RECENT DEVELOPMENTS IN SIC-FIBRE REINFORCED TITANIUM SHAFTS

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Abstract

The main shaft of an aircraft’s engine transmits extremely high torques at elevated temperatures. Therefore, high strength materials with low densities are required. The torque capability of these shafts can be considerably enhanced by the application of composite materials such as silicon carbide fibre reinforced titanium alloys. Titanium matrix composites (TMCs) offer high specific strength and high specific stiffness at temperatures up to 550°C depending on the matrix alloy.
Engine shafts require higher torsion strength in one direction than in the other one. To meet these requirements specific designed tubular samples have been manufactured and tested. Considering the characteristic behaviour of SiC fibre reinforced titanium alloys a unidirectional angle ply lay-up promises optimum properties. To produce tubular samples with this special lay-up a special technique has been developed which requires neither costly machines nor time consuming processes.
Results have shown a maximum torque of the reinforced shafts nearly twice as high as unreinforced titanium shafts. The manufacturing process, experimental results and efforts to improve affordability will be presented. Not only efficiency of engines can be increased but also weight of other components in all sectors of the transportation industry can be reduced.

Introduction

The development of new gas turbines for aircrafts aims at an increase of efficiency and thrust-to-weight ratio [1, 2]. Therefore, materials with exceptional high specific strengths and stiffness along with high temperature resistances are required. Since titanium alloys are established in the compressor section of aeroengines for some decades, fibre reinforced titanium alloys (Titanium Matrix Composites – TMCs) are under development to increase the high strength level again. Silicon carbide fibres with a diameter between 100 and 142 µm are commonly used. As a result of advanced processing routes TMCs with a tensile strength of 2000 MPA and more and Young’s Modulus’ of 200 GPa can be produced reproducible [3]. The next step towards application are component-like specimens. The main shaft of an aeroengine is a critical component regarding safety reasons and high torque loading. Thus a precise knowledge of materials behaviour is a must. The progress in manufacturing, design and characterisation will be described in the following sections.

Titanium matrix composites and applications

TMCs are under development for about two decades worldwide. Researchers were spurred by the demand of the aeroengine manufacturers since TMCs promise exceptional properties at temperatures up to 550°C. Relevant components of gas turbines are blades, bladed rings (blings) and shafts. But none of these has been realised for serial use up to now. Reasons are lacks of knowledge in manufacturing and non-destructive testing. The costs for introduction of a new technology are still immense. Non-aerospace applications have been realised for racing cars, e.g. formula one. TMCs were used for parts of the engine, but this application has been prohibited due to new regulations of the FIA for materials in formula one engines.

Shafts of gas turbines are loaded by a high torque in one direction only. The opposite direction requires less strength. This enables unconventional design approaches considering the specific properties of TMCs. A unidirectional angle ply lay-up can be realized, which is nearly unknown for polymer matrix composites.

Unidirectional angle ply lay-up and design considerations

Titanium is a high strength matrix material compared to other light metals or polymers leading to a relatively low anisotropy of TMCs. Thus the strength in transverse direction is 15-30% of that in fibre direction depending on the fibre volume fraction. However, in contrast to polymer matrix composites the maximum strain in transverse direction is much below that in longitudinal direction, too. As a consequence a cross ply lay-up with TMCs will lead to an inefficient materials use, because the maximum strain is limited by the cross plies. Furthermore, thermal residual stresses occurring during consolidation will lead to a further reduction of the load capabilities of a cross ply lay-up. This means, the design rules cannot be transferred from polymer matrix composites.

Considering the stress state in a tube at torque loading, the high tensile strength of TMCs in fibre direction and the insensitivity to compressive loading in transverse direction a fibre orientation of 45° to the rotation axis becomes most effective (Figure 1).

