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# Wear-in behaviour of polycrystalline diamond thrust bearings

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ABSTRACT

Polycrystalline diamond (PCD) bearings are designed for use in harsh environments, including process-fluid-lubricated applications such as those in oil and gas drilling turbines. This paper discusses the wear-in behaviour of polycrystalline diamond thrust bearings. Laboratory test results are presented that show the roughness, profile, and coefficient of friction of the polycrystalline diamond wear pads as the wear-in of the polycrystalline diamond bearings progresses. Laboratory test results show a significant decrease in the surface roughness and a change in the profile of the wear pads. Measured values of the coefficients of friction reveal that the lubrication regime of PCD thrust bearings can move from boundary to mixed-mode and may even become hydrodynamic after wearing-in for a period of time under the right conditions. This mechanism can provide extended life for PCD thrust bearings in harsh environments.



## 1. Introduction

Diamond thrust bearings are comprised of annular rings populated with flat polycrystalline diamond (PCD) pads or inserts that run against one another to carry thrust loads. These bearings are often applied in down-hole drilling tools such as drilling turbines to capture the thrust created when a portion of the flow energy of the drilling fluid is transformed into rotary motion to power the drill bit. Bearing surface speed can be zero to 6.5 m/s and specific loading can range from zero to 70 MPa. The lubricant is most often the drilling fluid, which can either be water or petroleum based.

A suite of tests was conducted to understand the performance of these bearings during wear-in. Because the bearing wear pads are PCD, they possess extraordinary thermal and mechanical properties which lead to favourable wear-in characteristics. The friction measured was indicative of boundary lubrication slowly giving way to friction values that can only be explained by mixed-mode lubrication. This process seems to be governed by the ever-improving surface finish of the diamond as it wears in.

The fact that these bearings can operate in mixed-mode lubrication explains how it is often possible to achieve a bearing life of several thousand hours in drilling turbines. The advantage of diamond thrust bearings being that both boundary and mixed-mode lubrication suites them well.

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## 2. Polycrystalline diamond fluid-film bearings

PCD is formed by subjecting diamond grit to high temperature, 1500 °C, and pressure, circa 6 GPa, in the presence of a group VIII metal catalyst in a high-temperature, high-pressure press. The diamond grit is typically placed adjacent to a tungsten carbide (WC) substrate that provides a source for the catalyst metal and a structure upon which the PCD is formed. Under sintering conditions, which are similar to those used to synthesize diamond, the diamond grains grow together in the presence of the catalytic metal which infiltrates from the WC substrate. The sintered diamond forms a diffusion bond with the WC. The resulting material is a diamond cemented PCD structure with metal catalyst remnants distributed through the pore space which is approximately 10% by volume. Fig. 1 is a micrograph of a typical PCD structure that has been cut and polished. Fig. 2 shows a typical PCD compact. For the tests presented in this paper, the PCD is 2.0 mm thick and the WC substrate is 5.8 mm thick.

To improve the thermal stability of PCD, a portion of the residual catalyst may be removed prior to use. One example of this is PCD for use in oil and gas drill bits. The PDC inserts used in the test bearings discussed in the paper did not have the catalyst removed.

Conventional hydrodynamic bearings are typically constructed using one of four pad geometries: 1) tapered pads, 2) tilting pads, 3) spring-supported pads, and 4) stepped pads. These pad geometries contribute to the pumping action that generates the oil-film pressure between the opposing bearing surfaces [1]. PCD thrust bearings, on the other hand, are typically comprised of cylindrical pads, with the top of each PCD pad forming a planar bearing surface. This bearing surface is lapped to a roughness of approx-

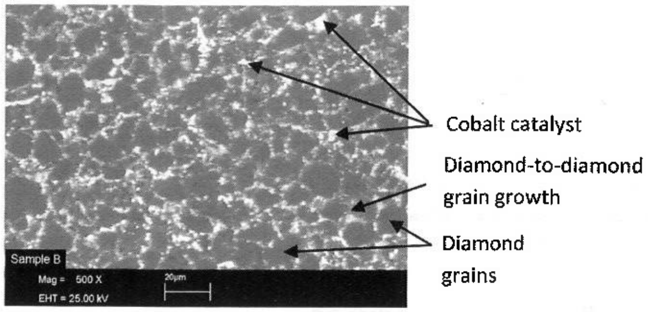


**Fig. 1.** Scanning Electron Microscope (SEM) micrograph of PCD at 500X magnification.

imately 1.0 μm arithmetic mean roughness (Ra). Although each pad commonly has a 45 degree bevel around its top edge, there is no stepped or tapered land normally machined in the PCD wear pads. In other words, the surfaces are flat and there is no physical wedge.

