Performance Testing of Composite Bearing Materials for Large Hydraulic Cylinders

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Introduction

Large hydraulic cylinders (LHCs) 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, a major LHC manufacturer 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.

The testing provides a basis for productive consulting with bearing manufacturers to help them improve key material characteristics of the utilized bearings. This unique investment will help the LHC manufacturer optimize the operational value of its 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 respectively the cylinder shell (piston bearing), the cylinder rod (head bearing) and the bearing material.

Given its function, key bearing properties that merit consideration include:

- Compressive strength
- Shear strength
- Tensile strength
- Compressive modulus of elasticity
- Static and dynamic friction
- Temperature range of application
- Thermal expansion coefficient

The LHC manufacturer developed several testing procedures to evaluate some of these properties, with a goal of collaborating with suppliers to improve the performance of these bearings.

Friction response of composite bearing material

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

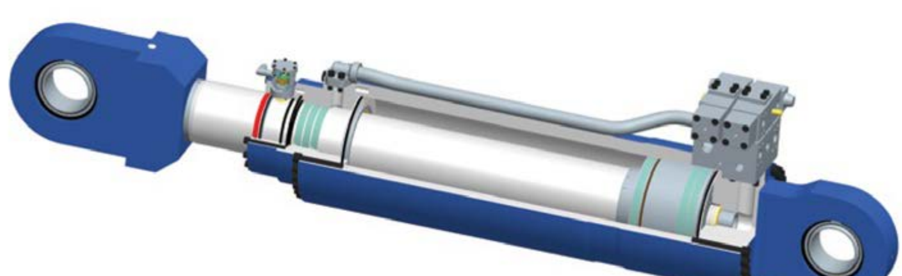


Figure 1 Location of radial bearings and seals in a hydraulic cylinder.

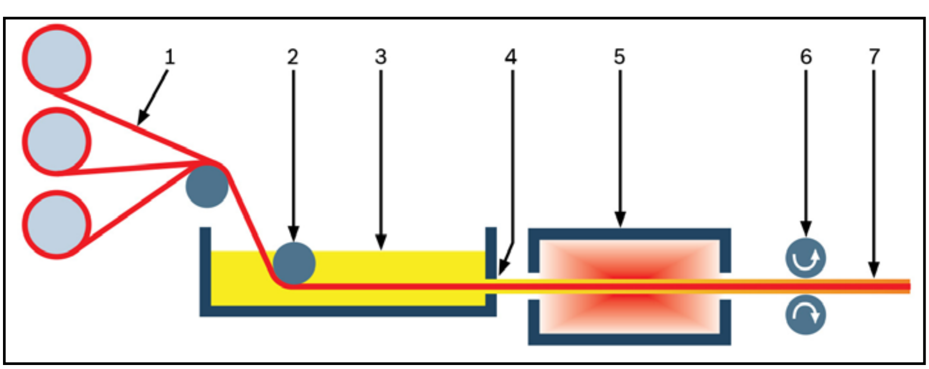


Figure 2 The key steps in the pultrusion process include: 1) continuous roll feed of reinforced fibers/woven fiber mat; 2) tension control roll; 3) resin impregnator bath; 4) resin-soaked fiber; 5) bearing die and heat source; and 6) fiber pull mechanism.

composite materials. These 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.

Bearing pultrusion production process

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 discussed in this article 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 (Fig. 2).

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)
- Distance of the different layers of fabric in the resin bath
- Pulling forces on the fabric during the process
- Incorrect curing time and/or temperature
- Post-curing process errors

Bearing Performance Investigation

A standard testing methodology was developed in order to investigate key radial bearing properties. Composite bearing samples from several suppliers were tested and analyzed, along with a standard composite bearing material currently used by the LHC manufacturer and created to the company's specifications.

The following tests were carried out:

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.

Friction test: This test is conducted to generate a Stribeck curve (Figs. 3–10), 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.

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.

