Drive & Control profile

White Paper

# Performance testing of composite bearing materials for large hydraulic cylinders

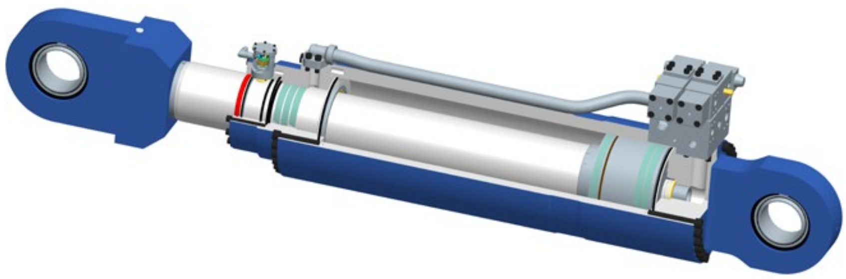


Figure 1: Location of radial bearings and seals in a hydraulic cylinder

**Introduction**
Large hydraulic cylinders (LHC) are integral components in the functioning of large machines in mechanically demanding, corrosive and abrasive environments, such as offshore drilling rigs. The materials utilized in these large-scale hydraulic systems must deliver reliable performance throughout their expected lifecycle.

One key LHC component is the radial bearing. Although a number of materials are utilized to create these bearings (such as aluminum-bronze, bronze and several thermoplastic materials, including UHMWPE), the most commonly used materials are composite materials. To effectively and reliably predict the longevity and operational performance of these composite radial bearings, Bosch Rexroth developed a testing method that examines the layer structure of the bearing, as well as its friction behavior; the company also developed a method to investigate how the bearing deforms as the result of being placed under a load, and then further imaging to assess the bearing's response to being under a load.

Bosch Rexroth developed this detailed testing procedure to objectively assess and predict the performance of multiple bearings offered by different suppliers; by investing in this process, Bosch Rexroth is able to make authoritative predictions about these bearings. The testing also provides a basis for productive consulting with bearing manufacturers to help them improve key material characteristics of the utilized bearings. This unique investment helps Bosch Rexroth optimize the operational value of the customer's LHC system.

**LHC radial bearing technology**
Hydraulic cylinders convert hydraulic energy into mechanical movement. The hydraulic cylinder consists of a cylinder body, in which a piston connected to a piston rod moves back and forth. For the most common single rod cylinder, the barrel is closed on the cylinder cap end by the cylinder bottom and on the cylinder rod end by the cylinder head, where the piston rod comes out of the cylinder.

Both the piston and cylinder head have radial bearings and seals. Figure 1 shows where the seals and bearings are located. The piston divides the inside of the cylinder into two chambers: the cap end chamber and the rod end chamber.

Radial bearings are used for guiding the piston through the cylinder shell and the cylinder rod through the cylinder head. The radial bearings may be exposed to high loads due to:

- Side loads on the cylinder rod
- Gravitational force, depending on the orientation of the cylinder in the application

- Small misalignments (e.g., as the result of gravitational force) in combination with axial compressive external loads

High shear stresses can also be expected in operation, caused by the (dynamic) friction forces between the cylinder shell (piston bearing), the cylinder rod (head bearing) and the bearing material.

Given its function, the following bearing properties are to be considered:

- Compressive strength
- Shear strength
- Tensile strength
- Compressive modulus of elasticity
- Static and dynamic friction
- Temperature range of application
- Thermal expansion coefficient
- Thermal conductivity and softening
- Electric insulation
- Dimensional stability
- Chemical resistance to hydraulic fluids
- Swelling of material
- Hardness
- Capacity for imbedding dirt

Bosch Rexroth has developed testing procedures to evaluate several of these key properties, with a goal of collaborating with suppliers to improve the performance of these bearings; this in turn helps contribute significantly to the superior longevity and reliability of Rexroth LHC systems.

**Composite bearing materials**

Although bearing properties such as strength, response to temperature, chemical resistance and electric properties are important, understanding a bearing's response to friction is crucial, because friction means wear, negative frictional behavior (such as stick-slip), frictional heat and reduction of the cylinder force efficiency (in other words, energy loss).

Currently, the most commonly used materials for LHC radial bearings are composite materials, which are the focus of Bosch Rexroth's testing processes discussed in this paper.

Composite bearing materials are technical fabrics impregnated with thermosetting resins, i.e., a polymer fabric reinforcement with a thermoset matrix. The most commonly used fabric material is polyester; the most commonly used resins for the matrix are polyesters and phenols. For friction reduction, dedicated additives are used, mostly PTFE powder.