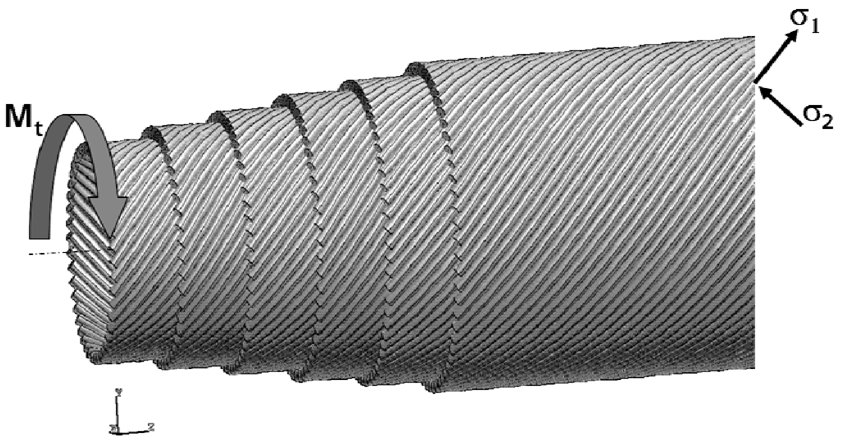

Figure 1: Fibre orientation and mean stresses in a tube with unidirectional angle ply lay-up.

To improve the understanding of the unidirectional angle ply lay-up micro-mechanical finite element analyses (FEA) has been carried out by Ansys-8.1. A representative volume element (RVE) according to Figure 2 has been chosen with edges aligned along the fibre direction. 8 plies of SiC-fibres with a thickness of 1.5 mm claded on both sides with 0.5 mm unreinforced titanium alloy were considered. Thus the total wall thickness is 2.5 mm. SiC-fibres were considered as ideal elastic while the titanium matrix behaves elasto-plastic with a tensile strength of 1000 MPa. The fibre-matrix interface is considered by contact elements. In the unloaded state these elements are under compression due to thermal residual stresses caused by processing [4, 5]. This means load can be transferred from matrix to fibre by friction.
The RVE was loaded stepwise starting from the unloaded state with process induced residual stresses in primary and secondary direction, respectively. The primary direction is defined as the load case in which the fibres are under tension, while secondary direction is the opposite. By this procedure the resulting strains were determined. The calculated shear deformation is displayed in figure 3. The difference between loading in secondary and primary direction becomes clear. Nonlinearities are marking the points of fibre-matrix separation and matrix plastification.

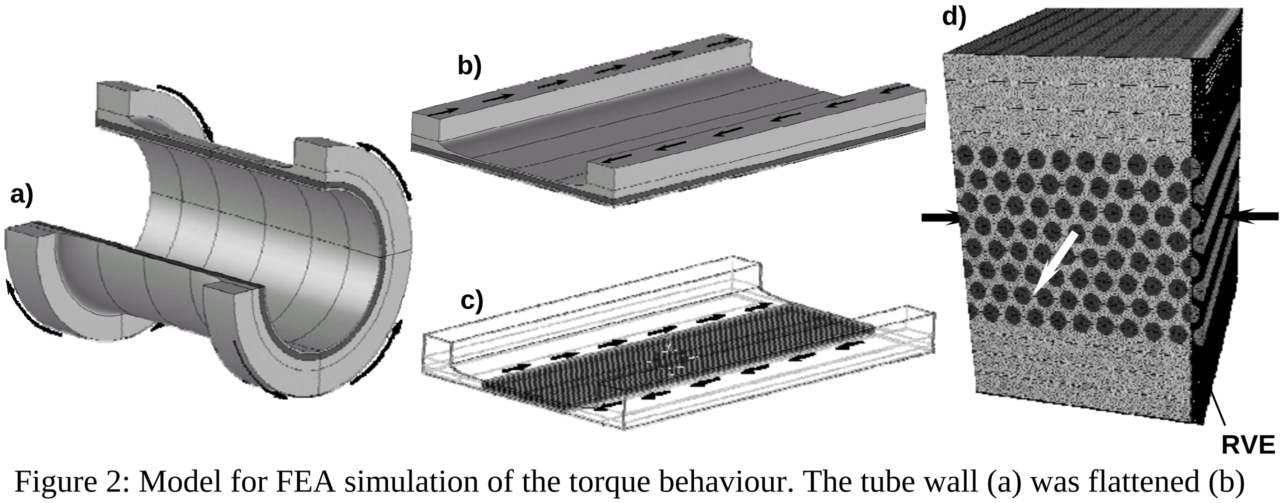

Figure 2: Model for FEA simulation of the torque behaviour. The tube wall (a) was flattened (b) to cut out (c) a representative volume element RVE (d) parallel to the fibres.

