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Technical Article

Improving Bearing Life
in Wind Turbine Mainshafts

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Improving Bearing Life in Wind Turbine Mainshafts

- The need for larger megawatt (MW) class turbines has increased, but scaling up traditional turbine designs has been problematic.
- Wind operators can select upgraded spherical roller bearings (SRBs) to improve bearing life in these challenging applications.

Abstract

During the early days of wind turbine development, the sub-megawatt class turbines typically used Spherical Roller Bearings (SRBs) in the mainshaft position with significant success. As the development need for larger megawatt (MW) class turbines increased, the existing SRB mainshaft bearing was "scaled up" in size and design. However, documented field failures in mainshaft SRBs for multi-MW class turbines highlighted / emphasized its limitations for this application.

In March 2011, the first Timken 230/600 Wear-Resistant SRB with Diamond Like Carbon (DLC) coatings on the rollers was installed into a GE 1.5MW turbine at a wind farm in New Mexico. Since its installation, the bearing was inspected twice, and the bearing was determined to be in good condition each time. With only light debris damage and no visible issues, the bearing remained in service. In 2018 this bearing was removed after seven years of service as the turbine was taken offline for non-bearing related issues. The bearing was then inspected by Timken following its return.

Similarly, a 230/600 Wear-Resistant SRB was removed from another turbine as part of a repower project following a service life of over 10 years. This SRB was installed in March of 2011 at a wind farm in Oklahoma and was removed from service in early 2021. This bearing also underwent in-service inspections in 2015 and 2017, and then a final detailed inspection in 2021 following its removal from service. The positive results of both post operation inspections are detailed below, demonstrating the benefit of the DLC coating in mainshaft SRBs.

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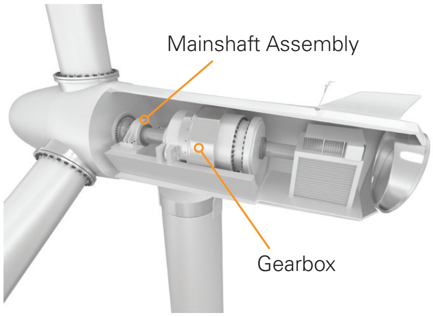
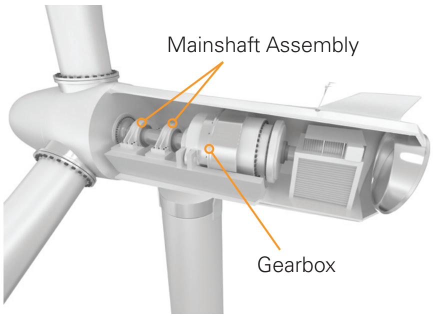
Figure 1:



Three-point mount mainshaft arrangement



Four-point mount mainshaft arrangement

I. Current State: Turbine Design

As measured by total MW, modular wind turbine designs dominate the industry and commonly use SRBs to support and carry the mainshaft loads. Classified as three- and four-point designs, Figure 1 illustrates the nomenclature.

The three-point mount in the left-hand illustration has a single support of the mainshaft loading with a single 2-row SRB in front of the gearbox. There are two additional support points located at the gearbox torque arms, which yield three support points. Advantages of the three-point mount arrangement utilizing SRBs include:

- Shorter nacelle package with reduced turbine mass
- High system deflection and misalignment capability
- Commercially economic and mature supply chain

These advantages are offset by distinct disadvantages. For example, during significant thrust loading from the wind, the downwind (DW) row of the SRB is fully loaded while the upwind (UW) row is commonly unloaded. When combined with an ever-dynamic wind regime, the load zone size and location changes creating dynamic roller operating conditions inside the bearing. Due to the required radial internal clearance (RIC) within the SRB, the axial deflections and moment loads also transfer to the gearbox planetary bearings and gears.

As the SRB wears during operation, this additional loading affects planetary gear meshes and bearing loads. The performance of the single SRB designs has experienced significant field failures much earlier than the intended design life of 20 to 25 years. These early failures have significantly increased field repair and lifetime operational costs. Similarly, the four-point mount uses two gearbox torque arms to help support the mainshaft; however, it uses two 2-row SRBs for the mainshaft support; which yields four-support points. Typically, the UW floating SRB predominately carries radial loads while the DW fixed SRB carries the majority of the wind thrust loading. This is an improvement over the three-point mount design, but there is increasing field evidence of premature damage to the DW fixed SRB location similar to that of the three-point mount design.

