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Design and validation of low-cost handling equipment for the use of Barkhausen Noise Testing in worm gears grinding burn detection

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Abstract. Worm gears in high-performance gearboxes are often exposed to extreme loads, which requires assuring high production quality. Therefore the most important final characteristics of the workpieces are provided by grinding. One of the most investigated issues of this machining method is grinding burns, who change locally the properties of the material. In many industrial applications, nital etching is used to detect grinding burn. Although it is considered a standard, new types of tests are of great interest in order to reduce costs and make online control possible. One of the Non-Destructive Testing methods is Barkhausen Noise Testing (BNT), which is utilized to assess changes in the surface layer of ferromagnetic materials, especially to monitor changes in their hardness and residual stresses. To obtain accurate measures using this technology the Barkhausen probe handling system is essential. Typically the sensor handling system is an Inline/robot component, an automated component, a semi-automated component, or a manual handling system. Considering this scenario, the use of a manual system could allow having important cost savings but has to be correctly developed to obtain reliable measures. The aim of this paper is to develop a handling equipment for the BNT probe able to assure an adequate level of accuracy and repeatability.

1. Introduction

It is quite common that gears in high-performance gearboxes are exposed to extreme loads, which requires assuring high production quality [1]. Therefore the most important final characteristics of the workpieces are provided by grinding. Grinding is the common collective name for machining processes that utilize hard, abrasive particles as the cutting medium [2].

One of the most investigated issues of this machining method is grinding burns, who change locally the properties of the material [3]. Grinding burn occurs when the temperature of the workpiece in the grinding zone rises above the tempering temperature of the material due to inappropriate grinding conditions, resulting in tempering and microstructural changes in the surface and sub-surface layer of the workpiece that may be accompanied with a reduction in strength, plasticity, and hardness, and may introduce unfavorable residual stresses [4, 5]. In many industrial applications, nital etching is used to detect grinding burn. Using this method, the components are treated with different chemicals until a discoloring of the damaged surface areas emerges. The results highly depend on dive time, the chemical concentration as well as the level of cleanliness. Therefore, highly experienced inspection staff is needed for comparable results [1, 6]. Nital etch inspection is universally recognized as a standard for grinding

burns detection [7]. Different methods for grinding burn inspection are presented in the literature [1, 3, 8], and are summarized in Table 1.

Table 1. Grinding burns post-mortem detection methods [3].

Name ot the test	Main advantages	Main disadvantages
Nital etching	Visual	Polluted and destructive
Surface microhardness testing	Sensitive	Requires preparation of the specimen, which is time-consuming and destructive
Metallographic testing	Sensitive	detection rate is not high, complex and destructive sample preparation
Visual inspection	Non-destructive, simple operation	Not reliable results /subjective evaluation
XRD residual stress testing	Non-destructive, high accuracy and comprehensive analysis	Limits on the geometry dimensions and harmful for the human body
Chemical composition analysis	Non-destructive and accurate	Complex equipment and operating difficulties
Eddy current testing	Non-destructive, non-contact, low cost, and fast response	Applicable only on conductive materials for near-surface defects. Easily influenced by many factors.
Magnetoelastic methods	Non-destructive simple to operate in multiparameter measurement and fast response	Non-standardized and limited detecting depth
Acoustic emission monitoring	Non-destructive and high sensitivity	Interference problems with other signal sources.

One of the Non-Destructive Testing (NDT) methods is Barkhausen Noise Testing (BNT), which is utilized to assess changes in the surface layer of ferromagnetic materials, especially to monitor changes in their hardness and residual stresses. BNT is based on the interaction between the external magnetic field and the ferromagnetic material [9].

However, there is still no scientifically validated knowledge about the influences and interactions of different material parameters resulting from the heat treatment on the Barkhausen noise signal. Therefore, no standardized guideline for the interpretation of inspection results exists up to now; each company uses its own test procedures [6].

As shown in Table 2 [9], the measured values are sensitive to the measurement strategy, the measurement device, and the sensor as well as the used measurement parameters. Hence, a reproducible sensor control is essential to minimize the influencing effects mentioned [6].

