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SENSITIVITY OF BARKHAUSEN NOISE MEASUREMENTS ON STEEL SAMPLES PRODUCED BY LASER POWDER BED FUSION

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Abstract. *The statistical understanding of the variability in magnetic Barkhausen noise signal, which is sensitive to the stress state and hardness of the material, is capable of providing a non-destructive method for a comparative evaluation of the residual stress state in steels. Therefore, it is essential to analyze the sensitivity of the method to the measurement conditions, that can alter the signal obtained using this technique, for a statistical evaluation of the results. The objective of this study is to evaluate the signal sensitivity in measurements with a Barkhausen noise sensor considering a gear involute geometry. A data-based approach for evaluating the signal consistency that includes repeatability and reproducibility of measurements in steels samples produced by laser powder bed fusion. Its objective is to determine factors that influence the uncertainty of the signal and the propagation of the error, such as sensor positioning, contact area and condition of surfaces. The analysis and interpretation of the parameters dispersion contribute to the investigation of the variability caused by the measurement device, the measurement conditions and the intrinsic differences between operators. The statistical understanding of the standard deviation of the Barkhausen noise signal, will allow the replication of the technique in a production line, making it possible to monitor microstructure deviations of a component in real time. Future research in the area of manufacturing and materials can increase the spectrum of non-destructive surface inspection solutions for problems not covered by existing methods. Through repeatability tests, a standard deviation of 16% was noted in the references between different operators, demonstrating that there is a need for standardization and statistical investigation of the measurement method with the purpose of increasing the robustness of the results.*

Keywords: *Residual stress, Measurement Robustness, Repeatability, Reproducibility*

1. INTRODUCTION

The MBN (Magnetic *Barkhausen* Noise) phenomenon happens by inducing discontinuous changes in the magnetization of ferromagnetic materials, under the influence of a continuously variable magnetic field. The signal strength is directly affected by the hardness and residual stress of the material being evaluated (Moorthy, 2008). Emerging as a highly capable method of evaluating microstructural parameters in ferromagnetic materials in real time due to its non-destructive characteristic. MBN and its applications have been studied in order to correlate the *Barkhausen* signal with material properties (Sorsa, 2012). This supports the need for a quantitative and qualitative understanding of the correlations between parameters extrinsic to the material that directly and indirectly influence the *Barkhausen* noise signal output.

In the current scenario to which the automotive industry is heading, electric vehicles are gaining prominence and with them, new drivetrain concepts are required to overcome the challenges of system efficiency, noise and vibration. Hence, additive manufacturing (AM), with its benefits of geometric freedom and new material possibilities, becomes an efficient solution to overcome the limitations of conventional manufacturing processes. However, AM metal processes, such as Laser Powder Bed Fusion (L-PBF), induce heterogeneous microstructure and residual stresses that can impact the mechanical performance of gears, despite the mentioned potential.

The present study, therefore, has the objective of investigating the main parameters that influence the signal strength, encompassing an analysis with different operators and different measurement conditions. Repeatability and reproducibility testing contributes to increasing the spectrum of nondestructive surface inspection solutions by helping to investigate signal robustness. Therefore, this study, which aims to analyze the sensitivity of the signal, also contributes to further research on surface integrity of additive manufacturing samples.

2. MATERIALS AND METHODS

The materials and methods section are divided in three subsections: the equipment used for the measurements, the measured samples, and the measurement procedure itself.

2.1 The *Barkhausen* noise signal analyser

The MBN analysis requires the use of a *Barkhausen* noise signal analyzer and sensor. The measurement process starts with the induction of an alternating magnetic field. Thus, by aligning the magnetic domains in the direction of the field, the measurement is carried out in the area covered by the sensor. These sudden changes in the magnetization of the material induce electrical pulses that generate the so-called Barkhausen jumps which are, in real time, captured by the analyser. The corresponding signal is then amplified, filtered and then displayed on the device's screen (Heiskanen, 2019).

