FIBRE REINFORCED CERAMIC MATRIX COMPOSITES FOR ADVANCED TRIBOLOGICAL APPLICATIONS

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Abstract

On the basis of their excellent tribomechanical as well as specific properties, ceramic matrix composites (CMC) with load-compatible fibre and textile reinforcement possess a high potential for advanced lightweight applications, particularly for dynamically and tribologically high-loaded automotive and railroad engineering components such as piston rods in automotive shock absorber systems or gliding elements for magnetic-levitation trains. The purpose of the realised research activities performed by the Institute of Lightweight Structures and Polymer Technology (ILK), ThyssenKrupp Bilstein Suspension GmbH and ThyssenKrupp Transrapid GmbH was the development of lightweight solutions for undercarriage modules made of advanced textile reinforced ceramics to upgrade driving safety and travelling comfort of vehicles for passenger and cargo accommodation. In addition to a cost-effective technology for the fabrication of ceramic fibrous composite structures, the key aspects of the development activities are illustrated in this paper culminating in practical implementations.

1 Introduction

Non-oxide ceramic matrix composites (CMC), based on carbon fibre reinforcements and silicon carbide or carbon matrices, represent an emerging class of high performance materials. These composite materials are characterised by well-balanced properties over a broad temperature range combined with a high lightweight potential [1, 2]. High performance ceramic fibrous composites prevent or attenuate the fundamental disadvantage of brittleness in monolithic ceramics. In this context the systematic embedding of a load- and function-compatible fibre and textile reinforcing architecture into a ceramic matrix allows the generation of quasi ductile damage tolerance behaviour. Besides a low density, a high stiffness and a sufficient hardness, these advanced ceramics feature an exceeding dimensional and thermal stability as well as an excellent thermal shock and wear resistance. Compared to classic engineering materials, this predestines fibre and textile reinforced ceramics to be an interesting alternative for advanced lightweight structures. Different types of these advanced materials are meantime available in reproducible quality and capture gradually novel applications in automotive and railroad sector, chemical and power engineering and aerospace.

Based on material- and structure-adapted dimensioning concepts [3, 4], increasingly powerful basic materials as well as cost-effective manufacturing technologies [5, 6] substantial technical advances have been achieved by the methodical development of fibre and textile reinforced CMC in recent years. This has enabled new applications to be opened up beyond conventional lightweight sectors such as aerospace or military engineering, where high temperature resistant CMC structures like jet engine vanes, space vehicle body flaps or satellite motor nozzles were already utilised [7-9]. However, the essential impulses for advanced lightweight solutions with high performance materials have come currently in particular from the automotive and railroad industries in terms of hybrid designs, high performance materials and advanced techniques for joining parts [10]. Due to the excellent specific as well as thermal- and tribomechanical properties of ceramic fibrous composites, this trend has greatly intensified, particularly in the power train and undercarriage section. Here, ceramic matrix composites have established themselves as standard materials for highly stressed assemblies like automotive brake and clutch discs [11, 12] or wheel brakes [13] for high speed trains (fig. 1). The constantly growing desire for improved travelling comfort and increased driving safety calls for modern lightweight construction concepts for tomorrow's automotive chassis systems like piston rods for shock absorber modules [14] or for innovative undercarriage components such as gliding elements for high speed magnetic levitation systems [15].

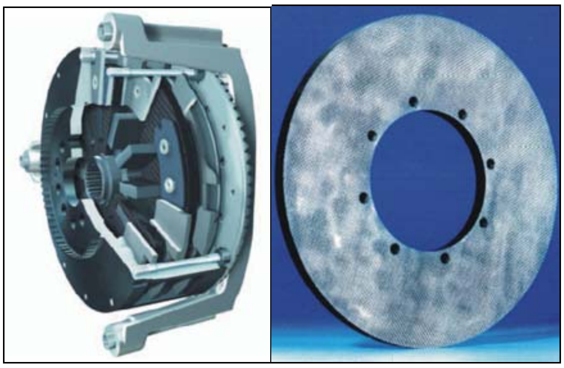


Fig. 1. CMC clutch for passenger cars and CMC wheel brake disc for high speed trains [16, 17]

2 CMC lightweight piston rods for automotive shock absorbers

As part of the research and development activities conducted by the Institute of Lightweight Structures and Polymer Technology (ILK) in cooperation with ThyssenKrupp Bilstein Suspension GmbH, an advanced lightweight piston rod made of carbon fibre reinforced silicon carbide (C/SiC) was developed for compression-loaded automotive single-tube shock absorbers. The purpose was to achieve a noticeable reduction in weight with a simultaneous minimisation of friction, wear and leakage inside the damper systems. In consideration of the operating mode as well as for the functional capability assurance of the dynamically and tribologically high-loaded piston rod, extensive theoretical and experimental investigations with regard to the load transmission, the surface qualities as well as the analysis of friction, leakage and wear behaviour were performed.