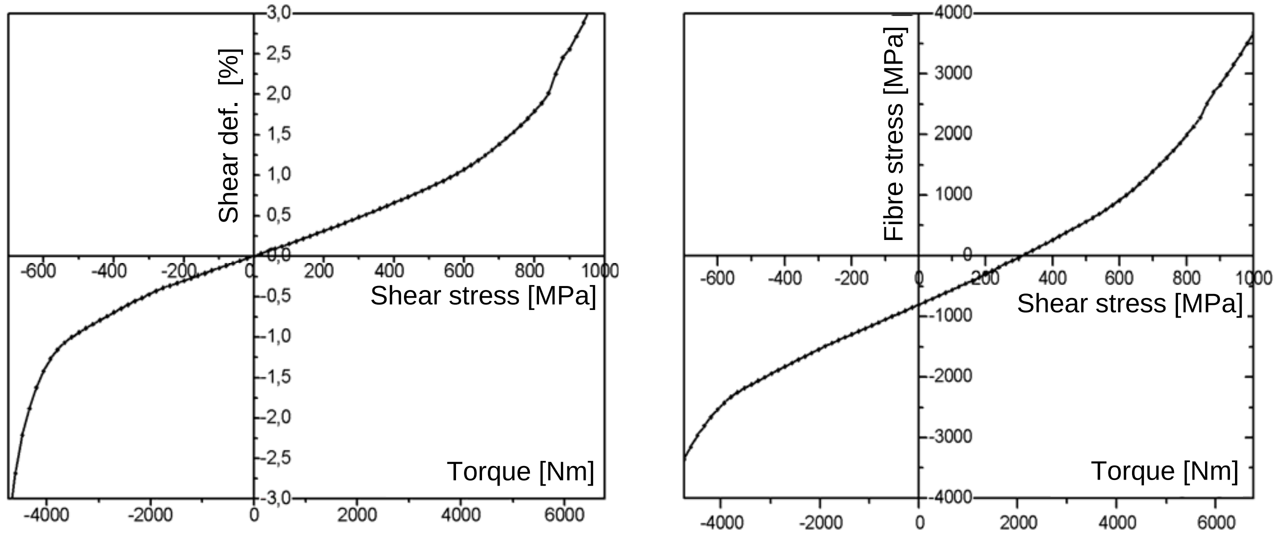

Figure 3: Results of the FEA. Left: Shear deformation as function of shear stress and torque, respectively. Right: Stress in the fibres, failure can be expected at a fibre stresses of about 3600-3800 MPa corresponding to an applied shear stress of ~1000 MPa.

Manufacturing of tubular samples

To validate the design several tubular samples have been manufactured. These have a diameter of 39/44 mm (inner/outer) and a length of 70 mm. The manufacturing process is shown in figure 4 schematically. A preform (not shown in the figure) is filled with cut and matrix coated fibres. The fibres are SCS-6 fibres from Specialty Materials, USA which are coated with Ti-6Al-4V with a thickness of 35 µm resulting in a fibre volume content of about 50%. The preform and thus the outer material of the final product is Ti-6Al-2Sn-4Zr-2Mo. Applying of an axial translation and rotation onto the fibre bundle leads to angular arrangement and pre-compaction of the fibres. The preform will be degassed and sealed gas tight by electron beam welding. The consolidation of the preform is performed by hot isostatic pressing. Finally the desired geometry is machined in such a way that the preform material forms the surface and the fibre reinforced core is not touched or damaged. The result is a 1.5 mm thick TMC-laminate claded by 0.5 mm monolithic titanium alloy on both sides. A gear toothing is applied by wire electron discharge machining on both end flanges to transmit the torque.

