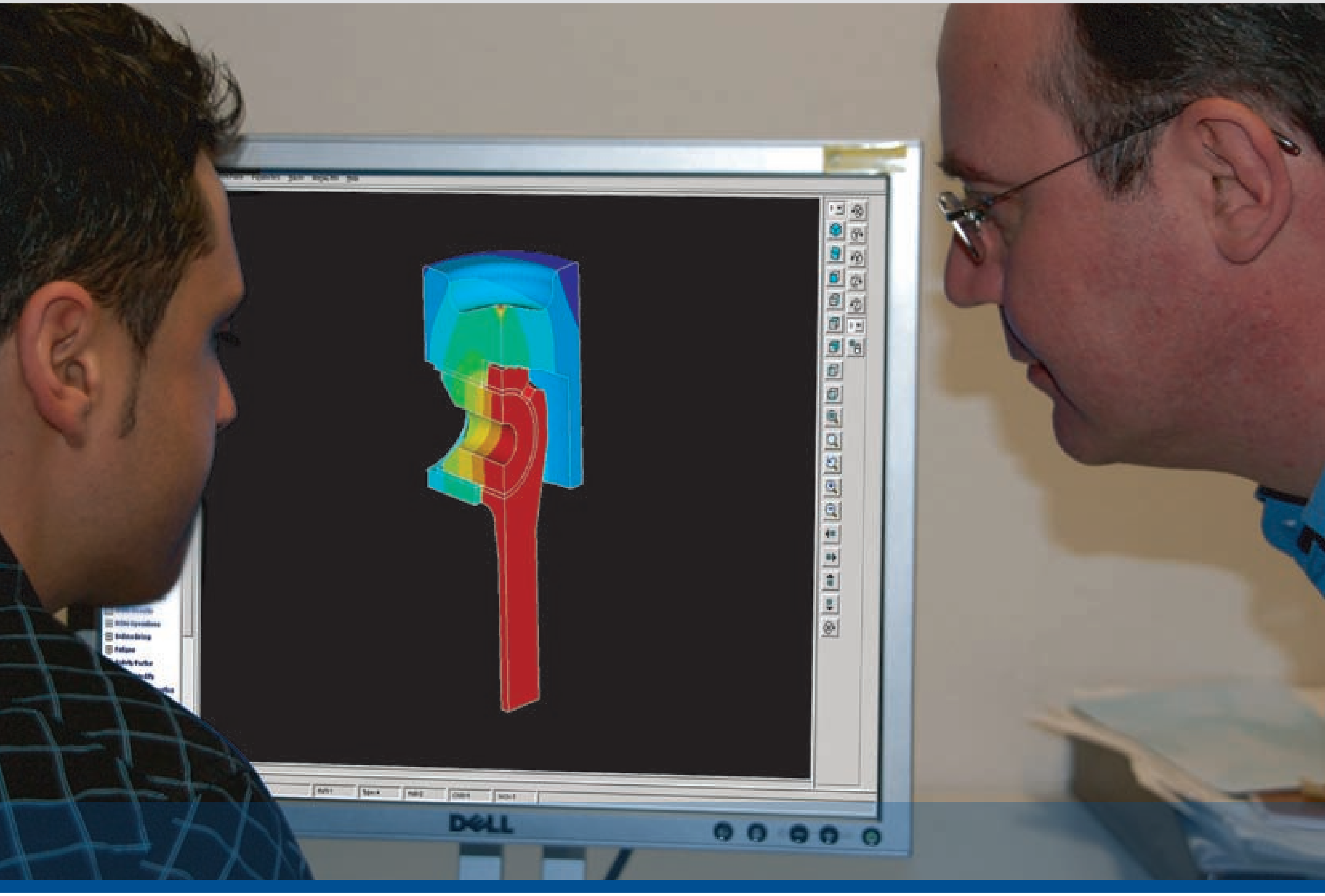

Technology Potential of Ceramic Piston Pins

What is the use potential of high performance ceramics for current and future requirements in engine manufacturing? The Fraunhofer-Institutes LBF and IWM are analysing this in close collaboration with industry partners from the motor and ceramics industry. The starting point of the ongoing investigations in this area is the piston pin used in diesel engines, because great development and sales potential are expected for this concept.