The measure of burns through BNT becomes even more difficult if you want to analyze worm gears (i.e. characterized by a complex surfaces). Karpuschewskia et al. [1] propose to do the measurement by a 7 axis robot to guarantee repeatability and analyze a module gear of $m_n = 2.88$ mm.
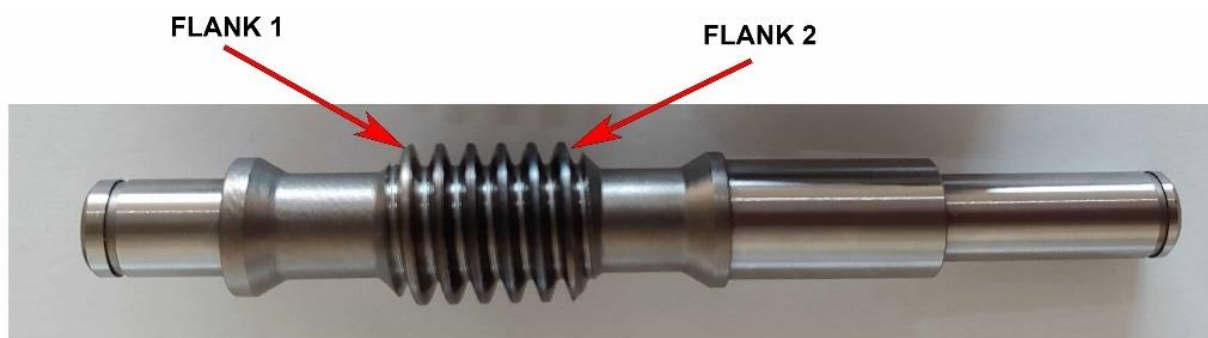
The industrial cost of a 7 axis robot (or the use of an evolventimeter) summed to the Barkhausen testing machine can result too expansive, especially in the case of worm gears, moreover on restricted tolerance due to small modules. By now no evidence has been found for the support of the Barkhausen noise analysis in worm gears. For this reason, the development of a new solution for support structure could have a big potential from an industrial point of view. The aim of this paper is to present an alternative low-cost solution able to be used by line operators for online quality control.

Table 2. General overview of the group of parameters that can affect Barkhausen measurements.

Material	Heat Treatment	Machining	Surface Integrity	Electromagnetic Properties	Measurement
Microstructure Grain size Grain shape Crystallographic defects Chemical composition Internal discontinuities Nonmetallic inclusions	Quenching Tempering Annealing Carburizing Toughening Magnetic	Magnetic holders (clutch)— remanence Number and type of machining Machining parameters	Roughness Waviness Roundness Hardness Residual stresses Scratches Microcracks Burns	Magnetic domain orientation Remanence Conductance Permeability Coercivity	Gauge type Gauge quality Surface type Surface quality Surface cleanness Temperature Magnetizing voltage Magnetizing frequency Filtering bandwidth Load force Calibration Environmental noise

2. Measurement issues detection

The experiment has been conducted using worm gear with the following specifications: m_n = 1,2 [mm], CD = 44,6 [mm], i = 1/60, z_1 = 1, z_2 = 60, material = 16MnCr5, where m_n in the normal module, CD is the center distance, i is the transmission ratio, z_1 is the number of threads and z_2 in the number of teeth of the crown gear. In Figure *1*1 is shown the flanks interested by the analysis.

Figure 1. worm gear used for the tests.

The BNT system used for the test is a StressTech 350 with probe S8088, with 5V as magnetizing voltage and 100 Hz as magnetizing frequency.

During research focused on technological process optimization, an experimental campaign has been conducted to obtain an evaluation of the grinding working parameters and their optimization; for this purpose, a Two-level Factorial Design of Experiments (DoE) has been used. In this paper, we use the test worm gears obtained by this factorial design with a specific focus on the development of a measurement system that can be used to analyze worm gears directly close to the grinding machine.

The parameters of the DoE have been chosen following the major influence parameter indicated from the state of the art of literature [3, 10] and checking the controllable parameters on the machine utilized for the test (production machine).

In the first phase of the project, the main scope has been to evaluate the capability of the Barkhausen Noise analysis without any support, i.e. using the probe by hand. Qualitative evidence of the impossibility and on the inadequate repeatability of the measurement is shown in Figure 2. In Figure 2 the magnetoelastic parameter value (*mp*) is the result of the Barkhausen noise analysis. An increase in *mp* value indicates an increase in residual tensile stress. A decrease in *mp* value indicates an increase in residual compression stress. The *mp* value is proportional to $V_{RMS} \times I_{RMS}$ where V_{RMS} is root-mean-square voltage and I_{RMS} is the root-mean-square current on the analyzer.
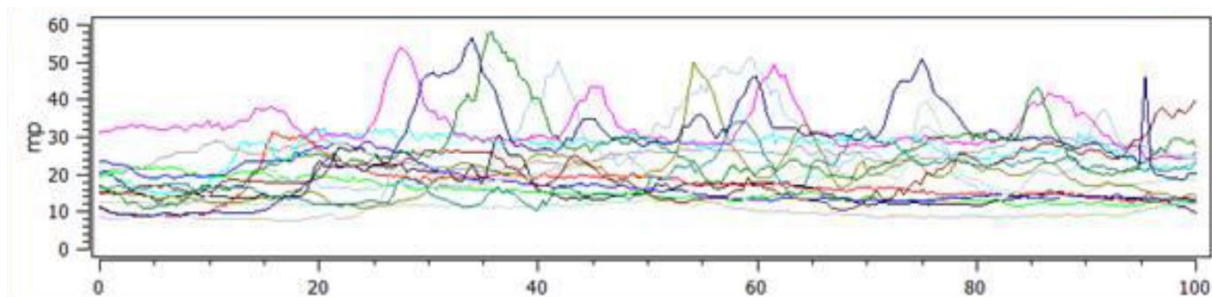

Figure 2. Barkhausen noise measures without any support.

