

Process-fluid-lubricated polycrystalline diamond bearings for application in marine hydrokinetic machines

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ABSTRACT

Polycrystalline diamond (PCD) bearings are sliding bearings that utilize sintered diamond for their contact surfaces. These ultra-hard wear surfaces make PCD bearings ideal for applications where the bearings are in direct contact with harsh or abrasive fluids. PCD bearings are currently used in down-hole oil and gas drilling tools, such as positive displacement drilling motors and drilling turbines, where they are cooled and lubricated by the drilling fluid.

New applications for PCD bearings are emerging in renewable energy where operating in the ambient fluid environment is an advantage. An example would be their use in Marine Hydro-Kinetic (MHK) machines operating in a submerged water environment.

Until now, it had not demonstrated that the necessary life to fulfill the requirements of renewable energy (which will require years of operation instead of hundreds of hours) had been achieved in PCD bearings. This paper presents recent tests conducted by the authors that have demonstrated that PCD bearings can operate in the fluid-film lubrication regime at surface speeds as low as 0.5 m/s in light oil (viscosity of approximately 6 cP). This is significant because it raises the possibility of extended operational life for PCD bearings and therefore effective application in MHK.

Keywords: polycrystalline, diamond, bearings, marine, hydrokinetic

1 BACKGROUND

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. Figure 1 is a micrograph of a typical PCD structure that has been cut and polished. Figure 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.

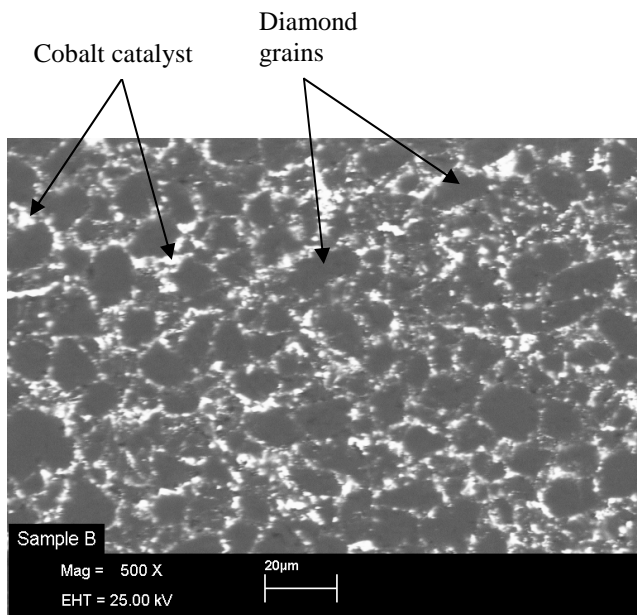


Figure 1: Scanning Electron Microscope (SEM) micrograph of PCD at 500X magnification.

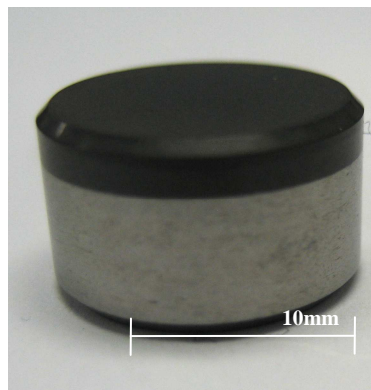


Figure 2: PCD compact.

PCD thrust bearings are comprised of annular rings containing circular arrays of PCD inserts. Figure 3 shows a typical PCD thrust bearing set.



Figure 3: PCD thrust bearing set.

The PCD surfaces on the bearing rings run against one another during the application of axial loads. These bearings are commonly used in down-hole oil and gas drilling tools such as positive displacement motors and drilling turbines. In these machines, the drilling fluid circulates through a positive displacement cavity or through a series of turbine stages to generate rotation in the drive shaft (and the drill bit). The thrust forces resulting from the action of the fluid on the turbine blades, for example, must be taken up by thrust bearings. PCD bearings are commonly cooled and lubricated with the drilling fluid, which is laden with abrasive particles that quickly damage other conventional bearing materials. PCD bearings make it possible to extend the life of the overall tool assembly. This is true even in low-speed, high-load applications where PCD bearings operating in the boundary lubrication regime have exhibited wear rates that allow the bearings to operate for well over one thousand hours [1].