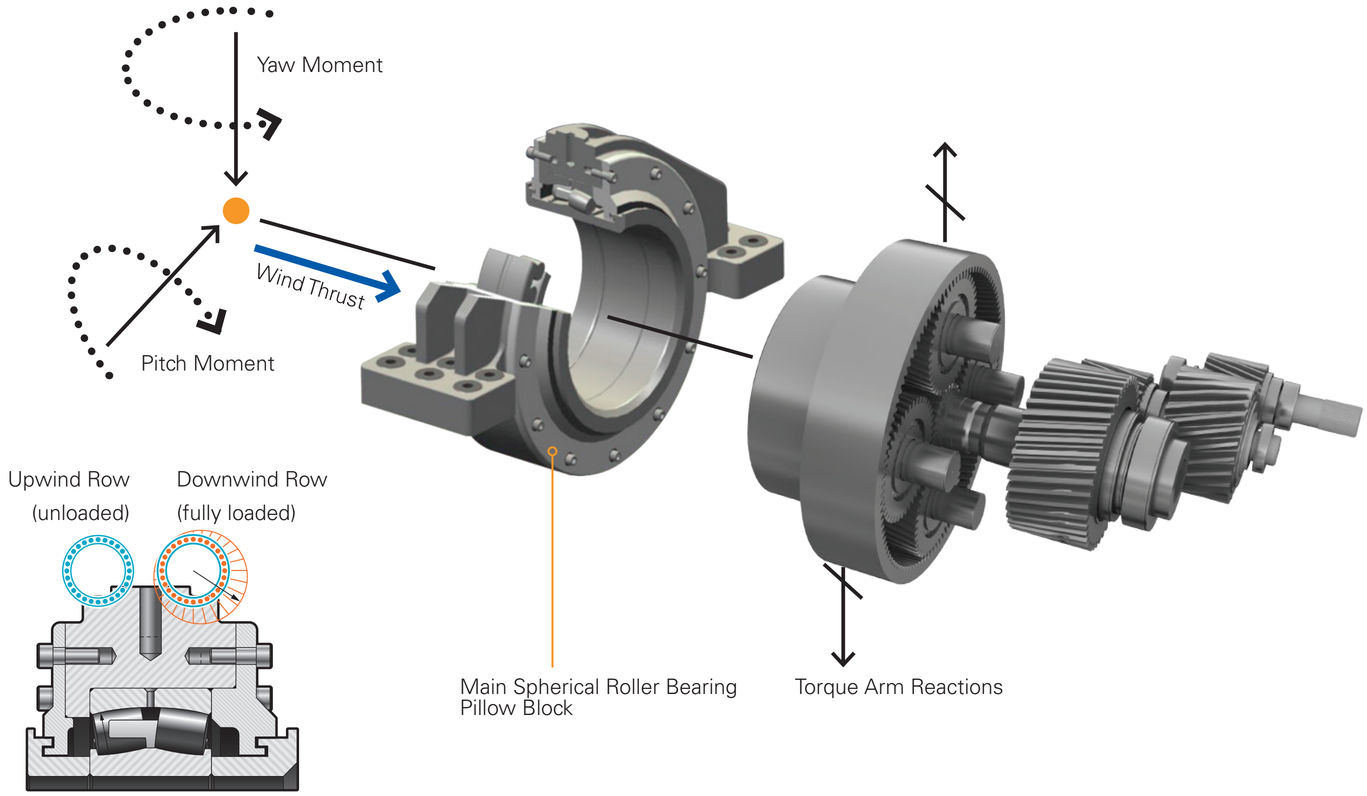
II. What is Driving the Change?

It is widely accepted that use of a single SRB in the mainshaft position in multi-MW class turbines is not the preferred design solution. This is demonstrated by the conversion of turbines > 5MW to tapered roller bearing mainshaft supports. The primary driver for the change in design philosophy is the premature damage of the SRBs seen in operation. The damage limiting the mainshaft SRB is not classic fatigue failure, but primarily micropitting leading to surface fatigue and wear.

The combination of dynamic loading and RIC results in these SRBs exhibiting unseating effects, abnormal load distribution between rows, roller skewing, high cage stress, excessive heat generation, low lambda conditions, Heathcoat slip, and roller sliding. An official maximum limit has not been established, but a conventional ratio of permissible thrust to radial loading deemed acceptable for 2-row SRB is approximately 25 percent.

Thrust loading in the application is many times significantly greater than this limit. With these high axial loads, only the DW row supports both the radial and thrust loading, while the UW row can be completely unloaded. This is a significant contributor to the micropitting damage and results in a less than ideal operating condition. Figure 2 depicts the unequal load sharing.

Figure 2: Applied loads and unequal load sharing



Field observations reveal that all three-point mount turbines are experiencing the same common damage modes, regardless of manufacturer. Although the damage takes longer to develop, many four-point mount arrangements are experiencing the same damage modes. These damage modes are the same and can include micropitting, edge loading, roller end thrust, single piece cage failures, cage and center guide ring wear, and debris damage. Images in Figure 3 below represent actual field damage from a variety of turbine models and MW classes. These unplanned main bearing replacements are costly and have significant impact on financial performance to the owner/operator.

Figure 3: Common damage in SRB mainshaft

1 MW

1.3 MW

1.5 MW

1.65 MW

2.1 MW

2.3 MW

Even when the wind turbine mainshaft is equipped with two SRBs utilizing a fixed/float arrangement, axial movement of the mainshaft still occurs due to bearing clearance. A fixed SRB carries the radial and axial load from the rotor while the floating SRB carries only the radial load. The mounted clearance plays a major role in permissible movement in both the radial and axial directions. Minimizing radial translation is beneficial on both the bearing and system performance, but a reduced mounted bearing clearance increases the risk of an operating preload and then the potential for thermal runaway.

III. Enhanced Solutions

Timken upgrade solutions are available for most multi-MW turbines. For original equipment manufacturers and aftermarket customers, options are available to increase reliability and improve system performance. One solution is Timken's Wear Resistant (WR) SRB with DLC coated rollers.

SRB Upgrades for Existing Turbines

For a direct interchange within existing fleets, Timken offers a WR SRB using engineered surface technology combined with Timken enhanced design and manufacturing. The wear resistant bearings protect raceways against micropitting by significantly reducing the contact surface shear stresses and asperity interactions. The engineered surface is a unique and durable tungsten carbide/amorphous hydrocarbon coating (WC/aC:H). It is two to three times harder than steel, 1-2 micrometers thick, and has low friction coefficients when sliding against steel. In steel bearings, the coating minimizes the adhesive wear mechanism that causes the failure.

With advanced engineered surfaces on the roller, the coating helps to polish and repair damage to the raceways that can occur during operation. The enhanced surface finish increases the effective lubricant film thickness and more efficiently separates the surface asperities. These improvements reduce the asperity interactions and shear stresses that cause wear and lead to increased bearing damage. Below, Table 1 shows a summary of the features and benefits.