The observed high scattering level produces an inadequate reproducibility and repeatability of the measure. The poor quality of the acquired measurement is mainly due to the difficulty of obtaining correct positioning, in particular, it is necessary to obtain:

- The parallelism between the worm gear and probe translation plan;
- Synchronism between worm gear rotation and probe translation;
- Constant inclination between the probe and analyzing surface.

As described in section 1 commercial solutions to solve these issues are the use of a 7 axis robotic arm or of an evolventimeter for the probe manipulation. These solutions are expensive and of complex use.
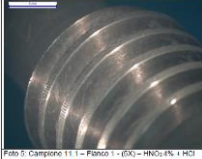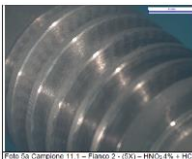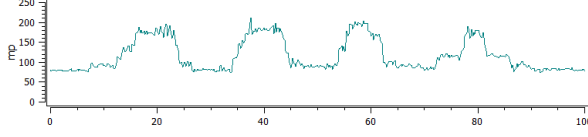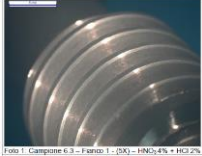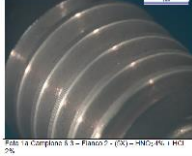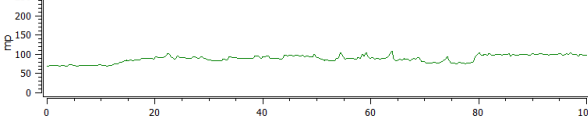
In this paper to comply with the low-cost, easy implementation and easy handling constraints we have developed a measure bench. Firstly, tailstocks support has been adopted. The introduction of this support has shows a first positive feedback on the possibility of implementation of the chosen approach. Indeed the possibility of concentrate on probe movement has reached the first results in terms of repeatability and reproducibility.

Table 3 presents a comparison between the results of the standardized Nital etch test and of BNT results obtained with a hand probe handling and a tailstocks support.

The comparison shows a correct matching between the two methods in detecting the presence or absence of the burns; BNT shows a clear increase in the *mp* value while Nital etch test shows optical evidence of the defect).

Even if these results are promising, the repeatability and reproducibility values are not enough for a standardized control. To realize support able to be used onboard the machine in the production line from the operator and with a reasonable measure quality a probe movement system is needed.

Table 3. Nital etch and BNT comparison. For the Nital etching is reported as an example for every worm gear of both flanks. For BNT is reported the acquired noise. BNT results are obtained with a hand probe handling and a tailstocks support.

Flank 1 Nital	Flank 2 Nital	Grinding burns evidence	BNT mp
		Yes	
		No	

In this scope, a new and low-cost measure bench is presented in the following [Figure 3, Figure 4]. The bench will be able to comply with all the constraints imposed, in particular:

