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MODELLING OF THE INFLUENCE OF FIBRE DISTRIBUTION ON RESIDUAL STRESSES AND STRENGTH OF TITANIUM MATRIX COMPOSITES

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Summary: Irregularities of fibre distribution due to processing have a significant influence on thermal residual stresses of titanium matrix composites (TMCs). It can be assumed that such deviations from the ideal fibre arrangement also lead to a decrease of mechanical properties, especially fatigue and tensile strength. This behaviour is simulated by a finite element model which allows to consider different degrees of irregularities. The dimensionless quality parameter Q_d enables the transfer of results to imperfect TMCs in complex components. A strong dependence of strength to the quality of fibre distribution was determined. This leads to definition of minimum mandatory requirements, which can be developed based on the results presented.

Keywords: Titanium Matrix Composite, TMC, Modelling, Thermal Residual Stresses, Fibre Distribution, Mechanical Properties

INTRODUCTION

Continuous fibre reinforced titanium matrix composites (TMCs) are attractive high performance materials for future aerospace applications due to their high specific strength and stiffness [1]. Different processing technologies are available to produce parts out of TMCs. Although there is a significant influence of final product quality on mechanical properties of TMCs, i.e. fatigue and tensile strength, little systematic work is accessible today considering the impact of processing on the loading capabilities of TMCs. One important attribute of TMC quality is described by the fibre distribution in the final product. Inhomogeneity's of fibre distribution has been identified as one important factor for strength degradation. The focus in the analysis of this behaviour are thermal residual stresses (TRS), due to the mismatch of thermal expansion. Investigations were performed to determine TRS depending on fibre arrangement. The calculation by finite element modelling delivers results corresponding well with experimental observations [2,3]. However, these simulations consider just an ideal fibre distribution, which usually does not exist in real composites.

Irregularities in the fibre distribution have a significant effect on the maximum values of TRS both in the matrix and the interface. The increase of TRS may cause a decrease of strength. Even cracks, i.e. in the interface, may occur during cooling down from processing temperature to room temperature without the influence of any external mechanical load. This behaviour is analysed by finite element modelling which considers different degrees of irregular fibre distribution. The composite system used in the present work is composed of the silicon carbide fibre SCS-6 from Textron with a diameter of 142 µm including the carbon coating of 3 µm and the titanium alloy Ti-6-4 (Ti-6Al-4V) as matrix. Fibre volume contents considered are 33 and 47%, respectively.

Applications as reinforced compressor blades or bladed rings (bling) in future jet engines do require a thorough understanding of the damage mechanisms and mechanical properties. Sometimes a large deviation between predicted and test results was determined. Neglected irregularities in the fibres or their arrangement may have contributed to the obtained discrepancy. Thus a simulation of material behaviour close to the real situation in existing reinforced specimens or components is necessary to predict important parameters, as e.g. the strength depending on defects in the composite.

There are different processing routes to produce TMCs. Basically they can be divided into two groups. One uses the fibres as delivered and consolidate them with the matrix directly to the final composite part. The matrix is processed as foil by hot isostatic pressing (HIPing) [4] or as powder by thermal spraying (plasma spraying) [5]. The other route is defined by coating the single fibres first with matrix material by magnetron sputtering or any other PVD-process. In a second step these coated fibres are consolidated by HIPing [6]. The first group of processes results in a composite with either an inhomogeneous fibre distribution or it requires a weaving wire to keep the fibres in position. Both defects are influencing the final properties of the composite material. Processes using matrix coated fibres prevent fibre touching without the need for any cross weaving.

Since a significant payoff by employing TMCs in future high performance applications can only be expected, if the high structural strength of the reinforced component can be guaranteed over the life time required, any factor reducing the high strength need to be determined and avoided. The present investigation points out the influence of irregularities in the fibre distribution on the mechanical properties. As a consequence, some suggestions for future TMC development are presented.