1 Introduction

The use of ceramic materials in the combustion engine has changed significantly with regard to the objectives. On one hand, certain expectations could not be fulfilled, e.g. the heat density engine. On the other hand, ceramic materials have proved quite suitable for mass production, e.g. inlet- and discharge valves based on silicon nitride (SN).

In the light of recent discussions on the reduction of CO_2 emissions in engine manufacturing, structural ceramics has again become interesting. This applies in particular to its suitability as a lightweight and temperature-resistant material, as well as its potential for reducing friction and wear. In the engine, where important functional components are exposed to high, partly combined mechanical and thermal loads, the use of ceramics seems appropriate from a technical perspective. In order to compete with conventional materials also in economic terms, ceramic components with enhanced functionality must be developed, which remove the need for other construction elements.

In this context, a project as part of the Fraunhofer-Demonstration Center „AdvanCer", was initiated by the Fraunhofer-Institutes LBF and IWM, which is being carried out in close collaboration with industry partners from the motor and ceramics industry. The aim is to evaluate the use potential of high performance ceramics for current and future requirements in engine manufacturing. The starting point of the ongoing investigations in this area is the piston pin used in diesel engines, because great development and sales potential are expected for this concept, **Figure 1**.

The focus is the use of ceramics as a material for the piston pin, **Figure 2**. Compared to steel, a weight reduction of about 25 % is expected. Therefore, for the verification of the calculation results and for the approval of an engine endurance experiment, durability tests with components on servo-hydraulic test rigs remain necessary.

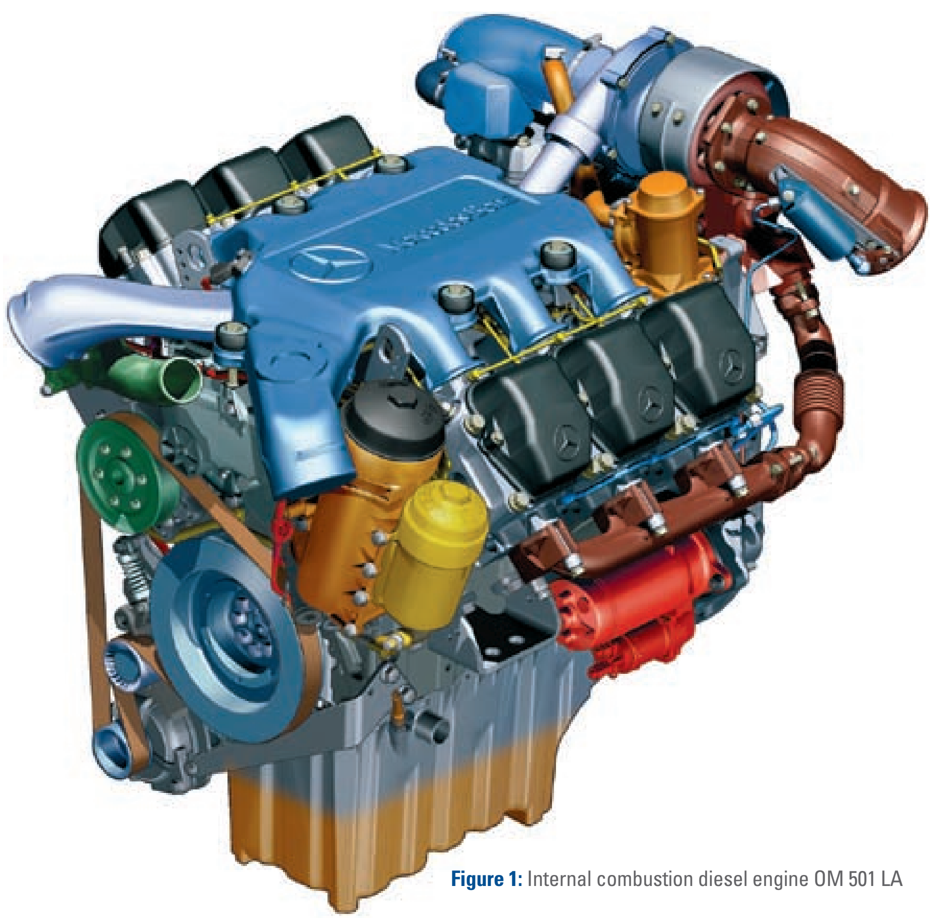

Figure 1: Internal combustion diesel engine OM 501 LA

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Figure 2: Ceramic (right) and steel (left) piston pin