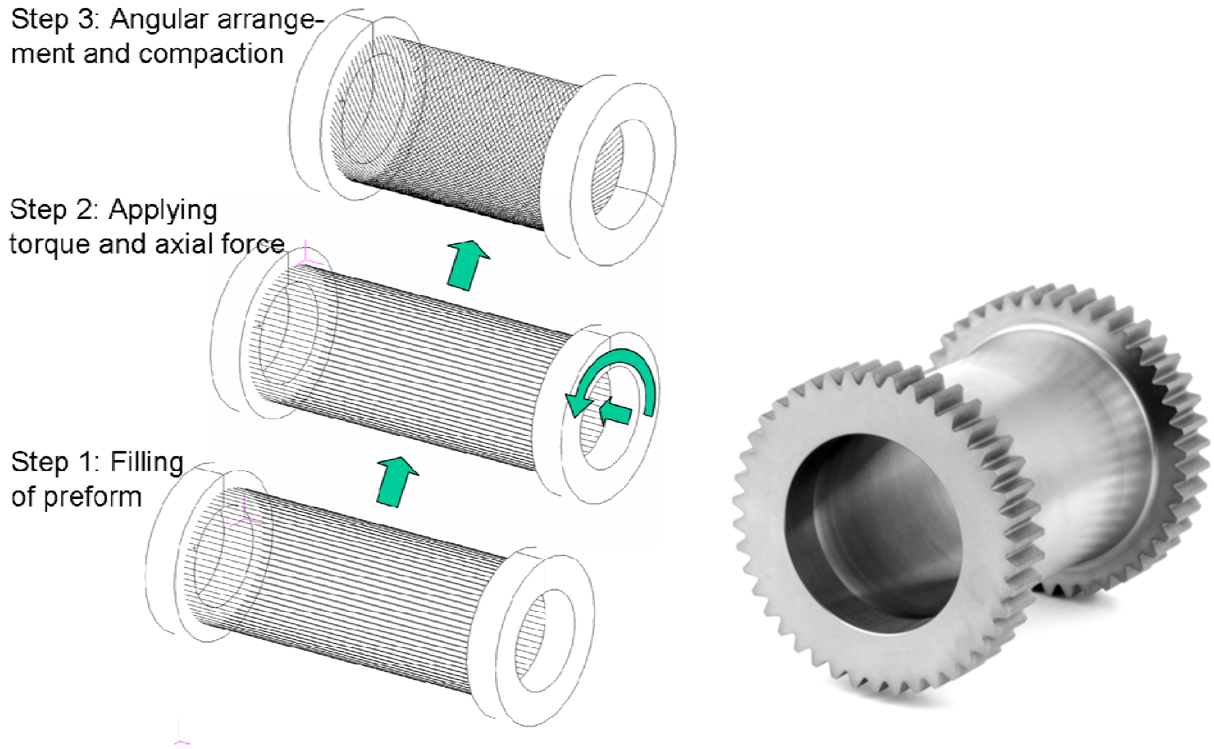

Figure 4: Scheme of the manufacturing route for the tubular specimens with unidirectional angle ply lay-up (left) and machined specimen with applied toothing ready for torque testing.

Experimental results

Torque tests have been conducted with the tubular specimens produced by the technique described above. The tests were carried out by loading-unloading cycles with a stepwise increased maximum torque until failure. The result of a torque test in primary direction is shown in figure 5. The grey curves display the results of tests with an unreinforced Ti-6Al-2Sn-4Zr-2Mo specimen as reference. An increase of stiffness as well as strength of the reinforced specimen by about 70% compared to the unreinforced counterpart can be obtained. Yielding of the TMC specimen occurs at about 650 MPa and first damages detected by the gap in the reloading response are visible when exceeding 800 MPa and becomes more significant above 900 MPa.

Figure 6 shows the test results of an experiment with torque in secondary direction. The maximum stress is nearly 60% below that of the test in primary direction. Yielding occurs at 170 MPa and first damages arise when exceeding 250 MPa. A significant axial strain is visible due to the pitch-up forces of the fibres under compression. The strain in fibre direction is nearly reversible indicating no fibre damage while the transverse strain is marked by a relatively high fraction of plasticity. It can be assumed that the fibre do not break before failure but the fibre-matrix interface separates.

