# Representative Sampling for condition monitoring of in-service wind turbine bearings: challenges and solutions over 10 years

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**Development of cost-effective and accurate methods are crucial for operational condition monitoring of wind turbine blade bearings. Based on the Theory of Sampling (TOS), a novel method for acquiring representative samples of lubricating grease from in-service wind turbine blade bearings has been developed over the last 10 years, in some respects similar to 'on-line' PAT approaches used for continuous process sampling. The new method is compared and evaluated to a comprehensive, fully TOS-compliant refence sampling performed on dismantled bearings, which is a complete analogue to 'stopped belt' reference sampling. Three case studies are reported with which to illustrate the merits of the new wind turbine bearing condition monitoring method, which is needed in the rapidly developing renewable $CO_2$-free energy supply chain. Seen in the context of the currently much accelerated need for a massive green transition, the market prospects for this wind turbine process sampling approach can hardly be overestimated.**

## Introduction

The development of wind turbine technology is an incredible and fascinating story. In the 1980s, the first onshore turbines of 20 - 50 kW were erected, but at that time very few had the imagination to see what this would lead to. The first larger offshore wind farm was probably Horns Rev 1 off Denmark's west coast with an installed capacity of 160 MW (80 x 2 MW), commissioned in 2002. At the end of 2021, globally 54,000 MW of offshore capacity were installed, and this capacity will certainly be 10 times larger by 2030. This rapid growth has taken place because technology and advanced materials have made electricity produced by offshore turbines so inexpensive that today, in many parts of the world, it can easily outcompete electricity produced from fossil fuels.

Therefore, offshore wind will be a decisive factor in the transition to a hydrocarbon-free society (as shown in the video accompanying this presentation). In just a few years, the first 'energy islands will be built, surrounded by very large numbers of wind turbines. These islands will each have an installed capacity of 10 to 30 GW! Presumably, a significant part of this electrical energy will be used on the islands themselves to produce hydrogen, which will be piped ashore much like natural gas is today.

As offshore wind becomes a crucial element in the supply of renewable $CO_2$-free energy, the need to ensure continuing high availability increases. This involves many aspects; this presentation focuses on how the condition of the grease lubricated components in offshore turbines, primarily blade and main *bearings*, can be monitored by analysing representative samples of grease from the bearings. A previous project,[1-3] investigated in technical detail how to sample grease from in-service blade bearings.

Below, the main points from this study are reviewed, after which three case studies are presented that document the suitability of grease analysis for determining the contemporary *condition* of blade bearings.

## Main components of an offshore wind turbine

An offshore wind turbine consists of the following main components: rotor blade assembly (hub and the three blades), nacelle and tower plus a transition piece (Figure 1). The rotor blade assembly consists of three blades with a bearing at the root of each blade. Blade bearings serve two purposes: i) connecting the blade, which is the unit that collects energy from the wind to the nacelle, and ii) to enable the blade to rotate around its longitudinal axis i.e., to change its pitch. Blade bearings are therefore also often termed 'pitch bearings' (Figure 2).

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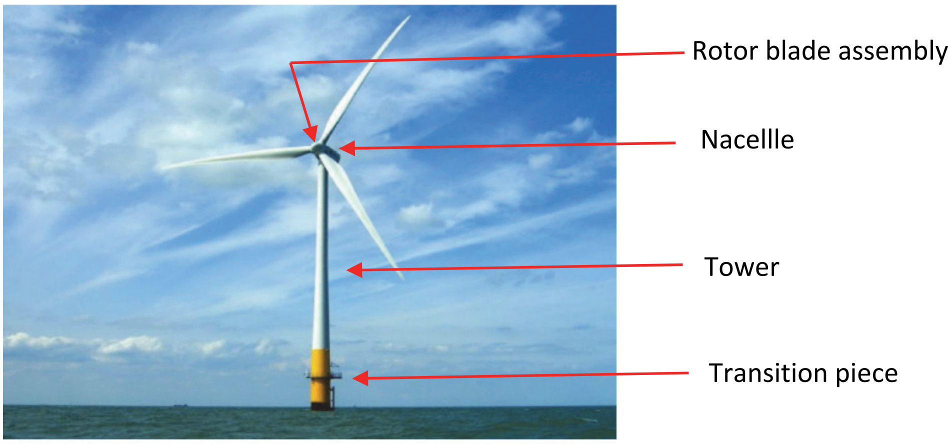



