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Compression Strength of Titanium Matrix Composites Depending on Fibre Volume Content, Fibre Orientation and Temperature

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SiC-fibre reinforced titanium matrix composites are marked by exceptional high specific strength and stiffness at temperatures up to 550°C. That is why these materials are considered as promising materials for components of future aeronautic gas turbines. Tensile and fatigue properties have been investigated precisely in the past. Although the compression strength of titanium matrix composites is expected to be very high there is a lack of knowledge and test results. To support the design of low pressure shafts for aeronautic gas turbines a test matrix has been set up to investigate the tension and compression properties of SiC-fibre reinforced titanium matrix composites with different fibre volume contents at room temperature and at 550°C. The tests were conducted in fibre direction and transverse to the fibres. Here, the results of the compression tests are presented and discussed.
In fibre direction the compression strength increases with increasing fibre volume content. At room temperature maximum compression stress values over 5000 MPa at room temperature and of about 3700 MPa at 550°C were reached. Thus the compression strength is more than twice as high as the tensile strength. Transverse to the fibre direction the strength is limited by matrix flow. The strength level is influenced more by temperature than by fibre volume content. The results show that compression strength especially in fibre direction is an exceptional property offering new opportunities for special applications.

Keywords: *titanium matrix composite (TMC), fibre, compression testing*

1. 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 gm 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].
Several loading conditions require compressive strength, too. These are components for torque transmission, for instance. Shafts of aeronautic gas turbines are not only loaded by very high torque but also limited by their outer diameter due to design restrictions. This results in high shear stresses within the shaft material. These shear stresses can be split up into a compressive and a tensile mean stress, respectively. Conventional design of fibre reinforced composite components considers these mean stresses as guide line for the alignment of the fibres. Thus, purely torque loaded tubes need to be reinforced by fibre aligned in +45° and 45° referred to the rotational axis. But also innovative design approaches require the knowledge of the anisotropic compression behaviour [4].
As a consequence of these design considerations a part of the fibres is loaded under compression in fibre direction as well as transverse to the fibre direction. To investigate the behaviour under longitudinal and transverse compressive loading compression tests with four different fibre volume fractions were performed on SiC-fibre reinforced Ti-6Al-2Sn-4Zr-2Mo-Specimens.

2. Experimental Procedure

Small and short specimens were prepared to avoid buckling under compression.

2.1 Specimen Geometry and Manufacturing

The specimens were produced by the matrix coated fibre route [3,5]. Hereby the SiC-fibres SCS-6 from Specialty Materials were coated with the matrix alloy (Ti-6Al-2Sn-4Zr-2Mo) by magnetron sputtering. These matrix coated fibres were put in the cavity of preforms from the titanium alloy. The preforms were closed gas tight by electron beam welding and hot isostatically pressed (HIP) to consolidate the composite material.
After HIP the outer unreinforced alloy was machined to final shape. The geometry of the specimens was defined to use the cylindrical reinforced section most efficient. Figure 1 and 2 are showing the specimens for longitudinal and transverse testing, respectively. The darker area in the middle of the specimens reflects the reinforced section which can be distinguished clearly from the unreinforced outer material.

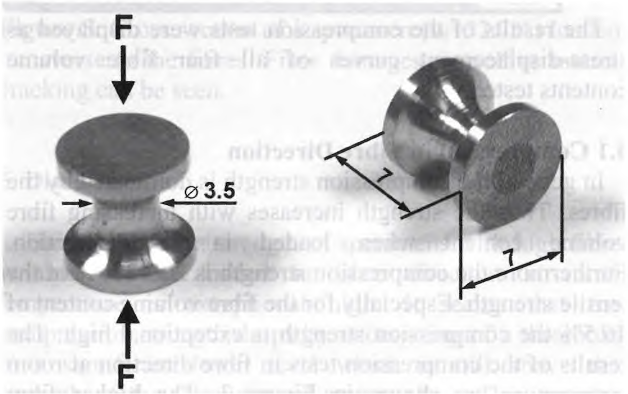

Figure 1. Compression specimens for testing in longitudinal (fibre) direction (0°). Dimensions in mm.

The coating thickness of the matrix coated fibres controls the resulting fibre volume content. Specimens were produced with four different fibre volume contents. These are 57.7%, 46.5%, 32.7% and 25.7% referred to the reinforced cross section. Considering the whole cross section including the unreinforced outer material the fibre volume content is lower.