PCD is well suited for bearing applications for several reasons. First, PCD is extremely hard, making the bearing surfaces resistant to damage from foreign particles. Second, as will be shown in this paper, PCD bearings can operate in boundary, mixed-mode and hydrodynamic lubrication regimes. Even in low-speed, high-load applications where the PCD surfaces are operating in the boundary lubrication regime, they exhibit wear rates that allow the bearings to operate for well over one thousand hours [2]. Third, the high thermal conductivity of PCD allows heat to be quickly diffused away from the points of contact, thus reducing the potential for thermal damage on the bearing surfaces. Finally, PCD bearings have the ability to improve their surface finish during operation. Results from tests summarized in this paper show that the surface finish of PCD bearings improves from 1.0 to 0.10 μm Ra in a period of 72 hours. It will be shown below that this wearing-in process results in what is believed to be mixed-mode/fluid-film development. This is significant because PCD bearings do not require expensive processes to finish the bearing surfaces to the flatness and surface finish requirements usually necessary in hydrodynamic bearings.

## 3. Bearings test set up

Fig. 3 shows a test bearing assembly, which consisted of one rotating and one stationary bearing ring. Both bearings rings were comprised of a circular array of cylindrical PCD wear pads set at a pitch circle of 59.7 mm. The wear pad diameter was 13.4 mm. The rotating and stationary rings contained 11 and 12 PCD wear pads, respectively. These wear pads were brazed into equally spaced pockets in their respective rotating and stationary stainless steel carrier rings.

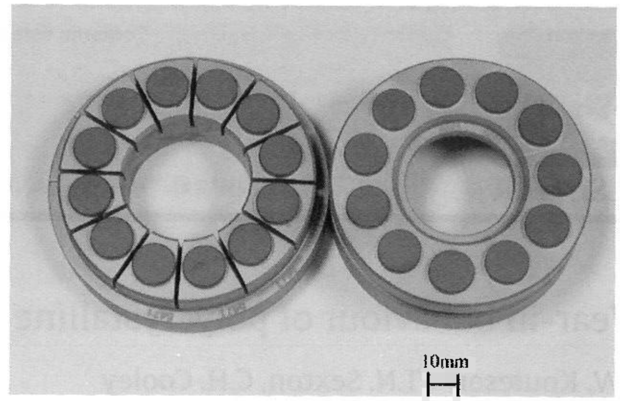


**Fig. 3.** PCD thrust bearing test sample.

All thrust bearing tests were conducted in the test apparatus illustrated in Fig. 4. The thrust bearing assembly was surrounded by a test chamber which served to retain the bearing cooling and lubricating fluid. Fluid entered the test chamber at location "A" through the stationary bearing ring and flowed around the individual PCD bearing wear pads on both bearing rings before exiting the chamber at location "B". In the process of flowing through the chamber, the fluid filled the chamber and completely submerged the bearings. All tests were conducted using Paratherm MR high-temperature heat transfer oil as the coolant (Paratherm Corp., West Conshohocken, PA).

An axial load was applied to the stationary bearing by a hydraulic ram as indicted by force "F" in Fig. 4. An electric motor provided the rotation to the rotating bearing. Friction coefficients were determined from torque values measured in a torque cell that was situated directly behind the stationary bearing. This torque cell had an uncertainty of approximately 9.7 N-m, resulting in uncertainty in the calculated friction coefficient of 0.005.

All tests were conducted using a constant sliding speed of 2.0 m/s (640 rpm). An axial load of 65 kN was applied for a period of 22 hours. The total test duration was 24 hours including a one hour loading up-ramp and a one hour loading down-ramp both ramps were linear. Friction coefficients were monitored during the up and down ramps to check for sudden friction anomalies, none were observed. Given a contact area of 933 mm$^2$, the specific loading at 65 kN was 69.9 MPa. The tests were conducted at a flow rate of 18.9 l/min, with a bulk fluid temperature of approximant 19 °C.