Through a built-in signal processor, the *Stresstech Rollscan 300* was used to handle the measurement signals from the *Barkhausen* noise sensor. In turn, the equipment is used for controlling surface quality and investigating near-surface defects involving changes in residual stress and microstructure in a wide variety of engineering materials. The Figure 1 illustrates the measurement mechanism.

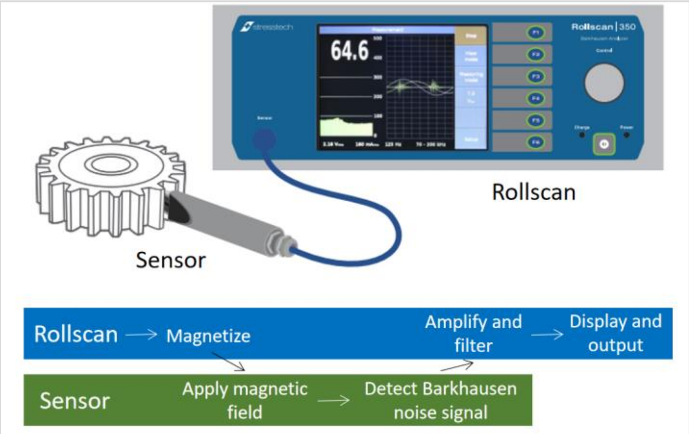

Figure 1. Schematic diagram of the equipment used (adapted from Heiskanen, 2019).

In order to understand and investigate the parameters that influence measurement sensitivity, the device's magnetization settings were also varied in the tests. Table 1 presents the main technical specifications of the equipment.

Table 1. Range of equipment settings used for *Barkhausen* noise measurements.

Setting	Unit	Range
Waveform	N/A	Sine
Voltage	Vpp	11-15
Frequency	Hz	100-125
Filter	kHz	70-200
Magnetoelastic parameter	mp	0-500

2.2 Measured samples

With the potential to push the boundaries of conventional manufacturing processes, additive manufacturing faces new challenges. These new solutions are closely associated with the residual stress (RS) variation resulting from the L-

PBF manufacturing process. This RS gradient across the component is critical for applications where the elements withstand severe cyclic mechanical loads, being susceptible to contact and bending fatigue (Davis, 2005).

With three specimens of additive manufacturing made with L-PBF technology, one gear and two rods. One of the specimen's geometry was a spur gear with 21 teeth, 2.85 mm of normal module and 22 mm of tooth width. In addition, measurements were conducted on a rod sample with 9.53 mm in diameter and 76.2 mm in length. The spur gear samples were manufactured with 20MnCr5 metal powder of 29 µm of medium size. The L-PBF process was performed in the Alkimat LaserFunde200 machine with a laser source of 200W power, a 550 mm/s scanning speed and a 0.1 mm hatch spacing. The power bed was heated up to 100°C and the filling strategy used was 5 mm islands. The deposition angle of the samples was 14° relative to the base. The stress relief heat treatment was carried out with heating to 650°C and slow cooling in the furnace.

2.3 Measurement procedure

In order to estimate the repeatability and reproducibility of measurements with the *Barkhausen* noise sensor, the experimental procedure was developed to observe the variation due to the measuring process when the operator measures the same part several times and to observe the variation due to the method itself by comparing the results of three different operators.

The repeatability test was designed for the operator to measure the same 21-tooth gear reference flank (T1, T2, T3... TN) in three series of test repetitions (N1, N2 and N3). Figure 2 depicts the gear specimen and the regions submitted to the measurement procedure.