2 Requirements for High-Precision Components Made of High-Performance Ceramics

2.1 Production and Processing

In contrast to the old fashioned clay based ceramic materials, partially known since several thousand years, modern high performance ceramics are produced by using highly pure, synthetic raw materials.

For the materials used in this project it is silicon nitride powder (Si_3N_4) for the „gas pressure sintered silicon nitride" (GPSN), or silicon carbide powder (SiC) for the „sintered silicon carbide" (SSiC). Additionally, so called sintering additives, are required in order to reach the formation of a dense microstructure during sintering.

These raw material powders were used with particle sizes in the range of a few micrometers. Within an intense grinding and homogenizing step, a typically aqueous suspension is prepared from these raw materials, in which all individual particles are optimally dispersed in the desired grain size distribution. In a subsequent process, this suspension is spray dried and then forms a free flowing homogenous granulate.

Pressed preforms made of this granulates have an adequate strength, which allows a so called green machining. Press- and machinability is reached by organic additives, introduced during the homogenization process. A near net shape green machining operation in the unsintered state is economically appropriate, in order to reduce the extent of the much more expensive machining of sintered parts. Depending on the complexity of a component, up to 80 % of the mass of the pressed preform must be removed during this operation, **Figure 3**. It also, has to be considered that the shrinkage during sintering is up to 20 %. A key criterion for the success of green machining therefore is the accurate prediction of this shrinkage, which is not always isotropic. Alternative processes, such as extrusion or injection moulding, reduce the costs for shaping operations but are only profitable with correspondingly large quantities, because of the high cost of the dies and moulds.

Prior to the final ceramic material forming sintering, a debinding process is executed, in which the abovementioned organic additives are decomposed and expelled. For the materials used in this project, the sintering proceeds in inert atmosphere. SSiC is sintered at 2000 °C in vacuum or in an argon atmosphere. GPSN requires a nitrogen atmosphere at approximately 1 MPa and 1800 °C. In order to prevent warpage by anisotropic shrinkage and intermediate softening of parts, special kiln furniture and a sophisticated positioning are necessary [8].

The final machining of the components can only be done by using diamond tools or laser processing, with correspondingly high costs. However, also large components can be manufactured - with the tolerances required in precision mechanical engineering.

The relevant materials are characterized by a high degree of hardness and stiffness and, for ceramic materials, high mechanical strength. Due to the lower raw materials costs SSiC components can be produced cheaper than GPSN. It is characterized by a very high thermal conductivity and can be applied at higher temperatures than GPSN. The thermal application range of GPSN

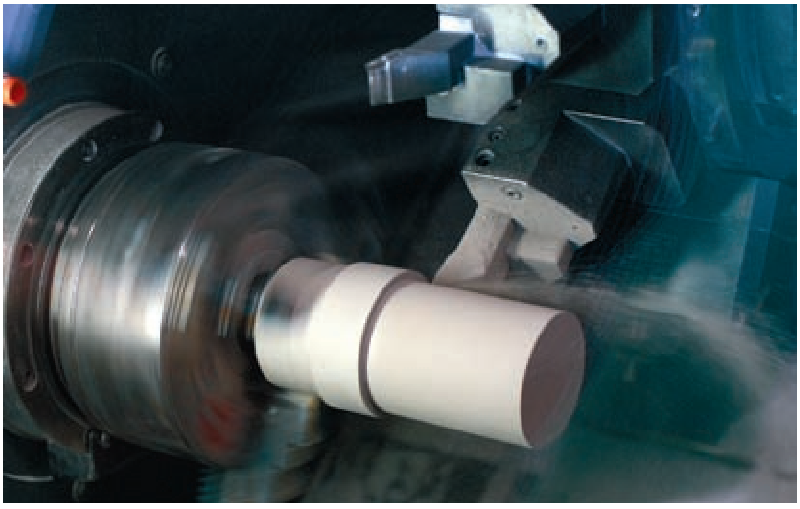

Figure 3: Green machining of a ceramic preform

Table: Material properties of Si_3N_4 and SSiC (Source: FCT Ingenieurkeramik)