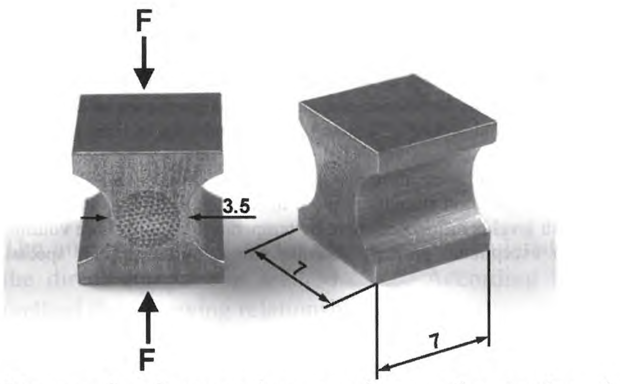

Figure 2. Compression specimens for testing in transverse direction (90°). Dimensions in mm.

2.2 Compression Tests

The compression tests were carried out by a mechanical testing machine. Extensometers were applied to log the displacement in loading direction as well as the transverse strain perpendicular to the loading direction. Due to the specimens geometry it is not possible to determine the real strain within the smallest cross section.

The loading for the tests on the 90°-specimens was applied via hardened steel plates. For the 0°-specimens this arrangement was not possible. The fibres showed such a hardness and the force was so high that the fibres damaged the steel and penetrate it. To avoid it hard metal plates intended for cutting tools were used in-between the specimens and the head of the testing machine. This arrangement enables a testing of the longitudinal reinforced specimens but sometimes the hard metal plates failed causing steps in the stress-displacement response.

3. Test Results

The results of the compression tests were displayed as stress-displacement curves of all four fibre volume contents tested.

3.1 Compression in Fibre Direction

In general the compression strength is dominated by the fibres. Thus the strength increases with increasing fibre volume content when loaded in fibre direction. Furthermore the compression strength is 200-300% of the tensile strength. Especially for the fibre volume content of 46.5% the compression strength is exceptional high. The results of the compression tests in fibre direction at room temperature are shown in Figure 3. The higher fibre volume contents exhibit compression strengths of more than 5000 MPa while the lower fibre volume contents fail at about 3000 MPa.

At 550°C the compressive strengths are between 2200 MPa and 3700 MPa in the order of the fibre volume content (Figure 4). In contrast to the results of the tests at room temperature the high temperature strengths are in a stronger relation to the fibre volume.

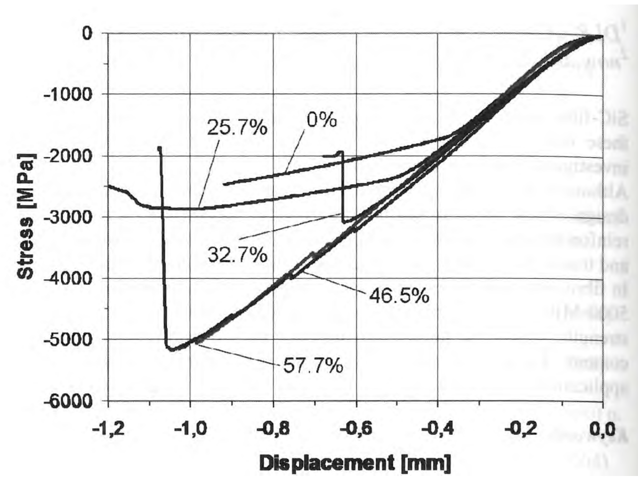

Figure 3. Stress-displacement curves of specimens loaded in fibre direction (0°) at room temperature. Unreinforced titanium alloy (0%) is given as reference.

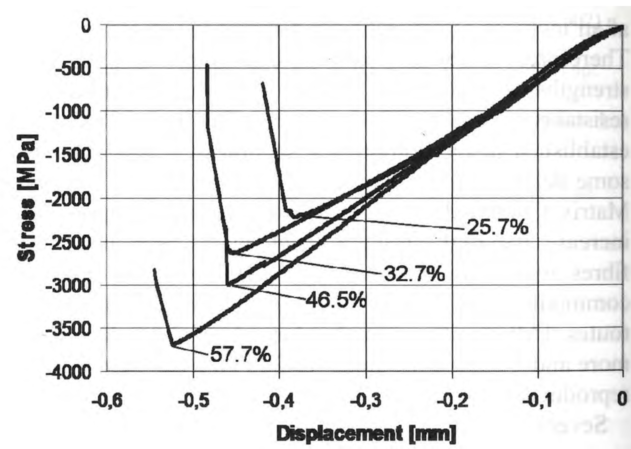

Figure 4. Stress-displacement curves of specimens loaded in fibre direction (0°) at 550°C.

