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TRIBOLOGICAL BEHAVIOUR OF TEXTILE-REINFORCED CERAMIC MATRIX COMPOSITES

Fibre and textile reinforced ceramic composites with silicon carbide as matrix material are gaining increasing importance for complexly loaded structures in high-temperature and tribological applications. Besides improving the strength, the main target of the reinforcement is to increase the composite toughness. Furthermore, using an adapted reinforcement an optimized thermo-mechanical property profile and an adaptation of the tribological behaviour of the anisotropic composite can be achieved. Therefore a specific arrangement of the fibres, the matrix and the fibre matrix interface have to be developed.

The objective of this paper is to present the anisotropic mechanical material properties of different fibre and textile reinforced ceramics which were experimentally determined in adapted material tests. Furthermore a detailed investigation of the tribological behaviour of ceramic composite was performed using pin-to-disk tests.

The results show clearly, that the material behaviour of fibre ceramic composites is essentially depending on the production procedure. Whereas the elastic structural behaviour of C fibre reinforced SiC ceramics made by the chemical-vapour-infiltration-technique is nearly isotropic, liquid-silicon-infiltrated SiC materials show a high degree of anisotropy, which has to be principally considered within the design process of fibre ceramic structures. The tribological tests indicate that reinforced ceramics exhibit an excellent tribological behaviour with low wear rates and coefficients of friction. In further studies adapted material pairing has to be developed for tribological applications.

Key words: **ceramic composites, mechanical behaviour, tribological behaviour**

WŁASNOŚCI TRIBOLOGICZNE KOMPOZYTÓW CERAMICZNYCH O WZMOCNIENIU TEKSTYLNYM

Kompozyty ceramiczne o osnowie z węglika krzemu i wzmocnieniu włóknistym lub tekstylnym zdobywają coraz większe znaczenie w budowie struktur poddawanych złożonym stanom obciążenia w warunkach wysokiej temperatury i tarcia. Istotnym zadaniem wzmocnienia jest w tym przypadku, poza poprawą wytrzymałości, również podniesienie twardości kompozytu. Zastosowanie odpowiedniego wzmocnienia pozwala także na osiągnięcie optymalnych właściwości termomechanicznych oraz wpływa na właściwości tribologiczne kompozytu anizotropowego. Wynika stąd potrzeba określenia specyficznego dla danego zastosowania układu włókien, osnowy oraz warstwy granicznej między wzmocnieniem i osnową.

W artykule zaprezentowano anizotropowe właściwości mechaniczne różnych kompozytów ceramicznych o wzmocnieniu włóknistym lub tekstylnym, które zostały doświadczalnie wyznaczone w specjalnych próbkach materiałów. Przeprowadzono szczegółowe badania własności tribologicznych za pomocą testów typu „trzpień na tarczy” (pin-to-disk).

Uzyskane wyniki pokazują jednoznacznie, że właściwości kompozytów ceramicznych o osnowie SiC wzmocnionych włóknami węglowymi są silnie zależne od technologii wytwarzania. Podczas gdy infiltracja metodą osadzania chemicznego powoduje uzyskanie prawie izotropowych własności sprężystych, infiltracja płynnym SiC skutkuje istotną anizotropią, która powinna być uwzględniana w projektowaniu z użyciem opisywanych materiałów. Wyniki badań tribologicznych potwierdzają również bardzo dobre właściwości tribologiczne tych materiałów - niskie zużycie i niskie współczynniki tarcia. Przedmiotem dalszych badań powinno być opracowanie par tarciowych dopasowanych do konkretnych zastosowań.

Słowa kluczowe: **kompozyty ceramiczne, własności mechaniczne, własności tribologiczne**

INTRODUCTION

Fibre and textile reinforced ceramic composites with silicon carbide (SiC) as matrix material are gaining increasing importance for complexly loaded structures in high-temperature and tribological applications. Besides improving the strength, the main target of the reinforcement is to increase the composite toughness. Furthermore, using a reinforcement an optimized thermo-mechanical property profile and an adaptation of the tribological behaviour (e.g. high or low coefficient of friction) of the anisotropic composite can be achieved through a specific arrangement of the fibres, the matrix and the fibre matrix interface [1].