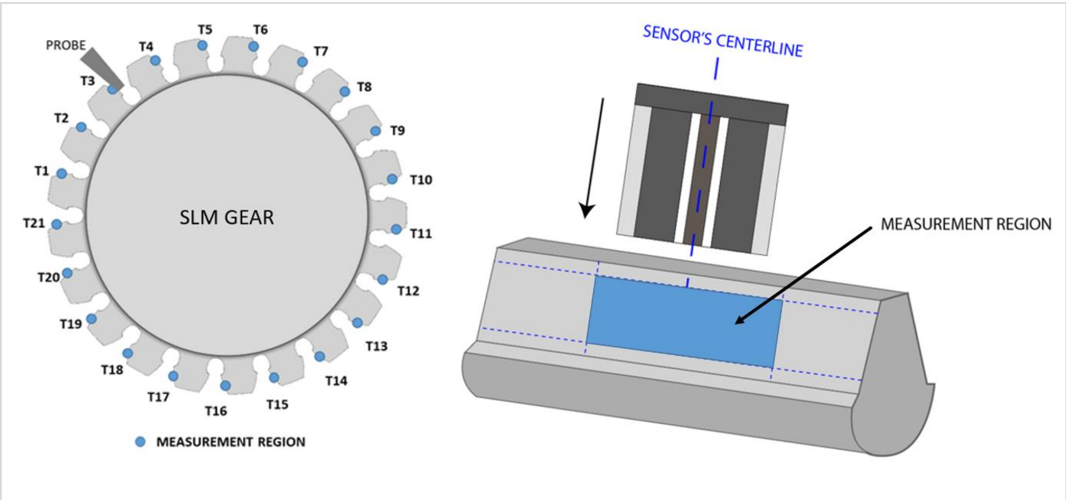

Figure 2. Schematic diagram of the measurement regions in the sample L-PBF gear

To also ensure the randomization of measurements, the order of measurement of the flanks was randomly defined for each operator. Table 2 clarifies the order of measurements.

Table 2. Measurement order of the tests conducted, the letter T stands for "tooth" (T1, tooth 1) and N for series (N1, series 1).

Region	N1	N2	N3
T1	1	8	19
T2	11	13	9
T3	7	4	11
T4	10	7	1
T5	17	11	13
T6	4	14	10
T7	2	3	6
T8	18	15	18
T9	9	10	8
T10	13	20	5
T11	3	2	4
T12	19	21	14
T13	12	17	3
T14	16	5	16
T15	5	12	12
T16	20	16	21
T17	15	9	2
T18	21	1	17
T19	6	18	7
T20	14	19	20
T21	8	6	15

Repeatability tests were also performed on the rod samples. The procedure followed the same logic for the samples L-PBF rod 1 and L-PBF rod 2. Figure 3 schematically represents the regions (A, B and C) of measurement. Then, tables 3 and 4 show the order of measurement for each sample.

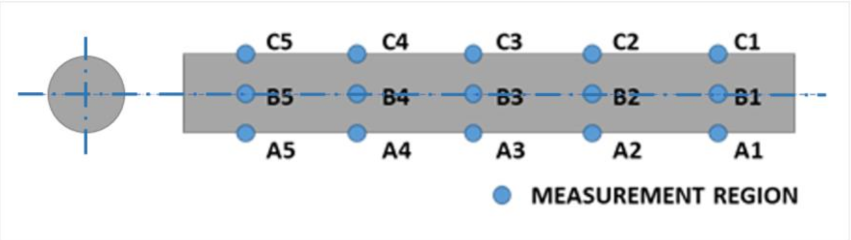

Figure 3. Schematic diagram of the measurement regions in the L-BPF rod samples.

Table 3. L-BPF rod (as built) measurement order.

Region	N1	N2	N3
A1	15	15	15
A2	5	9	4
A3	9	7	12
A4	4	13	2
A5	1	6	14
B6	10	11	1
B7	13	14	7
B8	15	3	10
B9	6	12	13
B0	12	4	8
C1	3	5	3
C2	7	8	11
C3	2	1	5
C4	8	10	9
C5	11	2	6

Table 4. L-BPF rod (stress relief) measurement order.

