WEAR DEBRIS MONITORING OF HYBRID AND FULL METAL BALL BEARINGS

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Abstract

Hybrid bearings combine traditional bearing steel raceways with ceramic rolling elements and can offer improved performance against their full-metal bearing counterparts, particularly within aerospace applications. Rolling element bearings are critical components that benefit from condition monitoring to prevent in-flight failures and enact proactive maintenance procedures. Wear debris monitoring is commonly used for these applications, to identify and diagnose the bearing fault modes. Bearing life tests were conducted to compare the degradation and monitoring differences between hybrid and full-metal bearings with debris monitoring. It was found that under identical Hertzian stress loads, the differences in the degradation curves between full-metal and hybrid bearings were negligible in comparison to overall bearing degradation variance. Furthermore, it was found that hybrid bearings experiencing rolling element pitting will generally lead to raceway spall.

1. INTRODUCTION

Rolling element bearings are critical components in most rotational equipment, especially aircraft gas turbines and transmission gearboxes for vertical flight. They are manufactured in different sizes and types depending on the operational environments, loads to support, and speed requirements. However, they often constitute the same component set-up, including the inner raceway, outer raceway, rolling elements and cage. All the elements except the cage are load carrying and withstand very high contact stresses.

Traditionally, raceways and rollers have been made of bearing steels like AISI 52100. New hybrid bearings have been introduced that combine traditional steel raceways with ceramic material rollers. These bearings have several benefits, particularly for high-speed applications mainly related to their lighter weight as outlined in Ref 1.

Bearing faults are often a critical aspect of engine health monitoring due to their frequency and/or criticality to operation. A common mode of bearing fault is rolling contact fatigue on the raceway surface, termed spall. Herein, a macroscopic crack propagates along the bearing raceway, discharging wear particles. Eventually this material loss impacts the bearing stiffness and causes excess vibration to the rotor assembly. While several research publications, such as Ref. 2, have explored the growth of raceway spall in full-metal bearings, there is little knowledge about spall growth phenomena in hybrid bearings.

Online oil debris monitoring (ODM) has been utilized for condition-based maintenance programs for critical bearings in aerospace applications. Debris monitoring sensors often use inductive technology to count steel and other metallic particles discharged from the bearings into the lubricating oil. This technology offers a real-time monitoring option with more data compared to traditional alternatives such as oil sample analyses and magnetic chip detectors. Monitoring of raceway spall growth using online debris monitoring for full-metal bearings is tried and tested in both industry and academia, such as in Ref. 3. It is commonly used to diagnose the bearing damage severity due to the strong correlation between discharged particle volume and damage volume on the raceway, as outlined in Ref 4. In other words, tracking the ODM counts discharged by the bearing is equivalent to tracking the spall level on the bearing.

This study will focus on evaluating the key differences between the degradation curves and features of hybrid bearing spalling to full-metal bearing spalling. To do this, accelerated bearing fatigue tests were conducted with ODM to track the degradation evolution. The Hertzian stress applied to both the full-metal and hybrid bearing were equal, and the speed was constant for both. The goal of the research is to determine if a transfer function or other considerations are required for spall growth under hybrid bearings in comparison to traditional understanding of full metal bearing spall growth.

2. EXPERIMENTAL SET-UP

Five single row 25-mm bore angular contact bearings were tested in this test program. All bearings had AISI 52100 raceways and were spun at 6,000 rpm. Three tests utilized AISI 52100 rolling elements, while the remaining two used ceramic Alumina Zinc rollers, setting up the hybrid bearing portion of the test. To accelerate the bearing tests, Rockwell C hardness indents were implanted on the inner raceway. This provides the starting point for damage growth and is a common method to initiate spall in bearing tests.

The bearings were loaded continuously at a load similar to typical take-off conditions in rotorcraft applications. The load was kept constant to mitigate its effects. It is noted that due to the material differences between ceramic and metallic rollers, the bearings were physically loaded differently in order to achieve the same Hertzian contact stress.

ODM measurements were performed utilizing a Gastops Ltd. 1/4-inch MetalSCAN ODM, which is able to detect all Ferrous particles above 65-microns. Tests were conducted to varying levels of damage but all surpassed 2,000 ODM counts.

3. SPALL TEST RESULTS

It can take millions of revolutions to initiate fault from the hardness indents. This timeline varies deterministically based on random effects, residual stress differences between the bearings, and slight variances in indent geometries.