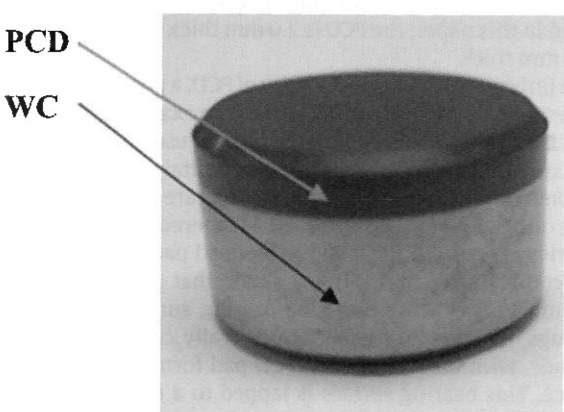


**Fig. 2.** PCD Compact.

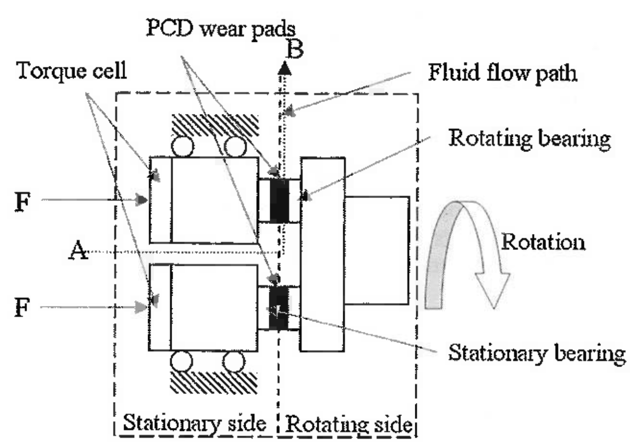


**Fig. 4.** Schematic of thrust bearing test apparatus.

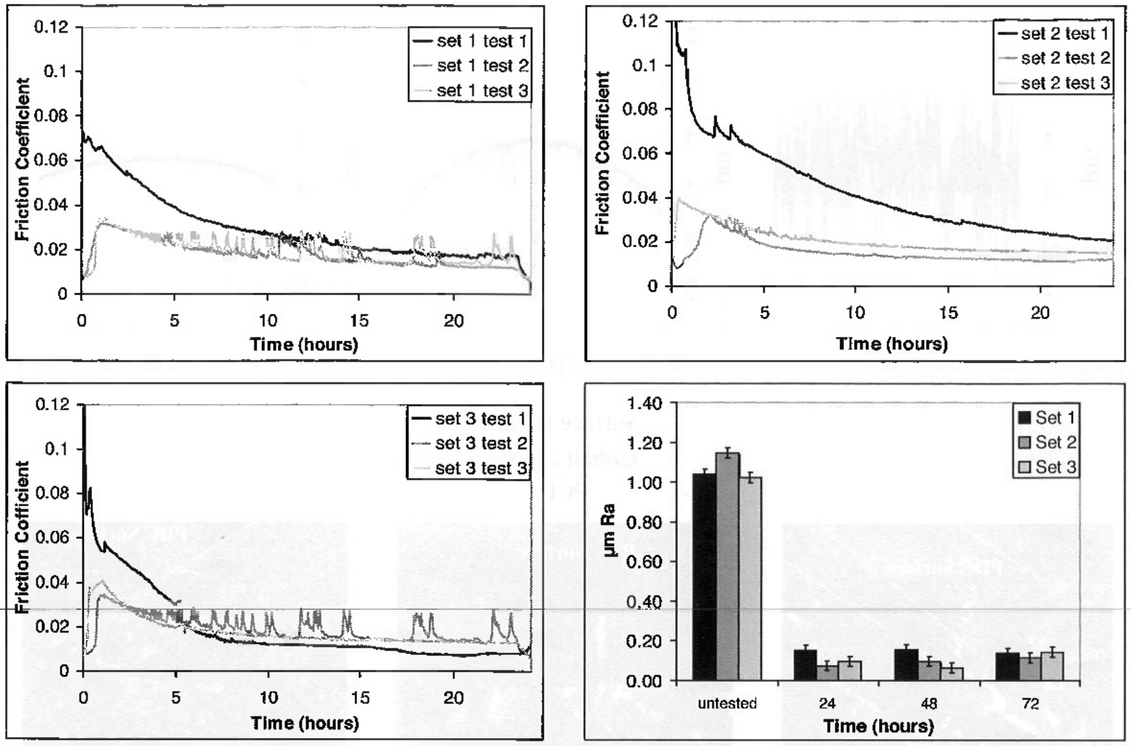


**Fig. 5.** Bearing coefficient of friction as a function of time for (a) test set 1, (b) test set 2, (c) test set 3. 4(d) shows the roughness measured before testing and after each test.