Because of the excellent mechanical and tribological material properties even at highest temperatures and the favourable chemical resistance, fibre reinforced ceramics have a wide potential for high performance applications, for example, high performance brake disks for aeroplanes, thermal shields for space vehicles (MIRKA) and slide bearings with excellent emergency

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running properties in the field of mechanical engineering [2, 3].

For the design of fibre and textile reinforced ceramic structures, first of all the anisotropic mechanical material properties have to be experimentally determined in dependence on the temperature. These data are needed in the form of so-called characteristic parameter functions for the analysis of the stress and strain fields [1, 4]. The anisotropic elastic properties are measured at the Institut für Leichtbau und Kunststofftechnik (ILK) in tension, compression and bending tests.

Furthermore a detailed understanding of the tribological behaviour is necessary to adapted the ceramic composite to the existing tribological requirements. Therefore the fibre reinforcement, the matrix system and the interface have to be selected to create an application-oriented property profile.

The anisotropic thermo-mechanical and tribological property profiles of various fibre reinforced ceramic composites made by chemical-vapour, liquid-silicon and the liquid-polymer-infiltration will be discussed in this paper.

FIBRE AND TEXTILE REINFORCED CERAMICS

Several production procedures for the manufacturing of textile reinforced SiC ceramics have been developed up to date: the isothermal and gradient chemical-vapour-infiltration (CVI), the liquid-silicon--infiltration (LSI), and the polymer infiltration and pyrolysis (PIP) [2]. Different research projects, founded by the German Research Agency (Deutsche Forschungsgemeinschaft, DFG), investigated the thermomechancial behaviour of different single and multi layered fibre reinforced SiC ceramics, which were produced by the a. m. procedures [1, 5]. An overview of the considered materials is shown in Table 1.

TABLE 1. **Investigated fibre reinforced SiC ceramics**
TABELA 1. **Badane materiały włókniste o osnowie SiC**

Material	Reinforcement	Manufacturer
CVI-BD-C/SiC	C-Toraca M 30 BD linen	MAN
CVI-BD-SiC/SiC	SiC-Tyranno BD linen	MAN
LSI-UD-C/SiC	C-Tenax T 300 UD	SKT
LSI-BD-C/C-SiC	C-Tenax T 300 BD sateen	SKT
PIP-BD-C/SiC	HT fibre BD linen	MAN

SKT:	Schunk Kohlenstofftechnik GmbH, Gießen, Germany
UD:	unidirectional reinforced
MAN:	MAN Kohlenstofftechnik AG, Karlsfeld, Germany
BD:	bi-directional reinforced

THERMO-MECHANICAL MATERIAL BEHAVIOUR OF FIBRE AND TEXTILE REINFORCED CERAMICS

For HT structures under extreme thermomechanical loads, fibre reinforced ceramics are applied especially in the form of multi-layered composites, where the single layer is reinforced with unidirectional rovings or with bi-directional fabrics. To fully exhaust the high potential for light-weight constructions of fibre reinforced ceramics, it is essential to arrange the UD- and BD-reinforcement of the single layers according to the occurring main loads. A broad knowledge of the structural mechanical interconnections and the basic anisotropic material behaviour is therefore required at first [1, 8]. To characterise the property profile of anisotropic fibre reinforced ceramics, the directional elastic characteristic value functions have to be determined [3].

In the dimensioning of components from fibre ceramics, continuous space approaches of mechanics are used as basis for mathematical treatment. In the course of this phenomenological continuum approach, the microstructural heterogeneous material structure will be treated macroscopically by the homogenization technique [4].