The following illustrations depict the structure of the bearing material:

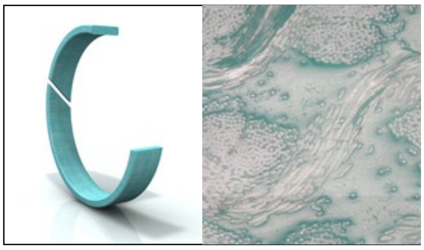


Figure 2: A composite bearing composed of polyester fabric impregnated with a polyester resin—bearing strip and cross section micrograph shown

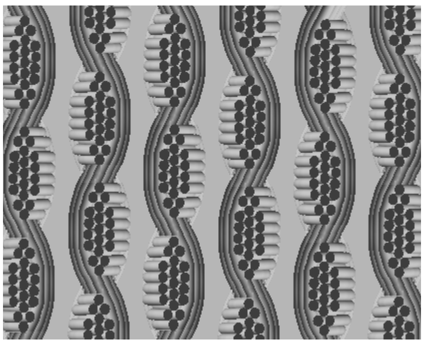


Figure 3: Illustration of bearing strip—polyester fabric structure

**Bearing pultrusion production process**

In order to better understand radial bearing performance and the properties that contribute to that performance, it is useful to understand how composite radial bearings are manufactured. While some bearings are manufactured via a pressing process, the most common method is the pultrusion process; the bearings referenced in this paper tested were manufactured using this process.

In pultrusion, multiple layers of fabric are pulled through a resin bath, where the liquid resin and some additives are present as a mix. When the fabric has gone through the bath, the resin is heat cured in a mold and can be tempered afterward (See Figure 4).

In the pultrusion process, the following process properties have an influence on the quality of the radial bearing:

- The fabric's speed through the process (particularly the curing process)
  - Excess speed can result in high internal stresses and insufficient resin polymerization
- Distance of the different layers of fabric in the resin bath
  - Too low or high: Results in air enclosures and unequal layer buildup
- Pulling forces on the fabric during the process
  - Excess pulling forces result in high internal stresses and micro cracks
- Incorrect curing time and/or temperature
  - Can cause insufficient resin polymerization and/or high stresses and cracks
- Post-curing process errors
- Insufficient post-curing time can cause high stresses and cracks

**Methods: Bosch Rexroth performance investigation**

Testing method: Bosch Rexroth has conducted testing on radial bearings from different suppliers. A standard

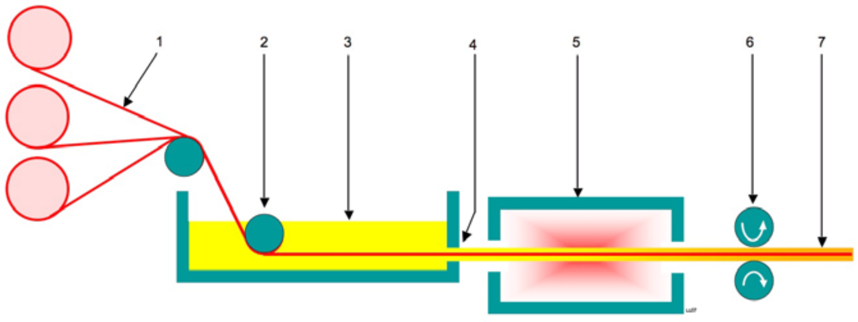



Figure 4: The key steps in the pultrusion process include: 1) Continuous roll feed of reinforced fibers/woven fiber mat; 2) Tension control roll; 3) Resin impregnator bath; 4) Resin-soaked fiber; 5) Bearing die and heat source; and 6) Fiber pull mechanism

testing methodology was developed in order to investigate key radial bearing properties. The following three tests were carried out:

1. Microscopic imaging: A micrograph of the cross section of the composite bearing is taken to study the composite's layer structure and possible defects. Micrographs are taken pre- and post-friction testing.

2. Friction test: This test is conducted to generate a Stribeck curve, which is made by measuring the friction on the bearing at different velocities and different loads. The magnitude of the load is varied, and two inclinations are used.

3. Thickness measurement: Before and after the friction test, the composite bearing's thickness is measured. Measuring the change in the bearing's thickness after putting the composite under loads provides an indication of the permanent deformation as a result of the load.

**Step 1—Microscopic imaging:** Cross sections were made both in the length and width direction of the radial bearing (see figure 5). The micrographs capture visual data related to the stresses that composite bearing material can undergo and the possible effects of those stresses, such as microscopic cracks, shearing of the different layers and deformation of the material. Micrographs also image air enclosures in the material, which can contribute to the weakening of the integrity of the resin-impregnated material.

The radial bearings were cut with great care: use of cooling water kept the material temperature low so that the bearing structure was not damaged. An image was made of the cross section with an optical microscope with a magnification of 100x.

The microscopic investigation revealed that the radial cross section gives information on the quality of the fabrication process. The transversal cross section gives more information about the composite layer structure and incidence of and distribution of air inclusions.