The published data for the heat transfer fluid reports a viscosity of 0.0074 Pa-s at 19 °C.

Each of the three bearing sets was tested three consecutive times, resulting in a total run time of 72 hours for each test set. Before and after each test, the bearing surface roughness and profile were measured using a profilometer. Following testing, one bearing was sectioned and polished for scanning electron microscope (SEM) evaluation. An untested laboratory bearing was also sectioned and polished for SEM evaluation.

In addition to laboratory bearing samples, a field worn bearing from a drilling turbine was evaluated. This bearing had operated down-hole under a variety of loads and speeds for approximately 1000 hours. The surfaced finish and profile of this bearing were measured and the bearing was sectioned and polished for SEM evaluation.

## 4. Results

Fig. 5(a)–(c) shows the friction coefficient as a function of time for the three tests conducted on each bearing set. Fig. 5(d) contains the surface finish values measured before testing and after each of the three tests for each bearing set.

Fig. 6 shows macro photographs of bearing pad surfaces for untested, laboratory tested, and field-worn bearings.

Profile results for the untested bearing, laboratory bearing, and field-worn bearing can be seen in Fig. 7.

Figs. 8 and 9 contain SEM images and optical images, respectively, of the untested bearing, tested bearing, and field-worn bearing. It should be noted that the diamond grain size in the untested and laboratory tested PCD bearings was larger than the grain size of the PCD used in the field worn bearing.

## 5. Discussion of results

As shown in Fig. 5, the friction coefficients in the beginning of the first test in each set were in the range of 0.05 to 0.11. These values are similar to those reported by Feng [3] for natural diamond lubricated with air, water, and liquid paraffin and by Cook [4] for PCD bearings lubricated in drilling mud. Referring to Figs. 6(a), 8(a), and 9(a), the surface topography of the untested