Assuming a linear material behaviour, the relationship of stresses σ_{ij} and strains ε_{ij} of fibre reinforced ceramics can be described under consideration of the influence of temperature by the tensor notation of Hooke's law

$$\varepsilon_{ij} = S_{ijkl}\sigma_{kl} + \alpha_{ij}\ T\ (i, j, k, l = 1, 2, 3) \qquad (1)$$

where S_{ijkl} represents a fourth order material tensor with 81 constants and T the temperature difference according to the state of reference. With the assumption of symmetry among the strain and stress tensor components and of an existing elastic potential, which is regarded as an unique function of the strain tensor components, the 81 constants are reduced to 21 independent values. Therefore the law of elasticity can be written in a „pseudovectorial" manner as

$$\varepsilon_i = S_{ij}\sigma_j + \alpha_i T\ (i, j = 1, 2, ..., 6) \qquad (2)$$

In fibre reinforced ceramics, a texture exists with respect to three independent, mutually perpendicular directions. In terms of crystal chemistry, this case is called orthorhombic anisotropy of orthotropy. This results in a material tensor consisting of 12 components, of which 9 are linearly independent of each other. For planar problems the assumption of an approximately plane stress distribution is allowed, thus equation (1) results in

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} + \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ 0 \end{pmatrix} T \qquad (3)$$

The relation between the compliances S_{ij} and the engineering parameters (E_1, E_2, ν_{12} and G_{12}) is given by

$$S_{11} = \frac{1}{E_1};\ S_{12} = -\frac{\nu_{12}}{E_1} = -\frac{\nu_{21}}{E_2}$$
$$S_{22} = \frac{1}{E_2};\ S_{66} = \frac{1}{G_{12}} \tag{4}$$

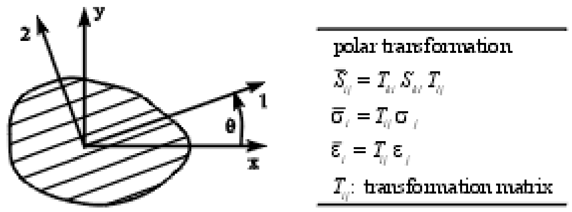

Fig. 1. Global and fibre adapted coordinate system

Rys. 1. Układ współrzędnych globalny i dopasowany do kierunku włókien

In order to determine the stress-strain relationship for an orthotropic plane structure within a global (x, y, z)-system of coordinates (Fig. 1), one has to apply a polar transformation of the stresses and strains as well as of the stiffnesses and compliances known for the (1, 2, 3) main axes system [4]. The illustration of the transformation correlation provides the design engineer with quite practical polar diagrams, which allow an immediate reading of the interrelation between the material constants oriented parallel to the main axes (basis constants E_1, E_2, ν_{12}, G_{12}) and the constants rotated by any angle θ with respect to the main axes.

Experimental investigation of the anisotropic material data

To entirely describe the elastic material behaviour of fibre reinforced ceramics according to equation (4), four independent basic constants E_1, E_2, ν_{12} and G_{12} have to be determined. In general, the modulus E_1 and E_2 as well as the Poisson's ratio ν_{12} can easily be measured in the direction of the orthotropic main axes system by uniaxial tensile tests or pressure tests. Contrary to these tests, which are characterised through relatively simple specimen geometry and testing arrangement, the examination of the shear modulus G_{12} needs a substantially higher technical effort. To avoid complicated shear tests, an alternative is to measure the modulus E_x of an arbitrary so-called „off-axis" direction ($\theta \neq 0°, 90°$) in an usual tensile test. Then the shear modulus can be calculated as follows

$$G_{12} = \left(\frac{\dfrac{1}{E_x} - \dfrac{\sin^4\theta}{E_2} - \dfrac{\cos^4\theta}{E_1}}{\sin^2\theta\cos^2\theta} + \frac{2\nu_{12}}{E_1} \right)^{-1} \tag{5}$$

$(\sin\theta \neq 0,\ \cos\theta \neq 0)$.

Because most fibre reinforced ceramics indicate an obviously non-linear deformation behaviour, it is necessary to distinguish between the tangent and the secant modulus according to DIN 29 971. Here the secant data describe comparatively well the technical range of the application of fibre reinforced ceramics [4]. Within the presented investigations, the material behaviour of single-layered UD- and BD-fibre reinforced ceramics, which were fabricated by the CVI, LSI and LPI technique, were characterized in tension tests. The tests at room temperature were performed by a Zwick tension/pressure testing machine 1475. For the measuring of the longitudinal and transversal deformation, strain gages or mechanical extensometers were used.