Technology	Description	Benefits
Roller Finishing	Low Roughness, Isotropic Finish	Reduced Asperity Contact & Stress
Roller Coating	WC/aC:H Coating	Increased Wear Resistance Increased Fatigue Life Increased Debris Resistance
Internal Geometry	Roller/IR Conformity	Decreases Roller Stress Reduces Potential Roller Skew Creates Favorable Traction
Split Cage	Two-Piece Machined Brass Cage with no Guide Ring	Lowers Possible Operating Forces Removes source of debris generation

Table 1: Timken WR SRB features and benefits

IV. Field Performance Results

7-Year Wear Resistant SRB

Introduction

In March 2011, the first Timken 230/600 DLC SRB was installed into a GE 1.5MW turbine at a wind farm in New Mexico. Since its installation, the bearing was inspected in 2012 twice which resulted in the bearing being classified as in good condition and was continued to operate in service. In 2018, the bearing was removed after seven years of service as the turbine was taken offline for non-bearing related issues. The bearing was then inspected by Timken following its return. The following section summarizes the condition of this bearing after 7 years of service.

Grease Sampling

Grease samples from this bearing were tested twice, once in November 2011 and once in July 2018. Based on the results of these two sample tests, the wear was considered low to moderate with some evidence of external contamination potentially as a result of past servicing of other components.

Date	Iron (Fe)	Copper (Cu)	Silicon (Si)	Water
11/01/2011	500-1,000 ppm	-	>1,000 ppm	>1,000 ppm
07/08/2018	>1,000 ppm	<500 ppm	<500 ppm	~ 50% decrease from 2011

Table 2: Grease testing results

Visual Inspection

All bearing components appeared to exhibit limited adhesive wear with only a few debris dents on the downwind row. The insignificance of wear level on races is indicated by the presence of visible grind lines from the races' original finish grind. Figures 4-6 show a visual inspection of inner and outer races and an upwind and a downwind roller after the bearing was removed from service. Both roller complements appear to be in very good condition after operation showing what is light circumferential lining and the raceways have just light lubricant staining.

Figure 4: Outer race after seven years of service

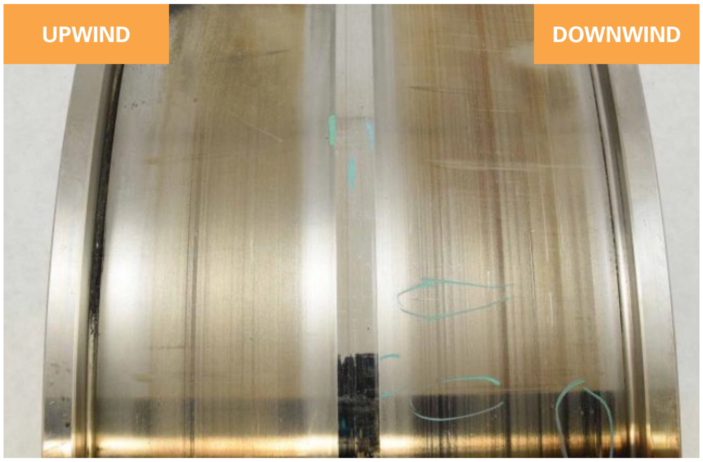


Figure 5: Inner race after seven years of service

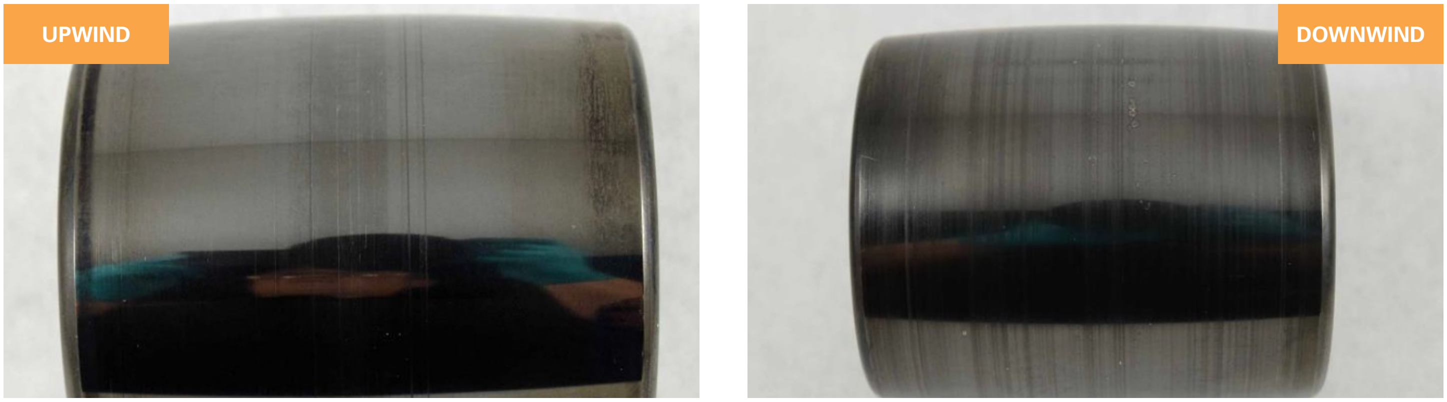


Figure 6: Upwind and downwind roller after seven years of service

Metrology

Following the visual inspection, a full metrology inspection was conducted on the bearing components. The outer race showed light polishing with as-expected upwind and downwind surface finishes. In addition to the good surface finishes, the grind lines are still visible as shown in Figure 3 above, which indicates little-to-no adhesive wear. Like the outer race, the inner race also produced as expected surface finishes with still-visible grind lines. The roller surface finishes were also as-expected post-operation. The upwind row showed very smooth finishes while the downwind row showed slightly higher finishes which is believed to have been caused by debris damage.

Component	Upwind Surface Finish (µm)	Downwind Surface Finish (µm)
Outer Race	0.30	0.27
Inner Race	0.26	0.20
Roller	0.07	0.11

Table 3: Post-operation surface finishes

Outer ring profiles experienced some deviation from form. This could be caused by slight deformation rather than a representation of surface wear, visual appearance of raceway and presence of grind lines confirm this theory. Similarly, the Inner ring exhibited minimal signs of wear as well as minimal deviation from design intent. Much like the inner race, the roller profiles were in very good condition post-operation showing minimal signs of wear or deviation from intended profile.

