Barkhausen noise technique for Non-destructive characterization of mechanical components
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Abstract
The Non destructive methods play an important role in quality insurance of mechanical parts, as they allow the detection of voids in mechanical parts. NDT specialists are now faced to new demands from the market. So, customers want to know the mechanical state of the material of the part, its stress state, the grain size, or if the material had the good heat treatment, or if it has the good case depth. So, CETIM developed adapted skills to help material characterization, based on using electromagnetic techniques mainly. Barkhausen (or ferromagnetic) noise is one of the methods used by CETIM to characterise the materials. The paper will discuss different applications of Barkhausen noise technique:

- Residual stress characterization, evaluation of case depth, mainly for gears, motors and compressors manufacturers, and grinding burn detection.

Recent developments concerning hardened parts showed that some heat treatment processes are now steady and well mastered, and there is a need for a precise assessment of the quality of heat treatment. So, this technique is able to estimate with great accuracy the hardening depth. A retained austenite excess and the presence of carbides can be detected with the correct precision, thanks to the development of a sensor and specific signal processing systems. In this paper, we present three examples of method applied to industrial products: stress relaxation control on engine cylinder, hardened gears quality control and grinding burn detection of helical gears.

Keywords: Material characterization, Barkhausen noise, ferromagnetic noise, stress state, grain size, heat treatment, case depth, hardening depth, grinding burns
1. **Introduction**

Structural reliability, security facilities and product quality are key requirements that must be met in many industrial sectors. The main challenge is to detect defective parts or that may become defective during manufacture or during in-service inspections component. Industries today are under pressure to enhance the reliability and safety of products, while improving their criteria of productivity.

The development of thermal and mechanical surface treatments generates a growing need for the provision of means for characterization and quality control of materials. These treatments such as surface hardening, shot peening, carburizing are commonly used in industry to improve the performance of metal parts against fatigue and wear. The material health controls implemented are usually destructive, expensive and polluting, with a low response time for effective monitoring of the quality of the process. However, the approach of the 100% quality and the increasing level of demands of customer, especially for safety parts, require more rapid and reliable control of the entire production, all at a reduced cost. The nondestructive methods electromagnetic eddy current, hysteresis and Barkhausen noise cycle represent very interesting alternative to characterize the microstructure and the stress state of the material. This paper discusses the results of the studies performed in CETIM about this topic. The examples presented below mainly concern the method of Barkhausen noise.

2. **Principle of the method implementation**

The method of Barkhausen noise (also called ferromagnetic noise) is only applicable to ferromagnetic materials. When a ferromagnetic part is positioned in an excitation magnetic field $H$, the macroscopic magnetization of the steel (hysteresis loop) is accompanied by movement of Bloch walls (surrounding the WEISS areas). Each movement produces a small variation of the magnetic flux and the sum of all trips that occur in cooperation, form a significant change in the magnetic flux, easily measurable with a magnetic sensor (raw signal in red). This flux variation is called Barkhausen noise. This principle is illustrated in Figure 1. Barkhausen noise is usually analyzed by RMS envelope. It is bell shaped (gray curve).

![Hysteresis curve](image)

**Figure 1**: Principle of Barkhausen noise generation
The movements of the Bloch walls are more or less constrained by the microstructure (grain size, phases in the presence ...) and the stress state of the material. The characteristics of the RMS noise signal depend significantly on these two parameters.

A chain of Barkhausen noise measurement has four components, as shown in Figure 2: excitation circuit, detection probe, signal conditioning, signal processing.

![Excitation and Detection](image)

Figure 2: Diagram of a Barkhausen noise instrumentation

3 Presentation of industrial applications

Quality Control of carburizing

The quality of cementing is based on several criteria: the hardened depth, surface hardness, the austenite residual rate, the profile of surface stresses, etc..

In the case of carburizing, the surface (martensitic) and the heart (bainite) give rise to two more or less distinct signatures according to the applied magnetic field (Figure 3 a), the first result in a lower signal amplitude A2 located at high fields and the second strong signal A1 located at lower fields. The ratio of the two amplitudes A_2/A_1 correlates well with the hardened depth (Figure 3 d).
Figure 3: Principle characterization of case depth by Barkhausen noise: (a) generation of noise, (b) example of signals measured on a 17CrNiMo6-gear module 4 3.75 (c) microhardness measured on these gears, (d) curve correlation between the depth to 550 HV after microhardness filiation and Barkhausen noise parameter measured.

However, if the control is done after grinding the gears, changes in surface stresses induced by grinding are likely to impact the hardened depth measurement. Figure 4 shows the sensitivity of the Barkhausen noise versus the surface stresses produced by the grinding on the teeth of a gear. We determined that to the extent these variations are limited between 0 and 300 Mpa. Uncertainties of depth measurements by Barkhausen noise are of the order of ± 0.2 mm.