**Figure 1. Component of a windmill.**

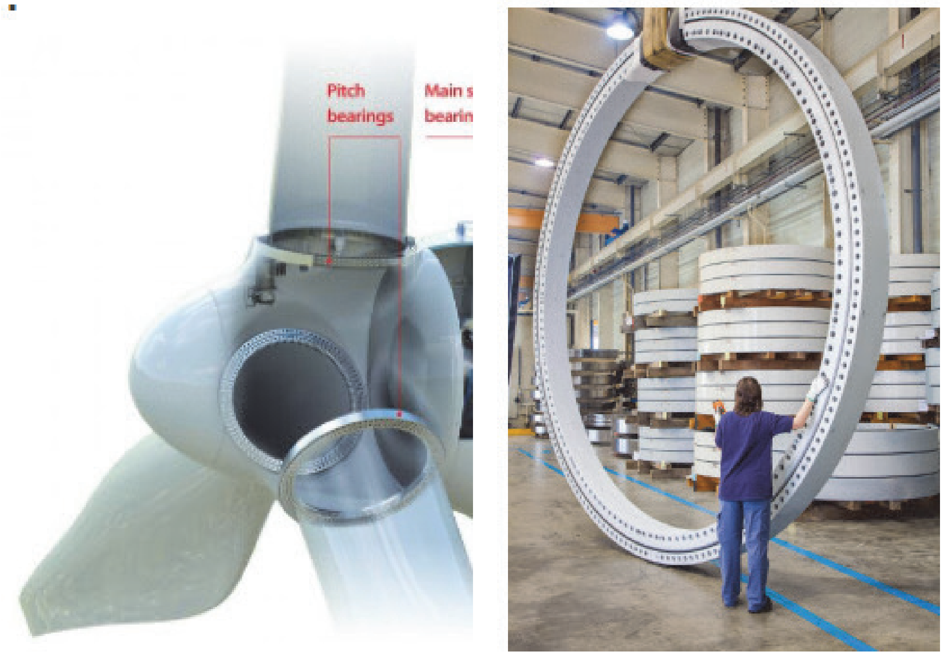



**Fig.ure 2. Rotor blade assembly (left) and complete blade bearing (right).**

## Representative sampling of grease from blade bearings

When a blade bearing has been assembled, it is no longer possible to access its active part, i.e., the space between the outer and inner races to take grease sample(s). However, in operation there is a continuous supply of new grease to the bearing, and the excess grease is pressed out and collected in containers located on either the outer or inner race of the blade bearing. These containers are accessible for taking in-service grease samples (Figure 3).

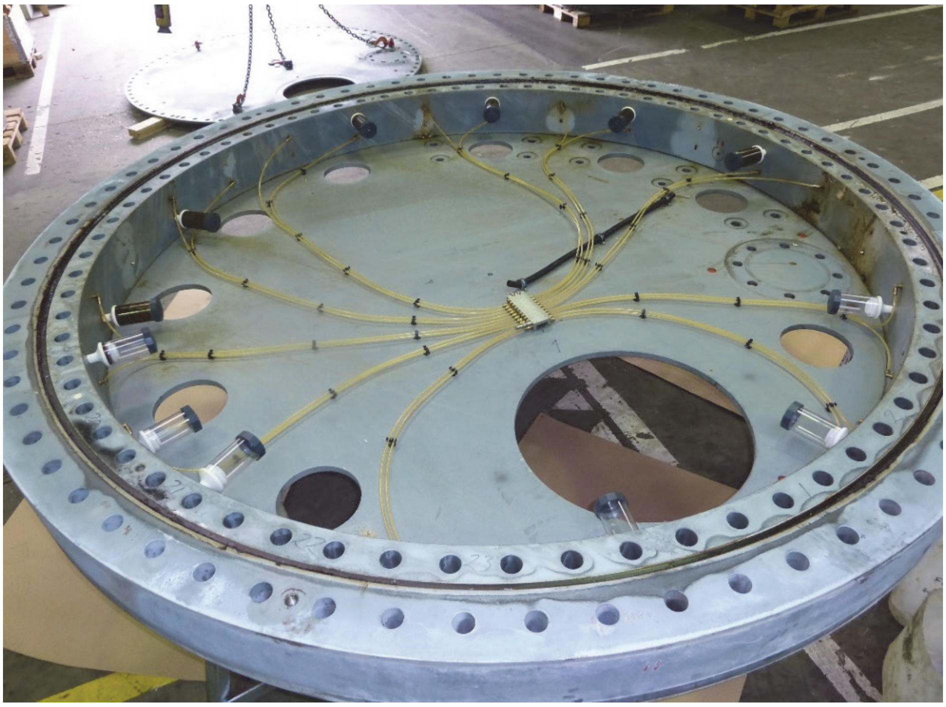


**Figure 3. Blade bearing in a 3.6 MW turbine with grease collecting devices ("Grease cups") fitted to the inner ring. The Grease cups are accessible for sampling of in-service grease samples used for condition monitoring.**

In a previous study[3], a full 3D-heterogeneity characterization of the grease in the active zone of blade bearings has been developed and described full detail. A summary will suffice for the present purpose.

