



HAL
open science

Detection of the Early Stages Contact Fatigue on Gear Fatigue Testing Using Magnetic Barkhausen Noise

Bruno Lima, Ronnie Rego, André Oliveira, Thiago Oliveira

► To cite this version:

Bruno Lima, Ronnie Rego, André Oliveira, Thiago Oliveira. Detection of the Early Stages Contact Fatigue on Gear Fatigue Testing Using Magnetic Barkhausen Noise. ICRS 11 - The 11th International Conference of Residual Stresses, SF2M; IJL, Mar 2022, Nancy, France. <hal-03998013>

HAL Id: hal-03998013

<https://hal.science/hal-03998013v1>

Submitted on 20 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-SA 4.0 - Attribution - ShareAlike - International License

Detection of the Early Stages Contact Fatigue on Gear Fatigue Testing Using Magnetic Barkhausen Noise

Bruno Lima^{1,*}, Ronnie Rego¹, André Oliveira¹, Thiago Oliveira²

¹*Aeronautics Institute of Technology*

²*Federal Institute of São Paulo*

*Corresponding author: brunobhol@ita.br;

ABSTRACT

The Magnetic Barkhausen Noise (MBN) is a micro-magnetic non-destructive testing method that has the potential to be used in an industrial environment, as a fast comparative test to detect surface damages. There is a lack of studies in the literature covering the application of this technique for detecting temporal degradation over the lifetime of a component. The objective of this study is the assessment of the MBN signal evolution during the lifetime of gears, in order to detect contact fatigue failures in their early stages. Fatigue testing was performed in three gear samples to induce a residual stress relaxation until a contact fatigue failure occurs. The MBN signal was monitored in regular intervals of testing cycles to correlate the signal evolution with residual stress relaxation. The results show a remarkable variation on the MBN signal caused by the operational loads during the tests. A significant increase in the was observed right before the occurrence of the gear failure. Taking into account the gear lifetime and considering 0% the condition as manufactured, and 100% when the failure occurs. The failure was detected with 17 % of the gear life before it occurs.

Keywords: *Barkhausen noise; Residual stress; Relaxation; Fatigue; Gears*

1. Introduction

The development of wind energy generation technology in the last few years has surprised even the most optimistic industry players. Ahead of the projections and despite lingering perceptions, the cost of wind energy has been declining over the years, turning wind energy competitive even with conventional generation technologies across the top global markets, even without subsidies [1]. One of the most relevant problems, which currently remains unsolved, is the fact that wind turbines are designed to last 20 years, but critical failures occur in much shorter periods. Most turbines require significant repairs and even complete overhauls in the 5-7 years range [2]. In this scenario, the gearbox appears as the principal factor for the declining price of energy. That fact is attributed to the technology evolution, which, unfortunately, is balanced by premature critical failures that appear in the gearbox

The integrity of a component can be altered by the operational loads, environments action, and even by accidental events. To meet the demand for reducing maintenance costs, the concept of structural health monitoring has been increasingly studied in the last few years. Structural

* Corresponding author. Brunobhol@ita.br

Health Monitoring consists to give, at every moment during the life of a structure, a diagnosis on the surface integrity of the constitutive materials of the component [3].

Monitoring the cyclic relaxation of residual stress during gears operation is a technical challenge that makes it difficult to assess its effect on remaining life. The most common techniques for residual stress measurement are only suitable for periodic measurements in a laboratory environment [4]. The Magnetic *Barkhausen* Noise technique (MBN) is included in this context as a non-destructive method, which is sensitive to residual stress variations through variations on the micromagnetic properties of the material. The MBN allows to monitor a micromagnetic response when the material is exposed to a magnetic field, and this response can be correlated to the residual stress [5]. In this context, the MBN technique can be a relevant advance to realize *in situ* inspections on wind turbine gears since the equipment is portable and easy to be used.

In this study, three gears are used to perform fatigue tests. During these tests, the MBN signal will be monitored in regular intervals of number of cycles, mapping the evolution of the signal from the as-manufactured condition until the occurrence of a failure. With this approach, it will be possible to understand whether MBN signal monitoring can be used to detect fatigue failures in their early stages.