Hydrodynamic lubrication occurs when a fluid film develops between opposing bearing surfaces, resulting in complete separation. This in turn results in very low friction and little or no bearing surface wear. If hydrodynamic lubrication can be achieved in PCD bearings, it is expected that their life could be virtually infinite.

Conventional hydrodynamic bearings are typically constructed using one of several pad geometries, including tapered and tilting pads. These pad geometries contribute to the pumping action that generates the oil-film pressure between the opposing bearing surfaces [2]. 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 approximately $1.0 \mu\text{m}$ arithmetic mean roughness (R_a). 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.

2 THRUST BEARING TESTS

A series of tests were conducted by the authors to evaluate the ability of PCD bearings to operate in the hydrodynamic lubrication regime. Two bearing designs were evaluated, with the bearings being tested in both oil and a water/glycol mixture.

2.1 Test Setup

All bearing tests were conducted in US Synthetic's thrust bearing test machine. A schematic of the bearings in the test machine can be seen in figure 4.

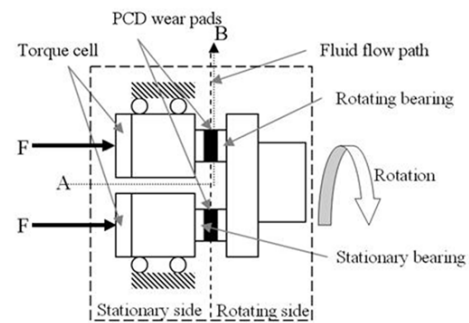


Figure 4: test bearing schematic.

Two thrust bearing designs were evaluated. The first was comprised of 13.4 mm diameter cylindrical PCD inserts as shown in figure 3. The stationary and rotating bearings contained 12 and 11 PCD inserts, respectively. The second design utilized 19.1 mm diameter wedged-shaped inserts as shown in figure 5. The stationary and rotating bearings contained 15 and 16 inserts, respectively. The inserts on both bearing designs were equally spaced on a 59.7 mm diameter pitch circle.



Figure 5: PCD thrust bearing set with wedged PCD inserts.

The wedged insert design was used in an effort to improve the ability of the bearing to generate fluid-film separation between the opposing bearing faces. The wedged inserts on the rotating bearing were spaced very closely together in an effort to create a relatively continuous runner.

Lubricant was circulated through the bearings during testing. The fluid flowed through the inside diameter of the stationary bearing ring (location A in figure 4) and then around the PCD inserts on the stationary and rotating rings. The lubricant exited the test chamber at a point above the test bearings (location B in figure 4), resulting in the bearing assemblies being completely submerged during testing. The lubricant flow rate was a constant 18.9 l/min for the entire duration of each test.

A total of three tests were conducted, including one test using the cylindrical PCD insert design and two tests using the wedged insert design. The cylindrical and wedged insert bearings were tested using Paratherm MR high-temperature heat transfer oil as the lubricant (Paratherm Corp., West Conshohocken, PA). The wedged insert bearing was also tested using a water/glycol lubricant comprised of 95% water and 5% ethylene glycol by volume.

Prior to testing, the bearings were subjected to a break-in cycle at 400 rpm and 89 kN for at least two hours to

reduce the diamond surface finish from its as-manufactured value of 1.0 $\mu\text{m Ra}$ to a value of approximately 0.15 $\mu\text{m Ra}$.

All bearing tests were carried out at a constant axial load of 44.5 kN. The speed increased linearly from 0 to 3000 rpm (velocity of 0.0 to 9.4 m/s) over a period of 1000 seconds, after which the test was terminated.

The friction coefficient as a function of velocity was calculated from torque values measured during testing.