With a bearing dismantled for inspection, it is possible to conduct sampling of the active raceway in a representative fashion according to TOS, as illustrated in

. Dismantling allows sampling and full characterization of the variation and properties of the grease *along* the full 360-degree active zone of the bearing in the space between the raceways.

This sampling scheme, here termed the 3-D heterogeneity characterization, forms the reference against which the in-service grease sampling from grease cups is to be compared and evaluated. As this characterization is fit-for-purpose *representative[3]*, it is the best available estimate of the properties of the active raceway lot, be this in the form of an *average* over the full circumference of the bearing ring, or as a *mapping* of the peripheral compositional variation in the active zone between the raceways.

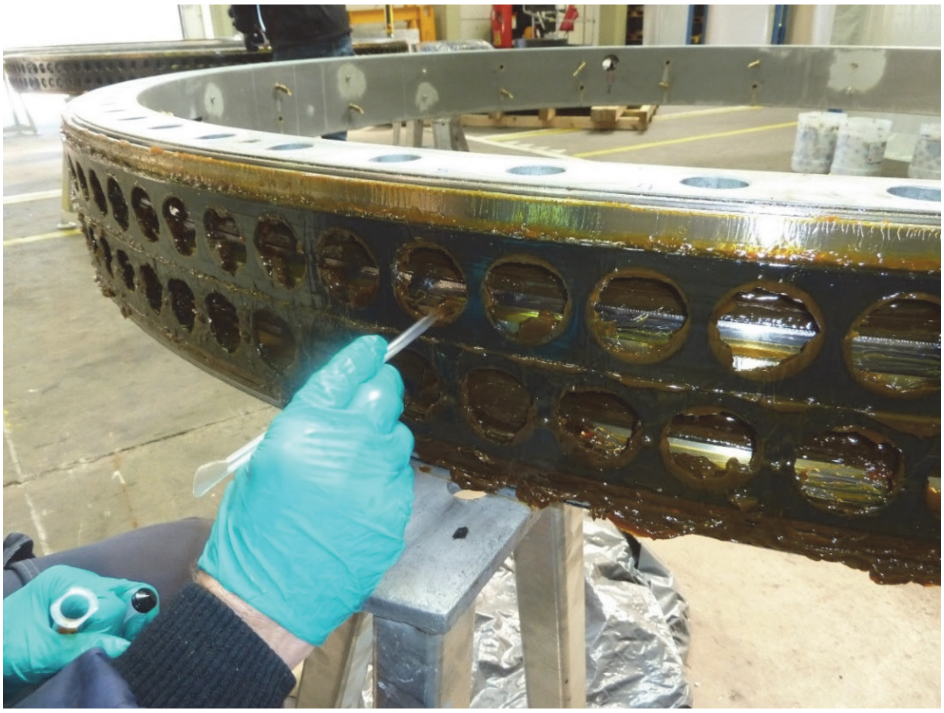


**Figure 4. Representative reference grease sampling (TOS) from a dismantled 3.6 MW blade bearing. Increments from every second ball support hole were taken for the 3-D heterogeneity characterization of the grease in the complete 360 degree active zone in the space between the raceways, furthering a reference analogue to "stopped belt" sampling.**

The analytes used in this reference characterization were i) content of ferro-magnetic iron, ii) water content, and iii) particle size distribution of wear debris. In total 175 grease samples were included in this comprehensive study and the results led to the conclusion that 'grease cup' sampling is a satisfactory *proxy* for representative sampling of an active raceway. Full documentation can be found here[3].

## Condition monitoring of blade bearings

Blade bearings have an atypical mode of operation, as they do not normally rotate when the turbine is in operation. This mode means that vibration analysis is not an option. Sampling and analysis of grease from blade bearings is today the only useful method for obtaining reliable data for assessing the operating condition of bearings.

The content of wear particles, size distribution and morphology are the most important parameters for assessing the condition of any grease lubricated bearing. COWI has developed dedicated analysis approaches which have proven to be suitable for mapping the condition of blade bearings over time. In our experience only wear particles larger than approximately 100 µm are relevant for a condition check of blade bearings. COWI's analysis program for used blade bearing grease therefore includes the following parameters:

- Content of ferro-magnetic wear particles, FdM-Fe (ASTM D8120)
- Size distribution of ferro-magnetic wear particles larger than 100 µm
- Microscopy of selected particles to determine type of wearing
- Water content (Karl-Fischer titration)

As a rule, samples of grease are taken from two randomly selected collection containers distributed along the complete inner or outer raceways a given bearing, see Figure 3.