Region	N1	N2	N3
A1	15	15	15
A2	5	9	6
A3	11	8	1
A4	12	14	13
A5	1	2	7
B6	8	7	11
B7	3	13	5
B8	6	6	9
B9	9	10	3
B0	14	1	2
C1	2	11	8
C2	13	4	12
C3	7	3	10
C4	4	12	4
C5	10	5	14

The reproducibility test was developed to compare the variation of results between three operators. To achieve this goal, it was defined that each operator would perform ten measurements on each sample in identical pre-determined regions. Ten measurements were performed in region T2 in the L-BPF gear, ten measurements in region B3 in the L-BPF rod (as built) and ten more measurements in region B1 in the L-BPF rod (stress relief), totalling thirty measurements for each operator. Table 5 shows the measured regions of the samples by each operator.

Table 5 – Measured regions of the samples for operator O1, O2 and O3.

Sample	O1	O2	O3
L-BPF gear	T2	T2	T2
L-BPF rod (stress relief)	B3	B3	B3
L-BPF rod (stress relief)	B1	B1	B1

To confirm the hypothesis that the sensor contact area with the sample is an influencing parameter of results, and to estimate the quantification of its influence, the sensor contact area was varied on a flat ferromagnetic surface to block its area of operation in terms of the ideal measurement area recommended by the manufacturer. The variation in the contact area of the sensor with the sample was performed as a function of the centerline of the sensor. The contact was blocked using an insulating rubber-based adhesive tape. Thus, the blocking condition was performed by distancing the sensor from the sample, illustrated in Figure 4.

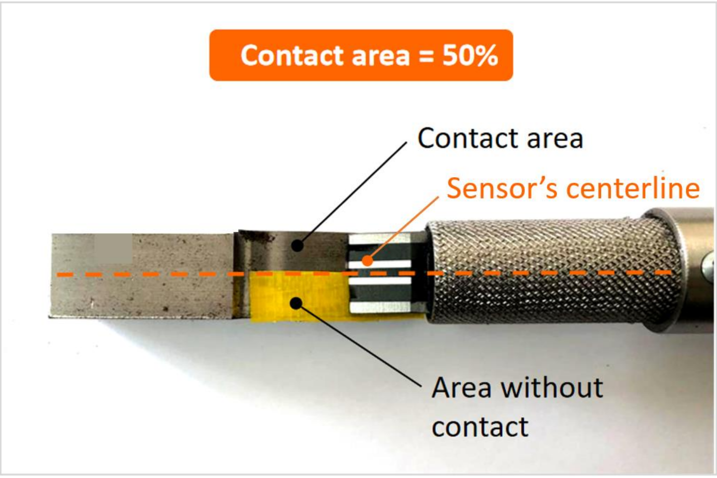

Figure 4. Schematic diagram of measurements as a function of the contact area.

For these tests, the contact area was varied as a function of the percentage of the sensor surface area in contact with the sample. The tests were divided into 100% (sensor surface area completely in contact with the sample), 50%, 25% and 0% (sensor surface area completely obstructed by the rubber-based adhesive tape).

To perform the repeatability, reproducibility, and sensor contact surface area tests on the samples, the equipment was calibrated according to the manufacturer's recommendations (Heiskanen, 2019). The procedure was performed separately before each test in order to adjust the equipment settings for the subsequent measurement on the respective samples. The signal strength of the MBN is expressed in terms of magneto-elastic parameter (mp). The equipment settings for each of the tests are presented in Table 6, 7, and 8, respectively.

Table 6. Equipment setting for the L-PBF gear tests with the magnetic *Barkhausen* noise sensor.

Setting	Unit	Range
Waveform	N/A	Sine
Voltage	Vpp	12
Frequency	Hz	125
Filter	kHz	70-200

Table 7. Equipment setting for the L-BPF rod tests with the magnetic *Barkhausen* noise sensor.

Setting	Unit	Range
Waveform	N/A	Sine
Voltage	Vpp	15
Frequency	Hz	112
Filter	kHz	70-200

Table 8. Equipment setting for the surface contact area tests.