2.2 Test Results

Friction coefficients measured during each of the three tests can be seen in figure 6. The speed is shown in terms of both the rpm and sliding velocity. Of the three tests, the wedged inserts tested in oil resulted in the lowest friction coefficient (below 0.001). In addition, this low friction value was achieved at a speed of only 150 rpm (0.5 m/s). When the same bearing was tested in water/glycol, the minimum friction coefficient was higher than the friction measured in oil (0.014 vs. 0.001), but still low in absolute terms. The bearing with cylindrical PCD inserts exhibited a minimum friction coefficient of approximately 0.012 when tested in oil.

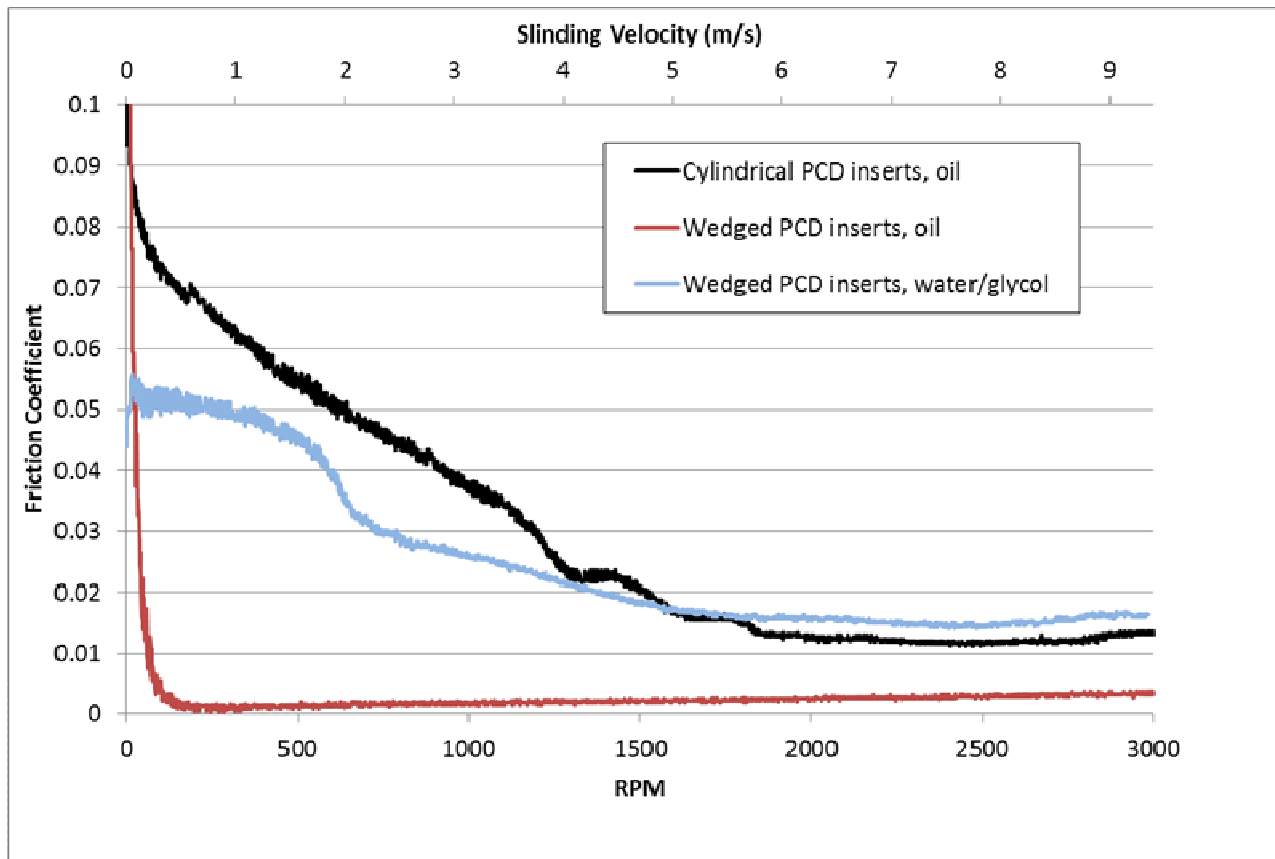


Figure 6: Thrust bearing test results.