The basic elastic characteristical values at room temperature, which were determined in the performed tensile tests, are shown in Table 2 for UD and BD fibre reinforced ceramics.

TABLE 2. **Experimentally determined elastic characteristic values**

TABELA 2. **Eksperymentalnie określone własności sprężyste**

Material	Tangent value				Secant value			
	E_{1T}	E_{2T}	ν_{12T}	G_{12T}	E_{1S}	E_{2S}	ν_{12S}	G_{12S}
	GPa	GPa	–	GPa	GPa	GPa	–	GPa
CVI-BD-C/SiC	133	133	0.07	26	82	82	0.06	15
CVI-BD-SiC/SiC	184	184	0.1	63	133	133	0.08	55
LSI-UD-C/C-SiC	185	7	0.43	12	132	7	0.22	14
LSI-BD-C/SiC	102	99	0.064	6	83	82	0.068	5
PIP-BD-C/SiC	64	64	0.063	15	56	56	0.063	16

EXPERIMENTAL ADHESIVE WEAR STUDIES

Adhesive wear studies were carried out using a pin-on-disc testing machine designed and fabricated at ILK. A pin of 7 mm diameter and 20 mm length made from three different PTFE gasket materials unmodified and modified with graphite or bronze was slid against the textile reinforced ceramic specimen with a diameter of 46 mm in a horizontal configuration. The pin was slid in a track of 36 mm in diameter with a speed of 0.5 m/s and a normal force of 100 N for 20 h. The sliding test was performed at 23°C in a first step at dry conditions and later with lubrication using oil. The frictional torque was continuously recorded by an attached microprocessor while wear was determined by measuring the reduction in the length of the pin after cleaning and cooling to ambient temperature. The test setup is shown in Figure 2.

The specific wear rate K_0 (m^3/Nm) was calculated from the following equation

$$K_0 = \frac{\Delta V}{LD} \tag{6}$$

where ΔV is the wear volume in m^3, L is the load in N, and D is the distance slide in m.

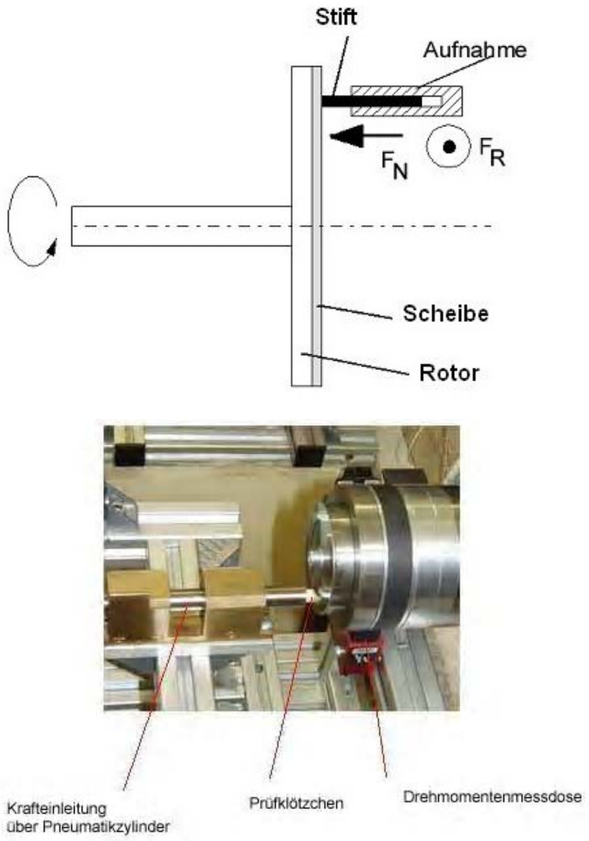

Fig. 2. Schematic and image of pin-on-disc machine

Rys. 2. Schemat i fotografia maszyny do testów „trzpień na tarczy”