THE FE-MODEL

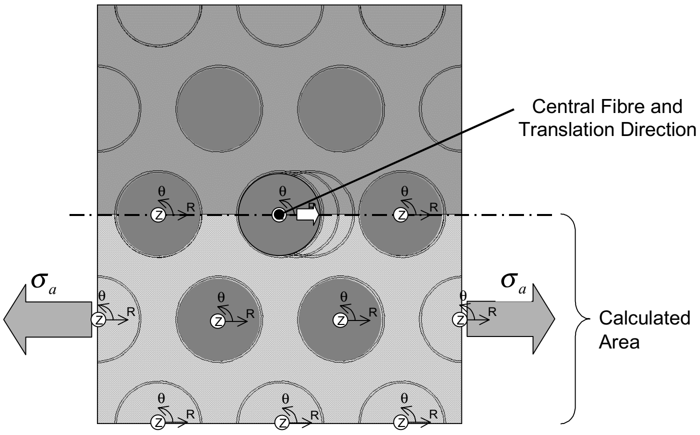


Fig. 1 - Geometric model for the hexagonal unit cell

The finite element model considers both, the SiC-fibres and its carbon coating with elastic properties, and the Ti-matrix with elasto-plastic properties. Tables 1, 2 and 3 are showing the properties of the constituents and its temperature dependence. These components are connected in a way, that no sliding occurs. The model consists of one central fibre which is surrounded by six fibres in a hexagonal arrangement. To obtain a model with exact boundary conditions it is filled up with ten semi-fibres. Each fibre has a diameter of 142 µm including the carbon coating of 3 µm. The remaining space is filled up with matrix. To reduce the time for calculation the model is cut in the symmetry line. Thus just one half of the model is simulated. The centre point of each fibre locates its own cylindrical co-ordinate system. This allows an interpretation of the stresses related to the single fibre. The boundary conditions are chosen in a manner, that the model represents a part of an infinite solid. A cooling scheme from 700°C to 20°C is simulated. Fibre volume fractions of 47% and 33% were selected for the calculations. To simulate the effect of inhomogeneity's the

Table 1
Properties of the SiC-Fibre (SCS-6, diameter 142 µm) and their temperature dependence used in the finite element model [2]

Temperature [°C]	Young's Modulus [GPa]	CTE [10^{-6}/°C]	Poisson Ratio
21	393	3.2025	0.25
93	390	3.3403	0.25
204	386	3.5437	0.25
316	382	3.7369	0.25
427	378	3.9197	0.25
538	374	4.0922	0.25
649	370	4.2543	0.25
760	365	4.4061	0.25

central fibre is shifted to a neighbouring fibre (Fig. 1).

Although the processing temperature of TMCs is about 950°C this is not the starting temperature for the analysis of TRS, because viscoplastic behaviour reduces the stresses at high temperatures. Taking this into account it is necessary to start the simulation at a stress-free temperature of 700°C and a cooling down to 20°C with elastic properties [8].

Table 2
Properties of the interface region used in the finite element model [7]

Modulus [GPa]	100
CTE [10^{-6}/°C]	4.86
Poisson Ratio	0.3
Thickness [µm]	3

Table 3
Properties of the Matrix (e.g. Ti-6-4) and their temperature dependence used in the finite element model. Yield Stress at room temperature 1000 MPa, Flow Modulus 0.7 GPa [2]

Temperature [°C]	Young's Modulus [GPa]	CTE [10^{-6}/°C]	Poisson Ratio
23	125	8.78	0.31
260	110	9.83	0.31
316	100	10.14	0.31
427	100	10.71	0.31
482	80	10.97	0.31
538	74	11.22	0.31
650	55	11.68	0.31
800	27	12.21	0.31

NEAR-REALITY-SIMULATION

Real TMCs, especially in large scale components, usually do not show an ideal fibre distribution (Fig. 2). To compare irregularities in different TMCs a dimensionless parameter is necessary. Therefore the quality parameter Q_d is defined. It can be determined by the following expression delivering the average deviation of the fibre spacing to the average fibre spacing:

$$Q_d = 1 + \frac{\sum_{1}^{n} \left| 1 - \frac{s_{fn} - d_f}{\bar{s}_f - d_f} \right|}{n}$$

where

Q_d ...	quality parameter for fibre distribution
n ...	number of measured fibre spacings
s_{fn} ...	n^{th} fibre centre spacing
$\bar{s}_f$ ...	average fibre centre spacing
d_f ...	fibre diameter

A value of $Q_d=1$ represents an ideal fibre distribution. Irregular fibre arrangements deliver a $Q_d>1$. Fig. 3 shows examples for the variation of quality parameters. It is obvious that the process using matrix coated fibres results in a Q_d closer to 1. A value of approximately 1.65 is equivalent to touching fibres.