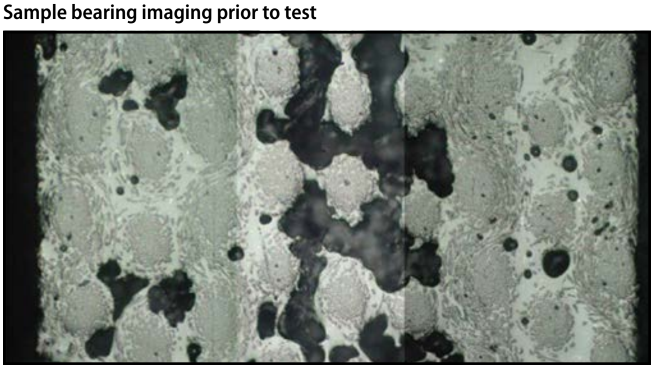
Step1 — microscopic imaging. Cross-sections were made both in the length and width direction of the radial bearing. The micrographs capture visual data related to the stresses that composite bearing material can undergo and the possible effects of those stresses, such as microscopic cracks, shearing of the different layers and deformation of the material.

Micrographs also image air enclosures in the material, which can contribute to weakening the integrity of the resin-impregnated material.

The radial bearings were cut with great care and cooling water was used to keep the material temperature low, so that the bearing structure was not

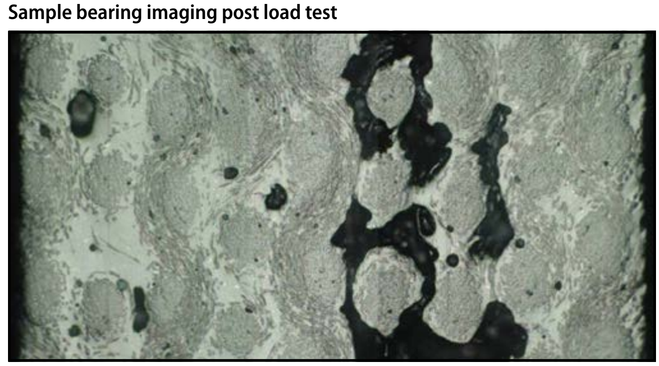
Results: Microscopic imaging—100× magnification

Sample bearing imaging prior to test



Transversal

Sample bearing imaging post load test



Transversal

LHC manufacturer standard bearing imaging prior to test

Transversal

LHC manufacturer standard bearing imaging after load test

Transversal

damaged. An image was made of the cross section with an optical microscope with a magnification of 100.

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.

Sample micrographs are presented below, comparing a sample of the LHC manufacturer's standard composite bearing material with bearing material provided by another manufacturer of composite bearings. Pre-friction testing and post-friction testing micrographs are shown for both.

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.

A special test rig was created, consisting of a cylinder rod which is driven by an electrical screw spindle. A bearing strip was 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 1 kHz. The test program was programmed in *LabVIEW* and was executed fully automatically.

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
	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.

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 shows the presence of stick-slip phenomena.

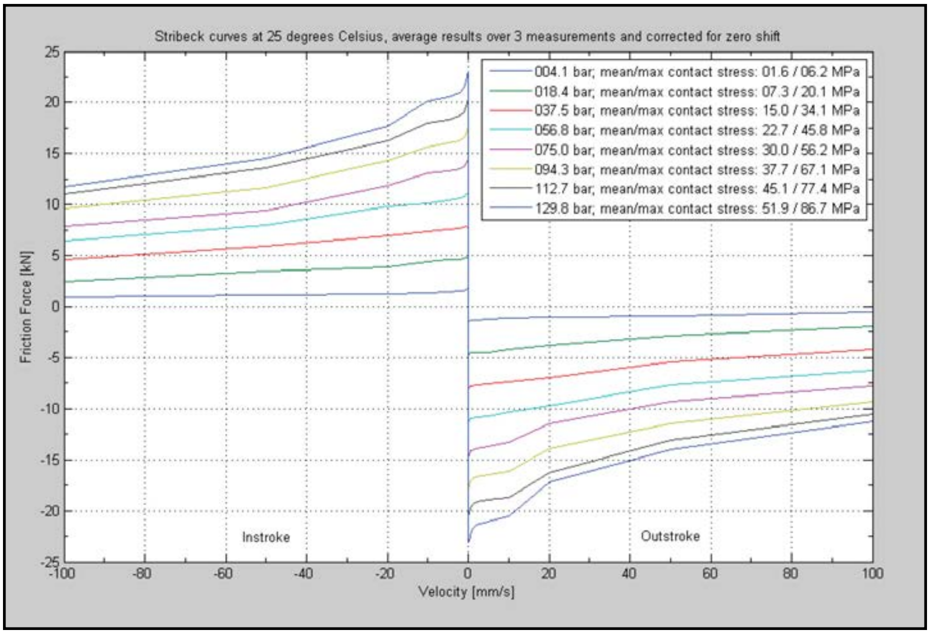


Figure 3 A Stribeck curve of supplier sample bearing material at 0° angle, general results at 25°C.