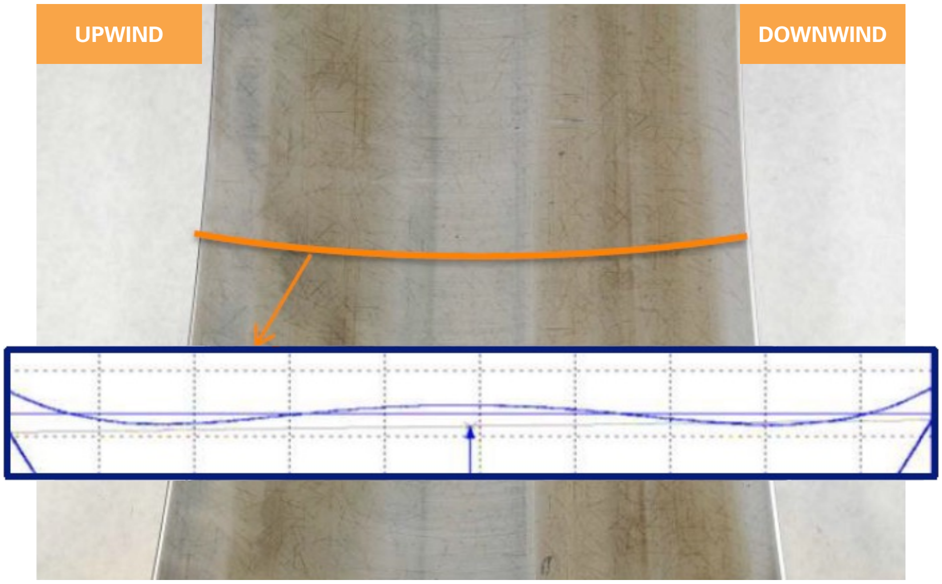


Figure 7: Outer race profile trace

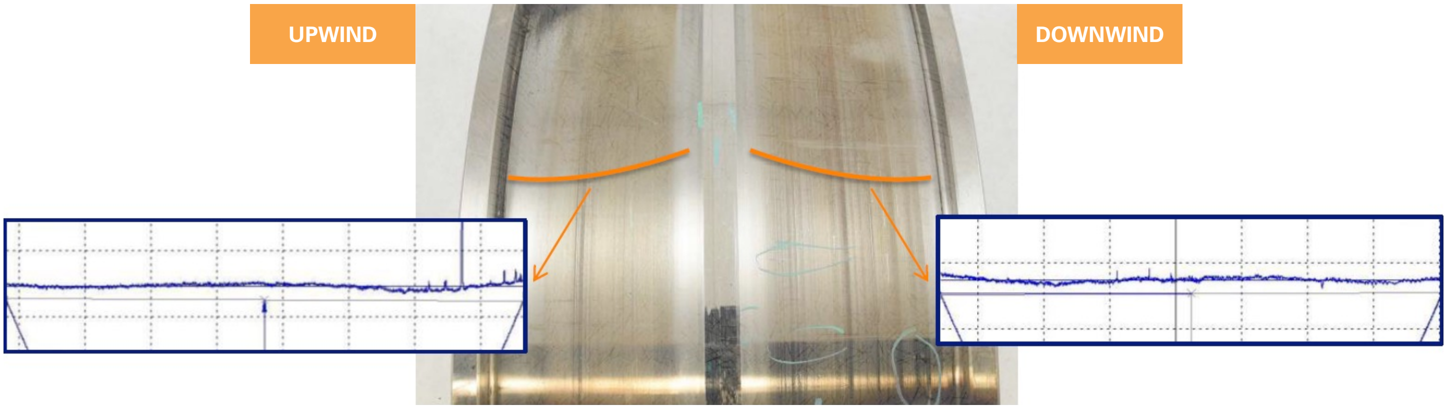


Figure 8: Inner race profile trace

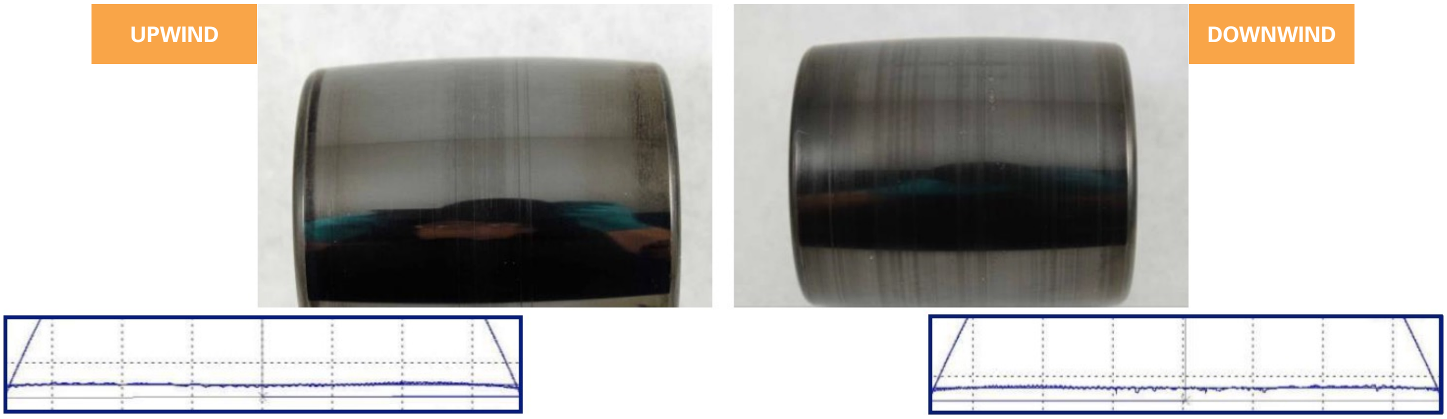


Figure 9: Upwind and downwind roller profile trace

Metallurgy

Surface hardness of each component remained in spec when inspected post-operation. Along with hardness, there were also no significant changes in the microstructure of each component. Both sets of results are summarized in Tables 4 and 5 below.