3.2 Compression transverse to Fibre Direction

Transverse to the fibre direction the compression strength is below the strength of the unreinforced matrix material. The difference in strength between the different fibre volume fractions is relatively low at room temperature (Figure 5) as well as at elevated temperature (Figure 6). A clear relationship of fibre volume content and compression strength is not visible.

The behaviour at room temperature shows smooth curves with a distinct hardening. In contrast to this the curves determined at 550°C are marked by a roughness indicating crack growth and development of micro damages.

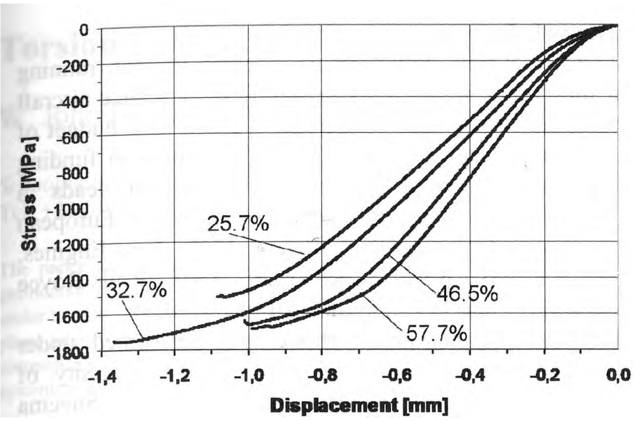

Figure 5. Stress-displacement curves of specimens loaded transverse to the fibre direction (90°) at room temperature.

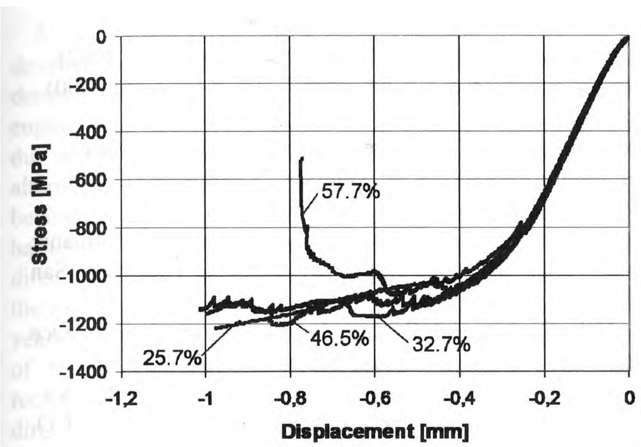

Figure 6. Stress-displacement curves of specimens loaded transverse to the fibre direction (90°) at 550°C.

4. Microanalytical Investigation

Cross sections. for microanalytical investigations were prepared.
In Figure 7 a specimen with 46.5% fibre volume content tested in fibre direction at room temperature is shown. A shear failure of the surrounding titanium alloy can be seen. Furthermore, a number of fibres were cut by the preparation of the cross section. It seems that the fibres buckled altogether in the same direction which is outwards the plane of the image. This suggests that the fibres supports each other to increase the stiffness and delays buckling.

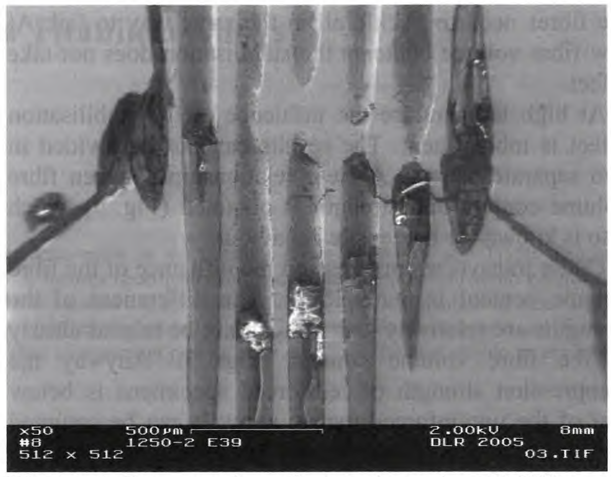

Figure 7. Cross section of a specimen (v_f=46.5%) tested in fibre direction at room temperature. Buckling of the complete fibre bundle can be seen.