For the tribological tests three textile reinforced ceramics with SiC matrix and stainless steal were considered:

Steel:	100Cr6, hardened and tempered, 59 ±1 HRC, grinded surface, $R_a = 0.2 \ldots 0.3$ µm
ML1:	PIP CF-SiC, reinforcement: T300J satin weave
SKT3:	LSI C/C-SiC, reinforcement: T300J satin weave
DLR:	LSI C/C-SiC, reinforcement: T800H plain weave

The damper oil Domestic 165 OA was used as lubricant, whereas the lubrication was performed using an oil soaked felt, which has wetted the surface of the ceramic composite. Two tests were carried out for every tribological pairing, and the characteristics of coefficient of friction and linear wear rate in dependence of time were determined.

To compare the experimental results specific wear data are applied. This data, which are termed as wear rates, are classified in three groups:

- speed of wear,
- intensity of wear,
- ratio of wear and throughput.

The speed of wear describes the derivation of the wear concerning the time of loading t, while the intensity is related to the sliding path l. For technical applications the linear wear is related to both time and length, whereas it is termed as linear wear rate:

$$w_{l/t} = \frac{W_t}{t} \tag{7}$$

$$w_{l/s} = \frac{W_l}{s} \tag{8}$$

Furthermore the wear coefficient k is defined, to eliminate the influence of the wear load

$$k = \frac{W\,v}{F_N \cdot s} = \frac{W\,v/s}{F_N} \tag{9}$$

were $w_{v/s}$ describes the quotient of volume of wear W_v and wear length s

$$w_{v/s} = \frac{W_v}{s} \tag{10}$$

With in the presented work, the linear wear rate is applied to characterise the tribological processes of the considered material pairs.

Figures 3 and 4 show exemplarily the determined curves of coefficient of friction to wear length for a selected material pair without and with lubrication. The comparison of the coefficient of friction and the calculated wear rates for different material pairs is presented in Figure 5 and 6.

