

Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Short communication

Polycrystalline diamond thrust bearings for down-hole oil and gas drilling tools

T.N. Sexton*, C.H. Cooley

US Synthetic Corporation, 1260 S. 1600 W., Orem, UT 84058, USA

ARTICLE INFO

Article history:

Received 6 September 2008

Received in revised form 5 January 2009

Accepted 5 January 2009

Keywords:

Polycrystalline diamond

PCD

Thrust bearings

Down-hole drilling tools

ABSTRACT

Down-hole tools used for drilling oil and gas wells are subjected to harsh environments where abrasive fluids, high loads and speeds, and high temperatures can cause tool components, including thrust bearings, to quickly fail. This paper discusses the advantages that polycrystalline diamond can provide when used as a bearing material in down-hole tools. Laboratory test results are presented that can be used to help predict the performance of polycrystalline diamond bearings in these down-hole applications. Results from two types of tests are presented including tests that measure bearing capacity and those that evaluate diamond bearing wear rates. Bearing failures, generated during laboratory testing, are discussed. These failures are very similar to those observed in down-hole drilling tools and indicate that thermal damage to the polycrystalline diamond structure is the main cause of bearing failure. Bearing wear rates measured during laboratory testing show that polycrystalline diamond thrust bearings can provide a long-lasting bearing solution for down-hole drilling tools.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Drilling for oil and gas makes use of drilling tools located in the drilling string. Their purpose is varied and includes such functions as providing rotation to the bit (mud motors and turbines), guiding the bit and string along a predetermined path (rotary steerable systems), making relevant rock formation property measurements, measuring drill string vibration, etc. These tools are subjected to the severe environment of the well bore deep in the earth near a vibrating drill bit.

Drilling tools frequently have moving parts that require the support of bearing systems. Traditional bearings are used but must be sealed from abrasive drilling fluids which makes implementation complicated. Drilling fluid-lubricated and cooled bearings, on the other hand, can be implemented with relatively simple design. Synthetic Polycrystalline Diamond (PCD) used in mud-lubricated bearings has proven to be durable, capable of extremely high loads and speeds, and able to deliver significantly longer life than other bearings. However, only limited data has been published about diamond bearing performance.

Crompton et al. [1] investigated the coefficient of friction and wear rates of natural diamond against itself and other materials. Mehan [2] looked at the wear performance of PCD using pin-on-disk experiments. He measured wear rates, investigated wear mechanisms, and concluded that wear of PCD was the result of individual diamond particles being dislodged from the composite diamond

structure. Keshavan et al. [3] and Cook [4] tested PCD bearings with an emphasis on determining friction and wear of PCD in thrust bearings. Since these papers were written, considerable progress has been made in improving polycrystalline diamond materials. The above work also concentrates on the mechanical aspects of wear and does not address the role that thermal loading plays on the ultimate failure and wear of the bearings. We have confirmed from evaluating field failures that thermal overloading is a common failure mode.

The purpose of this paper is to present recent work conducted on the overall performance and life of polycrystalline diamond bearings. Two goals are intended: first, to substantiate the suitability of PCD bearings for down-hole drilling tools and, second, to report on the development of laboratory test methods that provide a good measure of how these bearings will eventually perform in the field considering both mechanical and thermal loading.

2. Polycrystalline diamond as a bearing material

In the diamond sintering process, diamond grit is subjected 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. Under these conditions, which are similar to those used to synthesize diamond, the diamond grains grow together. The resulting material is a diamond cemented polycrystalline diamond 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.

* Corresponding author. Tel.: +1 801 235 9001; fax: +1 801 235 9141.
E-mail address: tsexton@ussynthetic.com (T.N. Sexton).