2. Magnetic *Barkhausen* Noise

Magnetic Barkhausen Noise (MBN) is a non-destructive technique employed for monitoring components made of ferromagnetic materials. The method is based on the detection of the signal emitted during the irreversible and discontinuous *Bloch* walls (BW) motion, which happens during cyclic magnetization and/or cyclic loading (Figure 1). On one hand, BW alignment and the corresponding MBN signal are strongly affected by the residual stress state. On the other hand, BW motion interferes with the microstructure (all crystalline defects), which strongly affects the free path of BW motion as well as the critical magnetic field necessary for the initiation of BW motion [5][6][7][8].

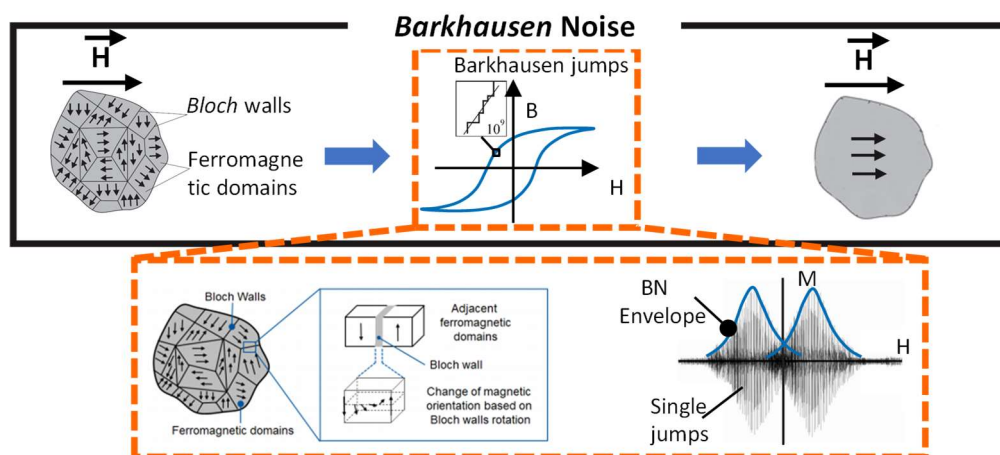


Figure 1 - Barkhausen noise: an external magnetic field is applied making the magnetic domains align with the external field generating Barkhausen jumps in this process [6][9].

MBN measurement can be classified into two categories: high-frequency and low-frequency MBN. The high-frequency measurement typically involves the use of a higher frequency of external magnetic excitation (> 10 Hz) and the analysis of the MBN signal is in the frequency range of 2–1000 kHz. The low-frequency measurement is typically performed at a lower magnetic excitation frequency (< 1 Hz) and the MBN signal is analyzed in the frequency range of 0.1–100 kHz. The maximum depth of the MBN signal that can be detected represents a limitation for the evaluation of changes in microstructure and residual stress in the depth

direction. Despite all the studies done with MBN, knowing the penetration depth of the technique in the test material according to the chosen parameters is still not a straightforward task. The only information that is consolidated in the literature is that the skin depth of the MBN is considered to be much lower in high-frequency measurement compared to low-frequency measurement. The statement is based on the effects of magnetic field penetration and attenuation of the high-frequency MBN signal [5].

The analysis of Magnetic *Barkhausen* Noise can provide indications about the studied material, such as hardness, microstructural changes, and residual stresses. It is also used as a complementary non-destructive evaluation (NDE) technique to both *Eddy current* probe sensors and magnetic flux leakage (MFL). Whereas *Eddy current* probe sensors and MFL are primarily applied to detect cracks, corrosion, and impurities in steel structures, MBN sensors are incorporated in the system to detect stress in the steel under evaluation [10].

3. Materials and Methods

3.1. Fatigue Tests

The study was developed in a dedicated rig for testing gears, it is based on the back-to-back concept, which allows the optimization of the load application [11]. The test rig has a unique configuration with four gearboxes, allowing the testing gears to be dimensioned for two distinct center distances 71 and 114 mm. These four gearboxes are connected by three lines of power transmission with different torque and rotational speeds. Among some of its specifications, the maximum torque on lines 1, 2, and 3 respectively are 500, 1000, and 3500 N.m., beyond that, the maximum rotation on line 1 is 7,000 rpm.

