Air bearings based on porous ceramic composites

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Abstract

Air bearings made of porous materials allow an equal air distribution on the bearing surface. In comparison with conventional orifice bearings, air bearings have a higher load capacity and stiffness. Their dynamic behaviour is improved due to many micro pores, which make the bearings less sensitive to internal and external disturbances. In this study, the characteristics of advances SiC-based fibre-reinforced composites and their utilization for the development of air bearings are discussed. The characteristics of these bearings were examined and the question for usability was addressed in principle. This paper presents the results of investigations and it demonstrated that fibre-reinforced ceramic have excellent mechanical and thermal properties. This material could replace current porous bearing materials in view of several difficult static and thermal conditions.

Keywords: Aerostatic Bearing, Ceramic, Machine Tool

1. Introduction

Air bearings utilise a thin film of pressurised air between the bearing surfaces to achieve a non-contact operation. In contrast to rolling contact bearings, air bearings avoid problems such as friction and wear since only air is used as lubrication medium. Characterised by a high damping and a silence operation, air bearings are ideal for high speed applications.

Currently, air bearings are used for precision applications like linear guidelines in measurement systems. For these applications, it is essential that the motions of air bearings are homogeneous and smoother than rolling bearings, so that the error correction is more effective. Moreover, air bearings are also used for high speed applications like bearings in motor spindles of precision tool machines. The bearings show no wear and have no heat problems even at high relative velocities due to the air gap between the bearing surfaces.

Pressure injected air bearings can be divided into two classes. Traditional air bearings are designed with one or more orifices and often combined with grooves to improve the bearing properties. Today, innovative air bearings used porous materials, so that a large number of micro canals control the airflow across the entire bearing surface.

In contrast of orifice bearings, porous air bearings are characterised by an excellent air pressure distribution across the surface and a high tolerance to bearing surface damage. Therefore, porous bearings have an improved dynamic and static behaviour.

Temperature gradients on machines with guidances based on air bearings can lead to displacements of the bearing surfaces and the reduction of the machine accuracy due to change of air gap or preload force. Therefore, apart from the improvement of dynamic and static properties of air bearings, it is also essential to optimise the thermal behaviour. The aim is to develop new materials that combine the excellent properties of traditionally porous bearing
materials and the thermal properties of ceramics.

In this paper, the authors presented the advanced ceramic composite CVI-SiC/SiC with an open porous material structure. The usability of this material as air bearing material was discussed. Moreover, the results of investigations were demonstrated for planar thrust bearings and an air bearing design with this material was presented.

2. Applications

Thrust bearings are used as precision guidances in precision measuring machines with micro resolution. Additionally, thrust bearings can be preloaded with vacuum that is an elegant solution to increase the bearing stiffness. Several thrust bearing pads with porous fibre-reinforce ceramic were developed for linear guidances at IWF. The bearing pads can be mounted directly by flange (see Fig. 2) or have an integrated ball joint with self adjustment.

![Air bearing pad with porous ceramic for linear guidances (flange coverage)](image)

The development of porous ceramic composite materials with their excellent thermal and mechanical properties allow the design of air bearings for the optimisation of high precision and high speed machines. Motor spindles for precision tool machines required a constant air gap for steady properties even at highest rotation speeds. Energy dissipation in drives and the air friction in bearings at high relative velocities lead to thermal displacements. The result is a negative influence of static and dynamic spindle behaviour. Ceramic bearings reduce the thermal deformations to a minimum. Therefore, a motor spindle with porous ceramic air bearings was developed at IWF for the investigation and optimisation of spindle behaviour (Fig. 3).

![Motor spindle with porous air bearings for precision turning machines](image)

The motor spindle consists of modular spindle housing with two integrated planar annular axial bearings and a journal bearing. The drive is flanged on the spindle housing and moved the spindle directly with up to 3000 rpm. The spindle diameters are 70 mm (radial bearing) and 200 mm (axial bearing), respectively.

3. Comparison of orifice and porous bearings

In orifice bearings the air is supplied to the bearing surface through a small number of precisely sized holes [1]. Since bearings with single orifice have a high pressure gradient between the orifice centre and the bearing boundary, a proper number of orifices are strategically placed on the bearing surface (see Fig. 4).

![Pressure distribution on the bearing surface for orifices (a, b) and porous bearings (c)](image)

Porous air bearings enable the supply of air equally across the whole surface of bearing, so that the air flow can be restricted and damped at the same time. This can be achieved by diffusing the air through a porous bearing material, so that a uniform pressure in the air gap is generated (also see Fig. 4). Compared
with orifice bearings, porous bearings have the highest load capacity and stiffness including high vibration stability.