2.1 Shock absorber functionality

Shock absorbers, which are mounted between the suspension and the auto body, are employed in passenger cars or commercial road vehicles to damp permanent vibration loading by roadway bumps or rapidly alternating driving conditions. Fig. 2 shows the basic design of a single-tube shock absorber. The piston rod transmits the resulting shock absorption axially into the vehicle bodywork supported by the piston rod. The tubular working cylinder is subdivided by the dividing piston into a gas compartment and an oil-filled working chamber. By means of spring washer valves integrated in the working piston the shock absorption is realised during the rebound stroke and the compression stroke. As the working piston moves on the so-called rebound stroke, the oil flows through special orifices embedded in the working piston and deforms the spring washers. Thereby, the piston rod moves out of the working cylinder. Meanwhile, the oil flows through a spring washer valve from the top chamber into the bottom chamber. As a result of the volume increase in the working chamber as well as the high pressure in the gas compartment, the dividing piston is displaced upward. When the piston rod moves on the so-called compression stroke backwards, the oil flows through the piston orifices from the bottom chamber in the top chamber. Consequently, due to the displaced oil volume the dividing piston moves down and compresses the gaseous medium in the gas compartment.

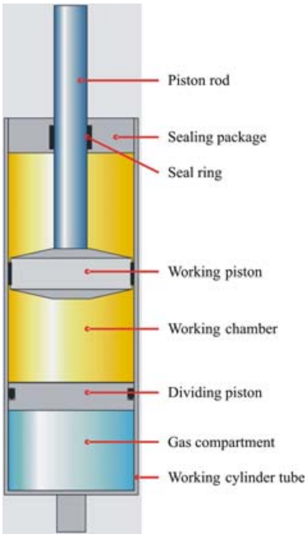


Fig. 2. Single-tube shock absorber design

2.2 Manufacturing process for C/SiC components

The fabrication of ceramic matrix composites based on the impregnation of multi-directional textile preforms can basically be realised by different manufacturing technologies. The fabrication of ceramic composite structures occurs normally in three steps. After layering and fixation of textile preforms in a moulding tool, the ceramic matrix material is infiltrated between the reinforcing fibres. Currently, there are different methods for the impregnation and infiltration of textile performs respectively such as matrix deposition out of a gas mixture, matrix formation via pyrolysis of carbon and silicon containing polymers as well as matrix generation by means of chemical reactions, sintering or electrophoresis of ceramic powders. If required, the CMC components can be optionally finished or provided with a surface coating referring to the matrix formation.

So far only gas and liquid phase infiltration techniques were industrialised for the manufacture of CMC. During the chemical vapour infiltration (CVI) the ceramic matrix is obtained by the decomposition of gaseous substances within the open porosity of the fibre perform [18]. Usually, a process gas and a catalyst are used to form the ceramic matrix. In contrast, the liquid silicon infiltration (LSI) is based on the impregnation of highly porous carbon fibre reinforced carbon (CFC) preforms by molten silicon at temperatures of more than 1420 °C and is characterised by the reaction of the liquid silicon with the solid matrix carbon to silicon carbide using capillary pressure [19].

The liquid impregnation of textile performs using polymeric organometallic compounds with subsequent solid phase thermolysis represents an advanced manufacturing method for the fabrication of large and complex near-net shaped CMC structures [20]. From an economic point of view, the decisive advantage of the so-called polymer infiltration and pyrolysis (PIP) technique is that proven shaping and consolidation processes for fibre reinforced plastic (FRP) fabrication like resin transfer moulding (RTM), fabric prepreging, pressing, autoclaving, filament winding (fig. 3) and braiding can be used for green body production. Targeted selection of the polymeric compound, active and passive filler additions and the number of re-infiltrations allow the matrix microstructure to be textured to specific customer and application requirements. In addition, compared to other infiltration techniques, the PIP process provides an ideal ratio between the production costs and the realisable thermomechanical material properties. Furthermore, this manufacturing technology requires comparatively low process temperatures and can be combined with other infiltration methods for re-densification.