Once a macroscopic fault initiates, metallic wear particles begin to release and are detected by the sensor. The time from test start to this point is called the incubation period. Figure 1 shows the incubation time for the collected tests. In order to conservatively differentiate between the incubation period and actual spalling, a conservative threshold of 100 particle counts is required. At this point the bearing is considered spalling beyond any reasonable doubt. Hybrid bearings were slightly faster in degradation initiation. Full Metal (FM) bearings were slightly slower in incubation, however, they were within the same range.

The incubation time is generally removed from analysis since the focus of this test program is spall degradation, not spall incubation.

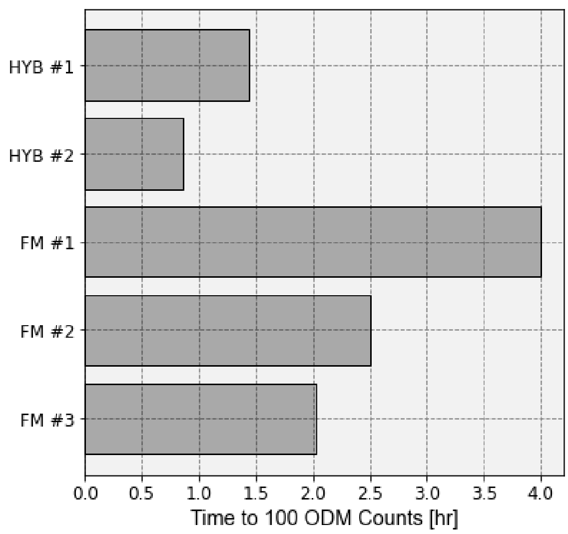

Figure 1: Display of incubation time of spall varying from 1 hour to 4 hours.

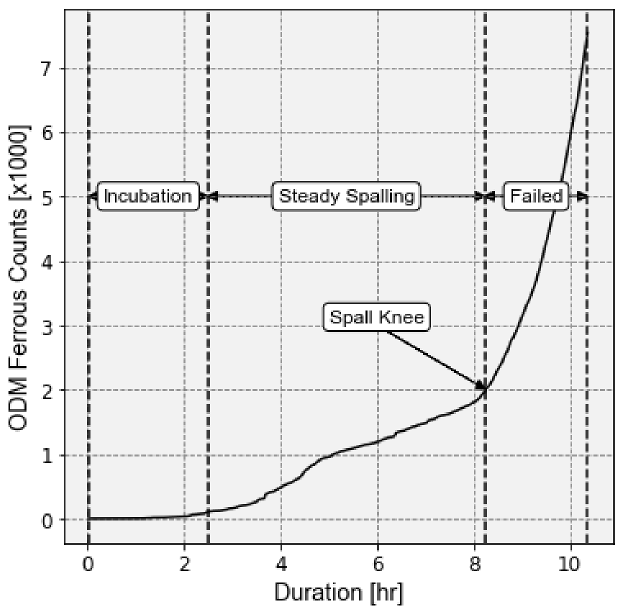

Figure 2: Display of standard bearing degradation curve beginning with incubation, followed by steady spalling, before the spall knee and rapid degradation of the bearing

Once the spall develops, it will continue to degrade at a steady rate. This can be affected by the load and speed, which is why they were kept constant for this test program. This spalling phase will continue until the spall reaches a critical point known as the spall knee. At this point the bearing is considered failed, and should be removed from service immediately. This characteristic bearing spall degradation curve has been observed in several tests, and is shown in Figure 2.

Note that these tests are at high speed and load conditions to accelerate the fault propagation. Tests in this trial generally propagated through the spalling curve within ten hours. However, field applications generally take 50 to 100 flight hours from incubation to the spall knee.

It can be observed by looking closely at Figure 2 that the incubation time ended slightly earlier than indicated by 100 Ferrous counts. This is to the conservative point mentioned above to ensure that there is no doubt the data considers only spalling degradation. In reality, once particles begin to discharge, the bearing is considered spalled and the incubation period completed. This difference is shown in Figure 3 where it is clear that the bearing begins spalling after about one hour of operation at a rate aligned with the steady spalling phase.