One of the first porous air bearing materials was carbon graphite [2, 3]. Subsequently, bearings produced from sinter materials like Al₂O₃ and sinter bronze [4] have been described. Here, we focus on a new ceramic material, called CVI/SiC/SiC, for the realisation of a new air bearing design.

4. Properties of ceramic composite CVI-SiC/SiC

Designing with ceramics is more difficult compared with steel, because steel is much more tolerant to local stress peaks and material flaws. These disadvantages of monolithic ceramic materials could be overcome by the development of ceramic composites. Such materials are synthesised from the assembly of two or more components in order to obtain specific material properties.

One of these ceramic composites is CVI-SiC/SiC, which is composed of a silicon carbide (SiC) fibre reinforcement imbedded in a SiC matrix during the chemical vapour infiltration (CVI). The three-dimensional SiC fibre architecture and the SiC matrix leads to a structure with an open porosity of 10 % to 15%, which makes it fluid-permeable (see Fig. 5). The porosity can be modified by variation of structure geometry and the controlled filling of this structure with SiC. The geometrical form of the pores is dependent on fibre direction, and lies between 100 µm and 300 µm for the test pieces. Semi-finished products like tubes and plates of different thicknesses were manufactured in a pilot plant.

Contrary to conventional monolith ceramics, the reinforcement with continuous fibres from SiC guarantees an increased tensile strength, fracture toughness and the elastic modulus of ceramic substantially. The SiC fibres catch the break in case of sub-critical crack growth, so that the main cause of brittle failure would be eliminated. In contrast to monolithic ceramics, pre-stress is not necessary for components made of CVI-SiC/SiC. In case of a structure with a fibre direction of 0° and 90°, the elastic modulus of CVI-SiC/SiC has been indicated to be 180 GPa to 220 GPa, the tensile strength lies between 300 MPa and 400 MPa [5 - 8].

For the realisation of a high accuracy in tool machines, it is essential to minimise the thermal deformation of machine components. Compared to steel, which has a thermal expansion coefficient of 11.8.10⁻⁶ 1/K, the thermal expansion coefficient of CVI-SiC/SiC amounts 4.10⁻⁶ 1/K, between 293 K and 573 K, and is much lower. In this background, CVI-SiC/SiC is an innovative material for the designing of spindles and bearings of precision machines.

Moreover, a favourable sliding behaviour of CVI-SiC/SiC leads to excellent dry-running properties. Tribology investigations showed an improved noise-reduced running under boundary and mixed friction conditions compared to monolith ceramics. The dry-running properties can be further improved by substitution of SiC matrix with carbon.

Due to the mechanic properties, the ceramic composite material CVI-SiC/SiC represents an ideal basis for the development of components for high precision applications. The adjustable porosity should enable the use of this material for aerostatic bearings in high precision spindles.

5. Planar thrust bearing

Fig. 6 shows the configuration of planar thrust bearing. In the upper part, the porous bearing material, the air inlet, and three distance sensors which measure the air gap are shown. In the lower part, a force sensor was mounted in the basic body.
The ceramic plates with a diameter of 40 mm were stuck in a universal adapter. The universal adapter served as a quickly disassemble of bearing material, since ceramic plates with different thickness were investigated. The thicknesses of the ceramics were changed by grinding and the bearing surfaces were finished by lapping. After machining, the bearing materials were cleaned to re-open the pores due to the presence of cooling fluid and grinding particles.

For the adjustment of the air gaps a reference mass was precisely positioned. The air gap could be adjusted in steps of 1 µm. The reference mass should substitute the guide surface. This equivalent surface was precision machined with a roughness of less than 0.1 µm.

5.1. Pressure profile in bearing gap

Fig. 7 shows the pressure profile of planar thrust bearing. The measurement was executed with an air gap of 10 µm and a supply pressure of 0.6 MPa. There is a difference between the expected profile of pressure and the measured one. Compared to the curve for an ideal porous bearing material, real materials have no constant pressure field over the bearing surface. However, the experimental data showed a curve with a similar trend. An approximate value for the gap pressure can be specified with 0.55 MPa for parameters stated above. This value is somewhat lower than expected, but it is consistent with the trend observed in the experimental data.

5.2. Load capacity of planar bearing

In Fig. 8, the results of load capacity at several supply pressures are presented. All curves show a tendentious similar behaviour. With decreasing air gap, an exponential increasing load capacity is demonstrated. The maximum value lies at 380 N for a supply pressure of 0.6 MPa and an air gap of 5 µm. With increasing bearing gap, the load capacity trended to zero.