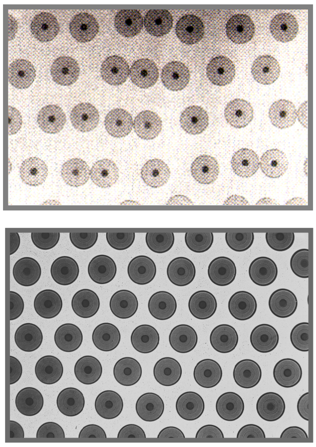


Fig. 2 - Examples for deviations in fibre distribution, upper image: irregular fibre arrangement with fibres in contact [9], lower image: near ideal arrangement produced by matrix coated fibres [10]

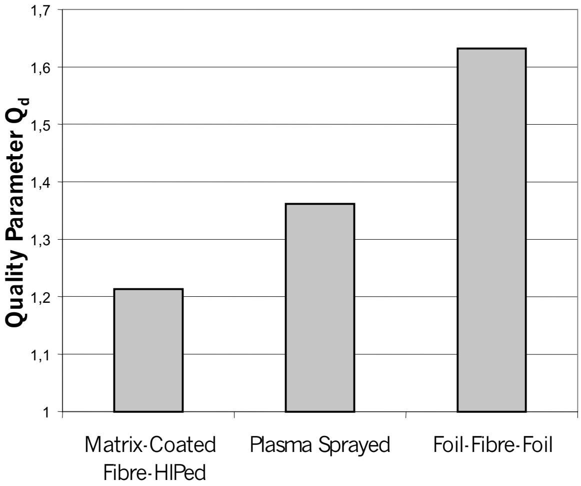
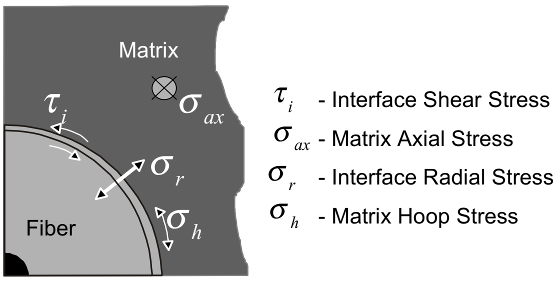


Fig. 3 - Average Quality parameters Q_d for different processing technologies (examples).

THERMAL RESIDUAL STRESSES

Due to the mismatch of CTE thermal residual stresses (TRS) are induced in TMCs during processing. TRS of the fibres are compressive anyway and distributed nearly homogeneous. However, TRS in the matrix are extensive tensile and vary significantly as a function of the location. Due to such irregularities and the sensitivity of the constituents the analyses is focussed on TRS in the matrix and the interface. Selected components of TRS are shown in Fig. 4. The results of the TRS calculation are summarised in Fig 5-9. Please note that only the maximum values are plotted in the diagrams except Fig. 8 which contains the minimum and maximum radial stresses. It is obvious that matrix axial and hoop stresses are only slightly influenced by Q_d (Fig. 6 and 7). In contrast to this the interface radial stresses are strongly increasing with increasing values of Q_d (Fig. 8). In this diagram the maximum and minimum values are plotted. The radial stresses are compressive nearly at one level all around the



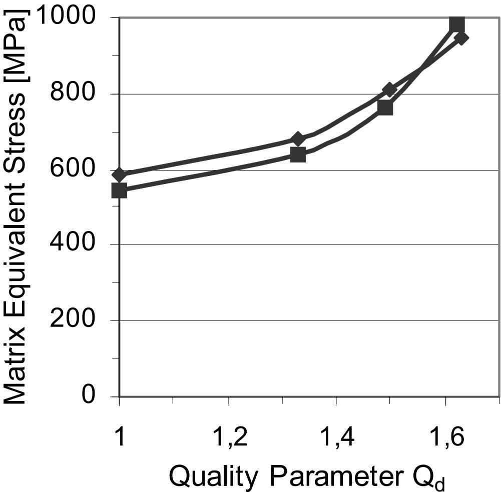


Fig. 4 - Selected components of residual stresses

Fig. 5 – Matrix Equivalent Stress

circumference of the fibre at ideal fibre distribution. However, with increasing values of Q_d radial stresses start varying with the location . At the higher fibre volume content and Q_d>1.55 radial stresses even becomes tensile. An absence of a radial interface strength would separate fibre and matrix in this case.