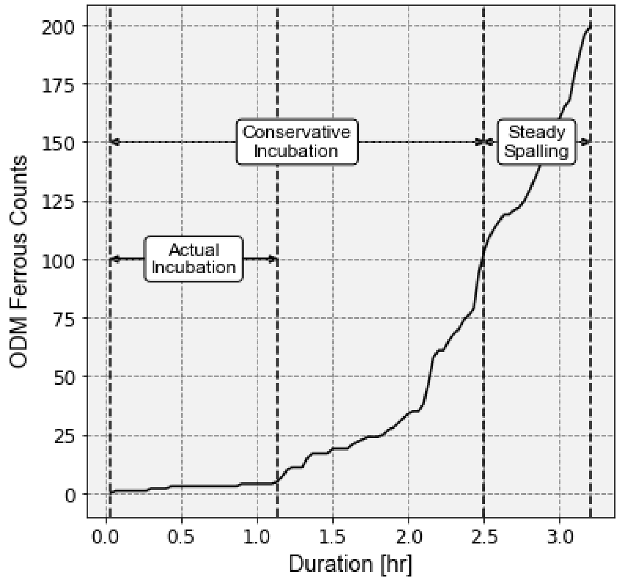

Figure 3: Zoomed in look at test from Figure 2 showcasing the actual incubation period against the conservative incubation period deployed for the analysis in this test

The spall knee is considered the endpoint of bearing life. At this point, the physical spall is long enough circumferentially that multiple rolling elements can descend into the spall at the same time. This results in an accelerated degradation rate and severe vibrations. This damage mode can propagate, impacting other components in the gearbox or can cause the cage of the bearing to rupture, leading to bearing seizure and catastrophic immediate failure. This jump in vibration post-spall knee is shown is shown in Figure 4. For this reason, beyond the spall knee, the bearing is considered failed, and is not considered in this analysis.

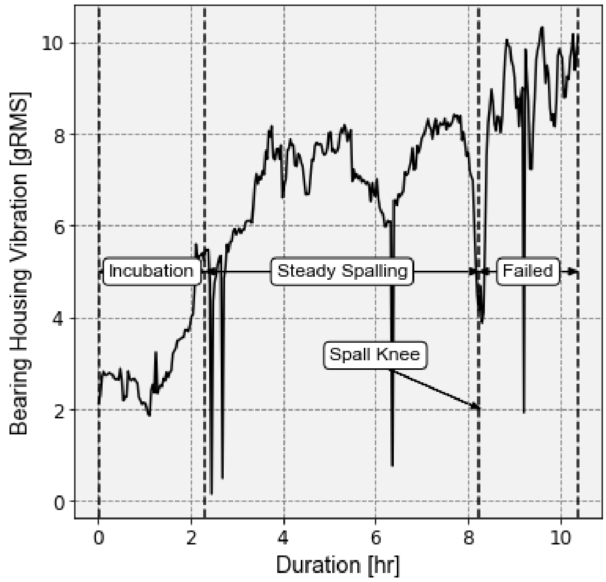

Figure 4: Vibration levels showing clear distinguishable stages between incubation, steady spalling, and the extreme vibrations experienced post spall-knee

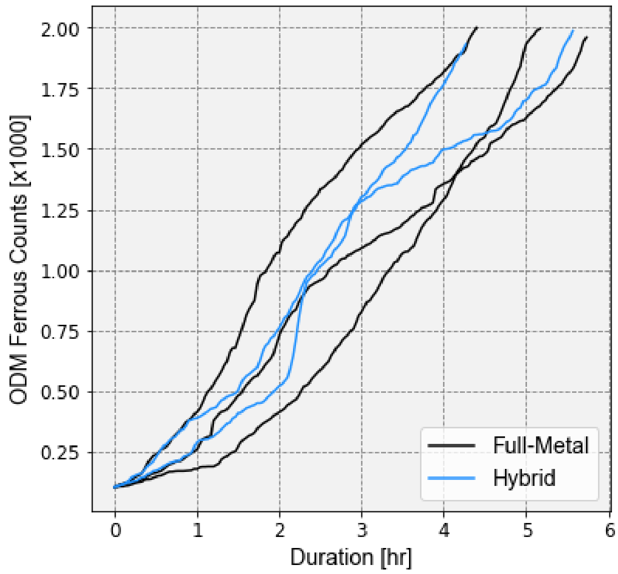

Figure 5: ODM Ferrous counts against time for all five tests (two hybrid and three FM) from incubation until the spall knee

The spall knee for this bearing occurs generally around 2,000 Ferrous counts, but not before. Thus, the bounds for the analysis of these spall tests have been set to be between 100 to 2,000 ODM counts, as per Figure 2. To recall, five tests were conducted, three FM, and two hybrid. All five tests adhering to these constraints are shown in Figure 5.