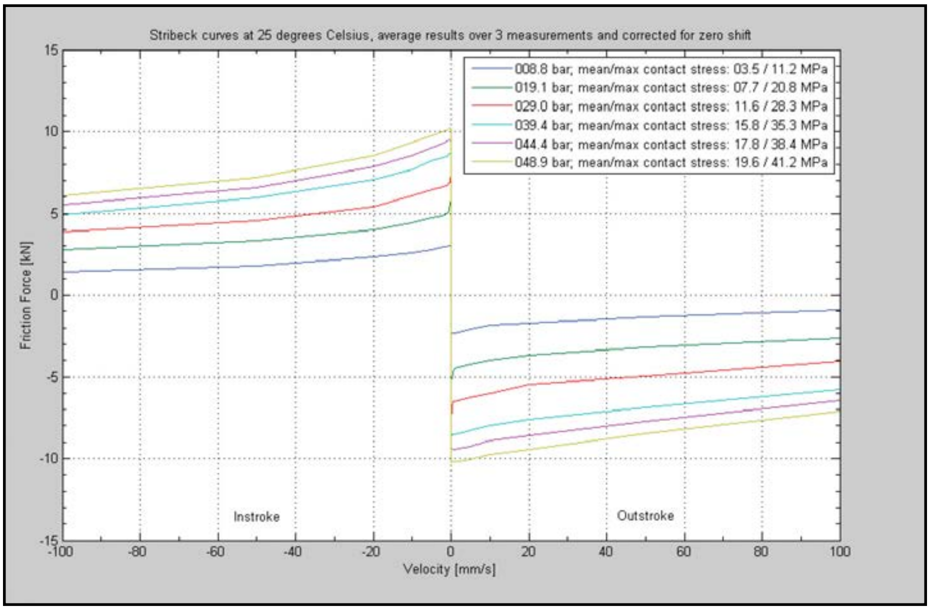


Figure 4 A Stribeck curve of supplier sample bearing material at 1° angle, general results at 25°C.

Friction test and stick-slip measurement findings:

- For the supplier-provided sample composite bearing material, 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: 16 kN
- For the LHC manufacturer's standard composite bearing material, a high level of friction was measured. Stick-slip was seen over most of the flat load test range — excepting the lowest load. With the test conducted at a 1° angle, this sample only demonstrated stick-slip at the highest load.
- Maximum friction 0° angle: 22 kN, 1° angle: 11 kN

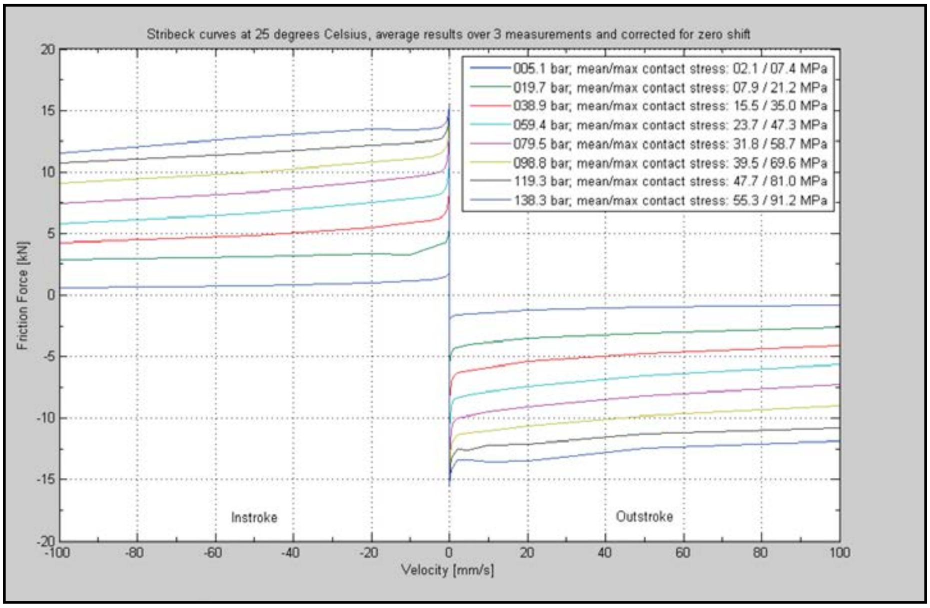


Figure 5 A Stribeck curve of LHC manufacturer standard bearing material at 0° angle, general results at 25°C.