However, the increase of maximum shear stresses at the interface are important too. Considering a maximum shear strength of the weak interface in the order of 100 - 200 MPa the results show that such a value can be reached by increasing Q_d alone. Thus the interface may fail without any additional load above this limit.

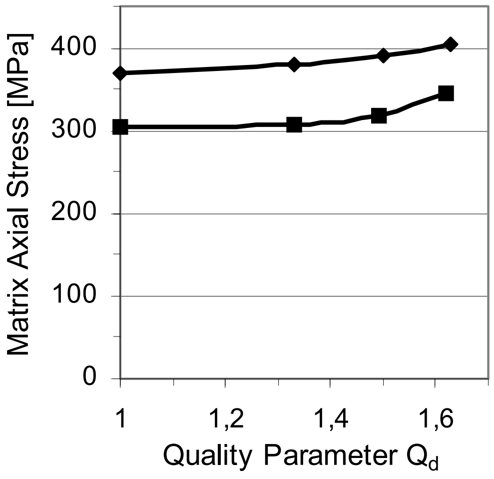


Fig. 6 – Matrix Axial Stress

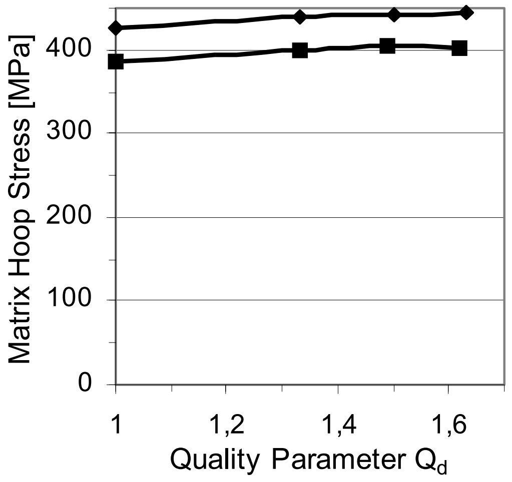


Fig. 7 – Matrix Hoop Stress

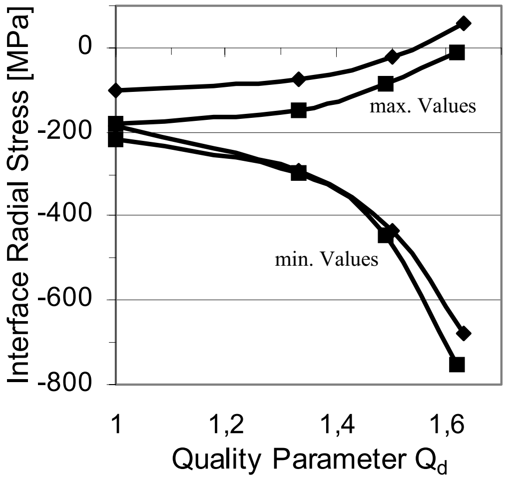


Fig. 8 – Interface Radial Stress

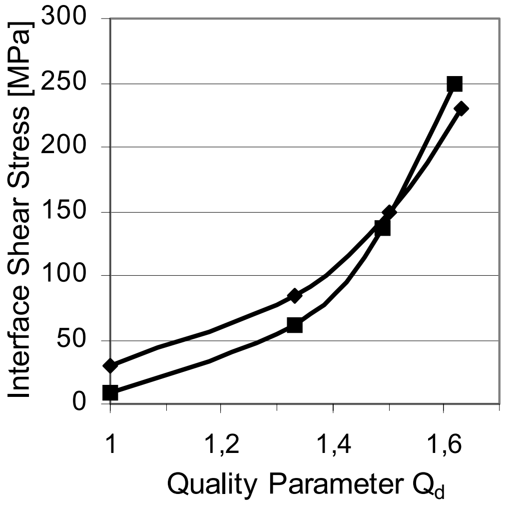


Fig. 9 – Interface Shear Stress

Fig. 5-9 - Residual stresses versus Q_d. Fibre volume content v_f=33% (■) and v_f=47% (◆), respectively