The tests were performed using helical gears with a normal module of 1.8 mm which has the application in automotive manual transmission. The gears present a Helix angle β of 30.5° and a normal pressure angle α of 14.5°. The manufacturing material is case-hardened low alloy steel and the pinion and gear have 31 and 37 teeth respectively promoting a transmission ratio of 1.19:1. To test this gear-pair, the parameters selected were a rotational speed of 3000 rpm, a torque of 210 N.m, and a temperature of 90 °C. At these conditions, the expected gear life was approximately 10 million cycles, and the failure mode was contact fatigue [12].

The test sequence defines three different tests that were interrupted at different load stages, Figure 2. The gray circles represent inspection points when MBN measurements were taken. As there is no record of the evolution of MBN during gear service life in the literature, it was decided to perform a more discretized first test, by conducting the inspection procedure at every 400,000 cycles. The expected lifetime of these testing gears is about 10 million cycles [12], with that, there would be approximately 25 inspections during the first test. This test was used to create a database to have a better understanding of the signal evolution over time, and thus optimize the following tests.

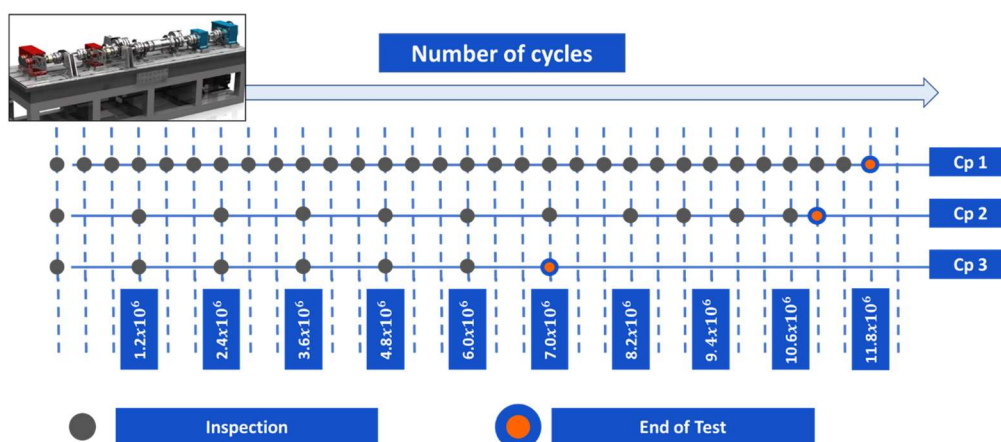


Figure 2 - Sequence of gear tests.

3.2. MBN Inspection

As the measurement region of the sensor tip had approximately one-third of the tooth width, it was decided to separate each tooth into three measurement regions, denominated “left”, “center”, and “right”. The inspection procedure consisted of measuring one tooth, skipping the next tooth, and measuring the next one. With this approach, sixteen teeth were measured in each inspection, Figure 3 exemplifies the inspection procedure. As fatigue is a probabilistic phenomenon, it would be very unlikely for a failure to appear only in teeth that were not being inspected [13]. This procedure leads to a significant reduction in the inspection time, without a meaningful loss of information, since the tests are highly time-consuming.

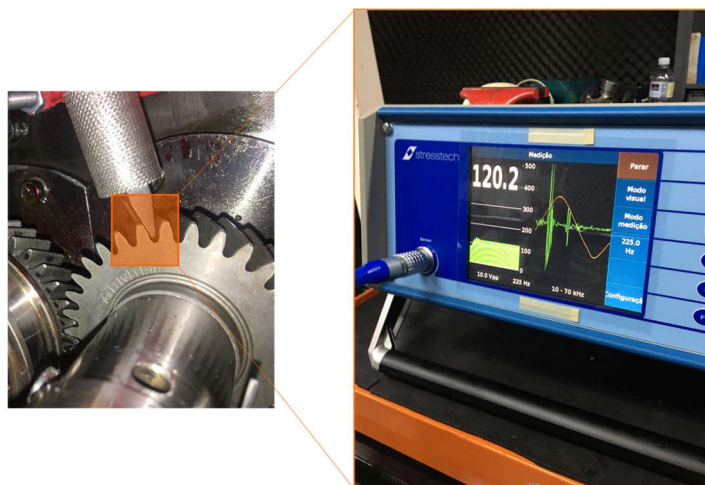


Figure 3 - Measurement procedure and measurement sequence with the MBN sensor.