Fig. 3. Near-net-shaping of piston rod green bodies using filament winding

The coating of carbon fibres with suited materials such as pyrolytic carbon (pyC) is a prerequisite for the development and fabrication of damage tolerant ceramic matrix composites [21]. This functionalisation of the fibre surface is realised under atmospheric pressure in the institute’s own fibre coating unit using the chemical vapour deposition (CVD) technique. The well directed calibration of the elementary fibre coating unit modules such as spool cabinet, reactor, winding tower and yarn transport system results in formation of rugged protective layer, creates a permanent layer growth and counteracts possible fibre damages. Due to the CVD technique, continuous deposition of the coating components on the fibre surface is performed in a cold-wall reactor (fig. 4) under an inert gas atmosphere enriched with elementary substrate compounds.

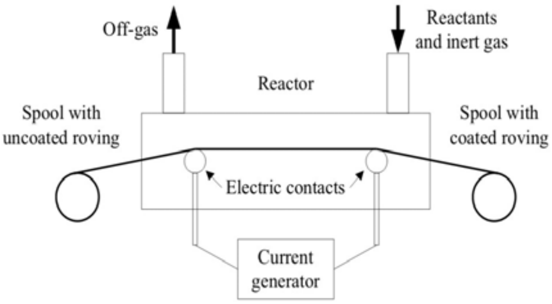


Fig. 4. Schematic layout of a cold-wall reactor with direct resistive heating

A direct resistive heating of the carbon fibres is successfully used for the heating energy input. The required heating is accomplished via an electric current flow through the fibres. The carbon fibre roving passes continuously two electrodes inside the reactor creating an electrical potential difference along the fibre path. This results in resistive heating of the roving between the two electrodes. The roving is exposed to the gaseous precursors only along this heated part of the fibre path. The main advantages of this fibre coating process are the technological robustness, a high productivity as well as an optimal energy and material efficiency.

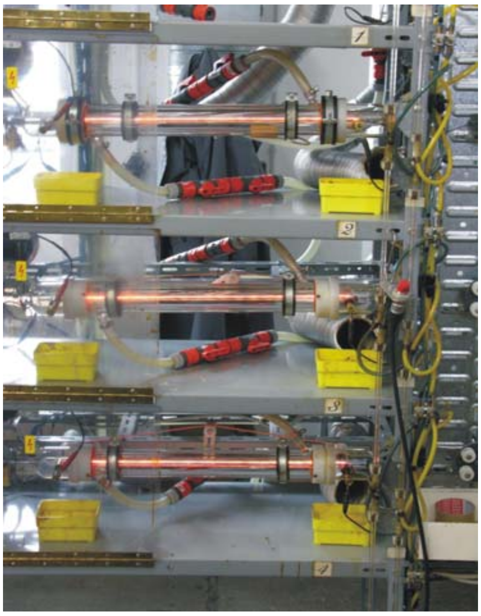


Fig. 5. CVD cold-wall reactors in operation

The reactor walls have to be cooled in order to prevent heating due to heat flux. This results in some condensations of partially pyrolysed coating precursors on the reactor wall which does not influence the deposition process. The fibre roving is heated approximately to 1000 °C and remains inside the reactor for about 10 seconds (fig. 5). In order to prevent fibre burning, it is necessary to perform the deposition process under an inert gas atmosphere. Both, desizing and coating are performed in one step. No additional unit for the desizing step is required.

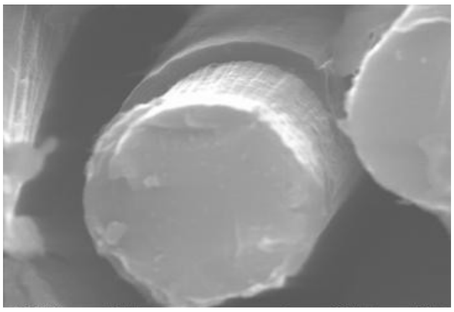


Fig. 6. PyC-coated carbon fibre filament

The special interface (fig. 6) has to satisfy two different requirements: First, it has to present a diffusion barrier between the reinforcing fibres and the ceramic matrix, preventing possible diffusion controlled chemical reactions between these two constituents of the composite. The second requirement is realised by a weak but controlled adherence between the fibre and the matrix. This results in several energy consuming mechanisms which produce a strengthening effect. The occurred gliding mechanisms of the matrix along the fibres are characterised by a crack diversion in the fibre/matrix interface as well as a crack bridging via the fibres with a crack-stop-effect at the fibre surface. As a result of successive micro crack formation and controlled fibre pull-out a pseudo-plastic material behaviour is generated preventing a catastrophic failure owing to brittle fracture.