Material properties	GPSN*)	SSiC**)
Density r [g/cm³]	3.21	3.15
Coefficient of elasticity E [GPa]	320	400
Poisson's number μ	0.28	0.2
Tensile strength R_m [MPa]	RT: 750 1200 °C: 450	400 400
Weibull Module m	>20	15
Hardness (Vickers) [GPa]	16	26
Fracture toughness K_{IC} [MPa $m^{1/2}$]	8	4
Coefficient of thermal expansion α bis 1000 °C [$10^{-6}K^{-1}$]	3.2	4.5
Thermal conductivity λ [W/mK]	30	100

* GPSN: gas pressure sintered silicon nitride
** SSiC: sintered silicon carbide

ends at 1200 °C. However, this material has a much higher strength and fracture toughness than SSiC.

The use of high performance ceramics in mechanical engineering is especially useful where components are not only exposed to mechanical but also to chemical and thermal loads at the same time. Due to their low density (about 3.2 g/cm³), these materials also have advantages in the field of moving components by reducing the accelerated masses. The brittleness inherent in all ceramic materials has to be considered in designing of high performance ceramic components. Additionally, there are technological constraints to an economic and reliable production, which necessitates an intensive dialogue between ceramists and engine designers in the development of components.

Initially, the geometry of the investigated ceramic piston pin is based on design of the metal part in actual series production, Figure 2. Silicon nitride was chosen, because it was already approved in terms of strength and manufacturing processes for engine valves [7]. Some material properties are shown in the **Table** [8].

2.2 Structural Durability

Before the dimensioning of a cyclically loaded component can be determined, the component stresses under operational loads must be defined. An accurate knowledge of the material properties, with the temperature dependencies, and the heat transfer coefficient and possibly the lubrication measures in the bearings are prerequisite for a reliable calculation of results. The finite element method (FEM), with its possibilities to solve even multiphysical tasks, is the state of the art. With the FEM calculation the system piston pin/con rod – including the bearing is considered. Because of symmetry reasons the creation of a 90° segment is enough, **Figure 4**. As is usual with nearly all diesel rods, the piston pin is mounted on floating bearings. This bearing is formed using contact elements, since a consideration of the hydrodynamics would have meant a very fine discretion and thus increased efforts [1].

In the analysis, both the mechanical and thermal loads have to be considered. On one hand, the piston pin is burdened mechanically by time-varying gas pressure and inertial forces, on the other hand thermally by the temperature changes in the combustion gases. The mechanical stresses are superimposed on thermal stress which determine the mean stress level and the stress amplitude. It should be considered that, in comparison to the mechanical stress, thermal stresses during the heating-up phase only slowly change until a stationary temperature distribution is set.

For the fatigue evaluation of the piston pin, the calculated stress states in the high stressed locations must be faced with the local endurable, calculated stresses for a required life time. Based on early investigations it can be assumed a number of $N=3\cdot10^4$ for start-stop cycles during the life time of the engine, while the cyclic stresses at the steady state occur about $N>2\cdot10^8$ [2].

A S-N curve, which was determined based on some unnotched ceramic samples under cyclic four-point bending, **Figure 5**, is shown in **Figure 6**. Characteristic for ceramic materials, as compared to metallic materials, is the very flat slope k=85. For ceramics, a fatigue limit in the classical sense does not exist.