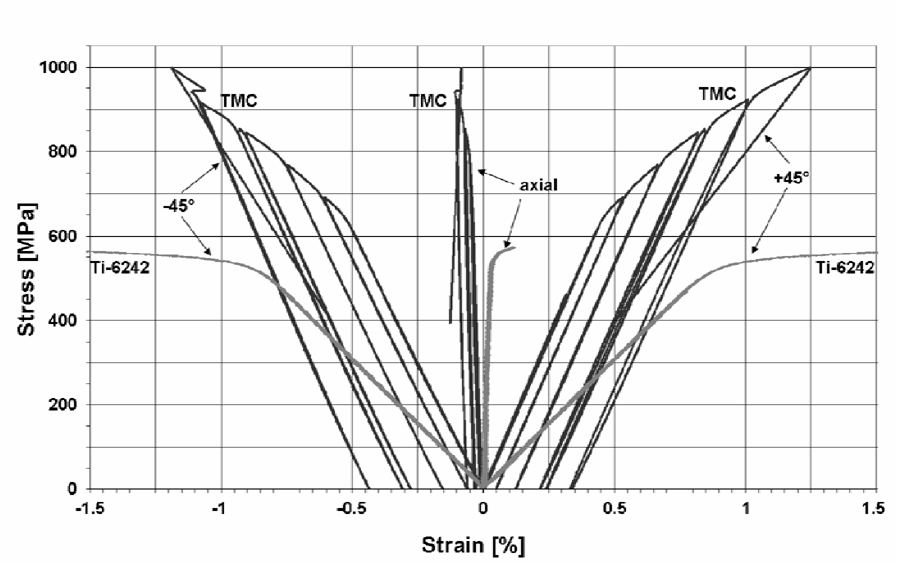

Figure 5: Stress-strain response of the tubular shaft testing in primary direction. Test results of an unreinforced Ti-specimen with the same geometry are given as reference. Strains were determined by 3-way strain gauges, where +45° indicates the fibre direction and -45° the transverse direction.

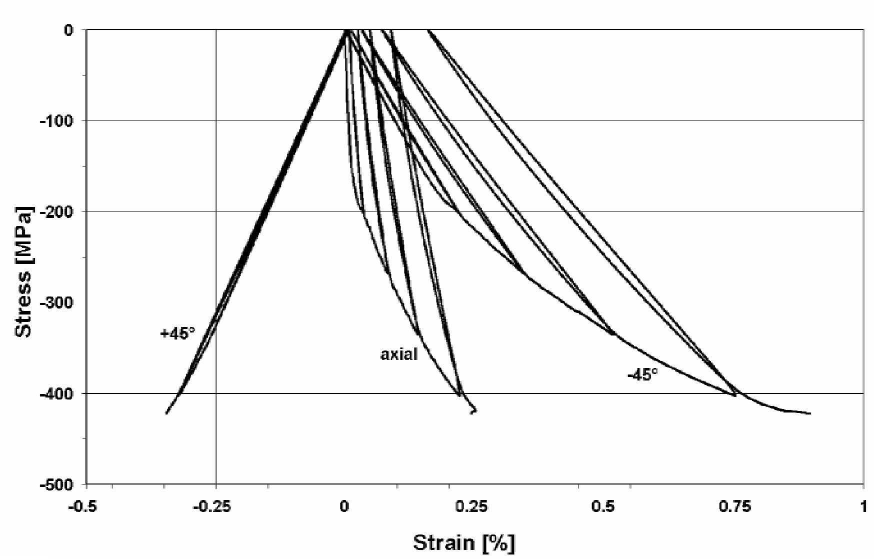

Figure 6: Stress-strain-response of the tubular shaft tested in secondary direction. Strains were determined in the same way as described by figure 5.

Other applications

TMC shafts can be used in many other aerospace and non-aerospace applications, too. The design concept described here allows torque transmission in one preferred direction. Besides gas turbines these are shafts for example for generators. But there are many more applications requiring torque strength in both directions. Since cross ply lay-ups are not efficient using TMCs other design approaches need to be applied. Some boundary conditions need to be considered. First, a consequent separation of plies with different orientations is necessary to avoid the negative

influence of the anisotropic thermal expansion. This can be realised by manufacturing tubes containing the different fibre orientations with different diameters which fit in each other. Second these tubes can be mounted with a preloading to overcome the disadvantage of the strain anisotropy. This means that the tubes are preloaded in such a way that the fibre strength is fully used and the low transverse strength of the composite does not hinder the use of the whole materials capabilities [6].
Considering these aspects, TMC tubes produced by the production route described above can be useful anywhere in the transportation industry where high torques need to be transmitted at lowest weight possible.