The near-net-shaping of the piston rods were achieved primarily by liquid impregnation of coated continuous roving with a powder-endowed polymeric suspension using the winding technique. This preceramic slurry consists of an organosilicon thermosetting precursor, suitable solvent and ceramic fillers. For improving green body ejection after the winding procedures a multi-separable winding core was used. After consolidation of the green body, the high-molecular polymeric educts underwent thermal decomposition in an oxygen-free muffle kiln atmosphere a ceramic solid composed predominantly of amorphous silicon carbide. During that direct synthesis low-molecular matters volatilised and reaction gases were released inducing a densification, what results in an irreversible volume shrinkage with a simultaneous pore formation inside the ceramic matrix. To reduce that fabrication-induced porosity the brown body was filled afterwards with the matrix material using several re-infiltration and ceramisation steps (fig. 7).

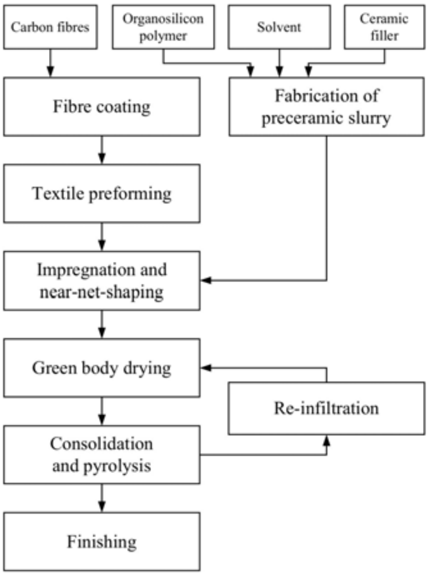


Fig. 7. Manufacturing of C/SiC components via polymer infiltration and pyrolysis (PIP)

2.3 Material characterisation

The preliminary design studies of fibre and textile reinforced CMC structures were realised on the basis of advanced analytic calculation models for the evaluation of stress and deformation fields. The calculation models are based on a modified 3D theory for anisotropic lightweight structures and consider the influence of multi-layered fibrous composites with multi-axial reinforcements [22, 23]. Based on the obtained results three variably structured textile reinforcing performs were selected for further investigations. In addition to a classic linen fabric, especially quasi unidirectional twill fabrics as well as a roving winding with a ±10° fibre deposition were applied (fig. 8).

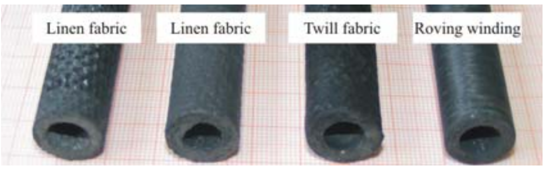


Fig. 8. Different textile reinforced C/SiC piston rods

By means of static and dynamic strength studies (fig. 9) at corresponding tubular geometries as well as microscopic analysis with honed C/SiC piston rods it could be obtained that C/SiC piston rods with ±10° fibre deposition tend to result in the specified requirements in view of the ultimate strength (fig. 10), the buckling stability as well as the surface quality. The lower strength values of fabric reinforced piston rods are primarily attributed to non-negligible fibre damages induced by the textile performing process as well as crimping inside the woven fabric what prevents a straight fibre orientation. Furthermore, it could be established that wound continuous fibre reinforced ceramic piston rods tend to have a lower surface roughness in final condition compared to fabric reinforced piston rods.