3 SUMMARY AND CONCLUSIONS

The friction results in figure 6 resemble the typical Stribeck curve shown in figure 7, which is used to demonstrate the transition of friction coefficients through various lubrication regimes. At lower speeds, asperity contact dominates and friction is high (boundary lubrication). As the speed increases, friction diminishes as a result of the partial separation of the surfaces by the developing lubrication film (mixed film lubrication). Eventually, the friction reaches a minimum value where full lift-off of the surfaces occurs (hydrodynamic).

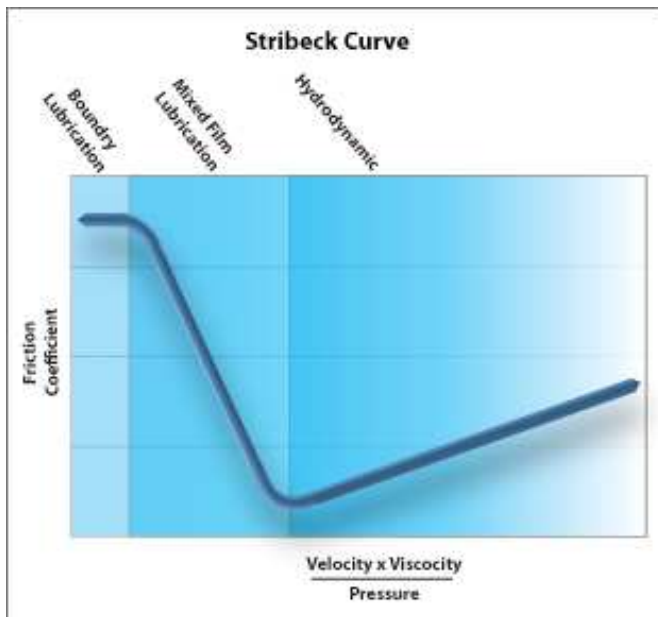


Figure 7: Stribeck curve.

Given the very low friction coefficients measured in the wedge-shaped bearing tested in oil, hydrodynamic lubrication was achieved. Although the wedged bearing tested in water/glycol and the cylindrical bearing tested in oil achieved low friction values, they may not have been completely hydrodynamic (as displayed in the higher minimum friction values associated with these two tests). It is the authors' opinion that they were at least operating in the mixed-mode lubrication regime and may have been fully hydrodynamic.

To be effective in MHK machines, PCD bearings will need to operate at very low friction to provide the extended bearing life required. Ultimately, it is the authors' goal to achieve full hydrodynamic lubrication in PCD bearings in water and to reduce the speed at which hydrodynamic lubrication initiates.

Even though the bearing tested in water/glycol may not have achieved full hydrodynamic lubrication, the friction

coefficient was still very low. It is the authors' belief that hydrodynamic lubrication can be achieved at still lower surface speeds in water/glycol. The tests summarized in this paper were conducted at a relatively high load. It is expected that lower friction coefficients could be achieved in water/glycol if tests were conducted at lower specific loads. In addition, the sliding velocity plays a significant role in the initiation of lift-off. Large MHK machines may be able to achieve the linear velocities necessary for hydrodynamic lubrication, even at relatively low rotational speeds.

Polycrystalline diamond has many desirable properties when considering its use in open or process-lubricated systems. Unlike most conventional fluid-film bearings, PCD bearings operate effectively even when the opposing surfaces are in contact (i.e. boundary and mixed-mode lubrication).

The three tests described above were limited in scope and were brief in time (approximately 16 minutes each). Additional tests are planned by the authors that evaluate bearing performance over a longer period of time and at other load and speed combinations. Furthermore, modifications to the bearing geometry will be evaluated to determine their effect on bearing performance.

REFERENCES

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