beyond the brittle fiber cracking must be known for damage tolerant design. Knowledge, how high cycle fatigue (HCF) of TMC is effected by thermal residual stresses and how these stresses can be altered, are key issues to improve the HCF strength of TMC for low temperature applications.

## 2 TMC bling overspeed spin tests

Figure 1 shows one of the TMC blings in the vertical vacuum spin rig for overspeed burst test. The ring body consists of 3 TMC rings (DERA SM1240)

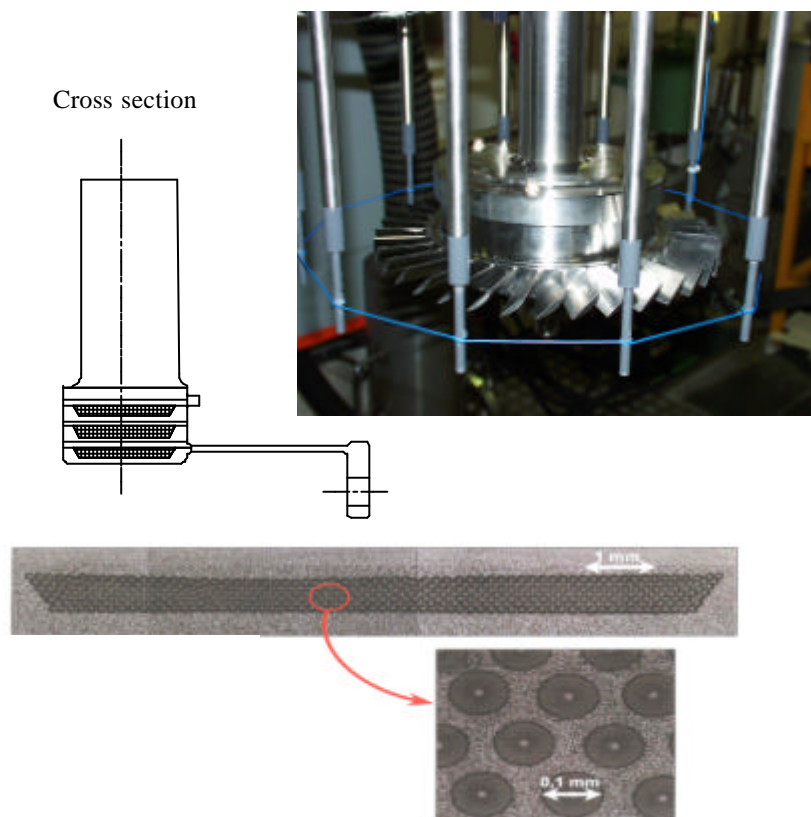


Figure 1: TMC bladed ring in the spin test rig

SiC fiber/Ti-6-4 matrix) with an average fiber volume fraction of 35% each, consolidated in a hot isostatic pressure HIP process. The bling blade tip diameter is 270 mm.

In test no. 1+2 burst speeds of 38600 and 37600 rpm were reached corresponding to a blade tip circumferential speed of 546 respectively 532 m/s. The inner diameter tangential strains of bling no.1 were measured at 4 circumferential positions (see Figure 2). At burst speed the maximum signal showed a strain value of 0.85% (i.e. 8500  $\mu\text{m}/\text{m}$ ). With a scale factor of 1.06 from the strain gage location to the maximum position this is equivalent to a maximum local strain of 0.90%. This scale factor is derived from an elastic-plastic (matrix) finite element calculation, which agrees quite well with the measured results of Figure 2. To predict the rotational speed, at which the matrix starts yielding, the thermal residual stresses in the composite are calculated first. These stresses are induced during cooling from processing to ambient temperature due to mismatch of the thermal expansion coefficients of the composite constituents.

For test bling no. 3 additional strain gages at the maximum position were applied and the spin test was successfully stopped without a burst event at a maximum measured local strain of 0.90%, which is identical to the burst strain of bling no.1. The inspection of this bling with nondestructive methods is still ongoing.

With these tests a bling rupture strain of 0.90% is demonstrated and reproduced, that is close to what is known from ideally flat laboratory test specimens (1.0%  $\pm$  0.04%) with an almost perfect fiber alignment.