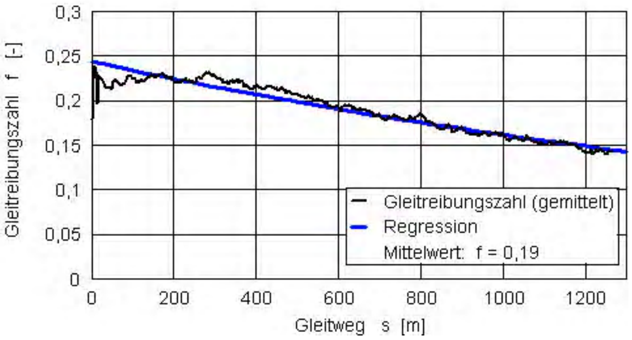

Fig. 3. Coefficient of friction for PTFE against ML1 for dry condition

Rys. 3. Współczynniki tarcia suchego między PTFE i ML1

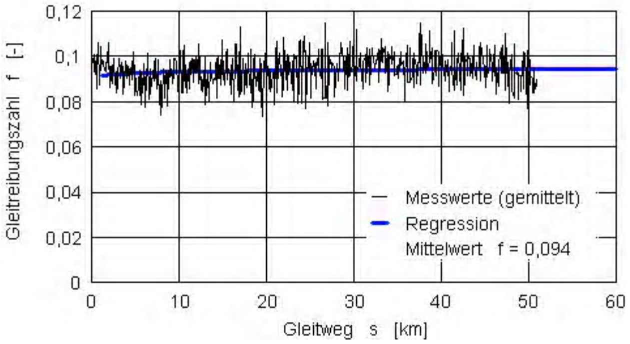

Fig. 4. Coefficient of friction for PTFE against ML1 for lubrication with oil

Rys. 4. Współczynnik tarcia między PTFE i ML1 przy smarowaniu olejem

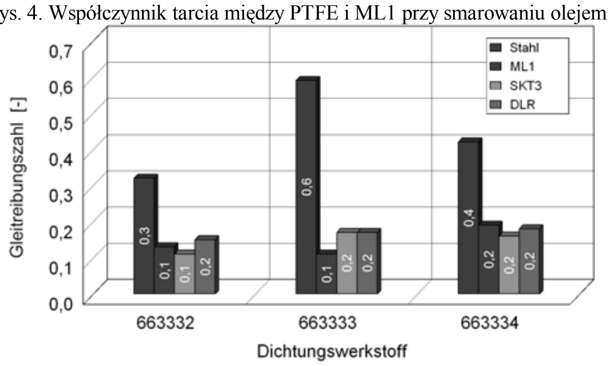

Fig. 5. Comparison of the coefficient of friction for different ceramic composite and steal for lubrication with oil (663332, 663333 and 66334 denote the PTFE gasket material)

Rys. 5. Porównanie współczynników tarcia dla różnych kompozytów ceramicznych przy smarowaniu olejem (663332, 663333 i 66334 są oznaczeniami materiału PTFE uszczelnienia)

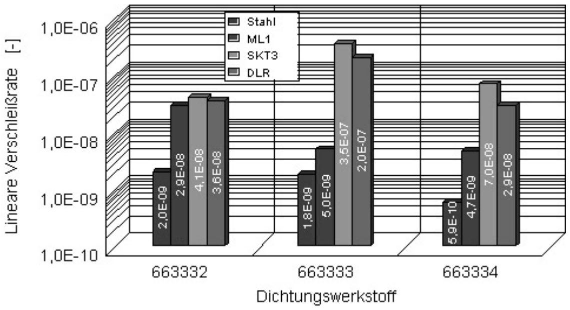

Fig. 6. Comparison of the linear wear rate for different ceramic composite and steal for lubrication with oil (663332, 663333 and 66334 denote the PTFE gasket material)

Rys. 6. Porównanie liniowych prędkości zużycia dla różnych kompozytów ceramicznych i stali przy smarowaniu olejem (663332, 663333 i 66334 są oznaczeniami materiału PTFE uszczelnienia)

Figure 3 shows that the coefficient of friction for the material pair PTFE and ML1 in case of dry conditions is at the beginning very high and reduces with proceeding sliding. For dry conditions strong wear of the gasket material occurs and the abraded PTFE closes the open pores of the surface of the ceramic composite, what leads to the reduction of the coefficient of friction. The coefficient of friction for the tests with lubrication using oil is very low for the whole test for the material ML1. Figure 5 shows, that the coefficient of friction is low for all tested textile ceramic composites in comparison to steel. In contrast to the good coefficient of friction, the wear behaviour of the material pairing appears to be very bad. While the ceramic composite shows no appreciable wear, the rough surface of the composites leads to unacceptable strong wear of the gasket material. Therefore an optimization of the system ceramic composite and polymer gasket material or an improvement of the surface is necessary.

CONCLUSIONS

Advanced fibre and textile reinforced ceramics offer high specific strength and toughness as well as with high specific stiffness and an excellent tribological property profile. These properties, which are desired for statically loaded structures in aircraft and aerospace industry and also in mechanical engineering, can be optimized in each case by the choice of the manufacturing process, by variation of the fibre volume, type and orientation of the reinforcement and by the layer construction. For the optimal design of fibre reinforced ceramics, first of all the anisotropic material data are needed in the form of so-called characteristic value functions for the stress and strain analysis of structures, which have to be determined in suitable material tests. Within the here presented research work, the anisotropic thermo-mechanical and tribological property profile of various UD- and BD-fibre reinforced ceramic composites made by chemical-vapour, liquid-silicon and polymer infiltration and pyrolysis were investigated.

The results show clearly, that the material behaviour of fibre ceramic composites is essentially depending on the production procedure. Whereas the elastic structural behaviour of SiC fibre reinforced SiC ceramics made by the chemical-vapour-infiltration-technique is nearly isotropic, liquid-silicon-infiltrated SiC materials show a high degree of anisotropy, which has to be principally considered within the design process of fibre ceramic structures. The tribological tests indicate that reinforced ceramics exhibit an excellent tribological behaviour with low wear rates and coefficients of friction. In further studies adapted material pairing has to be developed for tribological applications.

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Recenzent
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