**Step 2—Friction test:** For determining the friction characteristics of the bearing strips, Stribeck curves were generated, as well as stick-slip curves. A Stribeck (master) curve is created by measuring the friction at different loads and velocities. For these tests, Bosch Rexroth is using a special test rig consisting of a cylinder rod which is driven by an electrical screw spindle. A bearing strip is placed in a bearing housing which can be put under load by a hydraulic cylinder perpendicular to the rod. The complete bearing housing can be put under an angle, which can be slightly varied. Thus, the influence of the deflection curve of a cylinder rod on the bearing can be simulated.

Three measurement series (at temperatures 25°C, 40°C and 55°C) were carried out to generate a Stribeck curve at two angles (0° and 1°). The friction was measured with a load cell at a sample rate of 1kHz. The test program was programmed in LabVIEW and was executed fully automatically.

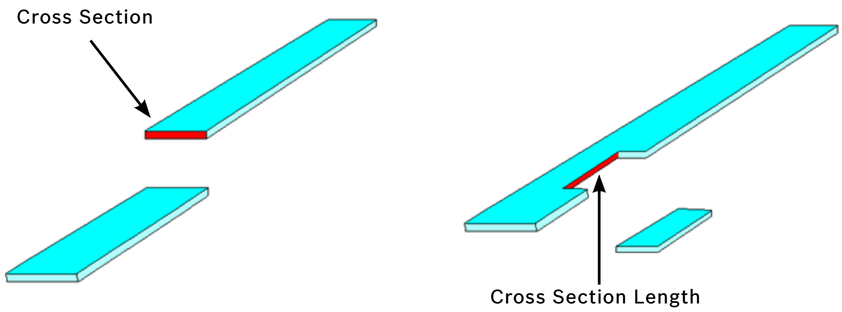



Figure 5: Location of the cross section for microscopic imaging

**The following test series were performed:**

*0° angle, temperatures 25°C, 40°C and 55°C*

| Load [kN] Approx.: | Velocity: |
|---|---|
| 8 | 0.1/-0.1 |
| 30 | 0.2/-0.2 |
| 60 | 0.5/-0.5 |
| 92 | 1/-1 |
| 123 | 2/-2 |
| 154 | 5/-5 |
| 184 | 20/-20 |
| 215 | 50/-50 |
| | 100/-100 |

*1° angle, temperatures 25°C, 40°C and 55°C*

| Load [kN] Approx.: | Velocity: |
|---|---|
| 10 | 0.1/-0.1 |
| 30 | 0.2/-0.2 |
| 45 | 0.5/-0.5 |
| 60 | 1/-1 |
| 70 | 2/-2 |
| 75 | 5/-5 |
| 215.5 | 20/-20 |
| | 50/-50 |
| | 100/-100 |

**Step 3—Thickness measurement:** Both prior to and after the friction test, measurements were made of the composite material's thickness to assess the change in thickness and permanent deformations.

**Comparison testing:** A series of radial bearing materials from multiple suppliers were tested by Bosch Rexroth; their performance was compared with a set of Bosch Rexroth standard quality bearing composites, whose standard properties and performance matched Rexroth's requirements for LHC radial bearings. This article provides a representative comparison of one sample bearing against the Rexroth standard bearing.

**Sample bearing test conditions:**
- Rod material: Steel
- Rod diameter: 100 mm
- Rod surface roughness (average of 9 measurements): Ra 0.29
- Bearing angle: 0° and 1°
- Lubricant: Shell Tellus 46

**Rexroth standard test conditions:**
- Rod material: Steel
- Rod diameter: 100 mm
- Rod surface roughness (average of 9 measurements): Ra 0.25
- Bearing angle: 0° and 1°
- Lubricant: Shell Tellus 46

**Results: Radial bearing comparison test**

*Sample bearing select Stribeck curves*

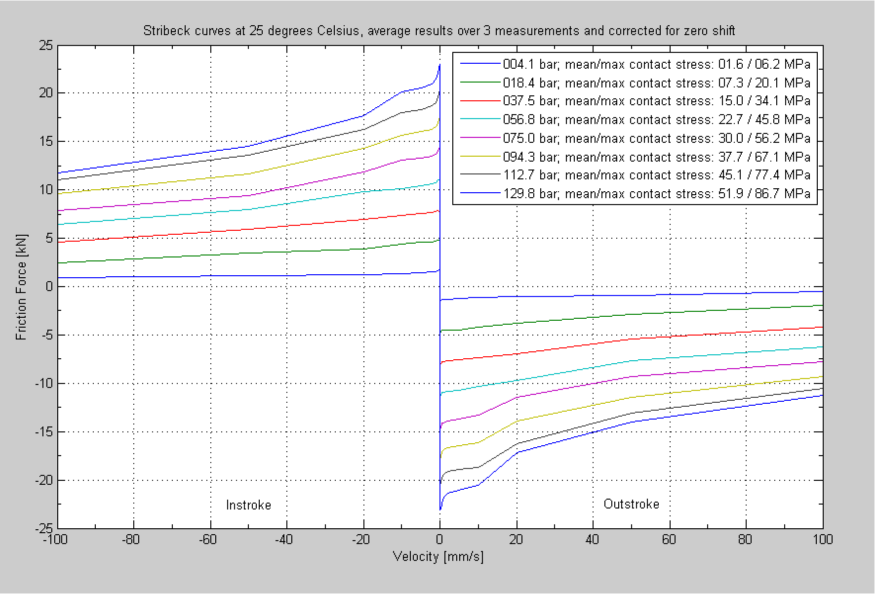



Figure 6: A Stribeck curve of BR non-standard bearing material at 0° angle, general results at 25°C