Setting	Unit	Range
Waveform	N/A	Sine
Voltage	Vpp	11
Frequency	Hz	100
Filter	kHz	70-200

3. RESULTS AND DISCUSSION

The results of the measurements on the gear are summarized in the Figure 5. The radial graph illustrates the geometry of the gear. It can be seen that not only there are points with greater signal divergence between the three measurements, but also regions of the sample with significantly different absolute values. The results demonstrate the difficulties of repeating the measurements on a complex geometry, as well as metallurgical differences that influence the magnitude and variability of the signal.

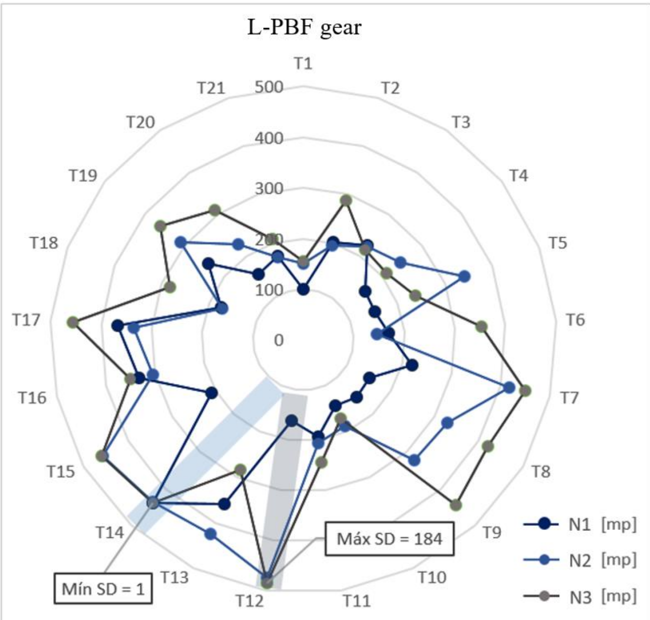

Figure 5. Results of the L-PBF gear measurements with the magnetic *Barkhausen* noise sensor.

In the measurements performed on the L-BPF gear, the largest standard deviation found was in the T12 region, caused largely by the disagreement between the N1 test series and the N2 and N3 series, which yielded close results.

The results of the measurements on the rods (as built and stress relief) are summarized in the figure 6. The larger standard deviations are caused by the divergence between the first series of measurement and the other two, showing the signal uncertainty even in a more controlled geometry.