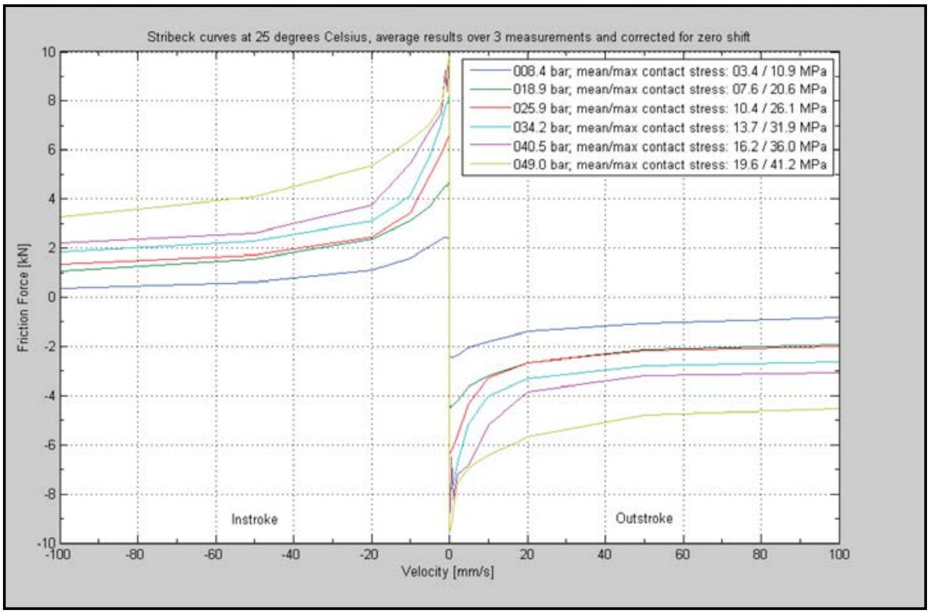


Figure 6 A Stribeck curve of LHC manufacturer standard bearing material at 0° angle, general results at 25°C.

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 shows the presence of stick-slip phenomena.

Supplier sample bearing stick-slip curves

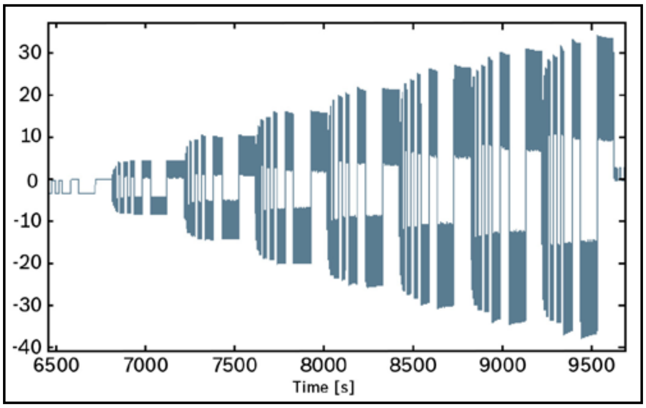


Figure 7 A stick-slip curve of BR non-standard bearing material at 0° angle.

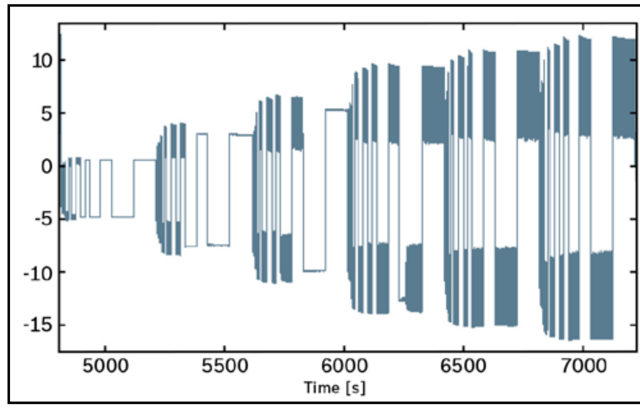


Figure 8 A stick-slip curve of BR non-standard bearing material at 1° angle.