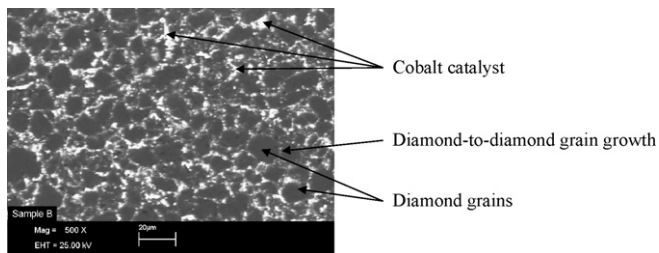


Fig. 1. Scanning Electron Microscope (SEM) micrograph of PCD at 500× magnification.

It is common practice to sinter the diamond on a tungsten carbide substrate which is a source for the metal catalyst. The substrate also provides a rigid support structure for the polycrystalline diamond table. In addition, the tungsten carbide substrate provides a convenient structure for brazing or otherwise attaching the diamond part to bearing rings, drill bits, or other devices.

In addition to being relatively tough (because of the random orientation of the diamond crystals), PCD is hard and abrasion resistant. It conducts heat approximately ten times better than steel. These properties provide for excellent performance as a bearing material. We know from Keshavan et al. [3], Cook [4], Feng and Field [6], and our experimental work that diamond rubbing against diamond in the presence of oil based and water based drilling fluids has a coefficient of friction between 0.05 and 0.08. Although this is low compared to other bearing materials, it is still not frictionless; and, under high loading, significant heat will be generated. It is, therefore, important that appropriate cooling be provided for these bearings to function properly. In down-hole drilling tools, this cooling is typically provided by the drilling fluid.

There are two bearing schemes that are often used as alternatives to diamond bearings in down-hole applications. The first employs several sets of ball bearings and races made from abrasion resistant steels. These bearings are drilling fluid-lubricated and are inexpensive and reliable. However, they suffer from erosion after a relatively short time, making life their main limitation. The second bearing type employs tapered roller bearings in sealed units. In general these are reliable but require the complication of sealing the bearing from the drilling fluid and pressure compensating the bearing assembly. The high surface speeds of sealing surfaces associated with high rotary speed applications limit these bearings.

Diamond bearings overcome both of the aforementioned obstacles but have what the authors believe to be a perceived economic barrier. Because initial costs are high, bearing life must be five to ten times longer than conventional bearings for diamond bearings to make sense economically.

3. Drilling tool applications for polycrystalline diamond bearings

Load, speed and temperature requirements for the bearing system will depend on the application. It is, nevertheless, possible to get an estimate for the demands from Table 1 which lists the conditions thrust bearings must withstand for a medium size 6 5/8 in. turbine and motor respectively.

Table 1
Typical loading for diamond thrust bearings.

| | Speed (m/s) | Load/contact area (MPa) |
|-------------------|-------------|-------------------------|
| 6 5/8 in. Turbine | 4–8 | 10–30 |
| 6 5/8 in. Motor | 1–4 | 90–110 |

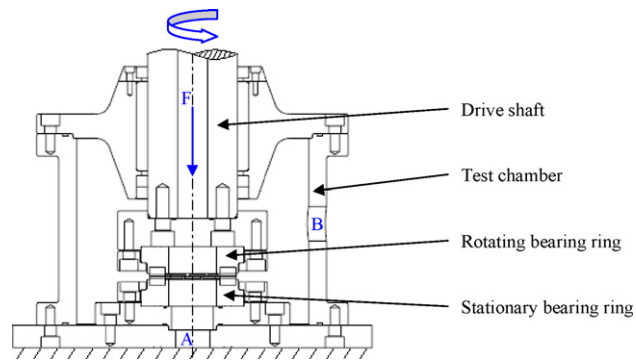


Fig. 2. Cross-section of thrust bearing test apparatus.