Location	Surface (HRC)	Comments
Outer	59.6, 59.7, 58.9	Hardness measurements of all components were within specification limits, indicating no significant change during operation.
Inner	59.5, 59.4, 58.1	
Roller – 1	59.0, 59.4, 60.4	
Spec	58.0–64.0	

Table 4: Post-operation hardness test results

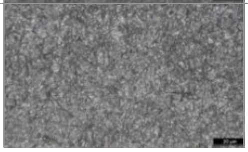
Nital Etch at 500x – All Cross-Sections from the Downwind Side of the Bearing			
Outer Race		Cross-section of outer race surface showing typical through hardened microstructure.	All surface and sub-surface microstructures matched expected outcomes for the material and heat treatment methods applied, indicating that there was no significant change in bearing metallurgy during operation.
Inner Race		Cross-section of inner race surface showing typical through hardened microstructure.	
Roller		Cross-section of roller body surface showing typical case carburized microstructure. (Note: DLC coating on the surface.)	

Table 5: Post-operation microstructure results

DLC Coating Inspection

To inspect the rollers, a best case and worst-case roller based on visual appearance was selected from each row resulting in four rollers in total. In addition to a visual inspection, the coatings underwent the Daimler-Benz Adhesion Judgment Scale which is a standard test for analyzing coating adhesion. The test creates an indentation in the coated surface, then analyzes for cracking or delamination of the coating around the indentation.

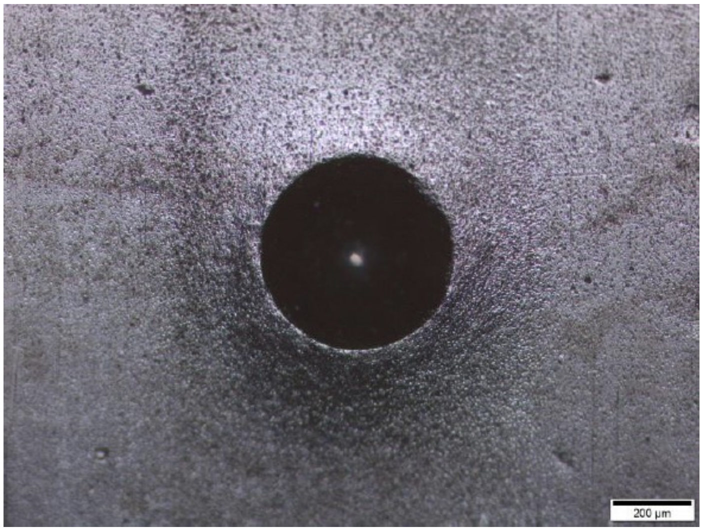


Figure 10: Benz Test Indentation

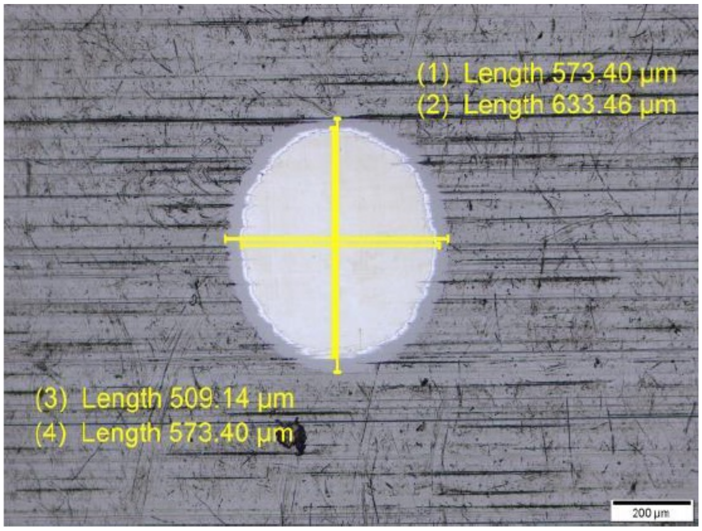
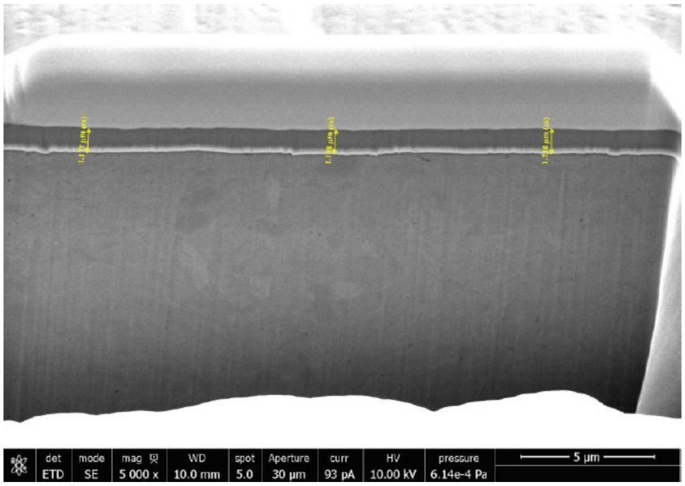


Figure 11: Calowear wear scar example

These coatings also underwent the Calowear thickness test, where a ball of a known diameter is used to make a wear scar on the coating with an abrasive solution. The diameter of this wear scar is then measured to determine coating thickness.