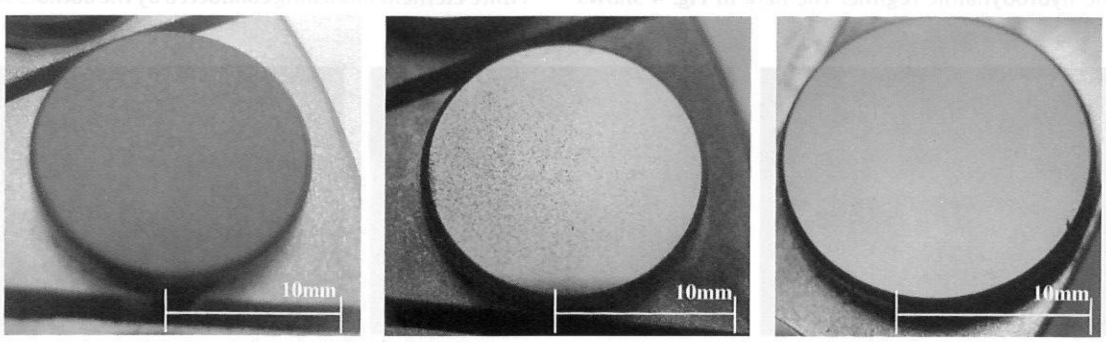


**Fig. 6.** PCD wear pad with (a) no test time, (b) 72 hours of test time (c) 1000 hours field run time.

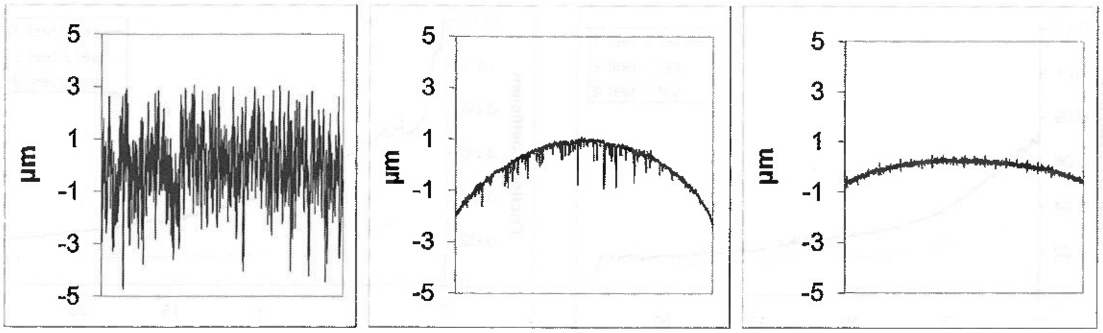


**Fig. 7.** PCD wear pad profile measured on a radial line over the entire diameter of the PCD wear pads of (a) untested bearing, (b) tested bearing, (c) field-worn bearing.

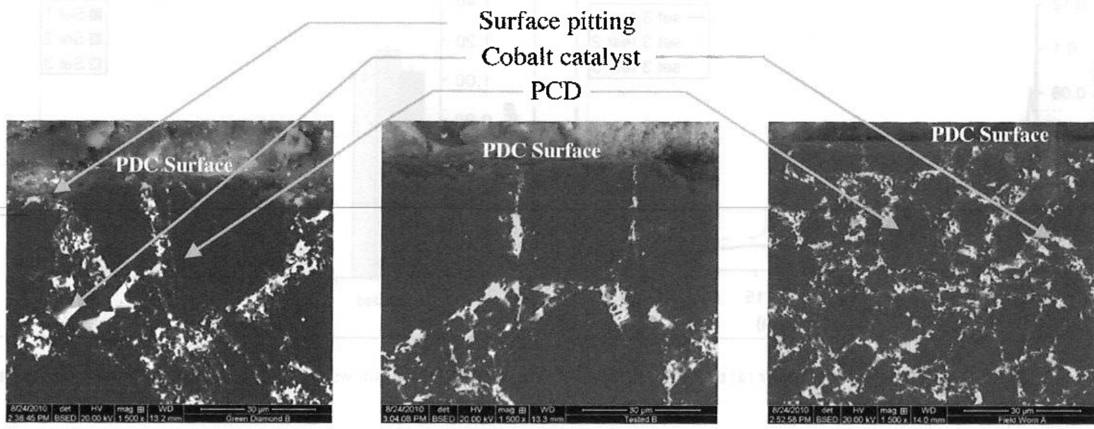


**Fig. 8.** SEM image at 1500X magnification of cross-sectioned PCD inserts from (a) untested bearing, (b) laboratory tested bearing, (c) field worn bearing.

bearings is relatively rough (approximately 1.0 μm Ra) and appears to be consistent with the high friction coefficients measured. During this early wear stage, asperity contact is occurring between the opposing PCD faces. At the points of contact, high temperatures result in graphitization or oxidation of the PCD as explained by Lin [5]. He hypothesized that this leads to smooth wear of the PCD surface. Hibbs [6] suggests that microchipping, where small flakes of individual diamond grains break from the surface, is also a possible mechanism in PCD wear. Although we did not specifically measure or observe either of these mechanisms we believe that the smooth wear is caused by one or both.

Referring to Fig. 5, the friction coefficients are significantly reduced in the first test of each set. The friction in the second and third test in each set is also lower initially and continues to decrease over time. Figs. 6(b), 8(b), and 9(b) show a visual improvement in surface finish after the completion of three laboratory tests totalling 72 hours. Measured surface finishes in these samples was between 0.10 and 0.14 μm Ra. According to Khonsari [1], friction coefficients of 0.001 are typical of conventional fluid-film bearings operating in the hydrodynamic regime. The data in Fig. 4 shows friction coefficients as low as 0.015. Tests were conducted by the authors [7] to generate Stribeck curves using the bearing geometry and lubricating fluid listed in this paper. These tests indicated that hydrodynamic lubrication occurs in PCD bearings at a friction coefficient of approximately 0.01. Based on this, it appears that the bearings in these tests could have been operating in the mixed mode and very close to hydrodynamic. This is significant because standard hydrodynamic bearings are not usually operated in mixed mode due to the damage that may occur to the opposing bearing surfaces. PCD bearings, however, operate effectively in both hydrodynamic and mixed modes.