LONGITUDINAL TENSION

Longitudinal tension means an applied tensile stress parallel to fibre direction. Due to the higher Young's modulus of the fibres they are carrying a higher amount of the applied stress. On the other hand the TRS in matrix are tensile. Thus the matrix stress has an offset at TRS level and increases slowly by increased applied stress until the yield strength. Fig 10 and 11 are showing the maximum of matrix equivalent stress versus applied stress in the range up to 1000 MPa. If the matrix reaches 1000 MPa it starts yielding. At an ideal fibre arrangement the

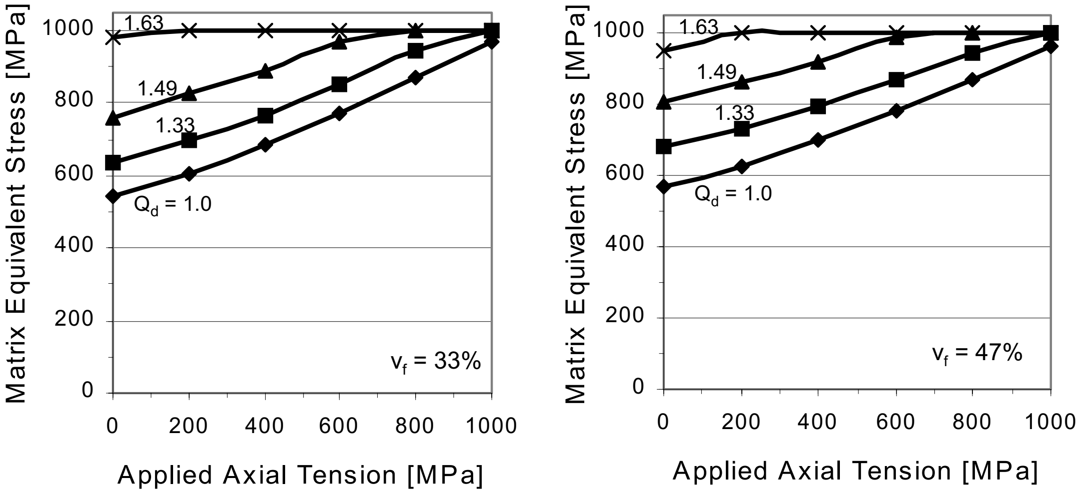


Fig. 10 and 11 - Matrix equivalent Stress as function of applied axial stress

matrix stress does not reach this limit. An increase of Q_d increases the peak of TRS and thus it is lowering the applied tension when first yielding occurs. Even the matrix yields just in a very small region in-between the location where the fibres are closest it need to be considered in further investigations.

Variation of fibre volume content influences the longitudinal behaviour slightly.

TRANSVERSE TENSION

Transverse tension means an applied tensile stress in normal direction to the fibres. The stress strain response observed in transverse tension tests is shown in Fig. 12. The first visible failure is fibre matrix separation, so called debonding. It occurs when both the radial component of TRS in the interface and its bonding strength is locally exceeded [9]. Thus a