4. COMPARISON OF HYBRID AND FULL-METAL SPALLING

Based on the test data presented in Figure 5 there is no distinguishable difference between hybrid and full metal bearing spall progression under identical loads and speeds. While this does not mean there is no physical difference in the spall growth based on the roller material, it is negligible within the overall variance of spall degradation. The hybrid bearing degradation curves being sandwiched in between two FM curves and almost identical to the third confirms this.

To showcase this further, consider two additional FM tests conducted at 3,000 rpm rather than the original test setting of 6,000 rpm. The distinction between the two sets of tests, shown in Figure 6, is evident and significant.

Furthermore, it was examined to see if the actual wear particles discharged by the raceway exhibited any differences. Since the wear particles from the raceway are all the same material, their size was examined via the MetalSCAN ODM sizing feature. Shown in Figure 7, there is clear overlap and nearly no difference between the particle size distribution between FM and hybrid bearings. This graph is cut-off at 600 microns due to very little particles (less than 1%) in order to preserve visibility of the smaller particle sizes. The systems used in this test can size particles up to 1,000 microns.

The data presented shows clearly that the material differences in the roller between hybrid and full-metal bearings are negligible within the standard bearing degradation variance. Furthermore, the particle size distribution is also nearly identical. These discoveries lend significant confidence that diagnostic and prognostic models developed using wear debris monitoring for full-metal bearings are transferable to hybrid bearings. No transfer function or model needs to be implemented to adjust the deployed models to new hybrid bearing technologies.

5. BALL PITTING TEST RESULTS

While no differences were observed in raceway spalling, there is still the question of roller pitting. Roller pitting is when the damage develops at the roller rather than on the raceway. This is quite rare and far less covered in academia and deployed monitoring programs.

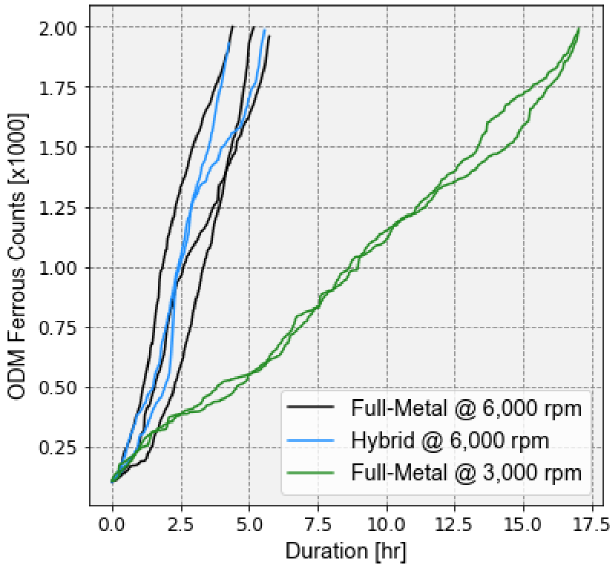

Figure 6: ODM Ferrous counts against time for all five tests at 6,000 rpm and two additional tests at 3,000 rpm showcasing the clear effect of speed, and negligible effect of roller material

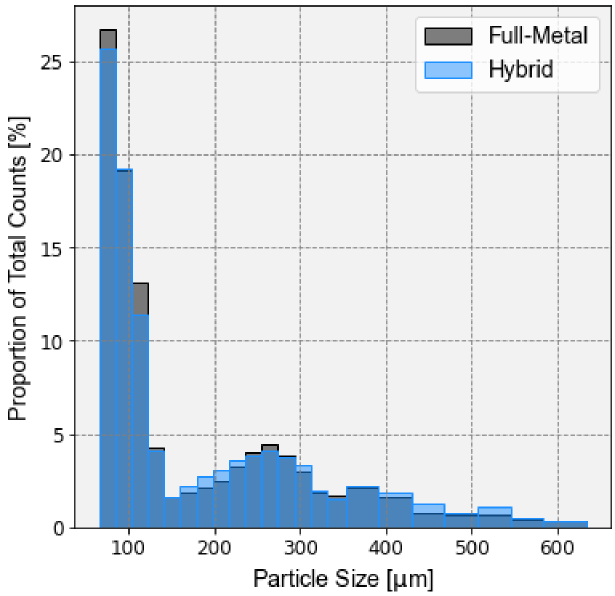

Figure 7: Particle size distribution of FM and hybrid bearings showcasing almost complete overlap and negligible difference in the size of discharged wear debris particles

The key difference is herein; the material difference will impact the monitoring tools. Debris monitoring is largely based on inductive technologies that are unable to detect ceramic materials used for hybrid rollers. For this reason, the ceramic ball pitting damage will go undetected. However, the question is how this affects the diagnostic models deployed for monitoring health.