For the further determination of the optimal operating points, the knowledge of the maximum load capacities alone is not sufficient. The investigation of the static stiffness of aerostatic bearing is of decisive importance, because frequent load changes arises in real operation. Since the measured gap pressures do not consider the real pressure distribution in the bearing gap, the stiffness was determined directly over the change of the load capacity curves. The stiffness values give an essential statement about the static and dynamic behaviour. It is also possible to determine the absorption behaviour of aerostatic bearing for different operating conditions.

Fig. 9 shows the stiffness of bearing for the supply pressure of 0.2 MPa to 0.6 MPa for an air gap up to
60 µm. With a supply pressure of 0.6 MPa and an air gap of 5 µm, the maximum stiffness lies approximately at 14 N/µm. With increasing supply pressure, the maximum value displaced in direction of smaller air gaps [9].

6. Journal bearing

The assembled and investigated journal bearing is shown in Fig. 10. The porous bearing material was press-fitted into the housing and was externally pressurised. Laser distance sensors were used for the measurement of the eccentricity of journals as the result of external forces. Nonporous journals in different diameters and segment lengths were investigated.

6.1. Optimisation of bearing size

With the help of the segment journals, different bearing sizes were integrated for their load capacity and stiffness in relation to the diameter/length ratio (L/D). The results were presented in the following dimensionless form:

\[
F = \frac{F}{L DP_s}
\]

for the dimensionless load capacity and

\[
S = \frac{SC}{L DP_s}
\]

for the dimensionless stiffness.

The variations of load capacity for different values of L/D are presented in Fig. 11. The relation between load capacity and eccentricity could be described as approximate linear. The values of load capacity increase for bearings with decreasing L/D ratios. For L/D ratios less than 0.5 the load capacity becomes smaller. Here, the load capacity for a bearing with L/D of 0.5 is also higher than that for bearings with L/D of 0.3 and 1.2.

The results of determination for stiffness showed the same behaviour (see Fig. 12). A maximum value of stiffness is achieved for an L/D ratio of 0.5. Furthermore, the curves show a degressive behaviour. This means, that the stiffness will decrease rapidly with increasing eccentricity.

In Fig. 11 and 12, it is clearly shown that there is an optimal bearing size, where the properties of aerostatic bearings have maximum values. This optimum depends on the porous bearing material, which has a characteristic air flow behaviour.
7. Conclusion and outlook

Aerostatic planar bearings and journal bearings were manufactured from fibre enforcement ceramic CVI-SiC/SiC. The bearings were tested under several conditions to evaluate the static behaviour. In the first part, the work was focused on the measurement of air pressure profile, load capacity and the determination of stiffness. In the second part, journal bearings with segmented journals for the optimisation of bearing size were investigated for its load capacity and static bearing stiffness.

Using ceramic planar bearings with a thickness of 2 mm and a diameter of 40 mm, an air pressure profile with an approximately constant pressure of 0.55 MPa and a load capacity of 320 N was achieved at a supply pressure of 0.6 MPa and 10 µm air gap. At a supply pressure of 0.6 MPa and 5 µm air gap, a maximum load capacity of 380 N and stiffness of 14 N/µm was determined. Bearings with a porous material like CVI-SiC/SiC demonstrated a good vibration stability under different air supply pressures.

For journal bearings, the measurements showed maximum values of load capacity and static stiffness at a length/diameter ratio of 0.5. Structured ceramics with different permeability and air flow characteristic can lead to variance of optimised bearing size. The bearing properties are also dependent on the material design like geometry or number of micro channels. A static and dynamic optimisation for air bearings should be provided by simulation.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>a</td>
<td>planar bearing radius</td>
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<tr>
<td>C</td>
<td>radial clearance</td>
</tr>
<tr>
<td>D</td>
<td>journal diameter</td>
</tr>
<tr>
<td>e</td>
<td>eccentricity</td>
</tr>
<tr>
<td>F</td>
<td>load capacity</td>
</tr>
<tr>
<td>E</td>
<td>dimensionless load capacity</td>
</tr>
<tr>
<td>h</td>
<td>air film thickness (air gap)</td>
</tr>
<tr>
<td>L</td>
<td>length of the journal bearing</td>
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<tr>
<td>L/D</td>
<td>length/diameter ratio</td>
</tr>
<tr>
<td>pS</td>
<td>supply pressure</td>
</tr>
<tr>
<td>pSp</td>
<td>pressure in bearing gap</td>
</tr>
<tr>
<td>S</td>
<td>static stiffness of the bearing</td>
</tr>
<tr>
<td>Sd</td>
<td>dimensionless static stiffness of the bearing</td>
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<tr>
<td>ε</td>
<td>eccentricity ratio e/C</td>
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### References