Fig. 9. C/SiC piston rods during structural testing

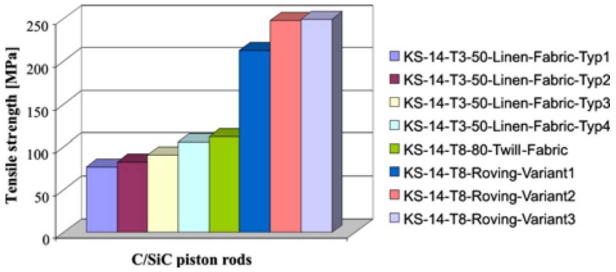


Fig. 10. Strength values of different textile reinforced C/SiC piston rods

Based on received conclusions and in view of lower basic costs during green body fabrication, a continuous fibre winding with a ±10° fibre deposition was selected as an appropriate reinforcing architecture. This special fibre armouring for the fabrication of C/SiC piston rods was solely used in subsequent for the structural optimisation.

2.4 Development of gliding surfaces and load transmissions

By dint of extensive tribological investigations, it could be verified that the manufactured CMC materials features excellent gliding properties. During the tribomechanical tests increased abrasion rates occurred at the seal rings due to the deficient surface roughness. This wear behaviour results in a non-tolerable oil leakage inside the vibration absorber. In consequence of this leakage behaviour, it was necessary to develop a surface coating conformed to the tribological requirements. Enfolding studies with different coatings demonstrated that a degraded layer composition (fig. 11), consisting of an intermediate layer and a nearly non-porous tungsten carbide and cobalt (WC-Co) wear protection coating, applied via high velocity oxygen fuel (HVOF) flame spraying, meet the requirements according the surface roughness, hardness and wear behaviour. After the thermal coating the C/SiC piston rod surface can be infiltrated with a modified epoxy resin to realise a complete gas and fluid impermeability.

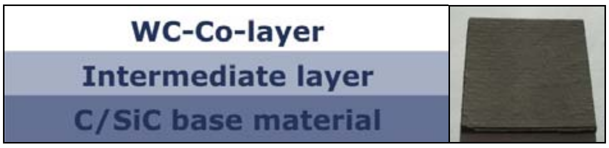


Fig. 11. Layer composition of wear protection coating and WC-Co-coated C/SiC specimen

The material-adapted joining technology plays a decisive role for the functional adaptation of a near-net-shaped CMC lightweight component into an existing technical system. To ensure the piston rod connexion at a standard working piston, it was essentially to integrate a piston- and body-sided adapter made of light metals preferably removable in the C/SiC piston rod. Hence, different load transmission elements in differential and integral design where analysed, in which form- and force-locked, adhesive bonded as well as combined connexions were taken into account. In this context, the casting connexion of a metallic adapter represents an interesting load transmission concept, which benefits from the fabrication-induced porosity and the high temperature stability of ceramic matrix composites. In this regard, different aluminium and magnesium adapters (fig. 12) were cast on the tubular C/SiC piston rod under vacuum using the gas pressure infiltration technique.

Fig. 12. CMC piston rods with cast-on aluminium (left) and magnesium working piston (right)

Fig. 13. C/SiC piston rod with internal round thread (left) and integrated metallic adapter (right)

Moreover, force-locked screw fastenings were developed for an advanced adaptability of the threaded tenons. By dint of a suitable winding core, an internal round thread (fig. 13) was produced directly from the winding process at the piston rod ends. To guarantee a loadpath-adapted fibre orientation in the screw thread zone, a special layer composition with compression windings and variably high yarn tensions was realised. By means of this material-compatible screw fastening the highest mechanical strength was obtained. In addition to the casting version, an efficient ease of manufacturing is required, because the screw thread fabrication need not any supplemental mechanical finishing. Further advantages are also a space-saving constructed size as well as the excellent technological reproducibility. Therewith, the basis for highly stressable load transmissions was created which allows the suitable integration of a tubular CMC lightweight structure into a present technological system and which possesses an eminent capability for high temperature stable and detachable join connexions.

3 Advanced gliding elements for high speed magnetic-levitation trains

As the basic concept of high-speed magnetic-levitation trains, the regular operation of the Transrapid vehicle, which is levitated and guided by magnets, is contact free. In particular, each levitation frame is supported by two levitation magnets according to the redundant dimensioning of the undercarriage. If one of the levitation magnets is being temporarily or permanently disabled, the levitation frame will be supported by a single magnet. However, in the unlikely case of both levitation magnets being disabled at the same time, the magnet levitation is replaced with mechanical support [24]. This system (fig. 14) consists of support skids with CMC gliding elements and tribologically optimised polymer-layers on the gliding strip of the guide way. The novel gliding elements, manufactured by Schunk Kohlenstofftechnik GmbH, were developed on the basis of advanced 3D carbon fibre reinforced carbon (CFC). In extensive experimental investigations and field analyses on the Transrapid test plant in Lathen (Germany), performed by the ILK and ThyssenKrupp Transrapid GmbH, the components of this tribologically high-loaded system were developed, analysed and optimised. Furthermore, the transferability of the performed pin-on-disc-analyses over high speed tests from laboratory scale to field tests should be verified based on the Transrapid vehicle TR08.