LHC manufacturer standard stick-slip curves

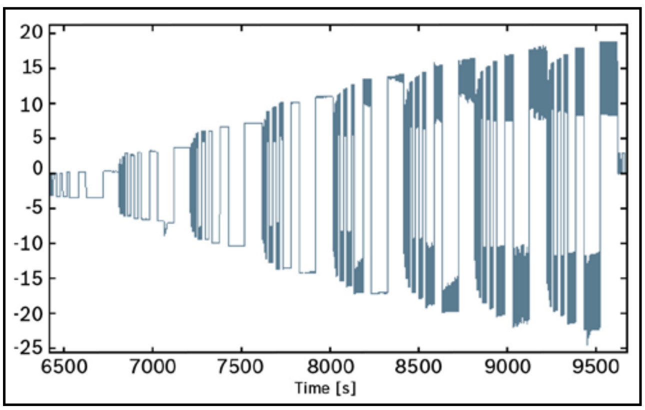


Figure 9 A stick-slip curve of BR standard bearing material at 0° angle.

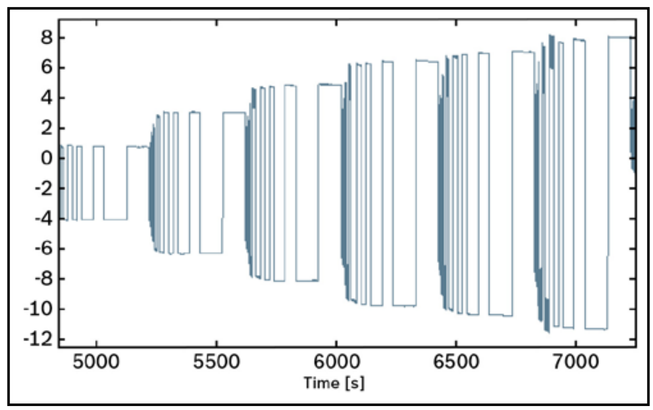
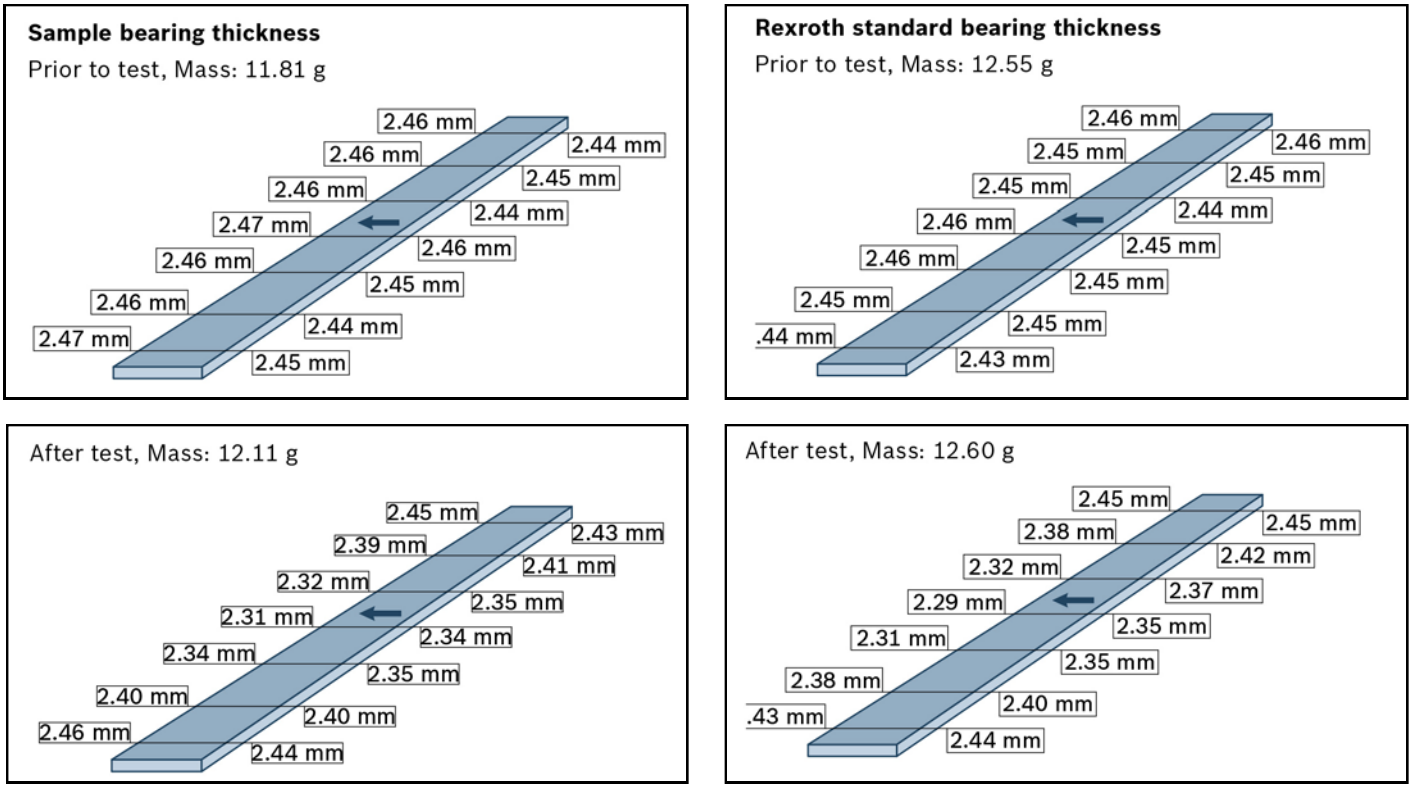