4. Polycrystalline diamond bearing testing

To better predict and improve the overall performance of our PCD thrust bearings, we have developed and carried out a series of laboratory thrust bearing tests. Two types of tests were conducted: (1) bearing failure tests and (2) bearing wear tests. The failure tests involved increasing the bearing load at a given speed until bearing failure occurred. These tests were performed to help better understand the capacity of the bearings and their resistance to thermal damage at high loads or speeds or both. They were also conducted in an effort to reproduce failures seen in PCD bearings following actual down-hole use. The purpose of the bearing wear tests was to establish diamond wear rates, making it possible to predict PCD bearing life in down-hole drilling tools. The wear tests were carried out by measuring the diamond wear after running at a certain load and speed for an extended period of time.

4.1. Bearing test setup

All thrust bearing tests were conducted in the bearing test apparatus illustrated in Fig. 2.

As can be seen in the test assembly in Fig. 2, the bearing test consisted of one rotating and one stationary bearing ring. Both bearing rings were comprised of a circular array of cylindrical PCD bearing inserts. These inserts were brazed into equally spaced pockets in their respective rotating or stationary stainless steel carrier rings. A PCD bearing test sample set can be seen in Fig. 3.

An axial load was applied to the rotating bearing through the drive shaft as indicated by force “F” in Fig. 2. The thrust bearing assembly was surrounded by a test chamber which served to retain the bearing cooling fluid and support the rotating drive shaft. Cooling fluid entered the test chamber at location “A” below the stationary bearing ring and then flowed around the individual PCD



Fig. 3. PCD thrust bearing test sample.

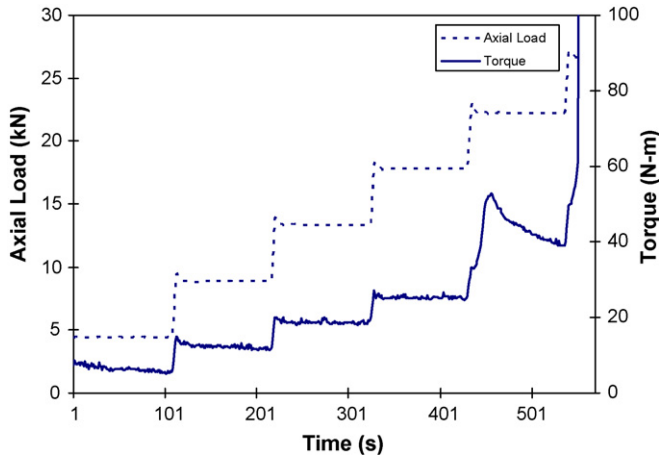


Fig. 4. Bearing axial load and torque at 1300 rpm.

bearing inserts on both bearing rings before exiting the chamber at location “B”. In the process of flowing through the chamber, the cooling 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).

4.2. Bearing failure test parameters

To understand the load and speed capacity of PCD bearings, several tests were carried out by incrementally increasing the bearing load at constant speed until bearing failure occurred. Two bearing samples were tested at each of the following speeds: 400 rpm, 700 rpm, 1000 rpm, and 1300 rpm. The bearings were comprised of 13.4 mm diameter PCD inserts spaced equally on a 59.7-mm circle with eight inserts on the stationary bearing ring and nine on the rotating bearing ring (see Fig. 3). The diamond-to-diamond contact

area between the rotating and stationary bearing was approximately 542 mm². All tests were carried out at a cooling flow rate of 18.9 l/min. Each test sample underwent a break-in cycle before actual testing began. The break-in cycle subjected the bearings to a 44.5 kN load at 400 rpm for 1 h. Following this cycle, the load was reduced to 4.45 kN. The load remained at this level for 2 min and was then increased to 8.9 kN. The load was subsequently increased every 2 min by 4.45 kN. The test was terminated when bearing failure occurred.