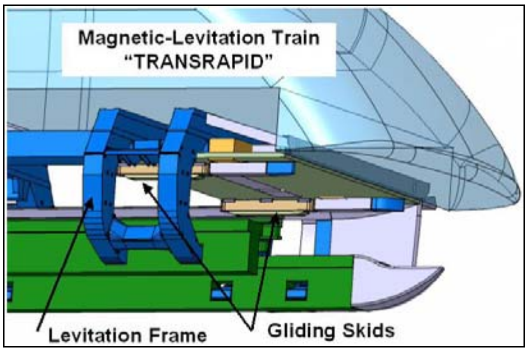


Fig. 14. Arrangement of support skids

3.1 Requirements on friction partners

The technical requirements for the support skid and the gliding strip are extremely high, for example, considering the 30 km long Transrapid link from Shanghai Pudong International Airport to the metro station Long Yang Road in the financial district of Shanghai. Both, support skid and gliding strip, have to withstand safely the mechanical and thermal loads, even if both magnets are disabled directly after leaving the Pudong station [25]. In practical experience the system can be used on concrete, hybrid as well as steel guide ways. In case of a steel or hybrid guide way with gliding strips made of nonferrous metals, polymers or ceramics, the surface coating of the gliding strip has two requirements: corrosion prevention and wear resistance against the sliding partner, especially the gliding elements of the support skids. Furthermore, it is important that the topcoat is characterised by a low coefficient of friction against the material of the gliding elements.

The function of the coating system applied on the concrete gliding strip is to prevent an extensive contact between CFC material and concrete and to ensure permanently a well-defined tribological process while gliding of the support skid on the gliding strip. Fig. 15 shows exemplarily the support skid and the used CFC gliding element. For the practical applicability, inspection and maintenance of the coating may only be executed in large time intervals.

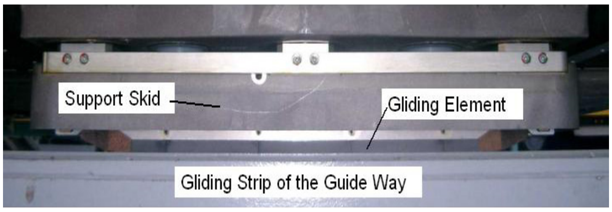


Fig. 15. Support skid with gliding elements

The requested properties of the coating system and the support skids can be summarised in some key aspects. In addition to high temperature stability and an excellent thermal shock, wear and corrosion resistance the gliding elements require a small coefficient of friction. By contrast, the gliding strips are in need of a good applicability for the tribological application with the employed gliding material particularly regarding the specified friction coefficient and a limited temperature development. A further demand on the gliding strip is a high coating adhesiveness at the concrete and the steel subsurface. A small wear of the coating during the support skid gliding on the gliding strip is another important specification. For quality insurance the application of standardized inspection methods is preferred.

3.2 Tribomechanical preliminary investigations

The extensive tribomechanical investigations were realised in three experimental steps, in particular basic studies using a standardised pin-on-disc facility, high speed test by means of a modified pin-on-disc facility as well as high speed examinations via a roller drum test rig.

To determine the friction and wear rate of the modified CFC composites and the selected coatings the ILK test rig for tribological analyses was adapted according to international standards (fig. 16). The tests generated first results for the characteristics of several coating systems in a sliding contact with a CFC-pin with regard to the friction coefficient (fig. 17) and wear resistance. As a conclusion, a coating system on the basis of polyurethane (PU) was chosen for further enhancement regarding the application on a concrete and also on steel subsurface. For this purpose high speed tests by dint of a modified pin-on-disc facility (fig. 18) were performed in a second development step.