The determined fatigue properties relate directly to the qualities of the materials and apply to the relevant materials and manufacturing parameters [4]. Here, besides the materials, the environmental factors also play an important role, be-

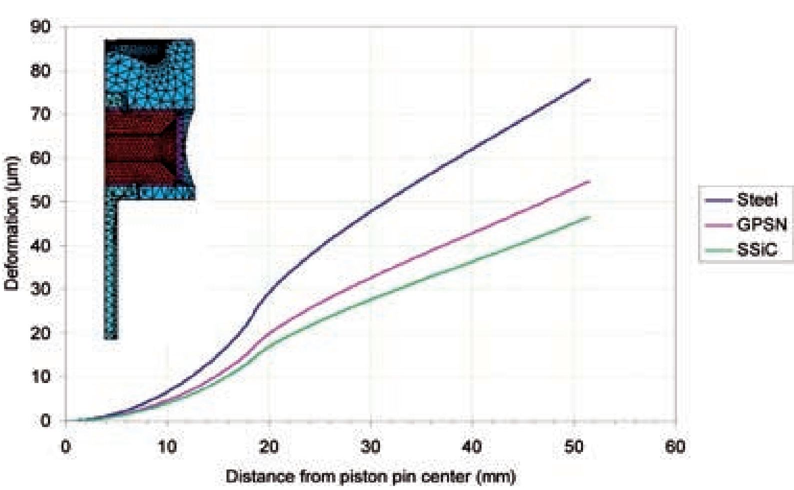

Figure 4: Calculation of piston pin

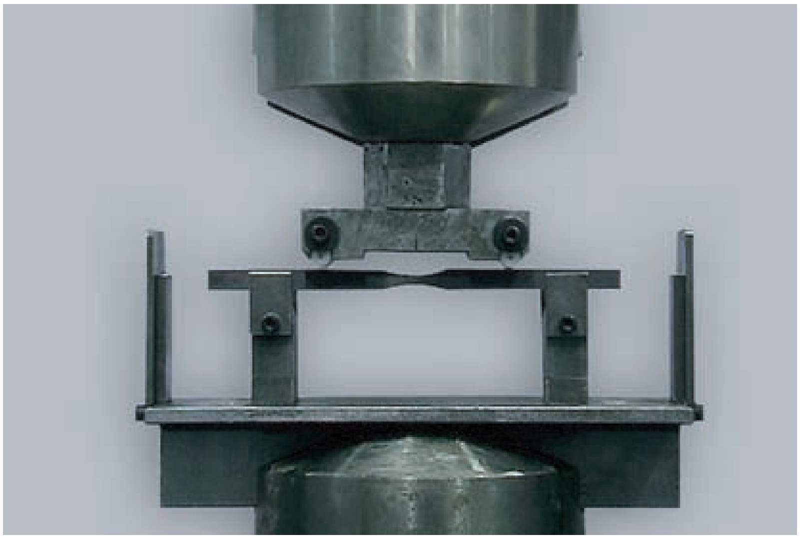

Figure 5: Test bench to accomplish cyclic tests with four-point bending

cause they can significantly influence the fatigue [2, 3, 5].

If critical parts of a component with increased stress concentration are to be evaluated, relevant properties, and where appropriate stress gradients, have to be considered.

Since in most cases there is a multiaxial stress condition in the most regions of a component, the uniaxial stress state of the sample must be transferred in a comparative state. For ceramic materials, the application of the normal stress hypothesis is recommended.

According to [4] ceramic materials with operating loads with variable amplitudes, which exceed the critical upper value, are not suitable. If the maximum value of the operating loads is below this value, no failure is to be expected.

At present, in addition to numerical investigations, fatigue tests with ceramic piston pins are being carried out. In this process, the piston pin including the piston, bearing cup and the con rod is loaded cyclically and biaxially in a test rig based on the load ratio of the egine, **Figure 7**. This allows the cyclically highly stressed parts to be determined.

2.3 Tribology

Besides the fatigue behavior, the tribological properties of the combination piston pin/connecting rod bearing are especially crucial for the future use of a ceramic piston pin. In order to show the tribological collective as well as to evaluate in a model experiment, various combinations of materials were tested in reserve pin-disk geometry at 120 °C with full and deficit lubrication according to their tribological suitability. The pin had a diameter of 10 mm and the ball cap a radius of 6 mm. With a normal force of 100 N, a stroke of 2 mm and a frequency of 20 Hz, the friction and wear of the materials were tested with a standard motor oil for three hours. The wear on the pin and disc were determined separately by measuring weight loss. Overall, in addition to the reference matching (steel piston pins, brass rods bearing) another six materials combinations with different machining, as well as full and deficit lubrication, were tested. Besides various ceramic combinations, a steel piston (or pin) coated with a diamond-like amorphous carbon layer (DLC) was compared to brass. DLC layers lead in many cases, some of them unlubricated tribo systems, lead to very low friction values and are very wear-resistant.