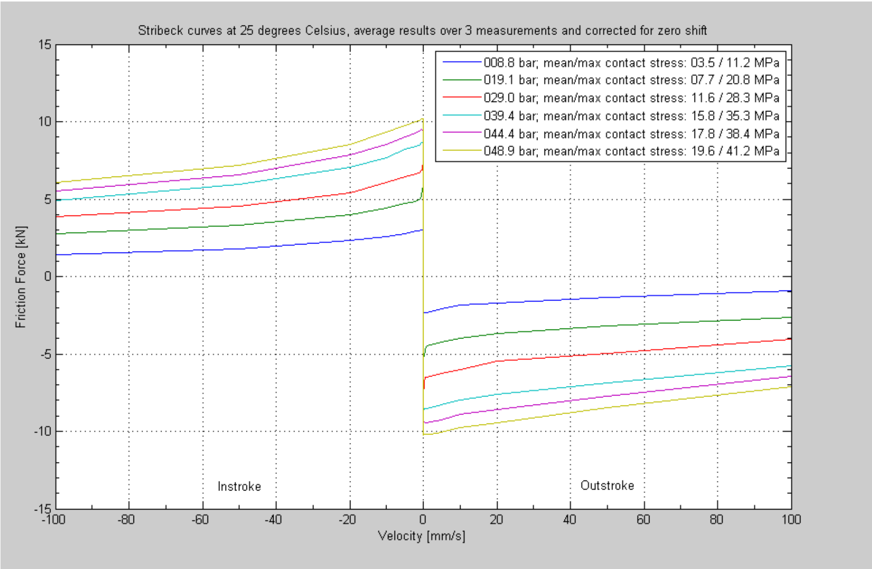



Figure 7: A Stribeck curve of BR non-standard bearing material at 1° angle, general results at 25°C

*Rexroth standard bearing select Stribeck curves*

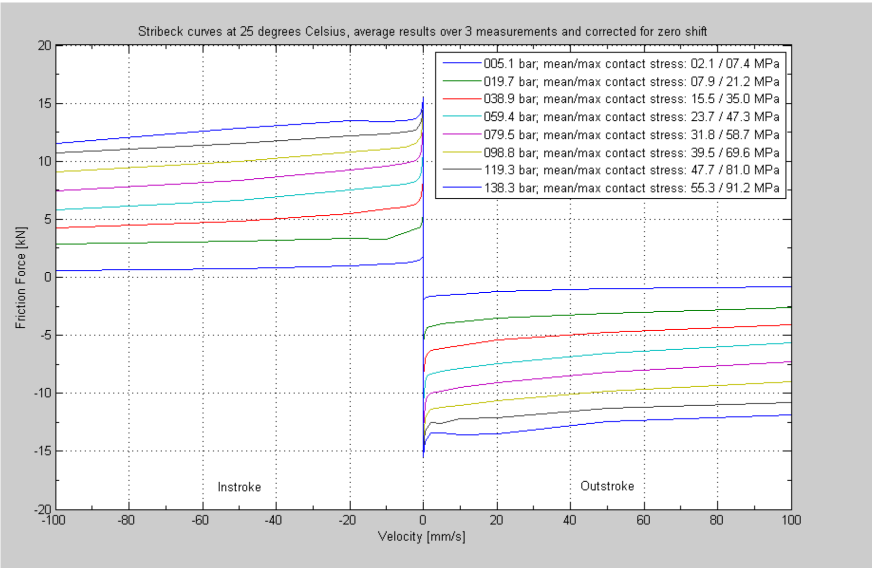



Figure 8: A Stribeck curve of BR standard bearing material at 0° angle, general results at 25°C