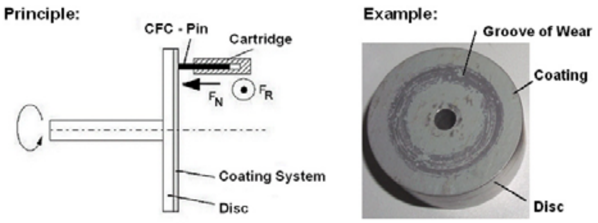


Fig. 16. Standardised pin-on-disc facility with example for basic tribological studies

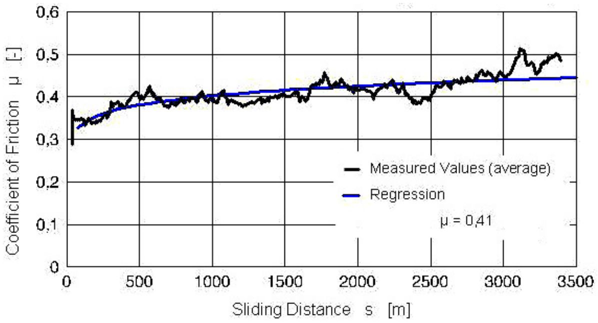


Fig. 17. Friction coefficient of special coating systems in contact with CFC

Subsequent to the pin-on-disc studies high speed tests by means of a roller drum test rig were realised. Moreover, the support skid in use mounted on a special test carrier equipped with several thermocouples is shown in fig. 19. The drum has a diameter of 4 m and a maximum peripheral velocity of

400 km/h. The left side of fig. 16 shows the measurement to capture the tribological data.

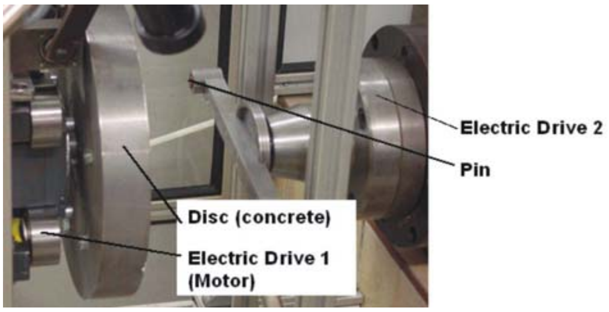


Fig. 18. High speed tests via pin-on-disc facility

Fig. 19. Roller drum test rig

With the aid of this special test equipment the CFC-gliding elements of the support skids were optimised. In the high speed camera photos of fig. 20 the failure of a 2D reinforced CFC gliding element is illustrated exemplarily.

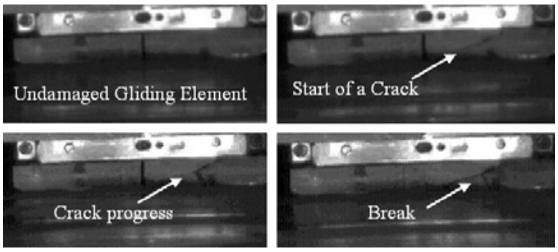


Fig. 20. Breakage of a 2D reinforced CFC gliding element

As a result of the obtained investigations and optimisations can be recorded, that classic gliding element materials such as grey cast iron or bronze fail in consequence of high temperatures at sliding speeds up to 400 km/h. Support skids with gliding elements made of high performance ceramics particularly based on a modified 3D carbon fibre reinforced carbon matrix (CFC) shows the best results. The tests gave first results of the characteristics of several coating systems with regard to the friction coefficient and the thermal behaviour. Furthermore, it is important that the topcoat is characterised by a low friction coefficient against the CFC-material. Basically, the coating system is composed of three layers:

- a corrosion inhibiting primer as inner layer,
- an adhesive agent based on epoxy resin as intermediate layer as well as
- a tribologically optimised topcoat based on polyurethane and modified via functional fillers as outer layer.

3.3 Qualification tests and verification

For the qualification of the developed coating system at the test facility in Lathen (Germany), the identification of the exact characteristics in operation, the gliding strip was coated of a 350 m long section of the concrete guide way. In this area gliding tests with a CFC support skid mounted at the Transrapid vehicle TR08 were performed particularly concerning different vertical loads and velocities. Moreover, practical studies with a special test device called “sulky” have been carried out to give explicit information about very slow vehicle crossing as well as deceleration and acceleration operations. Additionally, tests with special maintenance vehicles have been performed. In particular, the gliding strip coating resists the according wheel-loads.