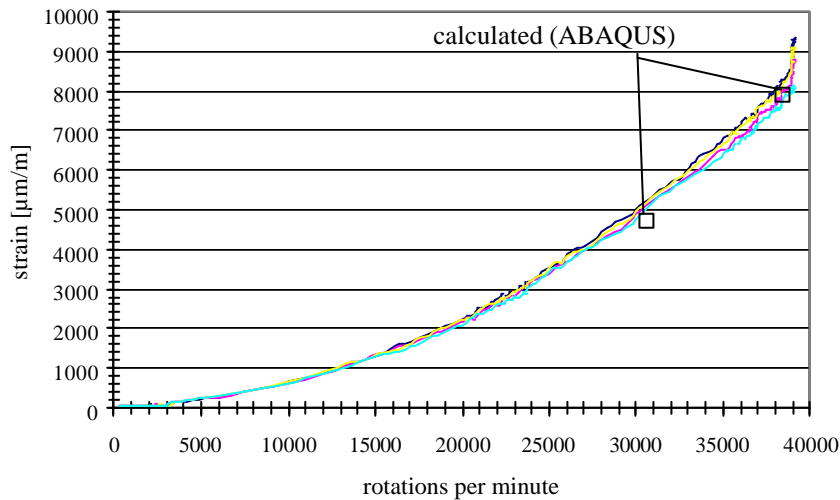


Figure 2: Measured bling inner diameter tangential strains

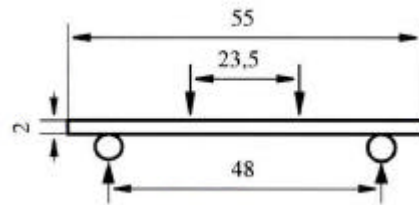
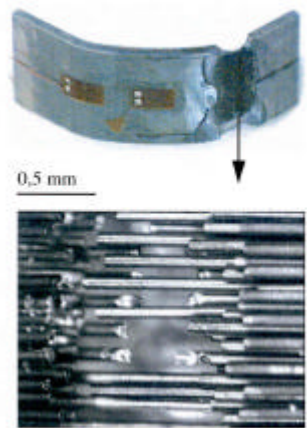
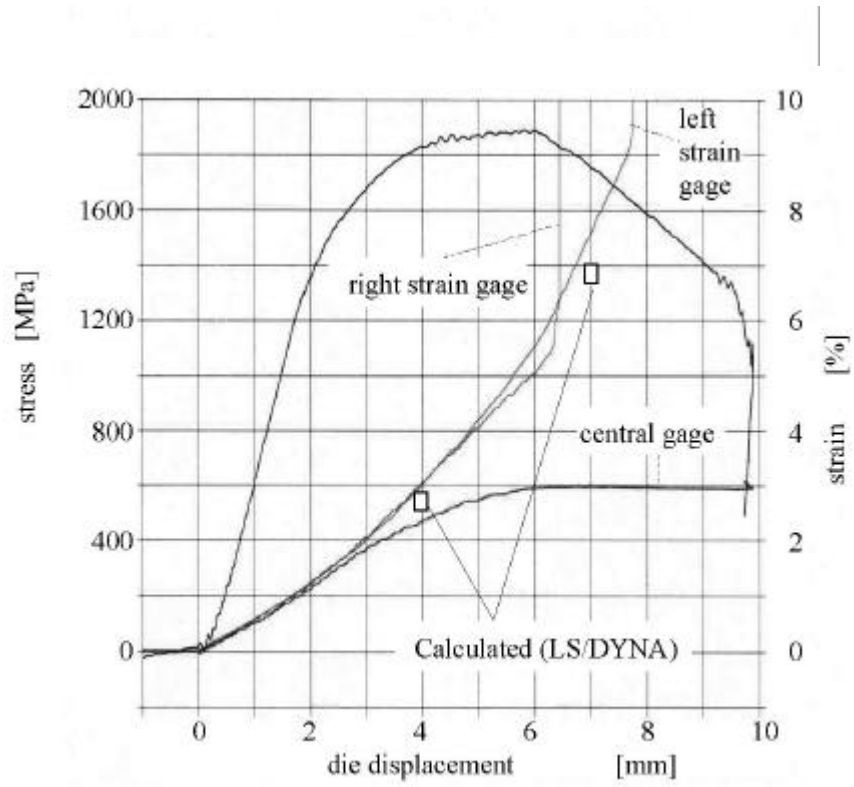