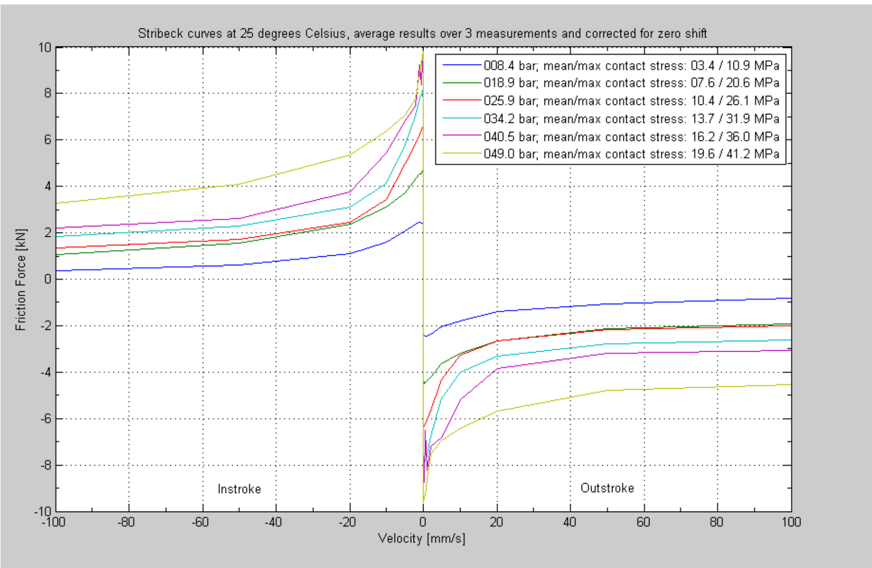



Figure 9: A Stribeck curve of BR standard bearing material at 1° angle, general results at 25°C

**Results: Stick-slip curve measurements**

Stick-slip curve measurements can show the presence or absence of stick-slip effects, and to what degree. The fluctuation in the friction line graph (circled in red) shows the presence of stick-slip phenomena.