- to ensure the **parallelism between the worm gear and the probe translation plan**, probe support has been provided mounted on a moving trolley, who can translate parallel to the worm gear axis. The probe support hole is orthogonal to the translation plan and insists on the worm gear axis;
- to ensure the **synchronism between worm gear rotation and probe translation** a gripper with inserts is introduced. The equidistance among the fulcrums of the gripper and the hole in the probe support guarantee that the gripper insists on the rotation axis of the worm gear. The inserts are extracted from the crown of normal production and are able to engage with the testing worm gear. In this way, no further design of the insert is needed. A couple of springs ensure the contact between inserts and worm gear. The presented system ensures a synchronism between worm gear rotation and probe translation;
- to ensure the **constant inclination between the probe and analyzing surface** the probe hole center and worm gear axis are guaranteed to be always incident. This, combined with the synchronized motion and fixing the probe using a dowel, guarantee the constrain respect.
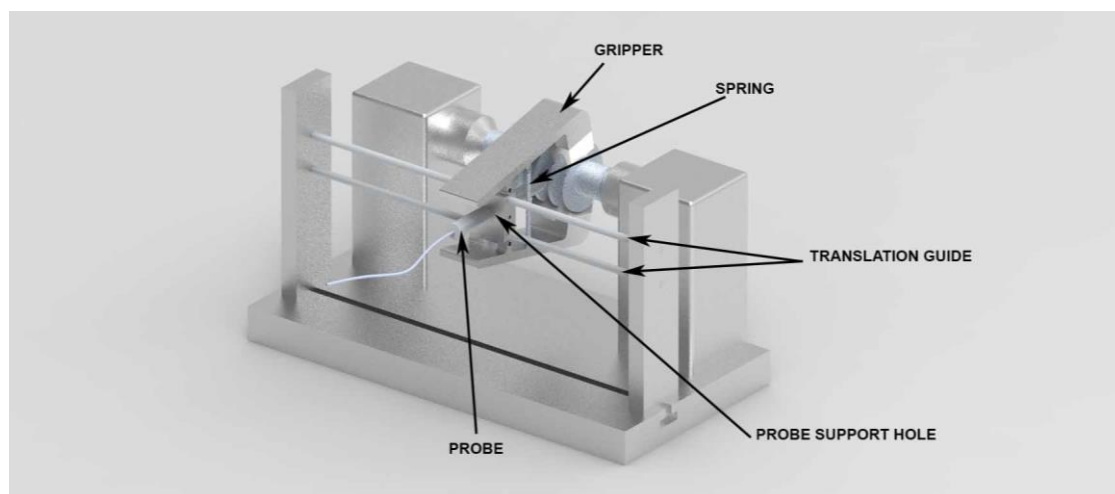

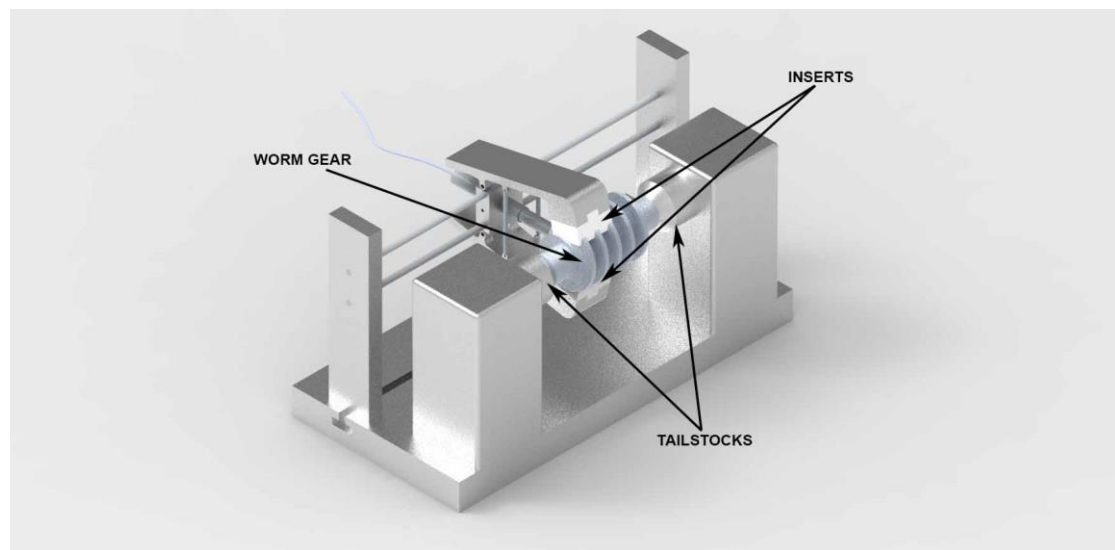**Figure 3.** measure bench, back side.

Figure 4. measure bench, front side.

3. Conclusions

Grinding burns in gears is a challenging analysis, especially in double curvature profiles. Barkhausen Noise Testing is a good alternative to the Nital etching standardized analysis and can give a faster and lower cost feedback respect all the alternative. Moreover, BNT can be implemented onboard machine or in the production line with no strict precaution on health and safety. As shown, manual Barkhausen noise probe handling is not able to provide reliable analysis on gears burns. The literature suggests using automatic support to analyze the surface with a complex surface. Nowadays no commercial low-cost and easy application are available for worm gears and no bibliographic evidence has been found of BNT in this kind of application. The proposed solution has been developed to assure parallelism between the worm gear and probe translation plan, synchronism between worm gear rotation and probe translation, and constant inclination between the probe and the surface under analysis. For this reason, the proposed solution is a valid alternative to the high cost and hard implementation commercial solution available and permits to solve the limits met on the handling probe problems as revealed the measures obtained. Moreover to the available solutions, leaving out the much lower cost, the presented solution can be installed on a transportable bench, giving the possibility to analyze pieces directly in the production area. Future work will concern the development of a system without tailstocks that will completely disengage the measure from a bench and simplify the insert management through a shape contour duplicator.

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