Based on that calibration of the equipment, the parameters selected were 11.5 V for magnetizing voltage and 180 Hz for magnetizing frequency. The filter bandpass chosen had a range of 70 – 200 kHz, this filter was selected because it is in the range of the high-frequency MBE measurement method. It is common to see values of 5 V and 125 Hz for the calibration of materials without case-hardening. As the case-hardening induces a high hardness at the surface, it is expected to be necessary higher voltage values due to the more difficult magnetization of the material. Also, the selected values of 11.5 V and 180 Hz are in agreement with what is observed in the literature [7][8]. The high-frequency range is more sensitive to microstructural modifications near the surface, between 10 and 40 μm , this distance range is where it is expected the appearance of subsurface cracks [5][12][14]. The calibration of the sensor for the material to be measured is of extreme importance to ensure the sensitivity of the sensor. This process adjusts the ideal parameters to the physical-chemical properties of the component to be studied

4. Results and Discussion

The three different tested gears were analyzed regarding the evolution of the MBN signal during the operation. Each gear presented different signal levels when compared to each other, having the mean signal of all teeth varied from 29 mp in test 01 to 42 mp in test 03. These differences can be related to the intrinsic deviations of the manufacturing of each gear. The tested gears are of the same model but were not produced from the same batch, and these differences can cause a significant residual stress variation [15]. When comparing the MBN signal between teeth of the same gear, tests 01, 02, and 03 presented only minor variations, showing homogeneity among the teeth. Despite the variations, the assessed MBN signal is in agreement with what is observed in the literature for case-hardened materials [5][16]. Figure 4 shows the radar graph with the MBN values measured in each tooth of the gears in the condition as manufactured. The MBN signal is presented in mp (magnetoelastic parameter) which is represented by the difficulty or ease of magnetizing the material.

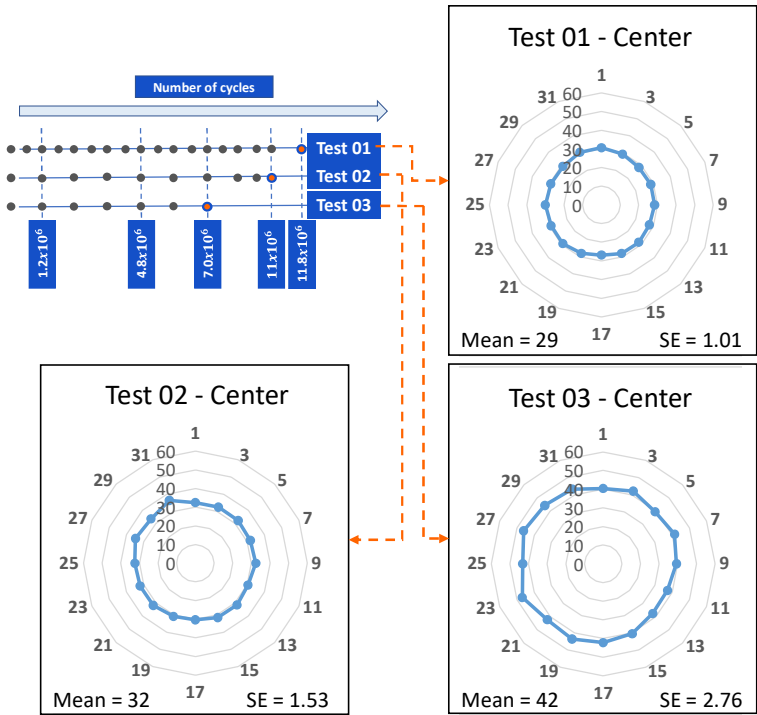


Figure 4 - MBN signal [mp] radar graphs between teeth of tests 01, 02, and 03 in the as-manufactured condition. The numbers around the largest diameter circumference represent the number of the measured tooth.

A very significant difference in the signal was observed after the first running cycles. A sudden increase in the MBN values was noticed in all tests. With a focus on the variation of this value, a parameter nominated ΔBN was used to correlate the evolution of the signal at different conditions of running cycles. This parameter uses the variation of the signal when compared to the previous condition, to establish situations in which the signal increase may represent a risk to the component. Considering the increase in the first inspection, after the first running cycles, the ΔBN varied from 51.51%, on the first inspection of test 01, to 62.44% on test 03. This difference is probably due to different conditions of stability of residual stress in each gear, causing different relaxation behaviors after a few running cycles. The cause of the increase in the MBN signal is probably due to the residual stress relaxation that happens in the first running cycles. It was expected since the literature shows the existence of significant residual stress relaxation in the first running cycles, this increase does not represent a risk to the gear integrity [17][18]. The visual inspection of the gear flanks did not show any difference between the tests, being present only the contact marks which are expected. Figure 5 presents the boxplot graphs of each test in the condition as manufactured and after 1.2 million cycles, each graph considers all the measurements of all teeth in the same gear. The MBN variation, represented by the ΔBN , was calculated using the mean value of the measurements.