Two tests were conducted where a pitted ceramic roller replaced a healthy rolling element in a healthy hybrid bearing. Under the specific loading conditions in these tests, the pitted ceramic roller very quickly initiated a fault in the raceway which developed into a spall that could be monitored using debris monitoring.

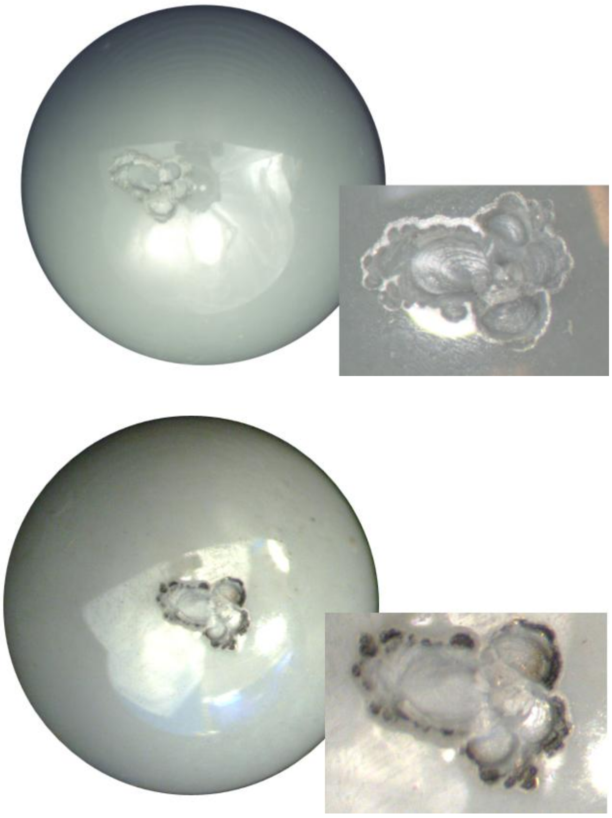

Figure 8: Pitting damage at the start (top) and finish (bottom) of one of the ball pitting test. At test completion, there was also some new minor pitting damage on the other side of the ceramic roller

Figure 9: Spall damage on raceway caused by pitted ball from both tests (test #1 is top, test #2 is bottom)

Damage occurred on the softer raceway material rapidly due to the pit on the harder ceramic roller. The damage on the pitted roller itself grew, mainly in depth, and a secondary smaller pit developed in one of the tests. Images of the pitted rolling element from test #1 are shown before and after in Figure 8. The majority of the damage developed was observed on the outer raceway, in both tests, shown in Figure 9. However, some minor damage was also observed on the inner raceway in the second test. The outer race contributed to nearly half of the bearing mass loss, with the cage and inner race accounting for the remainder, except for five percent of the mass loss accounted for by the rolling element pitting expansion.

Furthermore, there is a key difference between raceway initiated spall and roller initiated spall. In the latter, the spall initiates independently at multiple locations along the raceway due to the movement of the roller. Whereas in the former, the spall grows continuously as one body. This is shown in Figure 10, for one of the hybrid tests from Section 3.0.

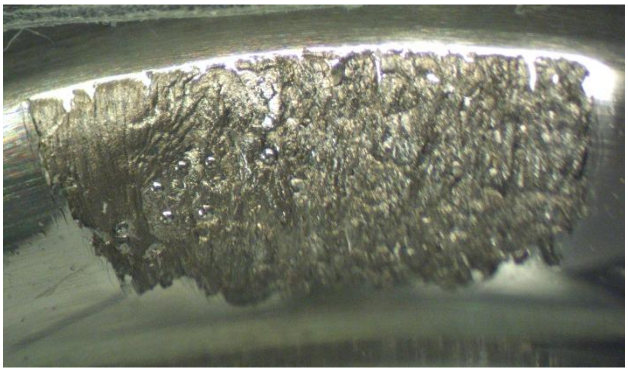

Figure 10: Single body spall damage on raceway caused by surface crack growth

Looking closely at Figure 9, it can be observed that some of the independently developed spalls have begun to grow and are larger than the less mature spalls. It is expected that as the bearing is run further, these minor spalls would expand and eventually combine into larger spalls.