Figure 3: Dynamic 4 point bending loading of flat TMC specimens - (displacement-strain curve, residual bending)

### 3 High speed - large strain loading of TMC structures

A second area, in which the applicability of reinforcement of titanium with SiC fibers is investigated, are aero engine compressor fan airfoils. The intention behind this concept is to improve the combined static/vibratory fatigue potential of titanium airfoils under regular engine operating conditions. To do so, additional requirements concerning flight safety, such as birdstrike and bladeloss capability, must be fulfilled. This requires an extraordinary damage tolerant design and structures being able to survive large residual deformations without a catastrophic failure (Frischbier, J. [13]). For TMC this means, severe (brittle) fiber rupture must not immediately lead to an overall structural failure (i.e. bladeloss). Fiber rupture without crack propagation into the monolithic titanium must be possible and the fiber volume fraction must not exceed a certain threshold, i.e. the residual strength of the monolithic titanium without fibers must be sufficient.

In a first step this was investigated with highspeed 4 point bending tests of TMC specimens as shown in Figure 3. The cross section of these specimens look similar to Figure 1 (a 1.0 mm through thickness fiber reinforced core with a fiber volume fraction of 35% and a 0.5 mm monolithic titanium boundary). With the available test equipment a maximum strain rate of  $10 \text{ s}^{-1}$  was achieved. For being able to limit the maximum strain to a defined upper level, the relation between bending deflection and maximum strain was precalculated with an explicit finite element code (LS/DYNA - see Figure 3). In this analysis the behaviour of the titanium matrix was modelled with a strain rate dependent piece-wise elastic-plastic material law. Beyond the fiber fracture strain of 1% the element stiffness in the composite area was reduced to a level, equal to monolithic titanium in the yield domain without the stiffness of the 35% fiber volume fraction.

Figure 3 shows the measured relation between the die displacement (specimen bending deflection) and the surface strains. In this test a maximum tensile strain of 10% was reached without any crack detection in the monolithic titanium, but with all fibers cracked.

This composite fracture behaviour was verified in impact shooting test on cantilever TMC specimens being more representative for the real airfoil TMC design concept (Figure 4 -8). These specimens (120x50x7 mm) are reinforced from hub to tip with 7 pre-manufactured TMC rods (see non-reinforced hollow specimen Figure 5 right), each with a 3 mm diameter composite core with a fiber volume fraction of 47% (SCS-6/Timetal834). The shots were performed with 0.05 kg cylindrical plasticine projectiles at impact velocities between 200 and 450 m/s. Here strain rates of up to  $310 \text{ s}^{-1}$  were reached, what is closer to a real aero engine airfoil birdstrike situation. Again the LS/DYNA calculation correlates quite well with the measured residual bending deflections (Figure 8) and even the calculated failure sequence could be verified. Residual surface strains above 20% were reached with complete internal fiber rupture but no crack detection in the monolithic titanium parts.