Outlook: Affordable processing routes

At present the production of TMCs is very costly. One reason are the costs of the SiC-fibres. Best quality of TMCs can be obtained via the matrix coated fibre route. But the coating process increases the costs further. To broaden the field of application a reduction of costs is a must while maintaining the properties as high as possible. Furthermore, the prices for titanium and its alloys increase more and more. For reducing the costs of titanium production new processes are currently developed. Some processes are based on the reduction of titanium dioxide in molten salts. However, a break-through has not yet been achieved. A promising variation is based on a titanium dioxide-carbon-composite-anode, by which the titanium is solved in the molten salt and deposited at the cathode. By using a cathode material possibly suitable for the reinforcement in composite materials, e.g. SiC-fibres, as the product of the electrolysis a titanium coated fibre is obtained. Compared to any other known routes, the process proposed is characterised by its drastically reduced number of processing steps, especially in regard to the process of titanium chloride production and the electrolytic magnesium reduction of conventional titanium extraction processes. Thus, it includes significant economical and ecological advantages [7].

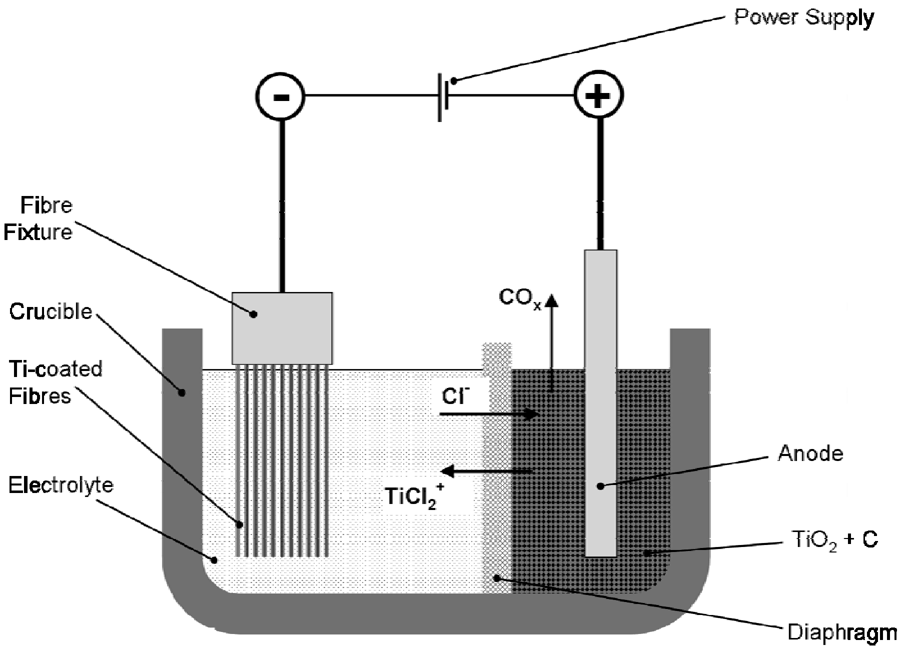

Figure 7: Simplified set-up of the electrolytic cell for coating of fibres with titanium using titanium dioxide and molten salts.

Another difficulty in the production of TMC components is the shrinkage during consolidation. To overcome this penalty new consolidation process are under development working pressureless. First results are very promising. This will allow realisation of complex geometries without the risk of fibre breakage and voids. The process and results will be presented elsewhere.

Conclusions

The design and manufacturing of TMC tubes for high torque transmission is described. Tests conducted on these tubes were performed and confirm the strength prediction by FEA. An increase of strength of about 70% can be obtained by reinforcing titanium alloys with SiC-fibres. Here, unidirectional angle ply reinforced specimens were presented, but design considerations for alternating torque were also discussed. The results shown here, can be used for design of these components, too. Approaches to reduce the costs for TMC production promise the wider use of TMCs in all sectors of the transportation industry.

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