In the following, three case stories are presented with typical examples of how analysis of grease can accurately determine the physical condition of bearings.

## Case Study 1: Blade bearings, 2 MW Turbine

Grease samples from three blade bearings, labelled A, B, and C, were examined for content of ferromagnetic wear debris. The results are shown in Figure 5.

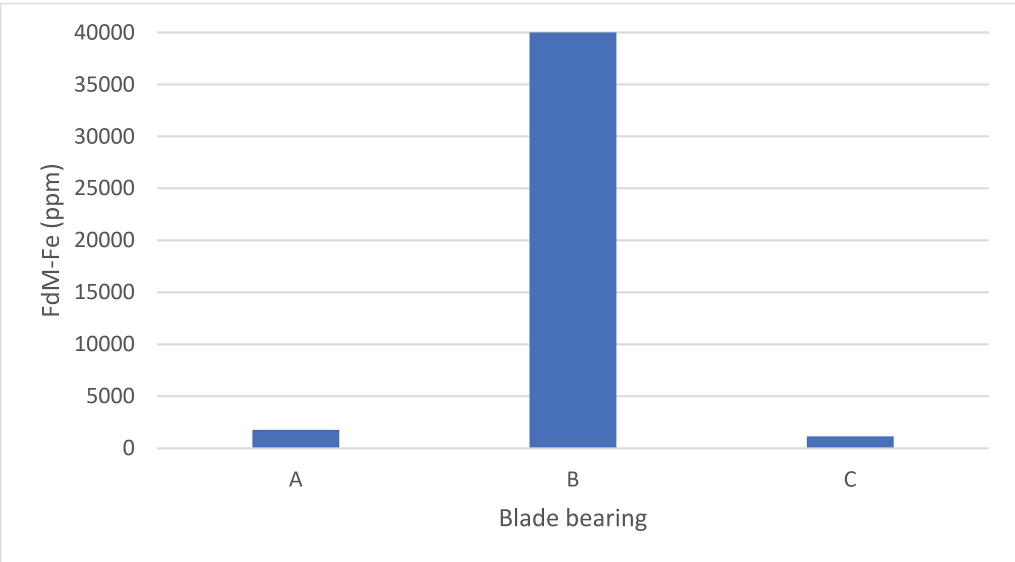



**Figure 5. Content of ferro-magnetic wear particles in the three blade bearings from a 2 MW turbine.**

Blade bearing B had a very high content of ferro-magnetic wear particles, significantly higher than the other two bearings. Ferro-magnetic wear particles were collected on a membrane filter, Figure 6. The number and size distribution of ferro-magnetic wear particles larger than 100 µm are shown in Figure 7. Figure 8 shows examples of very large wear particles in grease from blade bearing B.

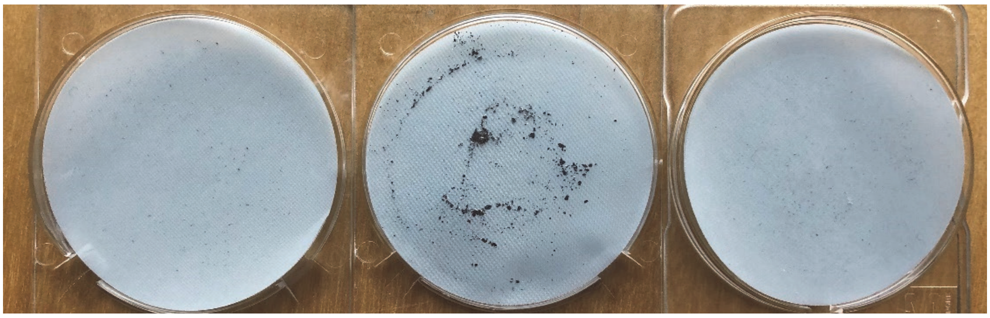
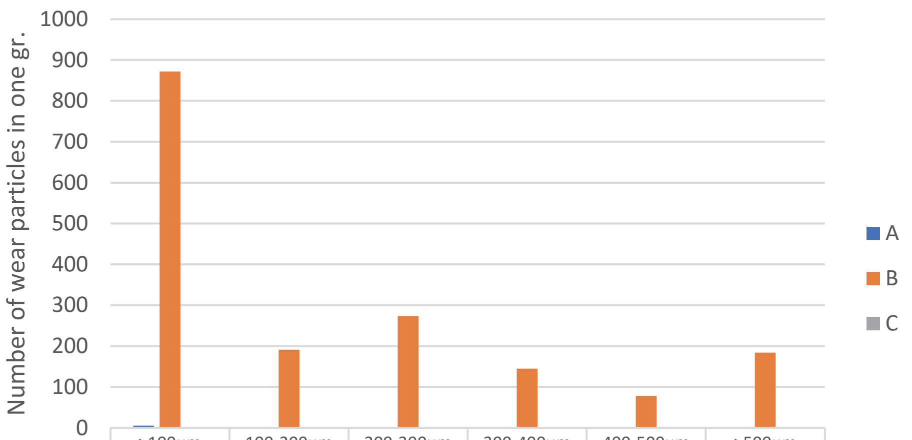