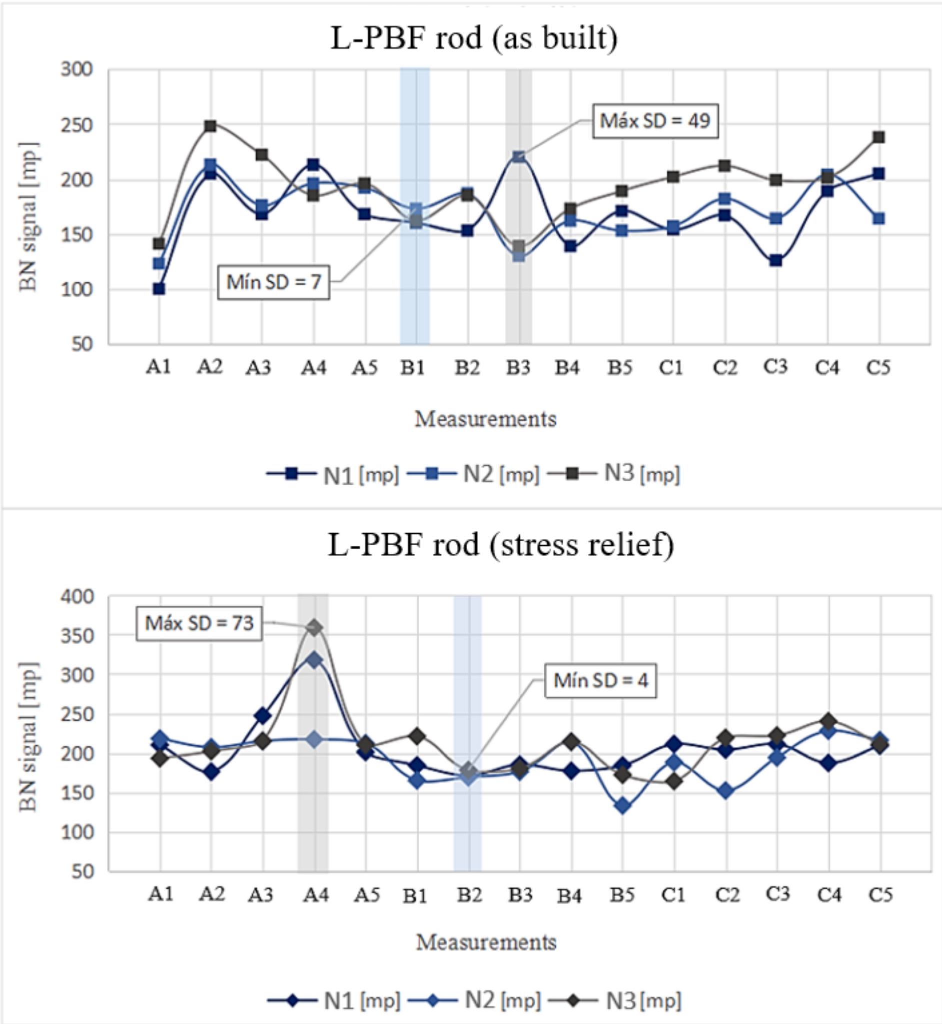

Figure 6. Results of the magnetic *Barkhausen* noise sensor measurements in the L-BPF rod samples (as built and stress relief).

To synthesize the results, the average of the repeatability test results was expressed in terms of percentage of standard deviation. The results were compiled in table 9.

Table 9. Analysis of signal variance in the repeatability tests.

Sample	**M1 Average [mp]**	**M2 Average [mp]**	**M3 Average [mp]**	**SD1/M1 Average**	**SD1/M1 Average**	**SD1/M1 Average**
L-BPF gear	210	218	193	43%	36%	32%
L-BPF rod (as built)	176	207	202	20%	15%	17%
L-BPF rod (stress relief)	247	215	215	18%	15%	21%

The first evidence in terms of change in the sensitivity of the Barkhausen noise signal occurs when is considered the presence of an involute geometry on the flank of the first sample, whose signal sensitivity was 20% higher than in L-BPF rod samples This fact demonstrates that factors such as the sensor's contact area with the sample surface and the positioning of the sensor itself can cause significant signal deviations in the results.

The same calibration logic of the previous measurements was used for reproducibility tests. In this procedure, samples of different materials went through a specific calibration to proceed with the tests. The results of sample measurements for each of the three operators are summarized in Figures 7 and 8.