Figure 4: Influence of surface stresses measured by X-ray diffraction after grinding operation on the response of the Barkhausen noise.
The Barkhausen noise method also enables the detection of excess residual austenite after carburizing. In this case, the peak position is the Barkhausen discriminant parameter, as shown in Figure 5.

![Figure 5: Detection of residual austenite excesses](image)

Generally, for the characterization of the depth hardened by Barkhausen noise, several influential parameters should be taken into account for the implementation of control such that the modulus of gear, material, type of cementation, stress and surface austenite and settings of the equipment. There is thus a need to adjust the calibration curve to the case of measurement. The process developed by the CETIM is currently applicable to modules pinion> 4 showing changes in surface stresses below 300 MPa. It not only helps to characterize the depth cemented with good precision, but also to detect any residual austenite of excess ($\gamma > 40\%$). The measurement accuracy depends on the number of influential parameters: it has a maximum uncertainty of the estimate $\leq 0.4$ mm if all variations due to process (nuance, process, load, part geometry ...) and measurement (micro-hardness filiation and Barkhausen noise) are taken into account. This difference is reduced to 0.1 mm if the control is carried out on a well-defined output (same carburizing process, same grade ...).

**Detection of grinding burns**

The poor conditions of rectification (dirty grindstone, lack of lubrication, too high speed, etc..) may cause a sudden heating, very localized on the surface of the part being machined, resulting in a drop in hardness and reduced compressive stresses or their inversion. The generated defect is generally designated by the term "grinding burn."

The severity of the burn correction generally increases with the temperature reached:
- At a low temperature ($<200 ^\circ C$) we have a "light damage" undetectable with Nital Etching. The hardness is unaffected but the compressive stress can be greatly reduced enough,
- At a temperature between 200 and 720 $^\circ C$, we may have a "burn income", the most common and easily detectable by Nital etching. Hardness drops proportionally with the temperature reached and the stress field tends to reverse,
- At a higher temperature corresponds to a "re-tempered burn" or burning white, hardly detectable by Nital etching. But it is usually surrounded by a zone of brown income that allows to locate it. The re-tempered areas are very hard and dangerous (risk of chipping or crack initiation). The stress field is disturbed.
To ensure the quality of a grinding operation, it is necessary to ensure on the one hand that the hardness of the material has not decreased (no alteration of the microstructure), and secondly to ensure that the constraints remain in residual compression end surface.

Several control methods can be used:
- Measurement of surface hardness is very difficult to implement due to the very low thickness of the burnt layer (~ 10 microns). Only a few laboratory facilities allow this measurement, but the control is not completely non-destructive.
- The measurement of residual stress in end surface can be performed by X-ray diffraction measurement. It is reliable but not suitable for production control as its implementation is long.
- The Nital etching is by far the most common method used in industry. This method is standardized. It is especially sensitive to burns income, but relatively insensitive to variations in residual stress (re-tempered burns). Its implementation is manual, not automated, non-traceable, and causes pollution into the environment.
- Detection by eddy currents is a widely used in industry, non-destructive method, thanks to the ease of automation control. However, it is not very sensitive to changes in surface residual stresses.
- The method of Barkhausen noise seems particularly well suited by its dual sensitivity: the microstructure and stress. With its increasing monotonic evolution when the compressive stresses decrease and the hardness falls, the Barkhausen noise increases with the severity of the burn income type. In the case of re-tempered burns, the signal strongly decreases. More, the measurement is sensitive to the early stages of heating, very early before the Nital etching could detect a variation of microstructure. The Barkhausen noise method is often used for the detection of grinding burn, by monitoring the signal during the grinding operation. This allows working on the machining conditions before a burning deemed dangerous appear.

The latest achievement of CETIM in this area has been to work on questions raised by LUFKIN France, manufacturer of gears for the automotive industry and energy. The development of the method was made using the "calibration parts" with more or less advanced burns: mild burn and average-income, re-tempered burn. This has allowed us to define the detection criterion and the procedure associated control, as shown in Figure 6.
Following this development, Lufkin France chose to replace the Nital Etching by ferromagnetic noise measurement (or Barkhausen noise). This method provides better detection of burns, with a simpler implementation and faster exploitation of data collected. Lufkin wants now to adapt the methodology to its production of helical teeth and to automate the control of 100% of parts produced in its plant located in Fougerolles (Haute-Saône).

4 CONCLUSIONS
From a broader perspective, we see that the development of electromagnetic technology meets a new industrial need: in this case non destructive testing is not only to used to check the health of mechanical components (defects of compacity, cracks, corrosion), but also to test mechanical or physical characteristics (depth of processing, grain size, stress, microstructure), in order to avoid the appearance of defects in use. Electromagnetic methods (Barkhausen, eddy currents ...) and ultrasound help to meet this demand, particularly in the following context:
- No destructiveness to avoid cuts for metallographic analyzes
- No pollution in harmony with the REACH Regulation
- Traceable, and compatible with automated tools for signal processing and data analysis
All these factors enable to foresee a significant development of non-destructive characterization techniques, and Barkhausen noise in particular.