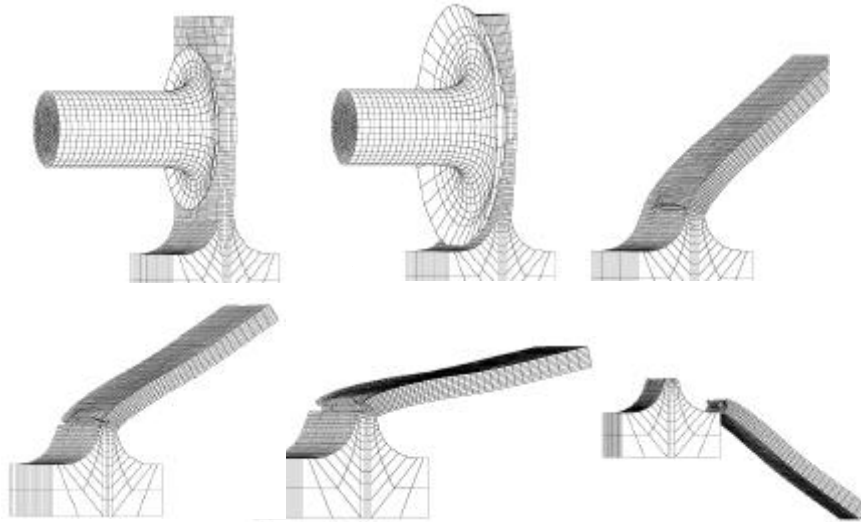


Figure 4: Analytical simulation of impact on TMC cantilever plates with 0.05 kg cylindrical projectiles (fluid material model) -  $v = 450$  m/s

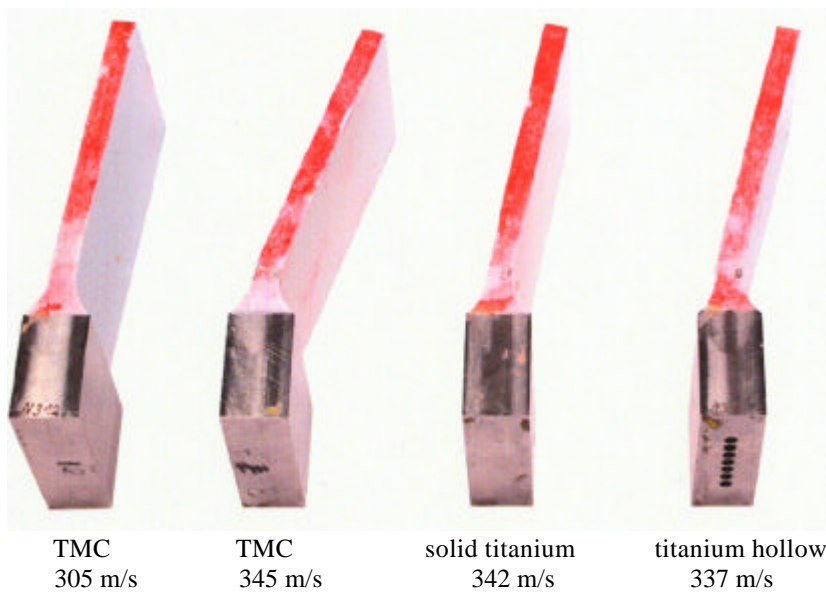


Figure 5: After shot residual deformations

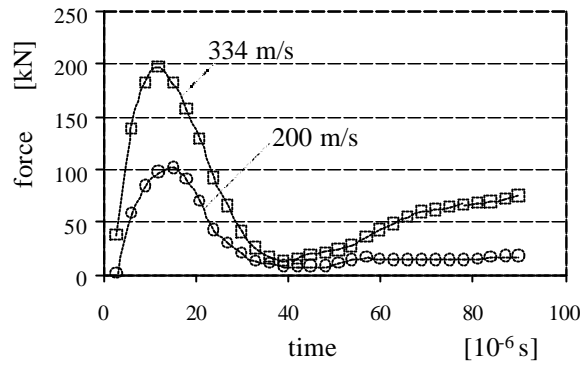


Figure 6: Calculated time history of the resulting impact forces

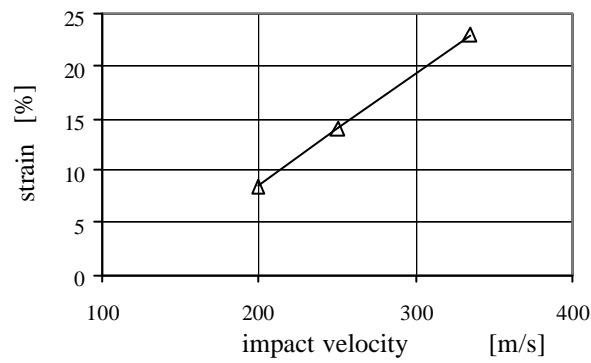


Figure 7: Calculated effective plastic strain (local surface maximum)