**Figure 6. Membrane patches with ferro-magnetic wear debris - from left to right blade A, B and C.**




| | >100µm | 100-200µm | 200-300µm | 300-400µm | 400-500µm | >500µm |
|---|---|---|---|---|---|---|
| A | 5 | 2 | 2 | 1 | 0 | 0 |
| B | 872 | 191 | 274 | 145 | 78 | 184 |
| C | 2 | 0 | 2 | 0 | 0 | 0 |

**Figure 7. Number of wear particles per gram of grease and their size distribution.**

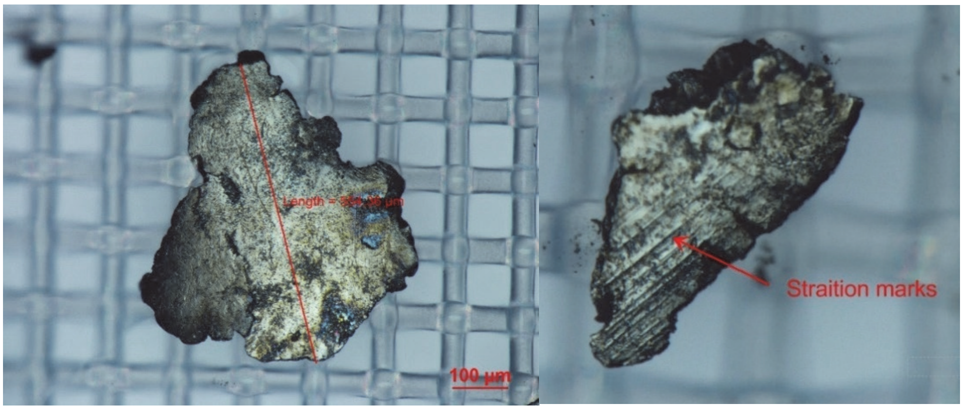



**Figure 8. Large wear particles observed in grease from blade bearing B. Note 100 µm scale bar.**

These results unequivocally showed blade bearing B to be so damaged that it had to be replaced. This assessment was confirmed when the bearing was subsequently opened for a closer inspection, Figure 9. It was clear that this bearing had reached the end of its safe usage.

**Figure 9. Appearance of blade bearing B, a deep groove ball bearing. Note the heavy peeling on the raceway and that several of the balls were cracked.**

## Case Story 2: Blade Bearings, 4 MW turbine after 10 years of operation

The same analysis program for ferro-magnetic wear debris was used as in case 1, with results shown in Figures 10 through 12. There is a remarkably large difference between the operating conditions of the three blade bearings in this 4 MW turbine after 10 years of operation. Blade bearing A shows no signs of failure while bearing B must be characterized as severely damaged. The bearing was subsequently replaced. Bearing C also has an elevated content of ferro-magnetic wear particles, but it was estimated that this bearing could stay in operation for a few more years.