4.3. Bearing failure test results

During testing, bearing failure was indicated by a rapid increase in friction and, consequently, bearing torque. Fig. 4 shows the axial load and torque measured during one test at 1300 rpm. The torque increase that signaled bearing failure can be seen in this figure. Bearing failure was also accompanied by degradation of the polycrystalline diamond as is shown in Fig. 5(a)–(c). Fig. 5(a) shows a PCD insert following normal operating conditions and before any degradation has taken place. The diamond surface is highly polished and contains no visible flaws or blemishes. Fig. 5(b) shows an insert in the early stages of failure. The highly polished surface is interrupted by portions of the sintered diamond that have begun to degrade. This diamond degradation is characterized by the breaking down of diamond-to-diamond bonds. In addition, some of the diamond converts to graphite as the diamond overheats during bearing failure. Fig. 5(c) shows a PCD insert in the advanced stages of failure. Significant damage to the diamond surface is evident and is accompanied by heavy chipping on the perimeter of the insert. During one bearing test, the bearing set was allowed to continue to run after reaching the condition shown in Fig. 5(c). Catastrophic failure resulted in which the entire PCD layer of each insert was destroyed and the bearing set seized.

It was found that the laboratory generated PCD insert failures, represented in Fig. 5(b) and (c), are very similar to failures seen in PCD bearings following use in down-hole drilling tools. Fig. 6 shows failed PCD inserts from bearings used in two different drilling

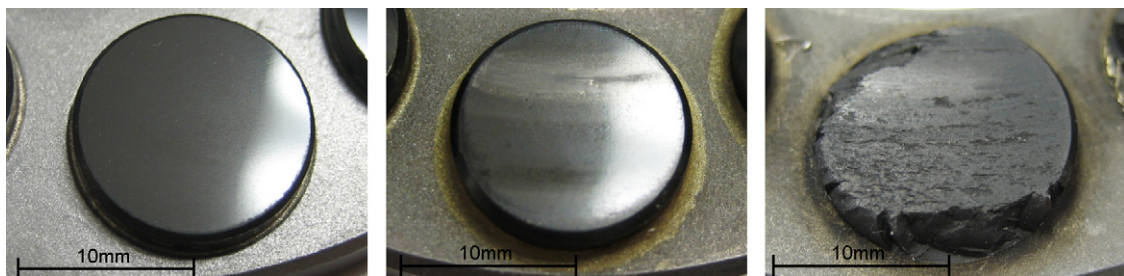


Fig. 5. PCD inserts with (a) no degradation; (b) early stages of diamond degradation; (c) advanced degradation.

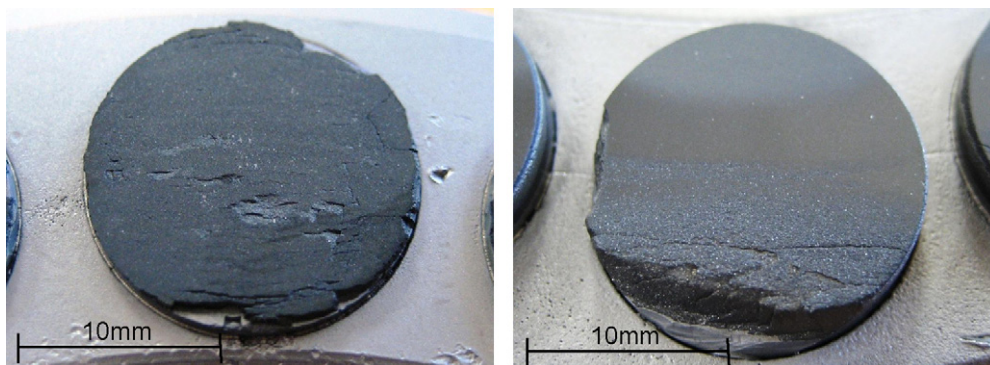


Fig. 6. PCD inserts from bearings used in two different down-hole drilling motors.