*Sample bearing stick-slip curves*

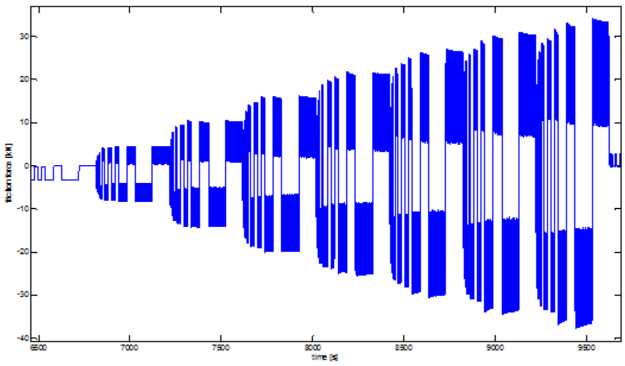



Figure 10: A stick-slip curve of BR non-standard bearing material at 0° angle

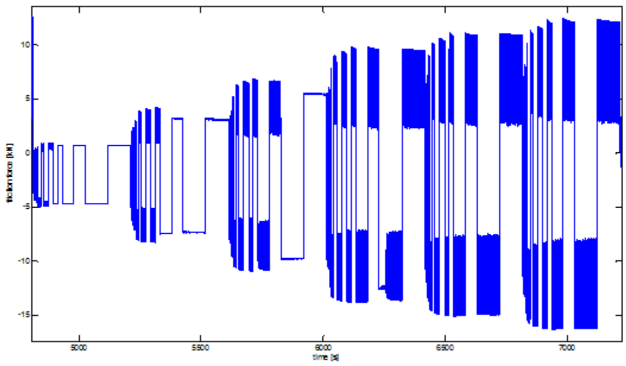



Figure 11: A stick-slip curve of BR non-standard bearing material at 1° angle

*Rexroth standard stick-slip curves*

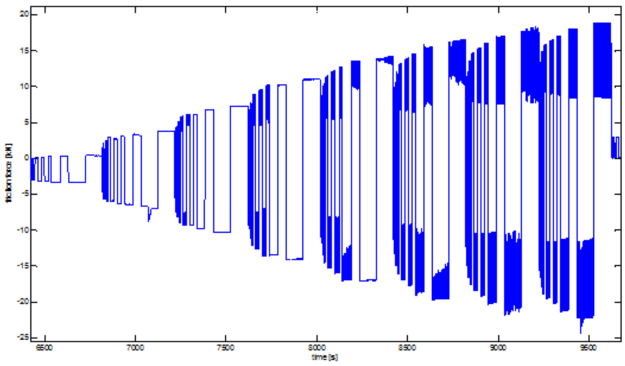



Figure 12: A stick-slip curve of BR standard bearing material at 0° angle

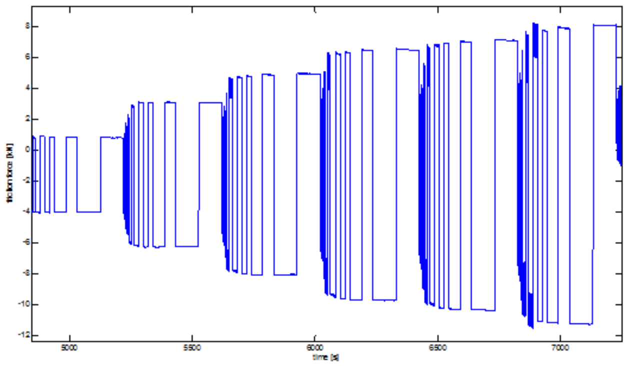



Figure 13: A stick-slip curve of BR standard bearing material at 1° angle

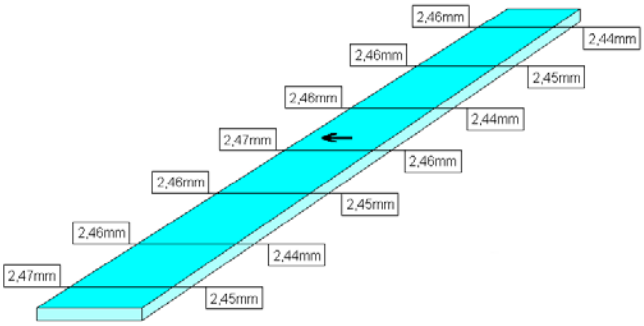
**Friction test & stick-slip measurement findings:**

- For the sample bearing, a high level of friction was measured. Stick-slip was measured over the whole flat load test range. With the test conducted at a 1° angle, the sample bearing material showed stick-slip at the lowest load.
- Maximum friction 0° angle: 38kN, 1° angle: 16kN
- For the Rexroth standard bearing: A high level of friction was measured. Stick-slip was seen over most of the flat load test range, except the lowest load. With the test conducted at a 1° angle, the Rexroth standard material only demonstrated stick-slip at the highest load.
- Maximum friction 0° angle: 22 kN, 1° angle: 11kN

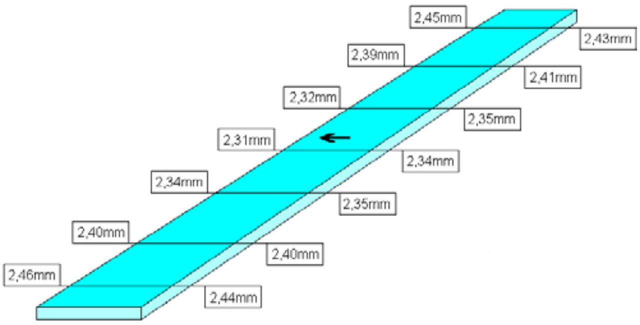
**Results: Bearing thickness measurement pre- and post-friction test**