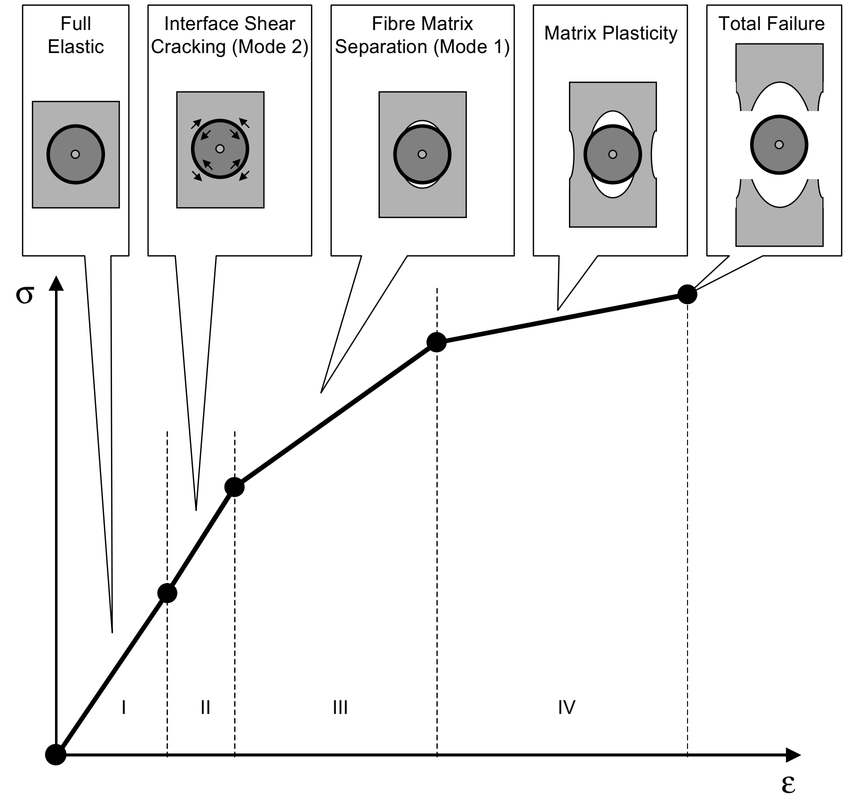


Fig. 12 - Stress strain response of transverse loaded TMC with determined damage events

mode 1 crack initiates and grows. This radial interface strength is assumed as about 170 MPa [10]. Fig. 13 and 14 are showing the maximum peak of radial interface stress as function of applied transverse load. The dotted line marks the strength and helps to determine the debonding limit.

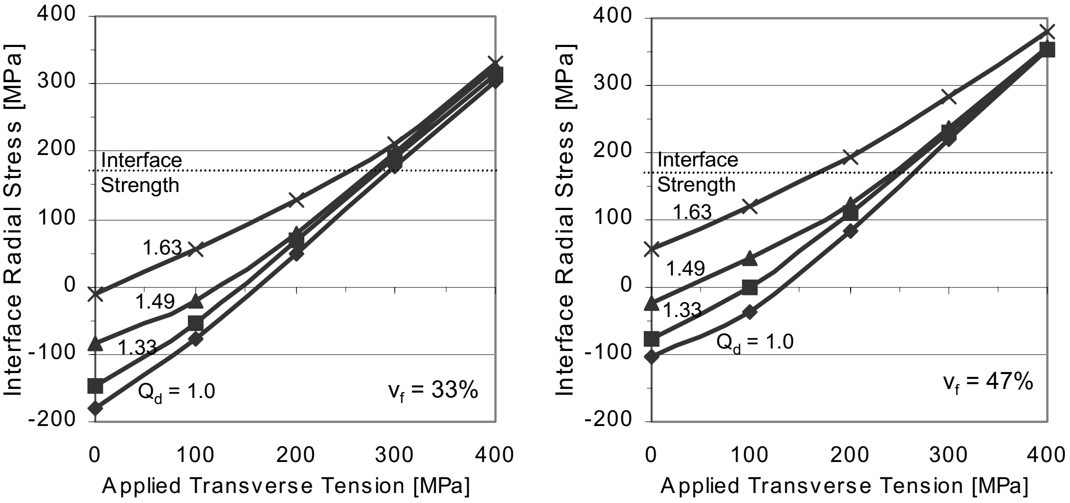


Fig. 13 and 14 - Interface-Radial Stress as function of applied transverse stress (Mode I Interface failure)

On the basis of an interface shear strength of 140 MPa, which is an average of different investigations [11,12], the interface shear failure (Mode 2) is the first damage event in TMCs under transverse tension, even before debonding occurs. It is not visible in the stress strain response due to very small displacements under this mode. The crack is kept closed by the radial TRS. Since this event is the first irreversible damage it is a very important limit for the design of transverse loaded components. Fig. 15 and 16 are showing the interface shear stress versus applied transverse stress. The assumed shear strength of 140 MPa is marked by the dotted line. The loading limit can be determined by this diagram.