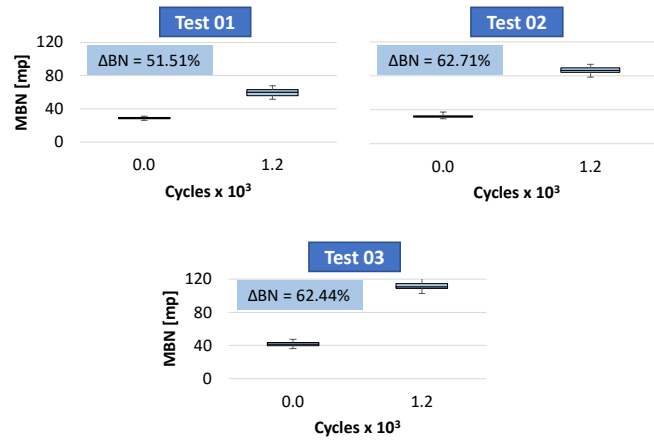


Figure 5 - MBN signal observed before running and its increase after 1.2 million cycles in each test.

After the first increase on the signal, all the tested gears entered into a region of MBN signal stability, having only minor variations or increases on the measurements along with the running cycles. The ΔBN parameter, which was registered to be higher than 50% in the first inspection, in subsequent inspections the ΔBN did not exceed 6% from one inspection to the next. This region with a small growth rate is similar to what is observed in a curve of residual stress relaxation caused by cyclic loads [18].

Figure 6 presents the MBN evolution of tests 01 to 03 and the respective gear flank of each test in the condition right after the signal presents the second significant variation. In all of them can be observed the stability behavior which occurs after the first running cycles. The small growth rate, represented by minimal variation in the signal, brings indications that significant variation on the surface integrity does not happen at this point. The sensitivity of the MBN signal to residual stress variations is a relevant point to be observed. At some point, which is different for each tested gear, the signal leaves the stability level and jumps to a higher signal level.

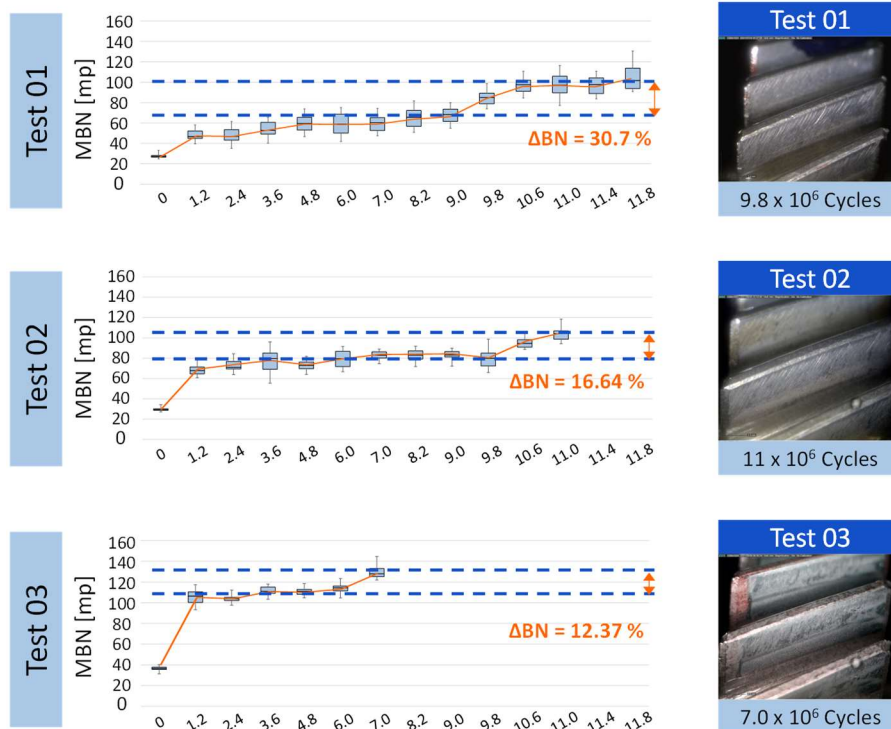


Figure 6 - MBN signal evolution of each test and its respective gear flank right after the increase of the signal after the stability region.