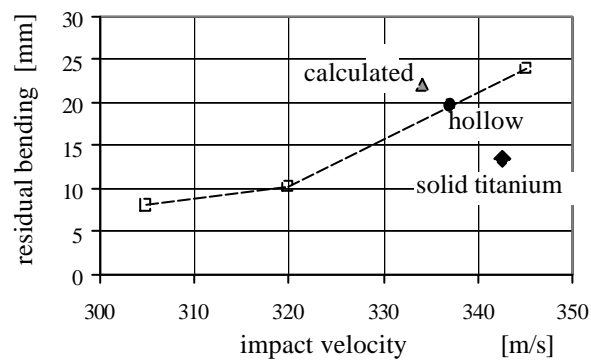


Figure 8: Measured residual tip deflection from impact tests

## 4 Fatigue Behaviour

Due to the mismatch of the coefficients of thermal expansion (CTE) between fibre and matrix material, thermal residual stresses (TRS) are induced during cooling from processing to ambient temperature (Durodola and Derby [1], Rangaswamy, et al. [2]). The TRS leave the matrix in tension and thus support crack nucleation and propagation in this constituent. On the other hand the state of TRS may be altered by creep, yield and temperature effects. Consequently the fatigue failure mechanism of TMCs is closely related to the conditions and the load history to which the component is subjected.

In the present study, the influence of stress level and temperature is analysed by finite element modelling to explain and predict the fatigue behaviour of TMCs observed in experiments. The dependence of the damage mechanisms on the loading condition is investigated by interpretation of the stress development during cycling (Hausmann, et al. [3]).

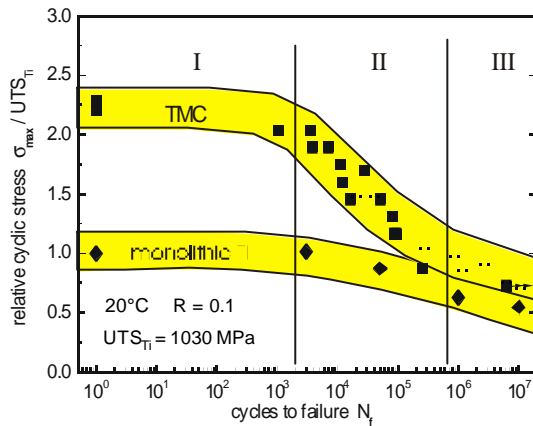


Figure 9: Normalised Wöhler curve for SCS-6/Timetal834 ( $v_f=47\%$ ) at RT

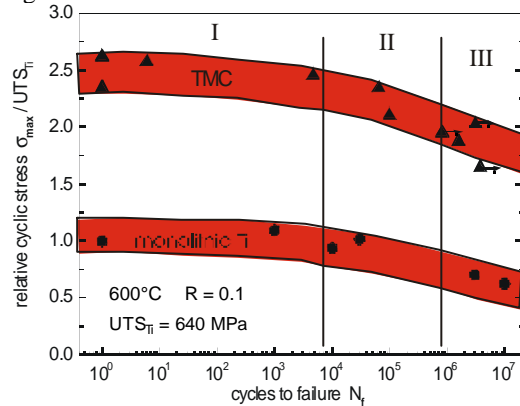


Figure 10: Normalised Wöhler curve for SCS-6/Timetal834 ( $v_f=47\%$ ) at 600°C.

Figure 9 and 10 show the Wöhler curves for TMC compared to the monolithic titanium alloy at 600°C and room temperature, respectively. Here the maximum cyclic stress is normalised to the ultimate tensile stress of the unreinforced matrix material. The diagrams can be divided into three regions. Region I represents the low cycle fatigue (LCF) regime with a high stress level while region III is in the high cycle fatigue (HCF) regime with low stress levels with a transition zone (region II) in-between (Peters, et al. [4]). The classical fracture mechanics approach for metals relates HCF to elastic deformation and LCF mainly to plastic deformation (Dowling [5]). This characterisation can certainly not be applied to TMCs since the fibres allow no plastic deformation and, furthermore, the composite behaviour is strongly influenced by TRS (Hausmann, et al. [6], Chandra, et al. [7], Bobet, et al. [8]).