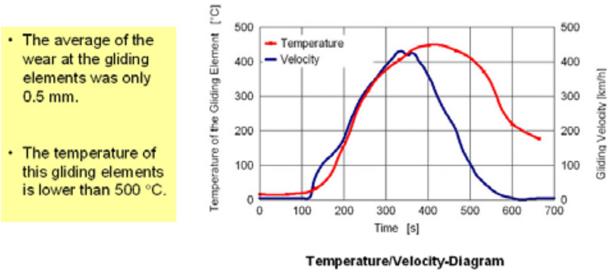
Fig. 21 shows the same section of the qualification coating of the gliding strip after the first and the 22nd gliding test with the Transrapid vehicle TR08. The proceeding discoloration of the white coating caused by the carbon of the gliding material can clearly be seen. The results of the performed tests concerning the CFC gliding material did not show any significant differences neither regarding the friction coefficient nor regarding the wear and temperature behaviour in comparison to gliding on pure or coated steel. In particular, the measured temperature of the gliding elements did not exceed 460 °C. The maximum thermal load capacity of the CFC gliding elements is given by more than 1500 °C. The evaluation of the adhesive strength tests performed at the qualification coating showed that the adhesion of the coating is even higher than the adhesion of the concrete itself. A summary of the derived friction properties of the coating system and the CFC gliding material is given in table 1.

Table 1. Friction properties of gliding strip coating and CFC gliding element

Specific value	
Abrasion of coating	≤ 5 µm (per support skid crossing)
Friction coefficient 40 km/h 400 km/h	 0,2 0,1
Gliding element temperature	≤ 460 °C (in 2 mm distance to the friction surface)
Adhesive tensile strength	≥ 4 MPa

Fig. 21. Gliding strip after the first (left) and the 22^{nd} crossing of the support skid

On the first commercial Transrapid route in Shanghai (China), support skids with gliding element made of an advanced 3D reinforced CFC material as well as a tribological optimized polymer guide way gliding strips are used for the first time [26]. In test runs of Transrapid vehicle with the developed support skid gliding elements and an accumulated sliding distance of 110 km, no wear of the gliding strips was measured practically. Fig. 22 illustrates further results of the tribological verification tests.



- The average of the wear at the gliding elements was only 0.5 mm.
- The temperature of this gliding elements is lower than 500 °C.

Fig. 22. Verification test results

4 Conclusions

Based on the results of extensive experimental investigations, the basis for tribological systems such as automotive shock absorber piston rods or maglev gliding elements was provided, which allow for a reduction in weight with a simultaneous minimisation of friction.

Compared to an equivalent standardised steel piston rod the developed WC-Co-coated piston rod made of carbon fibre reinforced silicon carbide (fig. 23) resulted in a weight reduction of up to 51 %. Simultaneously, a decrease in the arising frictional forces of up to 40 % was realised in combination with a PTFE seal ring, whereby the life cycle of the used friction partners was significantly increased. Furthermore, oil leakage during continuous superposition runs with one million load alternations was significantly lower than in a conventional shock absorber module. This provides the basis for an innovative vibration absorber system with a piston rod made of textile reinforced ceramics in a load-compatible, lightweight design with simultaneously ensured minimisation of friction, wear and leakage.

Fig. 23. C/SiC piston rod for automotive shock absorber systems

The novel CFC maglev gliding elements (fig. 24) and the special coated guide way gliding strips were already successfully tested under operating conditions in Shanghai and ensure the complete functional capability of the magnetic-levitation train Transrapid during velocities up to 500 km/h. In comparison to conventional gliding elements made of grey cast iron or bronze the developed CFC gliding element results in a weight reduction up to 65 %. The experimental results could be fully confirmed and exceeded. In this context, the gliding strip surface coating showed practically no wear. The qualification of the new CFC support skids and the tribological optimised topcoat were accomplished successfully for the Transrapid system. This developed tribological system can be used for both short and long distance applications. Here, tests with the Transrapid vehicle TR08 have impressively proven the transferability of the performed pin-on-disc-analyses over high speed tests from laboratory scale to field tests.

Fig. 24. Novel 3D textile reinforced CFC gliding element for maglev fabricated by Schunk

This highly specific automotive and railroad engineering applications demonstrate impressively the outstanding lightweight potential of textile reinforced non-oxide ceramics, particularly for high performance automotive and railroad components.

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