Cross sections of transverse loaded specimens are showing matrix cracks, too. With increasing fibre volume content the number of fibre damages increases. Several fibres are destroyed to many small particles. It can be assumed, that the higher distances of the fibres of the specimens with lower fibre volume content reduces stress peaks and stress concentrations and thus the particular loading of the fibres. In Figure 8 it can be seen that some fibres are not visible in the cross section. Empty holes in the matrix appear. It is assumed that these fibres failed and the fracture surfaces were displaced by the positive strain in fibre direction, which is here transverse to the loading direction. The positive strain which is transverse to the loading direction and transverse to the fibre direction causes some fibre matrix separation (debonding). In a small amount of specimens with high fibre volume content some fibres failed by transverse loading due to a collapse of the carbon core. This phenomenon was also reported in [6,7].

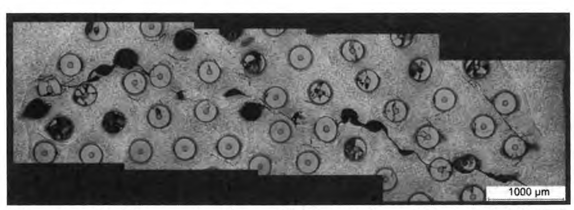

Figure 8. Cross section of a specimen (v_f=32.7%) loaded transverse to the fibres. Fibre damages as well as matrix cracking can be seen.

5. Discussion

The compression strength of specimens with high fibre volume content loaded in fibre direction at room temperature is exceptional high. It seems that the compression strength drops by undergoing of a threshold to a significant lower level which is still above the strength of the unreinforced matrix alloy. This may be caused by the stabilisation of the fibres which is given by the high stiffness at high fibre volume contents. The analysis of the cross sections support the assumption that

the fibres need to buckle all in the same way to fail. At low fibre volume contents the stabilisation does not take effect. At high temperature the influence of the stabilisation effect is more fluent. The results can not be divided in two separate classes. A clear relationship between fibre volume content and strength is obtained (Fig. 9) which also is known for the tensile behaviour.
Under transverse compression the influence of the fibre volume content is much lower. The differences of the strengths are relatively low and can not be related clearly to the fibre volume content (Fig. 9). Anyway the compression strength of reinforced specimens is below that of the unreinforced matrix alloy. It can be assumed that the main contributor to the strength is the yielding behaviour of the matrix. Otherwise micrographs of cross sections are showing different failure mechanisms regarding the fibres. High fibre volume contents lead to a higher amount of broken fibres.

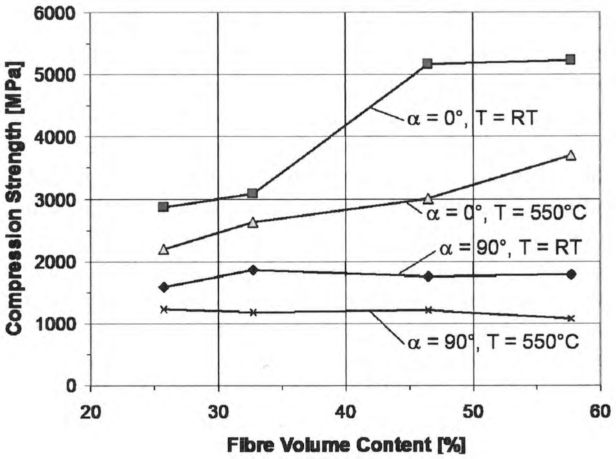

Figure 9. Comparison of maximum stresses of all specifications tested in relation to the fibre volume content.

6. Conclusions

It was expected that the compression strength of silicon carbide fibre reinforced titanium alloys is much higher than the tensile strength. The results presented here confirm these expectations. The compression strength in fibre direction is strongly related to the fibre volume content while the compression strength in transverse direction is slightly influenced by the fibre volume content. It seems to be dominated by matrix yielding. However, the transverse compression strength is also much higher than the transverse tensile strength [8]. The anisotropic behaviour seems to be reduced under compression loading.
The exceptional high strength under compressive loading in fibre direction is a property of titanium matrix composites which was neglected in the past. It may offer opportunities in special applications which were not considered up to now. The results obtained here will support the design and analysis of highly loaded shafts for aeroengines.

Acknowledgement
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