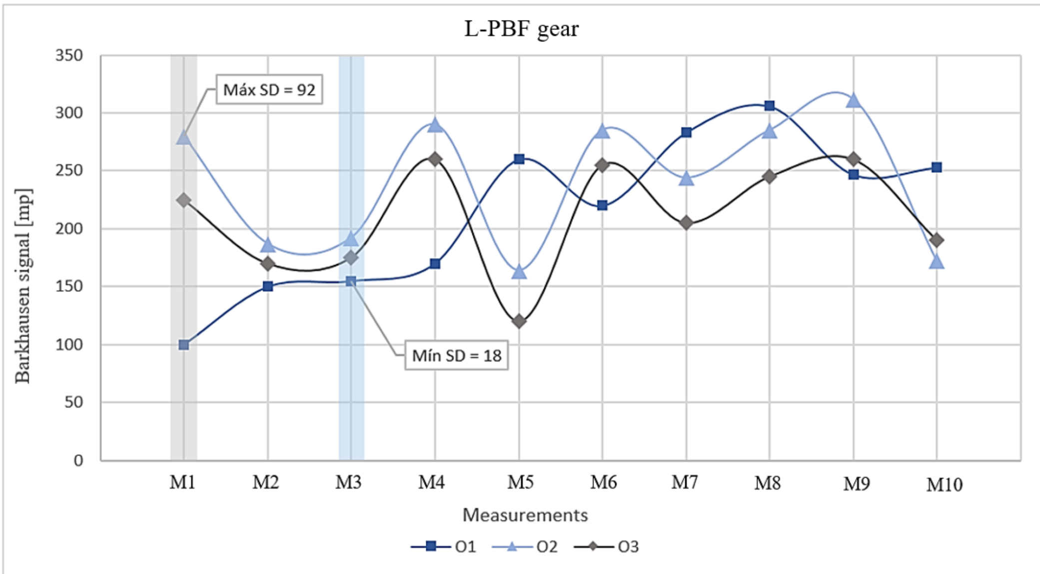

Figure 7. Results of the magnetic Barkhausen noise measurements in the L-BPF gear. The letter "O" stands for "operator" (O1, operator 1) and M for measurement (M1, measurement 1).

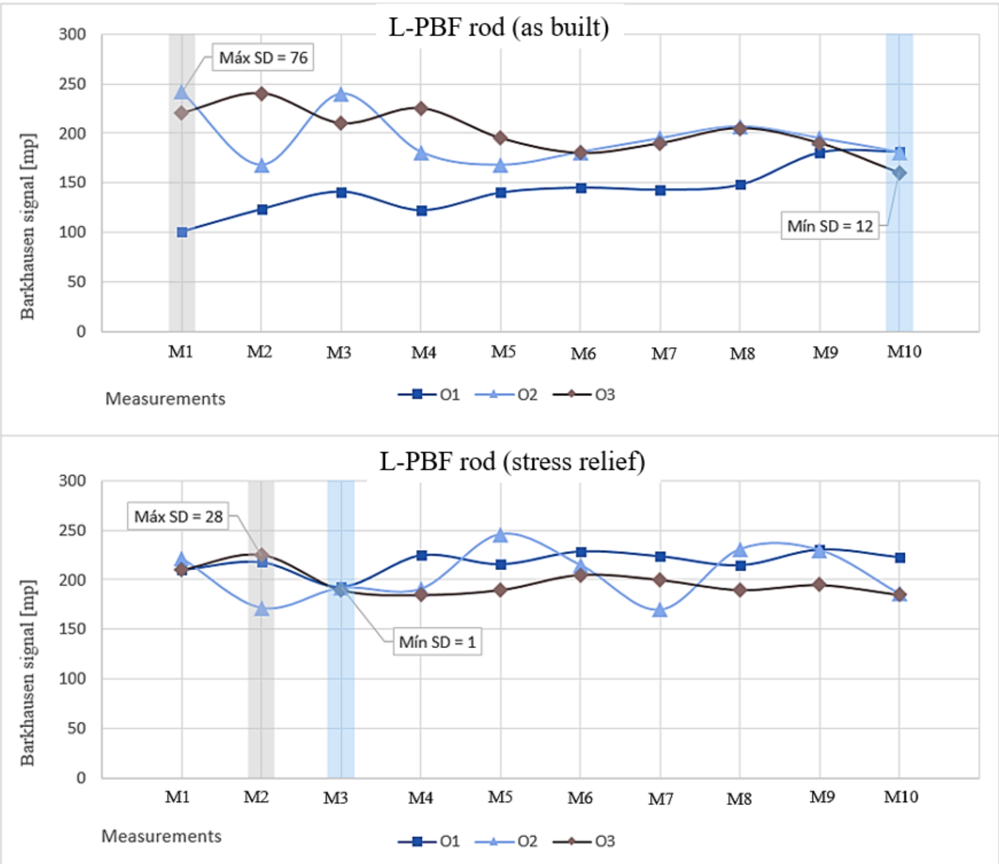

Figure 8. L-BPF rods (as built and stress relief) measurement results. The letter "O" stands for "operator" (O1, operator 1) and M for measurement (M1, measurement 1).