The improvement of fatigue strength by the reinforcement is obvious in all fatigue regions, however the improvement is highest at high temperature or high stress levels or both. Three different mechanisms can be detected. In the LCF regime at both high temperature and ambient temperature the matrix deforms plastically. Since the plastic deformation is limited by the rupture strain of the fibres it occurs in the first cycles only and afterwards extensive elastic response occurs. Thus the matrix yields to a balanced stress state. The elastic limit is shifted to a level close to the rupture strain of the fibres. This leads to an optimisation of the residual stresses for maximum strength of the composite. The factor of reinforcement (strength TMC / UTS unreinforced) is highest for this case.

The HCF regime at high temperature shows a time dependent behaviour. Similar to high stress loading in the LCF regime the matrix reaches an optimised stress state; but here creep mechanisms are the major factor instead of yielding. The factor of reinforcement is very high here also.

The third case is that of HCF loading at room temperature. Since the matrix stress is too low for matrix yielding and the temperature is too low for significant creep rates, the matrix cannot reach an optimised stress state. The matrix is pre-loaded by TRS which are tensile. Thus the matrix suffers the sum of TRS and a fraction of the applied stress. In connection with the lower ductility at room temperature the matrix is sensitive for premature matrix cracking. This leads to a factor of reinforcement which is modest compared to other regions.

The target of the research work was to improve the HCF strength at room temperature since it is the loading condition detected as weakest point of TMCs. The experimental series were accompanied by FEA to develop a suitable procedure. The purpose of the improvement is to reduce TRS in the matrix to prevent premature cracking. Considering the behaviour under LCF conditions a well defined pre-loading of the specimen enables a reduction of TRS. This can be reached by single tensile loading-unloading up to a strain causing no breakage of fibres. With respect to a rupture strain of 0.75% of the weakest fibre (which is a very conservative value) and a residual fibre strain of -0.16% in the "as processed" state the composite can be strained up to 0.9% without any fibre damage. The FEA predicts a reduction of TRS in the matrix in the axial direction due to the pre-straining procedure from 320 MPa in the "as processed"

condition down to 220 MPa in “relaxed” condition (Hausmann, et al. [9]). Figure 11 shows experimental results and FEA predictions of specimens in both conditions. In contrast to the results of tension-tension loading shown in Figure 9 and 10 here the experiments were carried out under fully reversed loading, which shows the effect of premature matrix cracking on total failure more drastically due to periodically opening and closing of initiated cracks leading to friction and shear stresses in the fibres (Nicholas, T. [11], Steyer, et al. [12]).

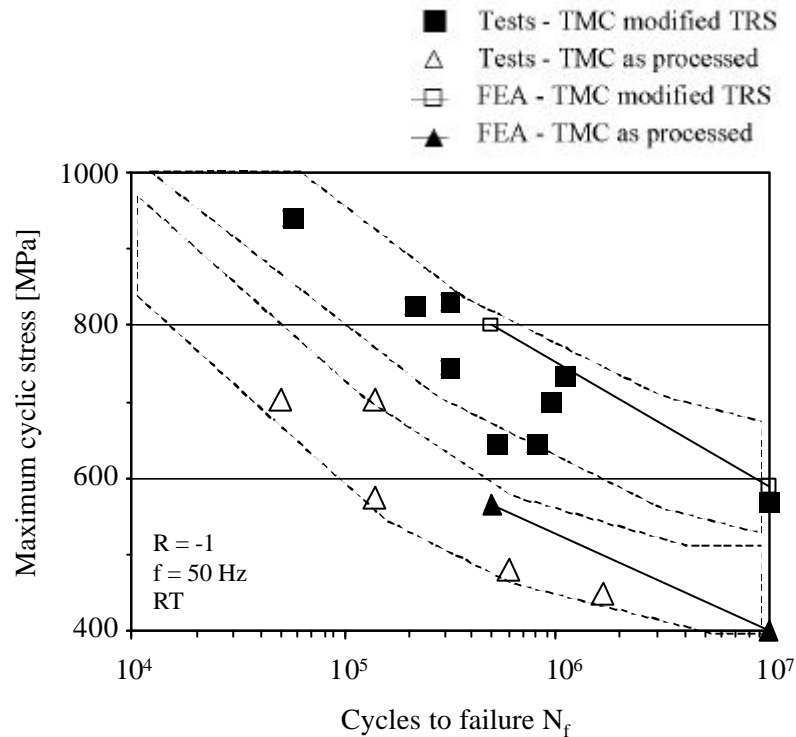


Figure 11: Influence of TRS modification on the HCF strength of SCS-6/Ti-6-2-4-2 at room temperature under tension-compression loading

Although the TRS are reduced in part only, the improvement of fatigue strength is obvious. The FEA marks an upper bound of strength since the Young's modulus of the constituents assumed in the analysis was a little higher than that of the material used in the experiments. Consideration of this shows the same strain range for both the experiments and the FEA.