Figure 10 A stick-slip curve of BR standard bearing material at 1° angle.

Friction test and stick-slip measurement findings:

- For the supplier-provided sample composite bearing material, 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 LHC manufacturer's standard composite bearing material, 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, this sample 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



Conclusions

During the investigation, significant differences were observed in friction test results and in layer buildup, i.e., air inclusions and cracks, between the LHC manufacturer's bearing material and the supplier's. There is an indication that air inclusions will give permanent deformation under load to the 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.

Various friction levels and differences between static and dynamic friction (stick-slip) were observed. The LHC manufacturer's composite materials showed the lowest dynamic and static friction tested under an angle; also, layer buildup was the most stable when compared to the supplier's sample.

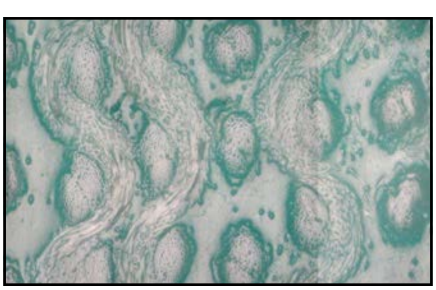


Figure 11

As a result, the LHC manufacturer undertook further refinements of its composite bearing material. The company also invested time and engineering resources to collaborate with the bearing supplier to optimize the pultrusion process. Improvements were made to help reduce cracks and air inclusions in the matrix and, therefore, the weak spots. This was done by adjusting the pultrusion process speed, yielding composite material matrix and layer structure that more closely aligns with the optimum structure for this type of material and application.

After optimization the LHC manufacturer performed a new test series including different hydraulic fluids and different life tests on a working LHC. Imaging results of a part of the new test series demonstrated improved performance.

It can be seen in (Fig. 12) after testing that only in the top, where the bearing strip is exposed to the highest loads (dynamic friction, shearing and stresses), are a few small cracks visible. In the material itself no air inclusions or cracks were present, which is a direct result of the optimization of the pultrusion process. **PTE**

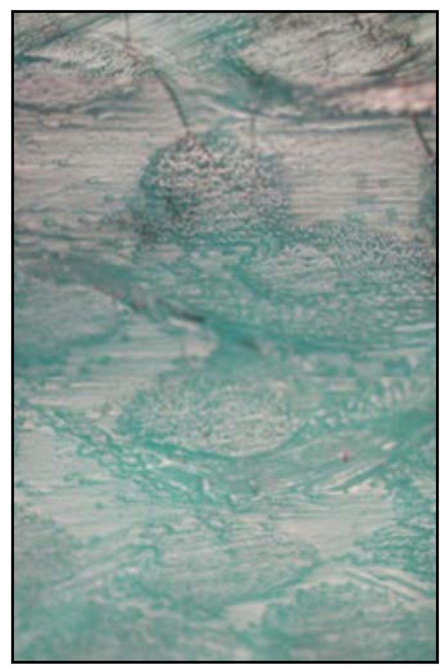


Figure 12

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