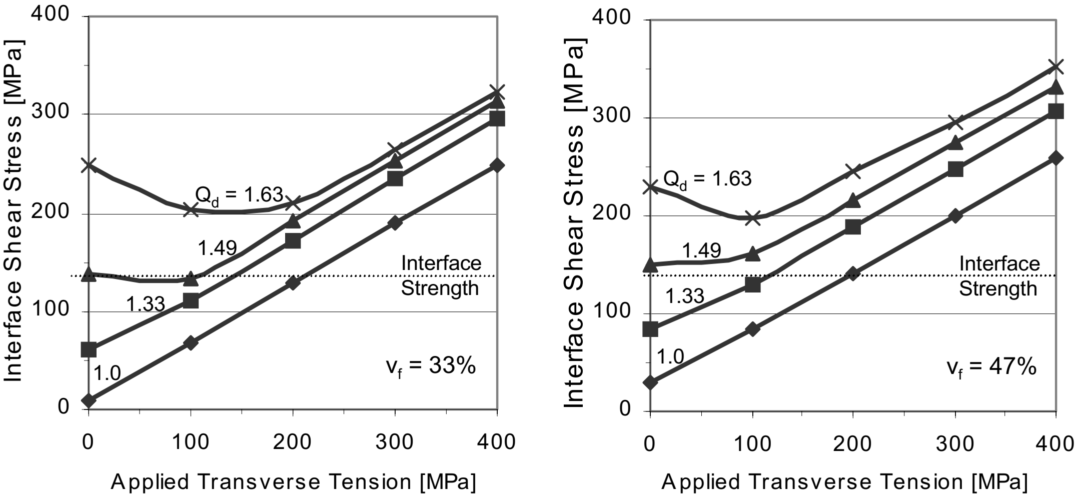


Fig. 15 and 16 - Interface-Shear Stress as function of applied transverse stress (Mode II Interface failure)

The combination of these two damage mechanisms leads to a damage map for transverse loaded TMCs as shown in Fig. 17. The limit for matrix plasticity can not be determined reliable by the used FEM model. For this a more complex model with gap elements is needed which is not part of the current analyses. A decrease of fibre volume content increases the stress level for transverse loads.

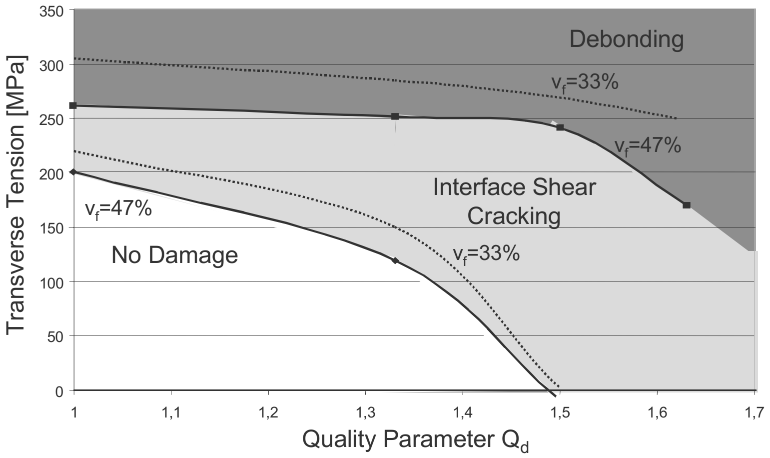


Fig. 17 - Damage Map for transverse tension of TMCs

EXPERIMENTAL RESULTS

Experiments to observe the described phenomenon of strength degradation are very difficult due to the limited feasibility of manufacturing specimens with defined irregularities. One practical way is to compare different test results and determine the fibre distribution afterwards. Such work is still running and results will be summarised soon.

Basically it is obvious that results presented in the past are scattering in a wide range. Furthermore mechanical properties of specimens produced by the matrix coated fibre technique can be found in the upper region of the scatter band. Thus processes delivering specimens with higher quality of fibre distribution are leading to better mechanical properties. The quantification of this observation is still under work and will be published later.

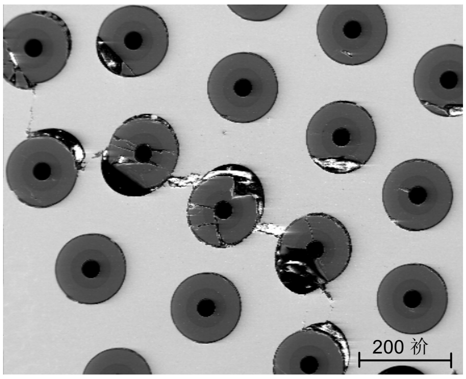


Fig. 18 - Crack path in transverse creep specimen

A second attempt to validate the simulation results can be made by observation of crack nucleation and their locations. This can be made by microscopic investigation of sections, especially of transverse loaded specimens. Fig. 18 shows the section of a transverse creep specimen. It is obvious that the crack follows a path in the matrix where fibres are closest. This supports the assumption that cracks initiate and propagate where TRS are highest.