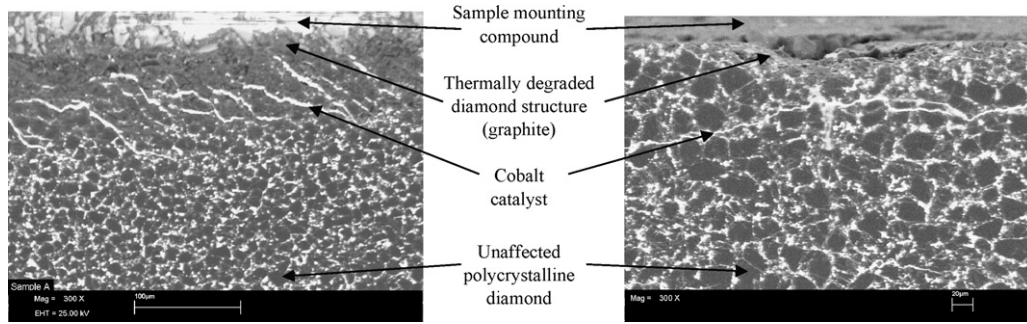


Fig. 7. SEM image at 300× magnification of cross-sectioned PCD inserts from (a) laboratory test bearings and (b) field-worn bearings.

Table 2 Thrust bearing failure test results.

| Test sample | RPM | Speed (m/s) | Load at failure (kN) | PDC surface pressure at failure (MPa) |
|-------------|------|-------------|----------------------|---------------------------------------|
| 1 | 400 | 1.25 | 102 | 189 |
| 2 | 400 | 1.25 | 116 | 213 |
| 3 | 700 | 2.19 | 57.8 | 107 |
| 4 | 700 | 2.19 | 62.3 | 115 |
| 5 | 1000 | 3.13 | 44.5 | 82.1 |
| 6 | 1000 | 3.13 | 40.0 | 73.9 |
| 7 | 1300 | 4.06 | 26.7 | 49.2 |
| 8 | 1300 | 4.06 | 31.1 | 57.5 |

motors. As with the inserts in the laboratory tested bearings, the PDC inserts in the field-worn bearings have a significant amount of degraded polycrystalline diamond, as is evidenced by the pitted wear surfaces in Fig. 6. In addition, both the laboratory tested and the field-worn bearings have significant chipping at the edges of the PDC inserts. Although the bearing failures shown in Fig. 6 did not result in down-hole tool failure, they were removed from the tool to prevent potential failure (due to bearing seizure) in any future tool runs.

To further evaluate diamond failure in the laboratory test bearings, a sample in the condition shown in Fig. 5(c) was sectioned and polished and then examined in a Scanning Electron Microscope. An SEM micrograph of the polished section is shown in Fig. 7(a). Fig. 7(b) contains an SEM micrograph of the field-worn insert shown in Fig. 6(b).

The top portion of the diamond table that formed the original bearing insert wear surface in Fig. 7(a) has seen significant thermal damage. The same is true in Fig. 7(b). This is not the case further from the wear surface in both PCD inserts, where the polycrystalline diamond structure appears to be undamaged.

Eight bearing samples were tested until bearing failure occurred as described above. Results from these tests can be seen in Table 2 and Fig. 8.

As seen in Fig. 8, the test failures were consistent and closely follow a constant power curve as shown by the best-fit equation and corresponding R^2 value displayed on the chart. Friction coefficients for each test were in the range of 0.05–0.08. These values are similar to those reported by Cook [4] for PCD bearings lubricated with drilling mud and by Feng and Field [6] for natural diamond lubricated with air, water, and liquid paraffin.

4.4. Bearing wear test parameters

We conducted additional laboratory tests to measure wear rates in PCD bearings. The bearings were constructed using 7.92 mm diameter PCD inserts spaced equally on a 59.7 mm circle with six inserts on the stationary bearing ring and 19 on the rotating bearing ring. The diamond-to-diamond contact area between the rotating and stationary bearing rings was approximately 137 mm². All