The treatment shown is the first attempt to improve the fatigue resistance at ambient temperature. FEA helps in understanding and developing the mechanism. The advanced usage of it predicts more effective ways to reduce TRS and thus greatly improve the HCF strength by thermomechanical treatment. Experimental investigations are still in progress and will be published later.

## References

- [1] Durodola, J.F., Derby, B., An Analysis of Thermal Residual Stresses in SiC and Al<sub>2</sub>O<sub>3</sub>-Fibres, *Acta Metall. Mater.*, Vol. 42, pp. 1525-1534, 1994
- [2] Rangaswamy, P., Prime, M.B., Daymond, M., Bourke, M.A.M., Clausen, B., Choo, H. and Jayaraman, N., Comparison of residual strains measured by X-ray and neutron diffraction in a titanium (Ti-6Al-4V) matrix composite, *Materials Science & Engineering A-Structural Materials Properties Microstructure & Processing*, Vol. 259, pp. 209-219, 1999
- [3] Hausmann, J.M., Hemptenmacher, J., Leyens, C., Kaysser, W.A., Influence of loading conditions on fatigue behaviour of titanium matrix composites, submitted to: *International Congress on Fatigue 2002*, Stockholm, Sweden, Vol. pp. 2002
- [4] Peters, P.W.M., Xia, Z., Hemptenmacher, J. and Assler, H., Influence of interfacial stress transfer on fatigue crack growth in SiC-fibre reinforced titanium alloys, *Composites Part A: Applied Science and Manufacturing*, Vol. 32, pp. 561-567, 2001
- [5] Dowling, N.E., *Mechanical Behavior of Materials*, Prentice Hall, Upper Saddle River, 2, Vol. pp. 832, 1999
- [6] Hausmann, J., Hemptenmacher, J., Kumpfert, J., Modelling of the Influence of Fibre Distribution on Residual Stresses and Strength, *ICCM 13*, Beijing, China, Vol. pp. 2001
- [7] Chandra, N., Ananth, C.R., Garmestani, H., Micromechanical Modeling of Process-Induced Residual Stresses in Ti-24Al-11Nb/SCS-6 Composites, *Journal of Composites Technology and Research*, Vol. 16 No. 1, pp. 37-46, 1994
- [8] Bobet, J.L., Masuda, C. and Kagawa, Y., Estimation of residual stresses in SiC/Ti-15-3 composites and their relaxation during a fatigue test, *Journal of Materials Science*, Vol. 32, pp. 6357-6369, 1997
- [9] Hausmann, J., Leyens, C., Hemptenmacher, J., Kaysser, W.A., High Cycle Fatigue Strength Improvement of Titanium Matrix Composites by Residual Stress Modification, *TMS Fall Meeting*, TMS Warrendale, Indianapolis, USA, Vol. pp. 2001
- [10] Boyer, R., Welsch, G., Collings, E.W., *Materials Properties Handbook: Titanium Alloys*, ASM International, Vol. pp. 1994
- [11] Nicholas, T., *Fatigue and Thermomechanical Fatigue Life Prediction, Titanium Matrix Composites - Mechanical Behavior*, Technomic Publ. Co., Lancaster, Vol. pp. 209-272, 1998
- [12] Steyer, T.E., Zok, F.W. and Walls, D.P., Experimental assessment of fatigue life and failure modes in a SiC/Ti composite, *Composites Science and Technology*, Vol. 58, pp. 1583-1591, 1998
- [13] Frischbier, J., Birdstrike Capability of a Transonic Fan Blisk, *ASME IGTI TurboExpo 1997*, 97-GT-482, Orlando, USA