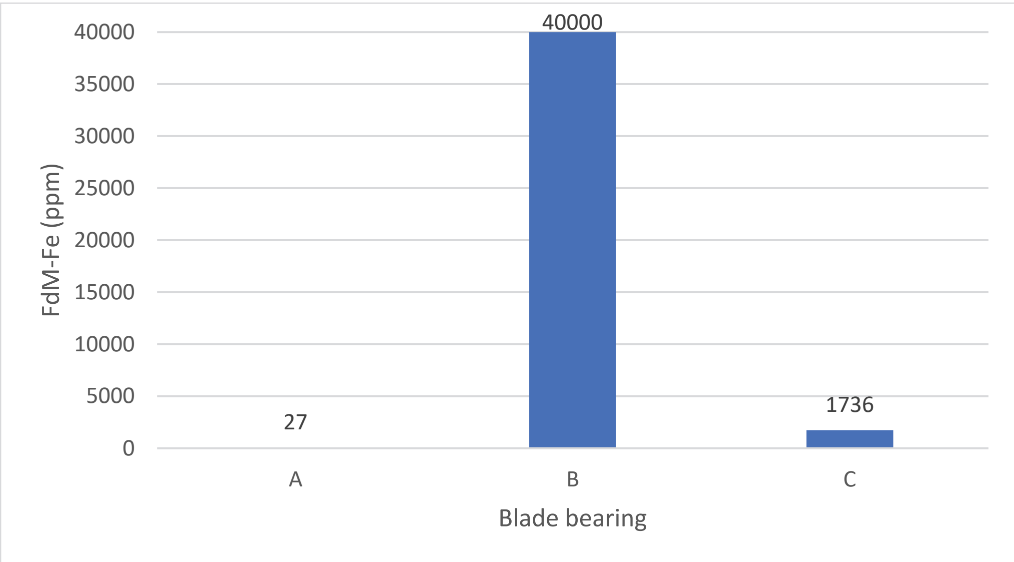
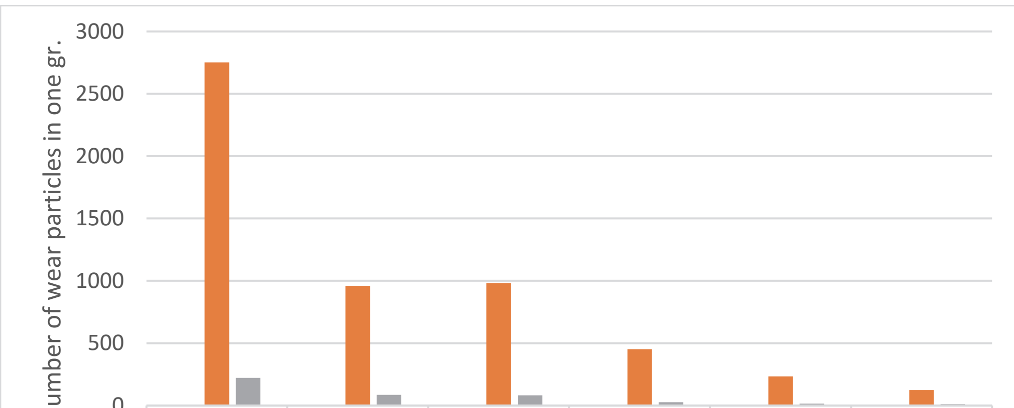



**Figure 10. Content of ferro-magnetic wear particles in the blade bearings from the 4MW turbine.**




| | >100µm | 100-200µm | 200-300µm | 300-400µm | 400-500µm | >500µm |
|---|---|---|---|---|---|---|
| A | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 2751 | 959 | 982 | 452 | 234 | 125 |
| C | 222 | 86 | 82 | 27 | 15 | 11 |