With full lubrication, from the viewpoint of friction, the two silicon carbide materials (SiC) (solid phase and liquid phase sintered SiC) displayed only a slightly higher coefficient of friction than the reference matching (steel / brass). On the other hand, the integrated wear in the SiC pairings in particular was significantly below the reference system. With deficit lubrication, the ceramics had significant advantages in terms of the tribological properties. Here, the friction of both the silicon nitride as well as of the SiC materials was significantly below that of the reference materials. In some cases, the friction with a lack of lubrication was almost halved. Only the DLC layers had a friction coefficient lower than that of the ceramic materials. In terms of wear, small advantages with ceramic materials were determined in comparison to a reference matching of steel/brass, with the overall results mixed. Some material combinations, in particular the DLC layers, showed a

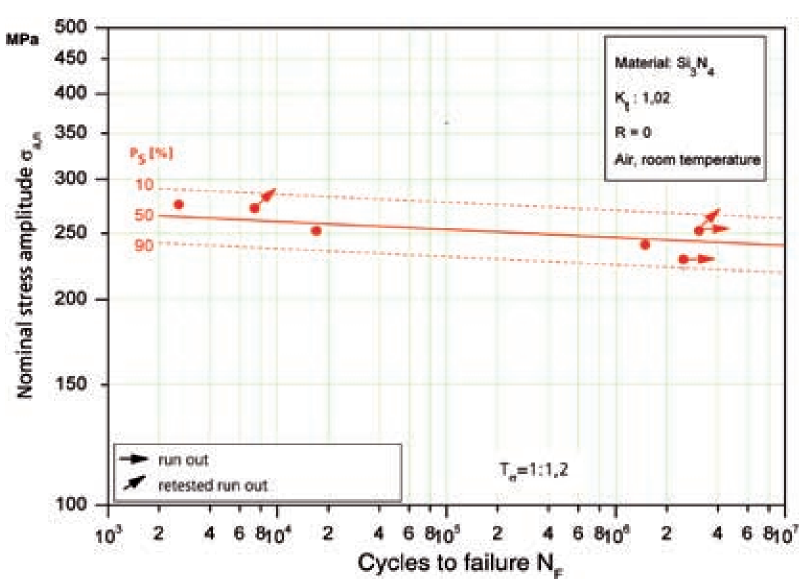

Figure 6: S-N curve for Si_3N_4, set up with unnotched sample under cyclic four-point bending

Figure 7: Component test rig

low wear similar to the reference system. Further experiments showed that the processing of ceramics has a decisive influence on the subsequent friction and wear behavior. In actual use, it is to be expected that, especially among deficit lubrication, besides weight reduction a significant reduction of energy loss due to friction will occur. With full lubrication no significant disadvantages compared to the reference samples are to be expected.

3 Summary and Outlook

Based on current research activities it can be expected that the use of silicon nitride ceramics for ceramic piston pins may lead to weight savings of approximately 25 %. Due to expensive experimental parts, lang running time and rising fuel prices, the options for continuous runs on the engine test bench are becoming increasingly limited. Therefore, the importance of FEM for comprehensive pre-optimization and experimental externally driven motor tests is continuously increasing. As a result, the piston pin is optimally designed with the help of numerical and experimental testing. Before the final proof of structural durability is accomplished in the actual engine, the component is dimensioned, with regard to a ceramic-adequate design, fatigue behavior as well as tribology. Regarding its mass-production use, economic factors play a crucial role. In the past, the example of the ceramic engine valve showed that manufacturing costs can easily be in the same range as that of metallic materials. Due to durability and tribology reasons silicium nitride materials are prefered – according to the recent research. Since engine development is still focusing on reduced fuel consumption and higher performance, the weight reduction of components and the reduction of friction and wear, in particular are important measures. In this context the use of ceramics in internal combustion engine manufacturing turns out to be very interesting.

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