As the tests progress, material removal continues to occur, albeit at a slower rate, and the resulting surface finishes becomes finer and finer. The most likely mechanism would be that described by Lin[4] where minute quantities of diamond, perhaps even on an atomic scale, are removed as a result of surface heating, which in turn leads to oxidation or graphitization of the diamond. Although the thermal conductivity of PCD is high, the temperature at the asperities may still reach the levels were graphitization of diamond occurs. Finite element modelling conducted by the authors showed surface

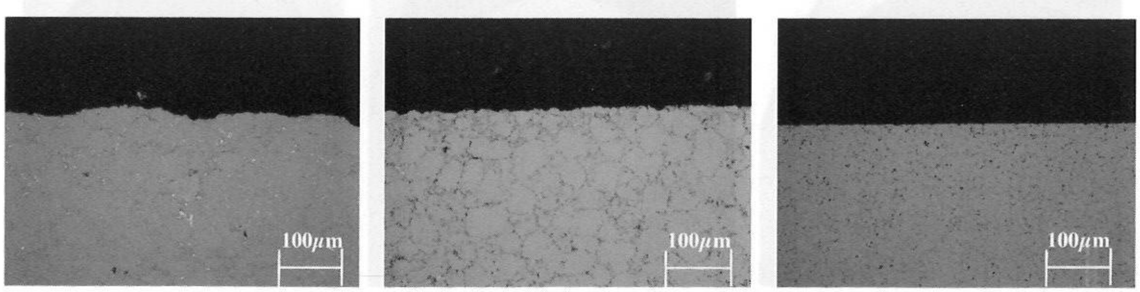


**Fig. 9.** optical image at 200X magnification of cross-sectioned PCD inserts from (a) non-tested bearing, (b) laboratory tested bearing, (c) field-worn bearing.

temperatures of approximately 300 °C under operating conditions similar to those used in these tests. Our finite element method, however, would not account for the higher temperature levels at the asperity contacts.

Fig. 6(c) shows the surface of a field-worn PCD pad. The surface finish of this pad is visually better than the surface finish of the untested and laboratory tested pads. The measured finish on this pad is 0.044 μm Ra, compared to the average value of 0.12 μm Ra on the laboratory tested bearing. This is likely explained by the approximately 1000 hours of service that the field-worn bearing underwent, compared to a total test time of 72 hours for the laboratory tested bearing. Longer operating time would most likely allow the PCD surface of the laboratory tested bearing to improve to a finish comparable to the field-worn bearing. The SEM and optical images shown in Figs. 8(c) and 9(c) of the sectioned field-worn bearing pad show a very smooth surface that is devoid of pits associated with the lapping process that are visible in the untested and the laboratory tested bearing.

Based on the SEM and optical microscopy analysis it is likely that the same material removal mechanisms that are operative in the laboratory are also at work during use of these bearings in the field.

Another observation made was that the profile of the individual pads changed over the duration of the test. Referring to Fig. 7(a), the surface of the untested bearing, although rough, was relatively flat. The surface of the tested bearing and field worn bearing shown in Fig. 7(b) and (c), on the other hand, have worn into a dome-like geometry. The magnitude of the height of the dome-like surface is approximately 3.0 μm in the laboratory tested pad and about 1.0 μm in the field-worn pad. Finite element analysis modelling has been conducted by the authors in an effort to predict the deformation in PCD bearings associated with frictional heat generation. Results of this modelling show a slight cupping of the PCD insert. During initial operation, the temperature of the PCD inserts increases. Differences in the thermal expansion coefficients of the PCD and the underlying tungsten carbide substrate result in residual stresses that cause a cupping-like deformation. The cupped surface would then preferentially wear on the outer edge of the PCD insert until the surface essentially becomes flat. As the surface finish of the PCD improves, frictional heat generation is lessened and there is some fluid film development. Consequently, the overall temperature of the PCD is reduced, deformation due to the residual stresses is lessened, and the now flat surface becomes dome shaped. Although it has not been proven, it may be possible that this dome-like surface acts as a "wedge" and helps contribute to the development of the fluid film.

## 6. Conclusions

As PCD bearings wear in, their surface finish improves, making it possible for them to transition from boundary to mixed-mode lubrication. It may even be possible to develop full fluid-films in these bearings given the appropriate break-in and operating conditions.

Operating in the mixed-mode or hydrodynamic regimes allow the bearings to generate less heat, resulting in more efficient operation, less wear, and longer life. This may help explain bearing life of over 3000 hours observed in oil and gas turbine drilling applications.

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