*Sample bearing thickness*

Prior to test, Mass: 11.81 g

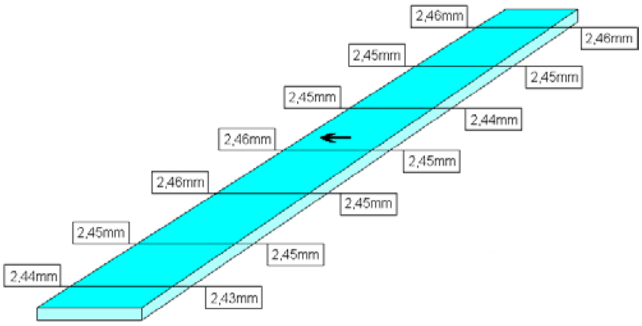



After test, Mass: 12.11 g

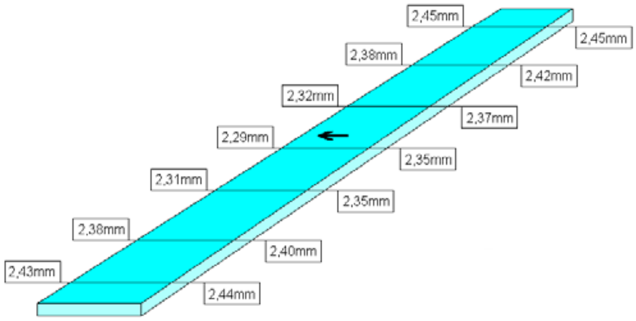



*Rexroth standard bearing thickness*

Prior to test, Mass: 12.55 g

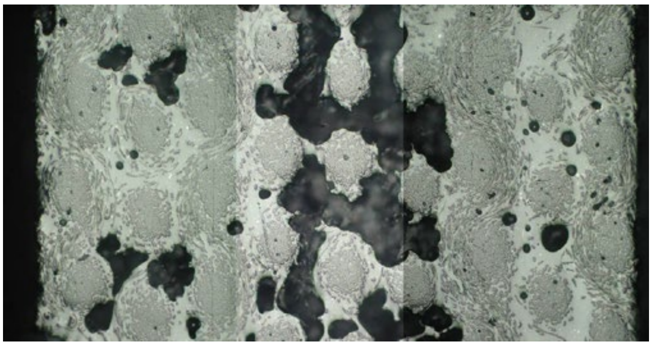



After test, Mass: 12.60 g

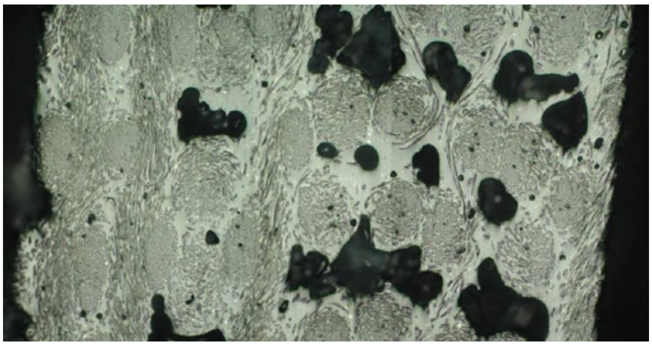


**Results: Microscopic imaging—100x magnification**

*Sample bearing imaging prior to test*

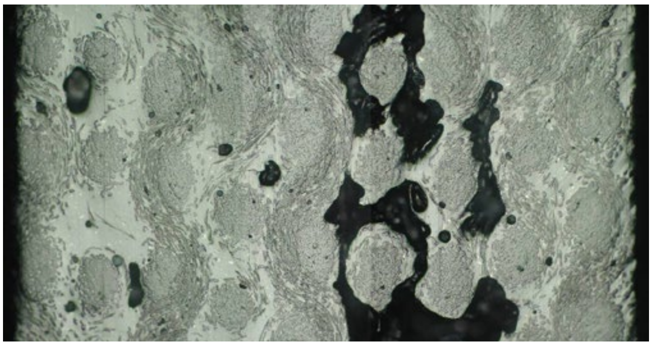


Transversal



Radial

*Sample bearing imaging post load test*



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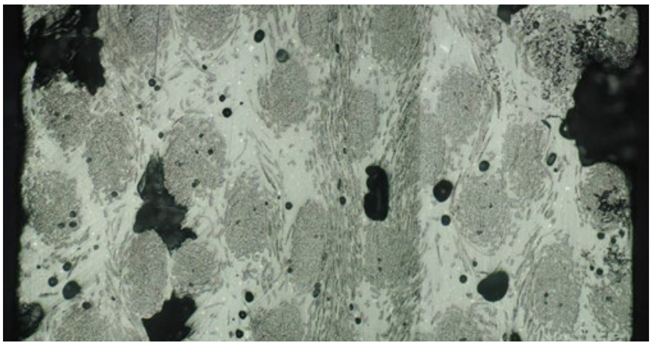
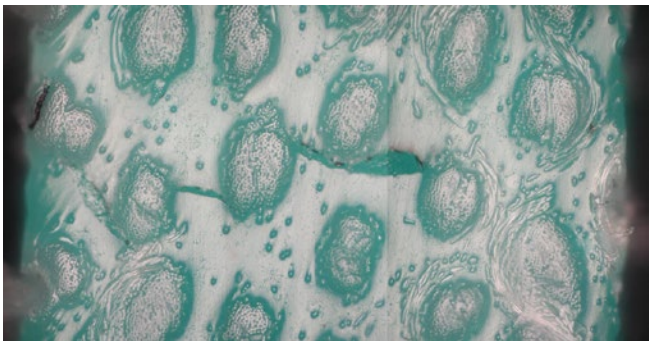
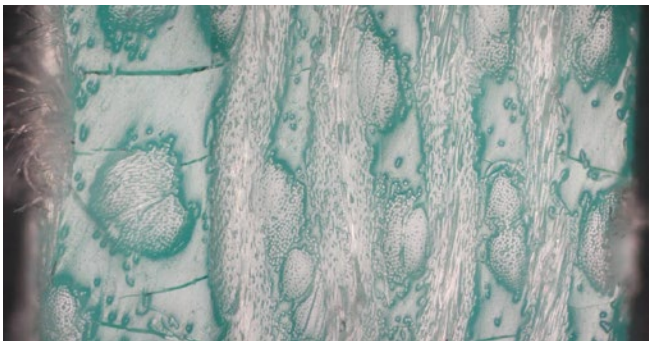