Assuming that interface shear cracking is the first irreversible damage event of TMCs under transverse loading the transverse fatigue limit can be expected at this level. [13] has shown that the transverse fatigue limit is one half of the proportional limit under monotonic transverse loading. The proportional limit is marked by fibre matrix separation or the area of debonding in Fig. 17. Taking a Q_d of about 1.35 – 1.4 into account, which is a realistic value for such a specimen, the stress level for interface shear cracking can be found at one half of the debonding limit. This confirms the behaviour in [13], in which, however, the stress levels are generally lower, since a different composite system was used.

DEFINITION OF QUALITY GUIDELINES

Often the influence of product quality on TMC component strength is neglected. One essential presumption for quantifying this influence is a guideline which describes necessary requirements. The definition of minimum mandatory requirements would help both the manufacturer and the customer to qualify the composite.

As mentioned above interface failure can occur without any additional load if the quality parameter Q_d is higher then 1.5. This value should be never exceeded in a TMC, to avoid a pre-damaged composite. The exact value of Q_d and the fibre volume fraction need to be determined for each material, to enable an initial judgement of the quality of the material. Furthermore the individual damage map is determined by the choice of the composite system and the loading conditions in the application. In a second step a process technique can be found which fulfils these requirements.

Basically it can be seen in TRS-Q_d curves that the stresses increases rapidly when Q_d exceeds about 1.3. At this order of magnitude the upper limit may be reached for TMCs in high performance applications. Such a high quality TMC can be obtained by advanced processes, which start with matrix coated fibres.

DISCUSSION

The current analysis was focussed on both matrix and interface stresses. Due to this the obtained results can be transferred to any load case inducing matrix or interface failure.

During longitudinal tensile testing of as processed TMCs at room temperature the point of first matrix yielding can generally be determined to be below the ultimate tensile strength. Thus during cyclic loading at high stress levels (e.g. low cycle fatigue testing) the matrix stress peaks will be reduced while the first cycles. Nevertheless the existence of a stress peak can still cause the initiation of fatigue cracks in the matrix. Especially high cycle fatigue loading at a low stress level is known to lead to crack nucleation and propagation in the matrix [14]. Due to the modelling in this investigation it can be anticipated, that cracks nucleate where the local stress is highest. In addition, the low stress levels during high cycle fatigue testing are not able to reduce any stress peak in the matrix by yielding. Thus any TRS peak lead to a matrix stress peak in the loaded state which may reduce the life time.

The limit for transverse loading is dominated by the interface strength. This is strongly influenced by the fibre coating, the processing and the choice of the matrix material. The presented results are made under the assumption of a constant interface strength, with respect to both shear and radial tension. An increase of these properties would increase the transverse TMC properties, but may decrease the longitudinal properties. The used values in this investigation lead to interface shear cracking as the primary damage event at room temperature. Since such a damage mechanism does not lead to a visible change in the stress strain response it needs special attention. It can be assumed, however, that this critical event limits the life of TMCs in transverse fatigue before normal fibre matrix separation occurs. Further investigations are under way to validate this assumption.

A large field for research, which is not considered in this work, is the influence of multiaxial loading. In addition multiaxial loading induces complex stress states inside the composite. Therefore the influence of longitudinal cyclic loads on TRS and the resulting new transverse properties need to be addressed.

Generally it is worth to be mentioned that TRS are decreased with increasing temperature. Thus the shown effects of irregular fibre distribution in TMCs are less significant at elevated temperature. This needs to be considered since many applications for TMCs are intended to be used at elevated temperatures.

CONCLUSION

The modelling of the influence of the fibre distribution on residual stresses and strength in titanium matrix composites (TMCs) leads to the following conclusions:

- Irregularities in the fibre distribution of TMCs cause a significant increase of the local thermal residual stresses in the matrix, leading to critical stress peaks in the interface regime.
- These stress peaks can reduce the static and cyclic loading capabilities of TMCs. Strong irregularities can already lead to a pre-damaged composite prior to mechanical loading.
- Applied transverse loads lead to interface shear cracking as the primary damage event. This event can not be observed by the stress strain response and needs therefore special attention.
- The degree of irregularities of fibre distribution can be quantified by the dimensionless quality parameter Q_d.

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