The signal stability was observed until the gears have reached 9.8, 10.6, and 7.0 million cycles in tests 01, 02, and 03 respectively. After that, in these three tests, the signal had a significant increase and the MBN signal left the stability region reaching a higher signal level. In test 01, the Δ BN almost had no variation after the first inspection. At 10.6 million cycles, the MBN signal had a significant increase of 12,33% when compared to the signal at 9.8 million cycles, and 30.7 % compared to the condition in 9 million. At this point, no indication of failure was observed at the surface of the teeth, indicating the occurrence of some phenomenon causing a microstructural alteration or a more expressive residual stress relaxation. The same phenomenon happened in tests 0 and 03.

Figure 7 presents the signal evolution obtained during test 01. At 10.6 million cycles, the Δ BN presented a variation of 30.7% in comparison to the last inspection in 9.0 million cycles. This value of variation represents an alert since the variation in all other inspections was less than 6%. After the increase at 9.8 million, it took only 2 million cycles more until the detection of a failure at the gear flank.

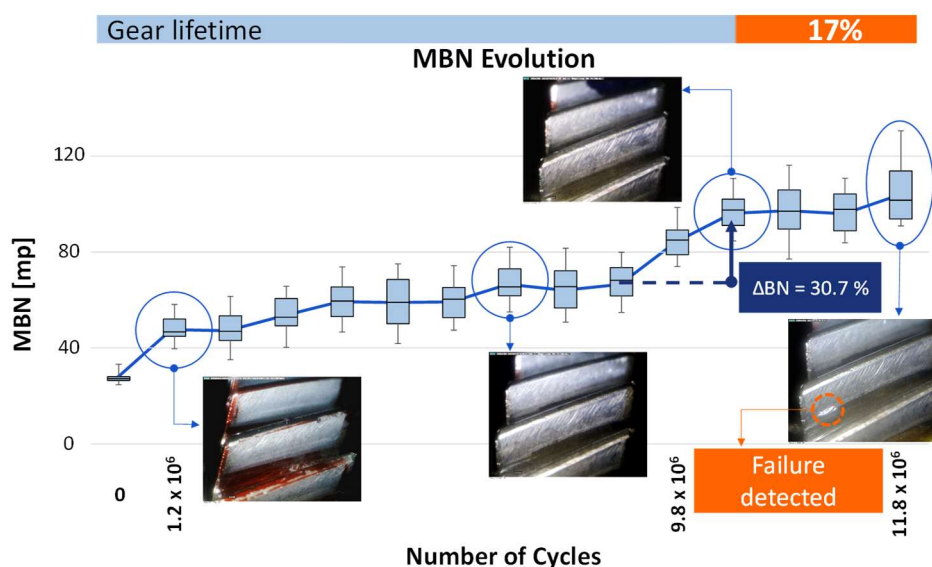


Figure 7 - Test 01 MBN evolution: the gear flank condition is presented in four different conditions

Taking into account the gear lifetime, considering 0% of life the condition as manufactured, and 100% when the failure occurs. The point in which the MBN signal had the second increase represented 83% of the gear lifetime. From the moment when a probable failure was identified by the signal increase until the failure itself occurs, this identification represented 17% of the gear lifetime before the failure became critical.

This result appears as a relevant advance, showing that monitoring the evolution of the MBN signal can be used to detect failures with enough time to acts preventively. Considering the wind energy sector, in which the designed life of the wind turbines is around 20 years, mapping the evolution of the MBN may provide the possibility of preventing catastrophic failures. Detecting a failure with 17% of the gear's life remaining will represent more than 2 years from the detection until the effective failure. This possible detection can bring the possibility to act preventively, reducing the downtime that a catastrophic failure can cause.

5. Conclusion

The monitoring of the evolution of the MBN signal was conducted in regular intervals of number of cycles in gears samples submitted to fatigue tests. It was shown that mapping this evolution can be the key to detecting contact fatigue failures in their early stages. The moment when the MBN signal left the stability region and reached higher values is the point of major interest. It represents that a significant microstructural change happened in the gear, inducing a more prominent residual stress relaxation.