The degradation curves provided by ODM Ferrous counts from these tests are shown in Figure 11. As noted in the hybrid bearing tests, there is some incubation period, however it was quite fast and it seems evident that roller pitting very quickly causes raceway spalling. The fact that the ceramic roller is significantly harder than the raceway material is likely a strong contributing factor.

The degradation rate is similar to that of straightforward raceway spalling, and within the overall variance. However, there is some notable difference in the wear debris particle size distribution compared to traditional raceway spall. This is shown in Figure 12, and is likely due to several minor spalls still too small to generate the larger particles from a single spall body. This justifies the skew towards smaller particles.

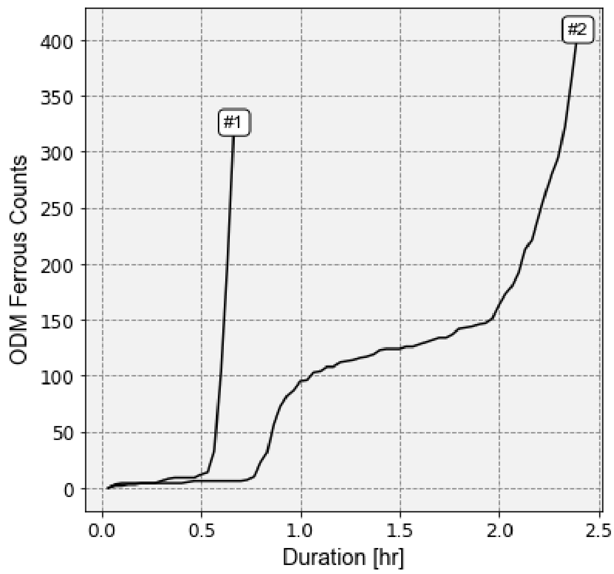

Figure 11: ODM Ferrous counts discharged during the pitting operation. The numbers refer to the pitting test number

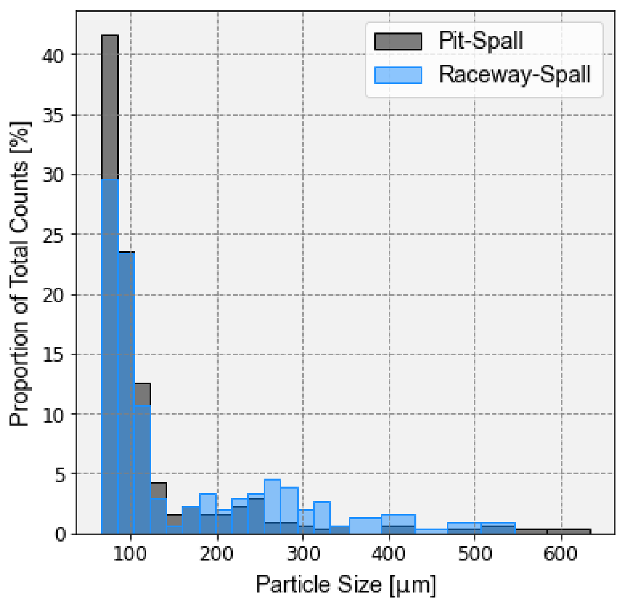

Figure 12: Particle size distribution of the pit-initiated spall from this section to the previously shown raceway initiated spall

The fact that pitted rolling elements very quickly initiate damage on the bearing raceways due to the hardness differences lends confidence that a pitted ceramic roller fault will be detected by debris monitoring once the raceway spall develops. Furthermore, the raceway degradation is far more severe, accounting for well over 50% of the total mass loss, with pitting at 5%.

It is expected that there may be some specific loading conditions that result in accelerated failure of the ceramic element, but more often then not, it is expected that steel components will fail at a faster rate and will reach a failed state prior to the ceramic element. The specific load conditions that initiate roller fault should be studied further.

6. CONCLUSION

There were several key discoveries in this paper that prove that inductive technology based oil debris monitoring can be leveraged for hybrid bearings in the same way as it has been for full metal bearings. The findings suggest that the related diagnostic and prognostic methods can be transferred as well. These key industry specific conclusions are justified due to the empirical findings detailed above including:

- Negligible difference in the degradation curves between hybrid and full-metal bearings at identical loads and speeds
- Negligible difference in the wear debris particle size distribution between hybrid and full-metal bearings
- No qualitative difference in spall shape between hybrid and full-metal bearings
- Quick initiation of raceway spall from pitted ceramic roller at multiple locations at similar degradation rates to raceway spall growth
- Skew of particle size distribution towards smaller particles due to multiple smaller spalls compared to larger single body spalls

7. REFERENCES

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