Measured Coating Thickness	
Best Case Upwind (Upwind 17)	0.97 µm
Worst Case Upwind (Upwind 23)	1.10 µm
Best Case Downwind (Downwind 17)	0.94 µm
Worst Case Downwind (Downwind 4)	0.96 µm

Table 6: Post-operation DLC coating thickness per Calowear test



Coating thickness was also measured by SEM using Focused Ion Beam Milling where material is removed perpendicular to the surface to show a cross section. Both inspections showed no discernable wear of the coating itself. A magnetic particle inspection was also performed that showed no indication of cracks on any of the rollers.

Figure 12: SEM measured FIB section

Measured Coating Thickness	
Best Case Upwind (Upwind 17)	0.95 µm
Worst Case Upwind (Upwind 23)	0.98 µm
Best Case Downwind (Downwind 17)	0.83 µm
Worst Case Downwind (Downwind 4)	0.85 µm

Table 7: Post-operation DLC coating thickness per SEM scan

Conclusion

The bearings did not show visual signs of significant surface wear or damage. Additional tests were performed with the following results:

- Visible grind lines indicate minimal adhesive wear occurred.
- Toward the end of service, some iron wear particles were present, which confirms minimal surface wear.
- Post-operation profiles and surface finishes do not show surface wear.
- No significant change in hardness or microstructure was observed, and the DLC coating was still within thickness specifications with good adhesion and no signs of surface cracks.

Combining the results of each inspection shows that the bearing was in excellent condition after over 7 years of operation and could have continued in service. This is lending to the DLC coating's ability to significantly reduce adhesive wear, which can potentially prolong mainshaft bearing life.

10-Year Wear Resistant SRB

Introduction

From the first batch of DLC SRBs produced by Timken, another 230/600 DLC SRB was installed in March 2011 at a wind farm in Oklahoma and removed from service early in 2021. This bearing underwent in-service inspections in 2015 and 2017 before ultimately being removed from service with over 10 years of service life due to repowering of the turbine.

Visual Inspection

Much like the 7 Year DLC SRB, all bearing components showed limited adhesive wear with minimal damage on the downwind row. Crosshatch grind lines are still visible on the outer race. Both roller compliments also appear to be in good condition after operation, showing only light circumferential lining and minor denting.