A more detailed investigation will be done to understand the correlation between the MBN signal increase with characteristics of surface damages. Complementary analyses with SEM and X-Ray diffraction can indicate whether there is the presence of subsurface cracks and residual stress relaxation. A more comprehensive approach will help to understand the cause and the influential factors in the increase of the MBN signal, that happens when the component is getting close to failure.

References

- [1] Deloitte. (2018). Global Renewable Energy Trends. Retrieved from: <https://www2.deloitte.com/global/en/pages/energy-and-resources/articles/global-renewable-energy-trends.html>
- [2] Rensselar, J. V. The elephant – Full-scale efforts are underway to solve the giant gearbox problems that are preventing these machines from reaching their full potential.
- [3] Balageas, D., Fritzen, C. P., & Güemes, A. (Eds.). (2010). Structural health monitoring (Vol. 90). John Wiley & Sons.
- [4] Kwofie, S. (2012). Relaxation of Residual Stress under Fatigue Load Described in Terms of Cyclic-Plastic Deformation Model. *Structural Durability & Health Monitoring*, 8(4), 295.
- [5] Moorthy, V., Shaw, B. A., Mountford, P., & Hopkins, P. (2005). Magnetic Barkhausen emission technique for evaluation of residual stress alteration by grinding in case-carburised En36 steel. *Acta Materialia*, 53(19), 4997-5006.
- [6] Karpuschewski, B., Bleicher, O., & Beutner, M. (2011). Surface integrity inspection on gears using Barkhausen noise analysis. *Procedia Engineering*, 19, 162-171.
- [7] Sorsa, A., Santa-aho, S., Warttinen, J., Suominen, L., Vippola, M., & Leiviskä, K. (2018). Effect of shot peening parameters to residual stress profiles and Barkhausen noise. *Journal of Nondestructive Evaluation*, 37(1), 1-11.
- [8] Neslušán, M., Minárik, P., Grenčík, J., Trojan, K., & Zgútová, K. (2019). Non-destructive evaluation of the railway wheel surface damage after long-term operation via Barkhausen noise technique. *Wear*, 420, 195-206.
- [9] De Oliveira Teixeira, Patrícia Helena. Application of the hall effect for the assessment of thermal damage due to the grinding process of gears. 2017. 113p. Dissertation of master of science in manufacturing technology – Instituto Tecnológico de Aeronáutica, São José dos Campos.
- [10] Chukwuchekwa, N. Investigation of magnetic properties and Barkhausen noise of electrical steel (Doctoral dissertation, Cardiff University), 2011.
- [11] Aslantas, K.; Tasgetiren, S.; Yalcin, Y. Austempering retards pitting failure in ductile iron spur gears. *Engineering Failure Analysis*, v. 11, n. 6, p. 935–941, 2004.
- [12] Da Silva, Rodrigo Metzger. Failure detection method of gear contact fatigue in a test rig. 2021. 118f. Dissertation of Master of Science in Materials, Manufacturing and Automation – Instituto Tecnológico de Aeronáutica, São José dos Campos.
- [13] Wulpi, D. J. Understanding How Components Fail. 3.ed. Metals Park: ASM International, 2013.
- [14] Rego, R., Löpenhaus, C., Gomes, J., Klocke, F., 2018. Residual stress interaction on gear manufacturing. *J. Mater. Process. Technol.* 252, 249–258.
- [15] Rego, R. R., Klocke, F., Gomes, J., Löpenhaus, C., Assessing the heterogeneity of residual stress for complementing the fatigue performance comprehension. *The Journal of Strain Analysis for Engineering Design*, 51(5), 347-357. 2016.
- [16] Knyazeva, M., Rozo Vasquez, J., Gondecki, L., Weibring, M., Pöhl, F., Kipp, M., ... & Biermann, D. (2018). Micro-magnetic and microstructural characterization of wear progress on case-hardened 16MnCr5 gear wheels. *Materials*, 11(11), 2290.
- [17] James MR. Relaxation of residual stresses an overview. In: *Residual stress*, vol. 4. Elsevier; 1987. p. 349–65.
- [18] Totten, G.; Howes, M.; Inoue, T. *Handbook of Residual Stress and Deformation of Steel* - ASM International. [S. l.: s. n.], 2002. E-book.