**Figure 11. Number of wear particles per gram of grease and their size distribution.**

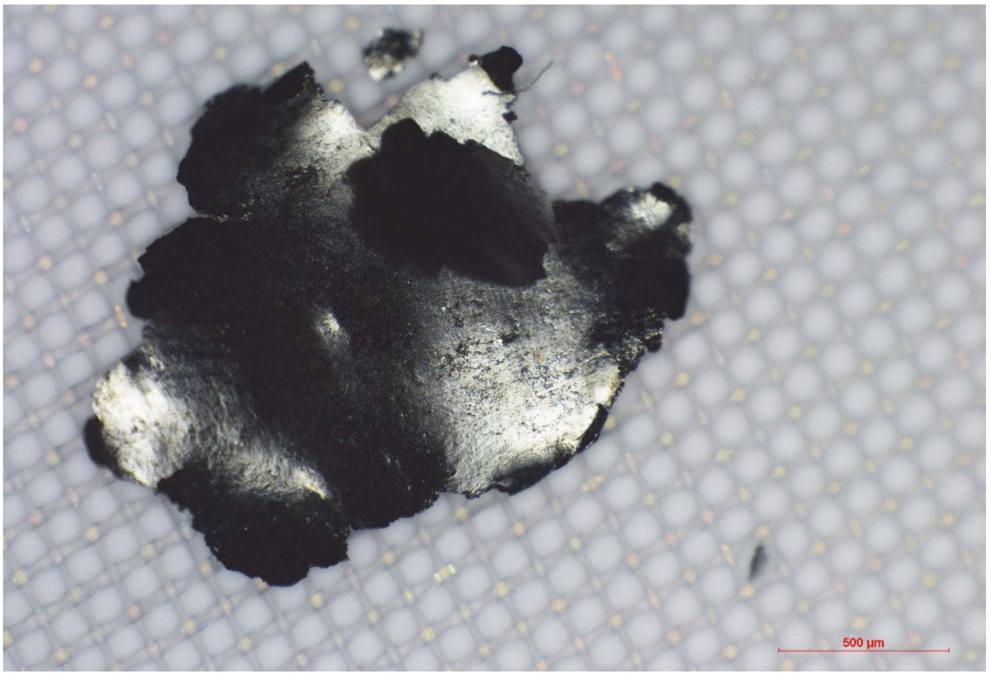



**Figure 12. Very large wear particle observed in grease from blade bearing B. Note 500 µm scale bar.**

## Case Story 3: Blade bearings, offshore wind farm. Turbine size 4-6 MW

Over the last five years, COWI has analysed a large number of grease samples from blade bearings in offshore turbines, which has led to some surprising and interesting observations. Based on this monitoring, it can be stated that well-functioning blade bearings show a low, constant content of ferro-magnetic wear particles. One might have expected that the number of dislodged particles would tend to increase as wearing continues as the bearing ages, but this is not the case. Figure 13 shows the FdM-Fe trend data for blade bearings without problems compared with a blade bearing (blade bearing C, turbine C01) that clearly has a high and increasing content of ferro-magnetic wear particles.

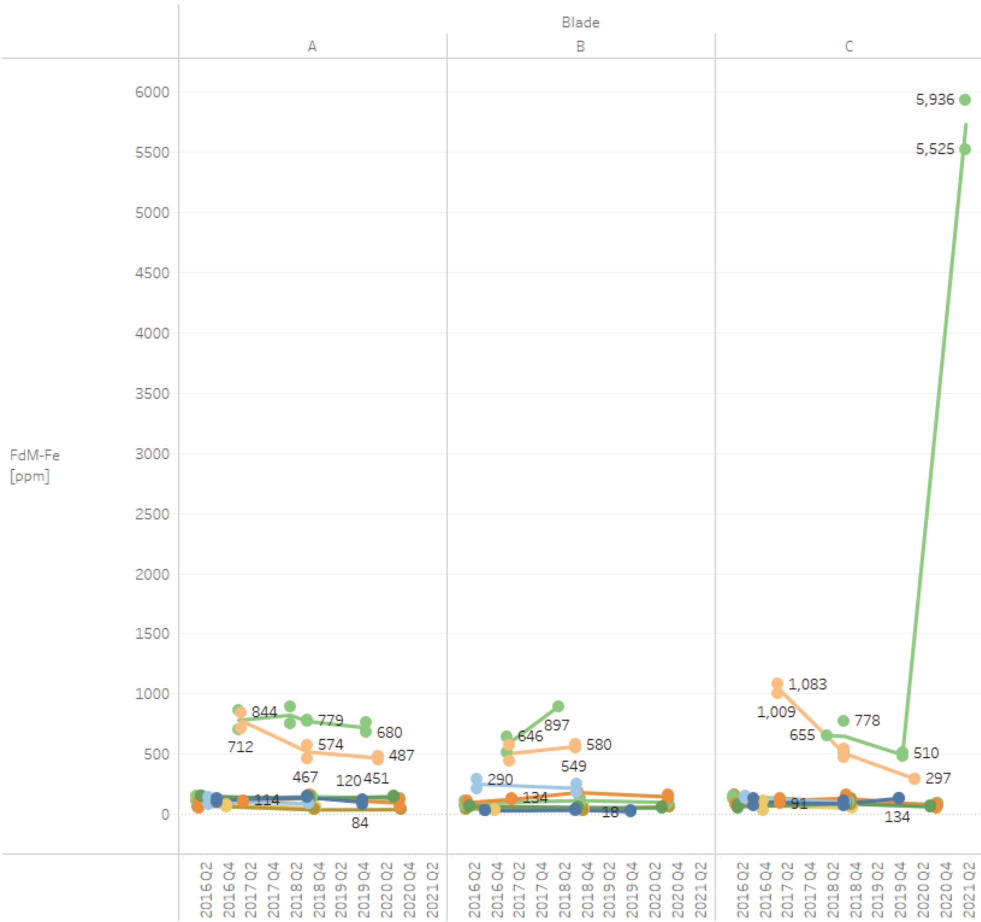



**Figure 13. FdM-Fe trend data for blade bearings without sign of faults (constant level of FdM-Fe) and one bearing (C, turbine C1, green line) with increasing content of ferro-magnetic wear debris clearly predicting premature failure of this bearing.**

Figure 14 shows the development in the defective blade bearing C. The graph shows the content of ferro-magnetic wear particles per gram of grease. The upper graph indicates the content of particles with a size in the range 300-400 µm, while the lower graph shows the content of particles larger than 500 µm. The presence of such very large wear particles indicates significant destruction of the bearing race which will lead to a significantly reduced service life for the bearing.