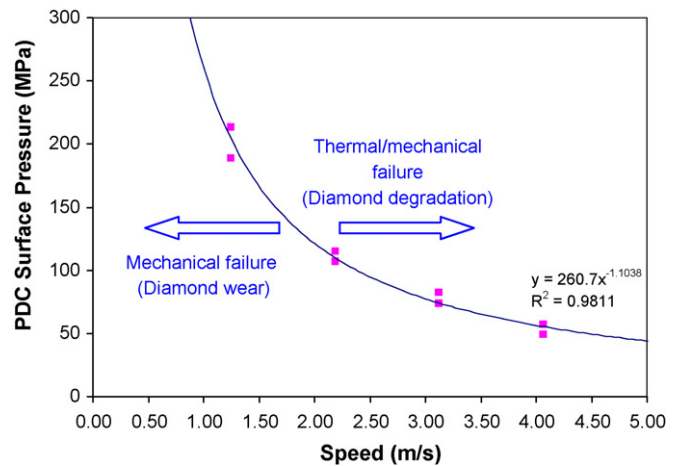


Fig. 8. Thrust bearing failure test results and best-fit power curve.

tests were carried out at a cooling flow rate of 18.9 l/min. Each test sample underwent a break-in cycle before actual testing began, similar to the one described in the bearing failure tests. Following the break-in cycle, the load and speed were adjusted to the desired test values, where they remained for the 8 h duration of the test. The thickness of each of the six stationary bearing PCD inserts was measured after the break-in cycle and after the completion of the 8-h period of the test to determine the total average diamond wear in the 8-h period.

4.5. Bearing wear test results

Diamond wear rates measured at six different test conditions can be seen in Table 3. Fig. 9 shows the wear rates graphically as a function of the PCD surface pressure times the velocity (PV).

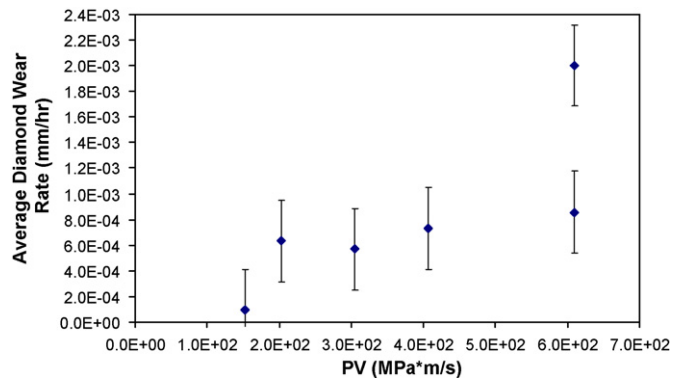


Fig. 9. Thrust bearing wear test results.

Table 3
Thrust bearing wear test results.

| Test sample | RPM | Speed (m/s) | Axial load (kN) | PDC surface pressure (MPa) | Average diamond wear rate (mm/h) |
|-------------|-----|-------------|-----------------|----------------------------|----------------------------------|
| 1 | 400 | 1.250 | 66.72 | 487.8 | 2.00E-03 |
| 2 | 200 | 0.625 | 66.72 | 487.8 | 5.72E-04 |
| 3 | 100 | 0.313 | 66.72 | 487.8 | 9.53E-05 |
| 4 | 400 | 1.250 | 44.48 | 325.2 | 7.32E-04 |
| 5 | 400 | 1.250 | 22.24 | 162.6 | 6.35E-04 |
| 6 | 700 | 2.188 | 38.12 | 278.7 | 8.59E-04 |

The error bars in Fig. 9 represent the diamond wear measurement uncertainty of ± 0.0025 mm.

5. Discussion of results

The PCD bearing failures summarized in Table 2 and Fig. 8 were caused by the individual PCD bearing inserts overheating at or close to the wear surface. As explained by Mehan and Hibbs [5], when the diamond temperature reaches approximately 800 °C in the presence of the cobalt catalyst, the diamond-to-diamond bonds break down and the diamond begins to convert to graphite. As can be seen in Fig. 7, local temperatures at the wear surface of this particular PCD insert exceeded 800 °C. This is evidenced by the destruction of diamond-to-diamond bonds and the degradation of the individual diamond grains. As the diamond at the wear surface breaks down, the friction coefficient increases, resulting in greater heat generation. This leads to higher diamond temperatures and further diamond degradation. The degraded diamond structure is much weaker due to the reduction in the quantity and strength of diamond-to-diamond bonds and, as a result, mechanical failure (as evidenced by the edge chipping seen in Fig. 5(c)) ensues.