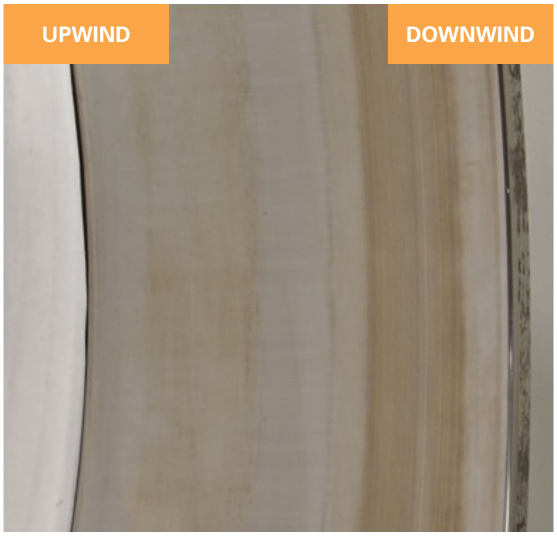


Figure 13: Outer race after 10 years of service

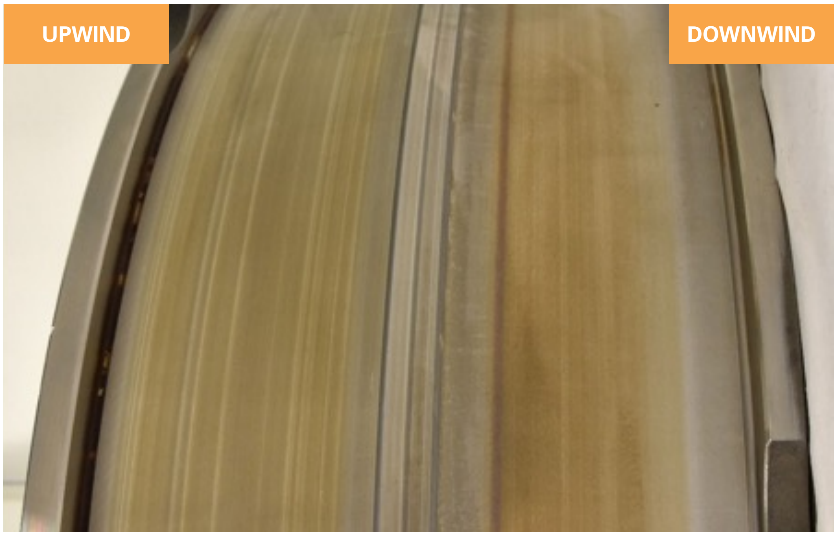


Figure 14: Inner race after 10 years of service

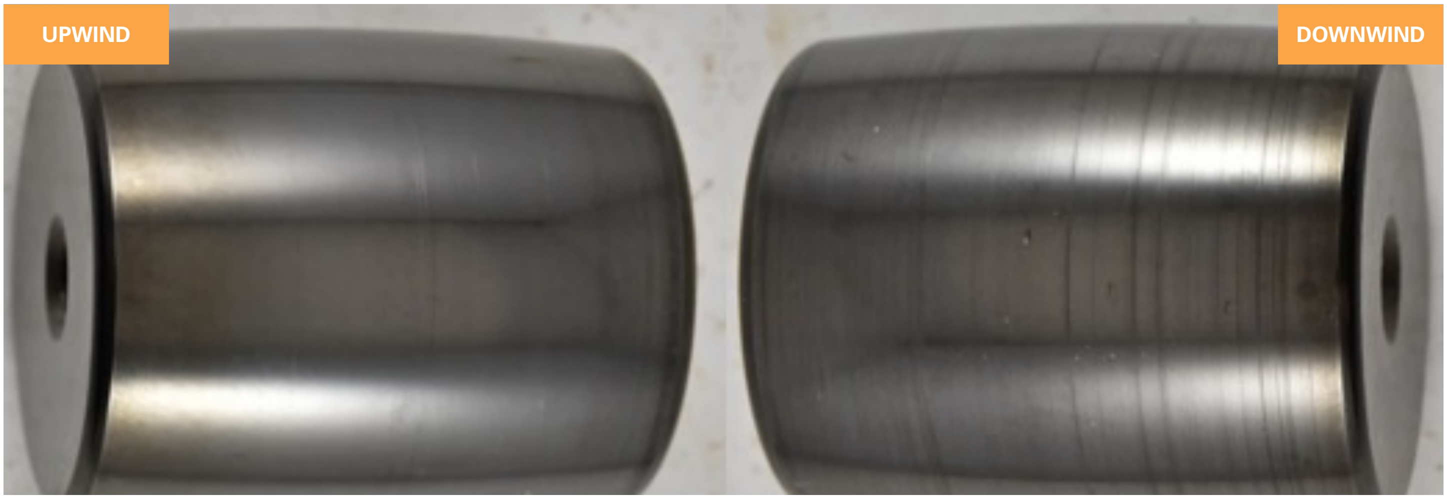


Figure 15: Upwind and downwind rollers after 10 years of service

Metrology

Following the visual inspection, a full metrology inspection was conducted on the bearing components. The inner and outer races showed light polishing with as-expected finishes in both the upwind and downwind rows. The still visible grind lines post-operation indicates little-to-no adhesive wear. The roller surface finishes are as expected with slightly increased roughness in the downwind row. This is a result of light circumferential lining as well as minor debris denting. Profile traces were also taken of each component. Each component showed little or no wear as shown by the levelized profile traces below.

Component	Upwind Surface Finish (µm)	Downwind Surface Finish (µm)
Outer Race	0.10	0.14
Inner Race	0.23	0.18
Roller	0.05	0.10

Table 8: Post-operation surface finish

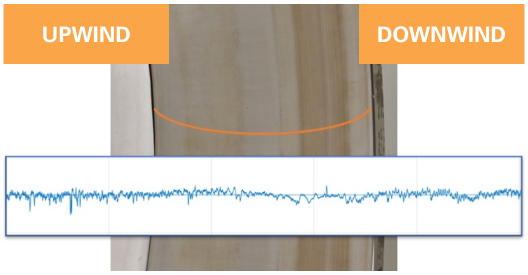


Figure 16: Levelized outer race profile trace

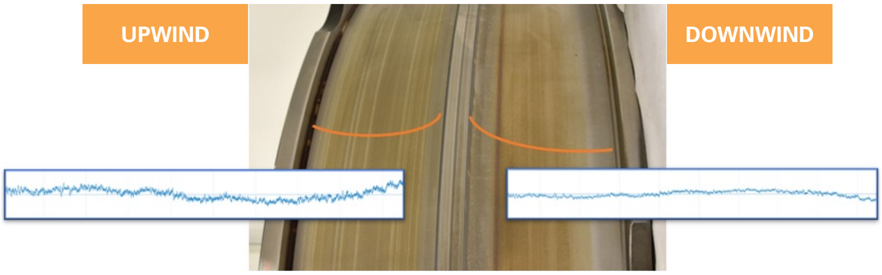


Figure 17: Levelized inner race profile trace

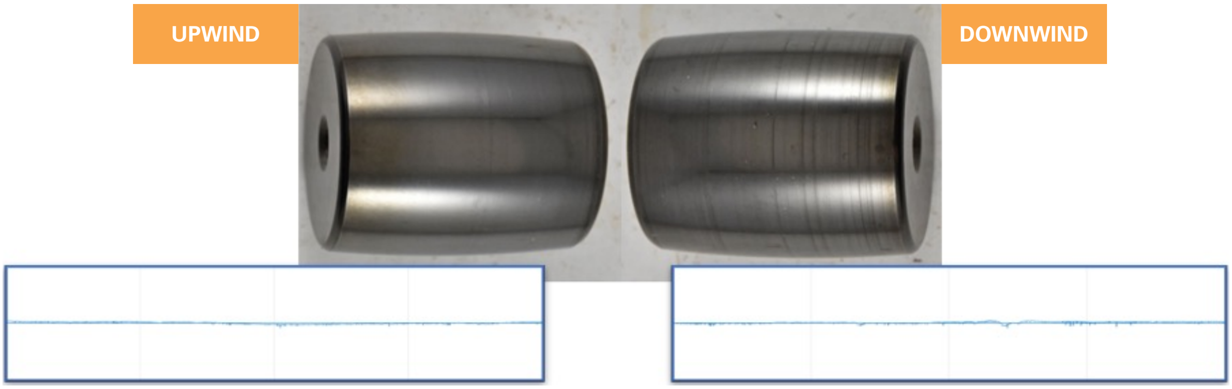


Figure 18: Levelized upwind and downwind roller profile traces

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Metallurgy

Surface hardness of each component remained in spec when inspected post-operation. Along with hardness, there were also no significant changes in microstructure of each component. A summary of these results can be found in Tables 9-10.