Radial

*Rexroth standard bearing imaging prior to test*

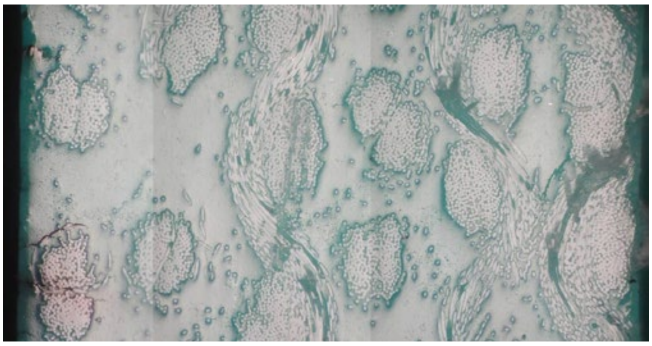


Transversal

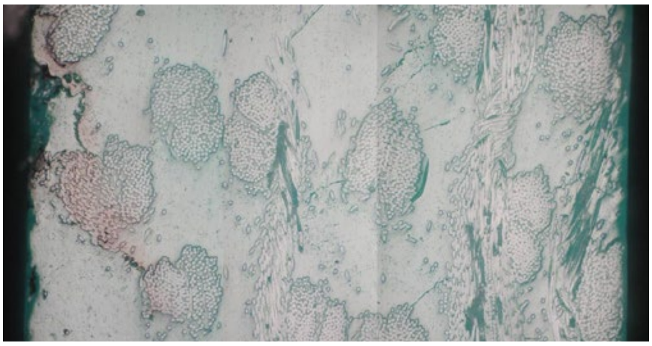


Radial

*Rexroth standard bearing imaging after load test*



Transversal



Radial

**Microscopic and thickness measurement findings**

*Sample BR non-standard bearing:*

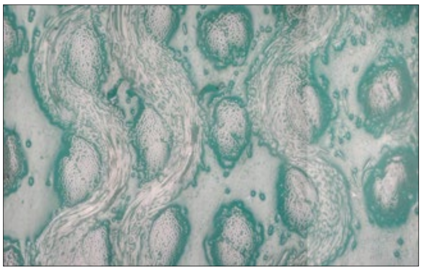
- After the test, the composite material had a deformation of maximum 0.16 mm and a few cracks.
- The structure of the tested material sample showed no cracks at the new strip; however, quite a few big air inclusions were identified with initial microscopic imaging, some of which underwent expansion after load bearing.

*Rexroth standard bearing:*

- After the test, the composite material had a deformation of maximum 0.17 mm and some cracks.
- The structure of the tested material sample had a minimum of air inclusions, but cracks were detected through post-load test microscopic imaging.
- A comparison of the microscopic imaging of the sample bearing and Rexroth standard bearing materials shows significant air inclusions in the sample bearing material, which expanded after friction testing. Although the Rexroth standard bearing material showed no evidence of air inclusions, stress cracking and some deformation was detected.

**Conclusions**

During the investigation, significant differences were observed in friction test results and in layer buildup, i.e., air inclusions and cracks. There is an indication that air inclusions will give permanent deformation under load to the radial bearing composite material, depending on the load over time. In addition, it can be seen that air inclusions and cracks will give rise to weak spots in the material.



Microscopic imaging of Rexroth bearing material after pultrusion process optimization

Also, various friction levels and differences between static and dynamic friction (stick-slip) were observed. The standard composite material used by Rexroth for LHC radial bearings did show the lowest dynamic and static friction tested under an angle; also, layer buildup was the most stable, when compared to the sample bearing composite. These findings were consistent with other sample bearing composite materials tested following the same methodology as the Rexroth standard bearing material.

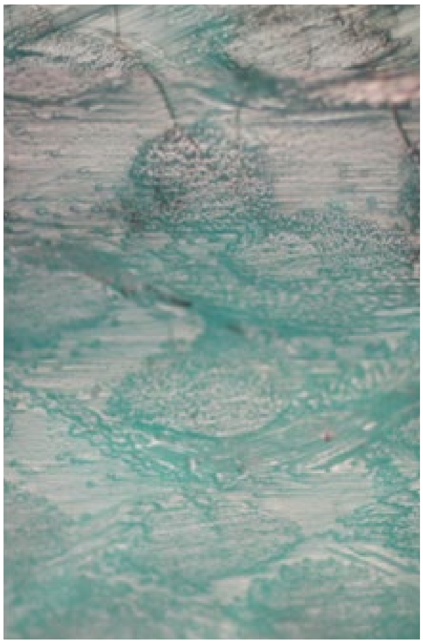
As a result, further refinements of Rexroth's standard composite bearing material were undertaken. Rexroth, in close cooperation with the supplier, optimized the pultrusion process and came to a higher standard. The goal of this optimization was reducing the cracks and air inclusions in the matrix and therefore the weak spots. This was done by adjustment of the process speed of the pultrusion process. As a result, the composite material matrix and layer structure more closely align with the optimum structure for this type of material and application.

After optimization, Rexroth performed a complete new test series including different hydraulic fluids and different life tests on a real cylinder. Imaging results of a part of the new test series are as follows:

*Cylinder test*

- Test cylinder shell diameter 200 mm/diameter rod 170 mm/ stroke 2,200 mm
- Test performed with 5% side load resulting in approx. 214.5 MPa

*Micrograph results after testing:*



After testing there are only a few small cracks present in the top of the sample where the bearing strip is exposed to the highest loads (dynamic friction, shearing and stresses). There are no air inclusions or cracks present in the material itself, which is a direct result of the optimization of the pultrusion process.

The Drive & Control Company

Rexroth
Bosch Group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