In contrast to the thermal/mechanical failure described above, results from bearing wear tests (Table 3 and Fig. 9) indicate that these tests measure the mechanical strength of the polycrystalline diamond, in the form of diamond wear. The diamond surface in all of the PCD inserts from the wear test samples had an appearance similar to the PCD insert shown in Fig. 5(a). The diamond wear surfaces were highly polished, with no evidence of thermal degradation present.

The constant power line in Fig. 8 represents the limit of safe operation for the particular bearing that was tested. Load/speed combinations above and to the right of the curve will lead to thermal bearing failure (for this set of test conditions), whereas those below and to the left of the curve will result in diamond wear without bearing failure as described above.

It can be noted that the surface pressures for many of the wear tests summarized in Fig. 9 fall outside the failure curve in Fig. 8. This is because the geometries of two tests samples are different. The failure test bearings employed 13.4 mm diameter PCD inserts, whereas the wear test bearings used 7.92 mm diameter inserts. The smaller diameter inserts allowed for more efficient heat transfer from the polycrystalline diamond, thus increasing the surface pressure sustainable before failure. Presumably, bearings with the 7.92 mm diameter PCD inserts tested under failure test parameters would generate a failure curve with surface pressures higher than those shown in Fig. 8.

6. Conclusions

Demanding requirements exist for bearings in down-hole drilling tools where high loads, high speeds, and abrasive fluids can cause conventional sealed roller bearings or drilling mud-lubricated ball bearings to fail quickly. PCD thrust bearings have been used as alternatives to conventional bearings in down-hole drilling tools and are seeing success in these demanding applications.

Laboratory thrust bearing tests at high loads and speeds have generated diamond bearing failures similar to failures observed in down-hole PCD bearing applications. Laboratory test failures have shown that PCD bearing failure is primarily due to thermal damage in the polycrystalline diamond table of the PCD inserts. Based on these laboratory failures, maximum operating limits for PCD bearings have been established. These limits can be used to evaluate the feasibility of PCD bearings in specific down-hole applications. In most cases, expected loads and speeds in these tools fall inside the maximum operating limits for PCD bearings, making them an excellent alternative to conventional bearings in down-hole drilling tools.

Wear data gathered in laboratory bearing tests has shown that PCD bearings exhibit low wear rates, even at relatively high loads or speeds or both. The exceptional wear properties of PCD bearings make them ideally suited for use in down-hole drilling tools. Based on the laboratory data gathered, PCD bearings operating at typical down-hole loads and speeds can last as many as several thousand hours.

Acknowledgements

We would like to thank Troy Campbell, Phil Meldrum, and Curtis Simons for manufacturing and testing the PCD bearings and US Synthetic management for granting permission to write this paper.

References

- [1] D. Crompton, W. Hirst, M.G.W. Howse, The wear of diamond, Proceedings of the Royal Society of London 333 (1973) 403–513.
- [2] R.L. Mehan, Dry sliding wear of diamond materials, Wear 78 (1982) 365–383.
- [3] M.K. Keshavan, B. Liang, M. Russel, Tribiological Properties of Polycrystalline Diamond and Its Application, Smith International, Inc., 1989.
- [4] M.W. Cook, Wear-resisting properties and application examples of PCD, Industrial Diamond Review 4 (1996) 107–111.
- [5] R.L. Mehan, L.E. Hibbs, Thermal degradation of sintered diamond compacts, Journal of Materials Science 24 (1989) 942–950.
- [6] Z. Feng, J.E. Field, The friction and wear of diamond sliding on diamond, Applied Physics 25 (1992) A33–A37.