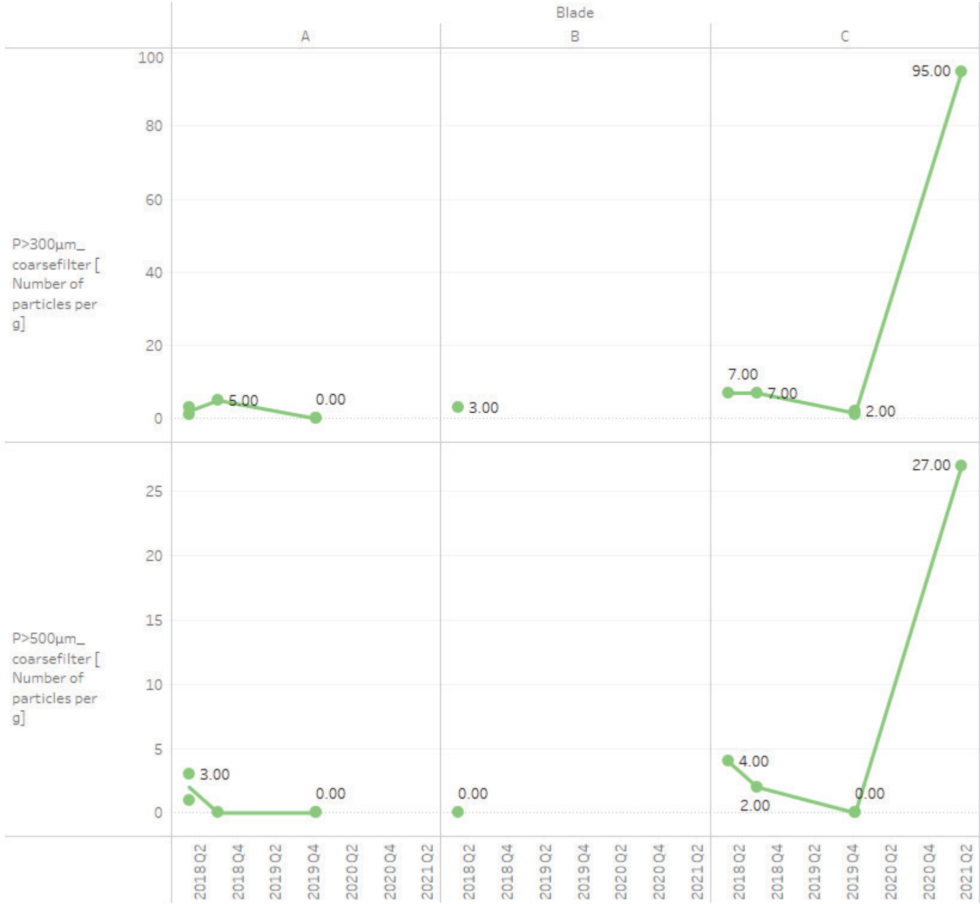



**Figure 14.1 Trend data for blade bearings without sign of faults (very low and constant amount of large ferro-magnetic wear particles) and the bearing C with significantly increasing content of ferro-magnetic wear debris.**

## Discussion

Offshore wind turbines in many countries of the world will become part of the backbone of the necessary transition to a $CO_2$-free renewable energy supply basis. Offshore wind turbines are extremely capital-intensive investments, for which reason cost-effective methods for operating and monitoring these assets are highly desirable. To solve this task, many different analytical tools (physical, chemical, artificial intelligence, AI) are used today to process today's readily available on-line data remotely onshore, with obvious needs for automation.

However, there are still main components, for which no documented method for continuous operational monitoring exists – yet, such as blade bearings. To monitor the crucial blade bearing component, the authors consider regular in-service sampling and analysis of bearing grease to be the most suitable method available today. The new in-service condition monitoring approach has many similarities with 'on-line' Process Analytical Technologies (PAT) approaches, used for TOS-compliant process sampling.

## Conclusions

Using the Theory of Sampling (TOS), it has been possible to develop a method for acquiring representative samples of grease from blade bearings in a wind turbine, which is a crucial prerequisite for development of an operational condition monitoring approach of in-service blade bearings.

With leading competence in tribology (the science of wear and friction), over the last 10 years, COWI has developed analytical methods targeting operational monitoring of grease lubricated bearings in wind turbines. These methods have been successfully implemented in several offshore wind farms - primarily in Northern Europe - but the full market roll-out has just begun.

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