The mean of the results of the reproducibility tests was expressed in terms of percentage of the standard deviation. The results are shown in Tables 10, 11 and 12.

Table 10. Analysis of signal variance in the reproducibility tests in the L-BPF gear sample.

Operators	Average [mp]	SD/Average
O1	214.4	31%
O2	241.1	23%
O3	210.5	22%

Table 11. Analysis of signal variance in the reproducibility tests in the L-BPF rod (as built) sample.

Operators	Average [mp]	SD/Average
O1	142.5	18%
O2	195.8	14%
O3	201.5	12%

Table 12. Analysis of signal variance in the reproducibility tests in the L-BPF rod (stress relief) sample.

Operators	Average [mp]	SD/Average
O1	218.4	5%
O2	205.5	13%
O3	197.5	6%

Observing the results for each operator, it can be seen that the greatest variation of the signal in the sample with involute geometry is a trend, showing the difficulty of measuring due to the geometry.

For the tests with the aim of investigating the influence of the contact area of the sensor with the sample, ten measurements were performed for each variation of the contact area of the sensor. Figure 9 summarizes the surface contact area test results.

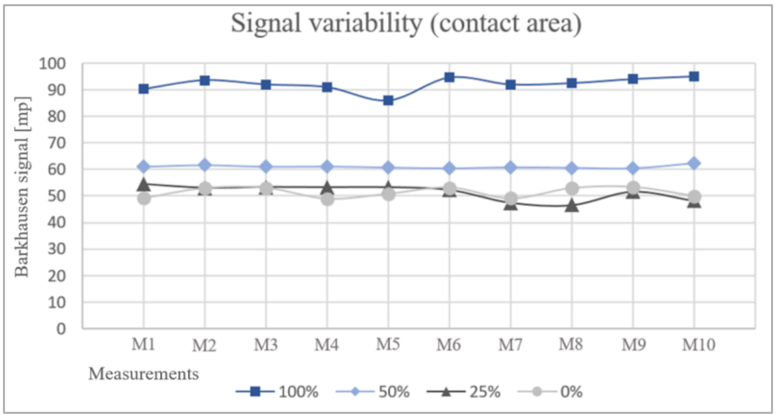

Figure 9. Analysis of signal variation as a function of the magnetic *Barkhausen* noise sensor contact area.

When evaluating the averages of the values as a function of the contact area of the sensor with the surface, it is noticed that the parameter directly influences the measurements in a non-linear way. This fact is immediately observed when comparing the values of the sensor completely in contact with the surface (contact area = 100%) with the measurement values with the sensor completely blocked (contact area = 0%), whose value is not null, representing 56% of the total value on average.

4. CONCLUSION

From the statistical analysis of the results, it was possible to identify that a parameter that relate the overall positioning of the sensor in relation to the sample during measurement significantly impact the results. Repeatability tests showed considerable signal deviations when evaluating samples of different geometries yet coming from the same manufacturing chain. It was noted that the control of the sensor's contact area during measurements is a fundamental factor for the results to remain concise and comparable.

In the reproducibility tests, an average difference of 16% of the maximum and minimum values found between operators was identified, showing that it is essential to certify whether the expected values for material failures overlap this tolerance.

Future work should propose the investigation of the *Barkhausen* signal combined with residual stress tests that will serve to demonstrate the signal differences found and perform a comparative analysis between parameters that influence the measurement with regions of metallurgical divergence that also influence the *Barkhausen* signal.

It is expected that this study may allow future studies in the field of identification and investigation of gear failures using the *Barkhausen* noise phenomenon. For the continuation of this study, new parameters that can influence the measurements will be evaluated in order to contribute to the *Barkhausen* noise method for fault detection being increasingly used to compose the spectrum of surface inspection solutions not covered by existing methods.

5. ACKNOWLEDGEMENTS

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