Location	Surface Hardness (HRC)	Comments
Outer	58.6, 58.2, 58.8, 58.5	Hardness measurements of all components were within specification limits, indicating no significant change during operation.
Inner	59.3, 59.6, 59.4, 59.4	
Roller – 1	61.2, 61.6, 61.1, 61.5	
Roller – 2	61,4, 61.4, 61.1, 61.0	
Spec	58.0–64.0	

Table 9: Post-operation hardness test results

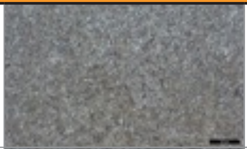
Nital Etch at 500x – All Cross-Sections from the Downwind Side of the Bearing			
Outer Race		Cross-section of outer race surface showing typical through hardened microstructure.	All surface and sub-surface microstructures matched expected outcome for the material and heat treatment methods applied, indicating that there was no significant change in bearing metallurgy during operation.
Inner Race		Cross-section of inner race surface showing typical through hardened microstructure.	
Roller		Cross-section of roller body surface showing typical case carburized microstructure. (Note: DLC coating on the surface)	

Table 10: Post-operation microstructure results

DLC Coating Inspection

The DLC coated rollers underwent a full coating inspection including a Benz Adhesion test, Calowear Thickness test, and an SEM thickness measurement. The Daimler-Benz Test is performed by denting the roller with a spherical probe of a known diameter to check for any cracks or delamination under extreme deformation. Calowear test involves using a ball of known diameter and an abrasive media to create a wear scar from which a coating thickness can be measured. The results of these tests indicate that even the worst condition rollers from each row passed all inspections, and the coatings are considered to still be in spec.

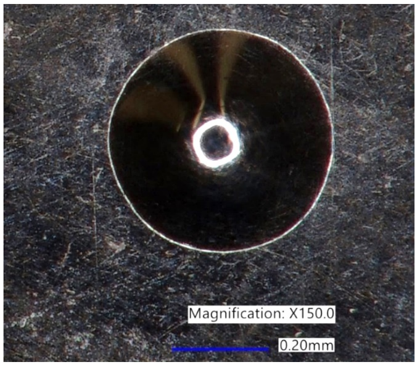


Figure 19: Benz Test Indentation

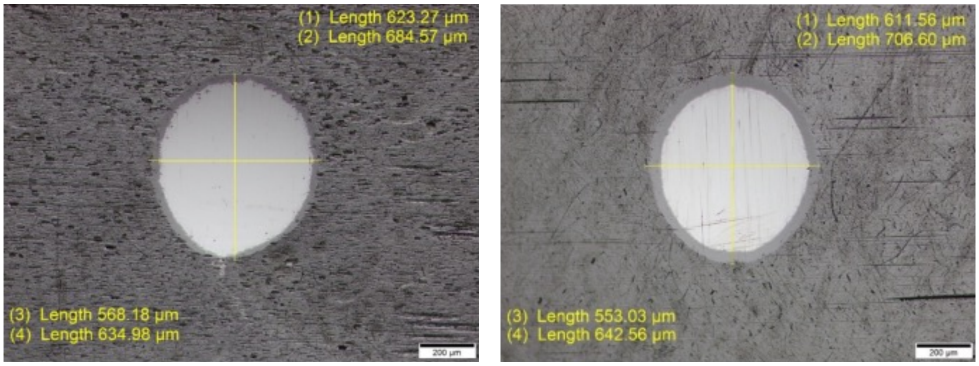
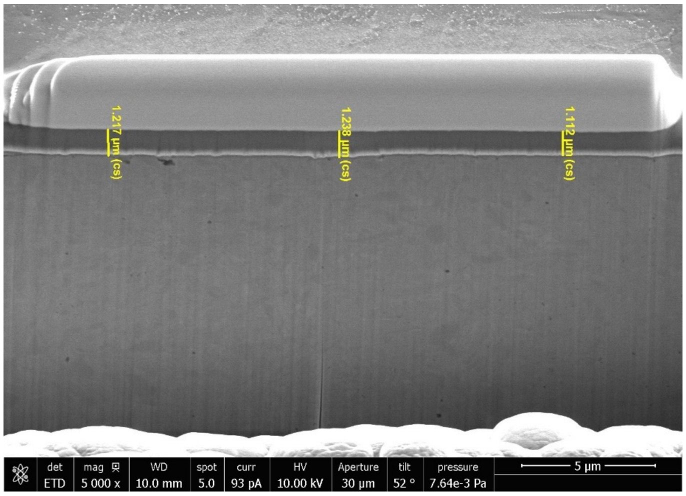


Figure 20: Calowear wear scar example

Measured Coating Thickness	
Best Case Upwind	1.25 µm
Worst Case Upwind	1.01 µm
Best Case Downwind	1.39 µm
Worst Case Downwind	0.79 µm

Table 11: Post-operation DLC coating thickness per Calowear test



Coating thickness was also measured by SEM using Focused Ion Beam Milling where material is removed perpendicular to the surface to show a cross section. Both inspections showed no discernable wear of the coating itself. A magnetic particle inspection was also performed that showed no indication of cracks on any of the rollers.

Figure 21: SEM measured FIB section

Measured Coating Thickness	
Best Case Upwind	1.30 µm
Worst Case Upwind	1.18 µm
Best Case Downwind	1.24 µm
Worst Case Downwind	0.92 µm

Table 12: Post-operation DLC coating thickness per SEM scan

Conclusion

Similar to the 7 Year DLC SRB, this latest bearing that was removed after 10 years of service did not show visual signs of significant surface wear or damage. Additional tests were performed with the following results:

- Visible grind lines indicate minimal adhesive wear occurred.
- Post-operation profiles and surface finishes do not show surface wear.
- No significant change in hardness or microstructure was observed, and the DLC coating was still within thickness specification with good adhesion and no signs of surface cracks.

Based on the results of the full damage analysis, this bearing is in very good condition after 10 years of service which further proves the success that the DLC coating has on mitigating damage caused by the inherent design of the SRB, such as micropitting and wear and therefore has the potential for prolonging mainshaft bearing life.

V. Conclusions

The seven-year performance results for a DLC SRB from Timken (one of the first installed) were previously published. In follow-up, we inspected the same bearing type after 10 years* of use. This is what we found:

- Both DLC SRBs, whether with seven or 10 years of use, were in excellent condition following post-service inspections.
- This demonstrates that the DLC coating, along with the other bearing enhancements, was effective in eliminating the primary damage modes of micropitting and wear in 3-point mount turbines.

**The bearing was removed when the wind farm was repowered.*

VI. References

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