# Evaluating Plastic Deformation by the Magnetic Barkhausen Noise

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**Abstract**. The Magnetic Barkhausen Noise (MBN) is a phenomenon occurring in ferromagnetic materials undergoing changes in magnetization. This phenomenon is very sensitive to material microstructural changes and, as a consequence, the MBN can be applied as a non-destructive monitoring technique for detecting plastic deformation in the material of mechanical components subjected to thermo-mechanical processes, such as machining and forming processes. Among the investigated cases, it is worth mentioning the texture effect in steel sheets produced by rolling process and the effect of drilling process in the steel material. The present work investigates, by MBN measurements, the microstructural anisotropy induced by the rolling process of steel sheets and its change due to elastic and plastic deformations. The results of the MBN mapping for characterizing the plastic deformation induced by drilling processes in steel sheets were correlated to a theoretical deformation map. The influence of tensile stresses in the MBN map is also reported. Finally, this study analyzes the influence of surface condition (presence of oxide layer and surface roughness) in the MBN measurement. The results indicate that both surface characteristics can affect the correlation between MBN and deformation. All in all, the MBN measurement was found to be an easy, fast and singular technique for plastic deformation evaluation.

## 1. Introduction

Industrial components, working under mechanical stressing, can undergo elastic or plastic deformations and have, in consequence, their material structure changed. These components are frequently steel made and, being steels magnetic properties very sensitive to material structural changes, magnetic measurements are potential techniques to be applied as non-destructive inspection methods for the detection of material changes.

Among the diversity of magnetic properties, there is one of special interest due to its high sensitivity to microstructure characteristics including grain size, carbon content, microstructure phases and residual stress. This property is the Magnetic Barkhausen Noise (MBN), first detected by Barkhausen [1], in 1919, while observing a cyclic magnetization of a ferromagnetic material. MBN signals are essentially generated by the motion of 180$^o$ magnetic domain walls of the material, these movements occurring around the coercivity point of a magnetic hysteresis loop. Among other variables, the strength of the MBN signal depends on the testing parameters, such as the maximum of the applied field strength, and on the microstructural features (grain boundaries, dislocations, precipitates, etc.) that act as pinning points for the moving domain walls or as domain generation sources [9]. In this way, the MBN signal that is read by an adequate instrument contains information on the material microstructure.

The MBN literature on characterization of the microstructural state of materials in several conditions is vast [2-13]. This fact increases and diversifies the possibilities of development of MBN based non-destructive inspection methods regarding material performance during processing and its applications in service. As examples of applications related to the material performance in service, it is worth mentioning studies evaluating the quality of ground finished [6] and treated surfaces [5] and material degradation [7, 8]. In addition, there are diverse specific studies on the plastic deformation of mechanically worked materials [9-13].

By using an adequate MBN measuring system, information can be obtained in an easy and fast way, either as "yes/no" information or as a mapping, without destroying the evaluated part. Nevertheless, the obtained information should be analysed taking into consideration some limitations of the technique: the sensitivity of MBN to a vast set of material features makes the technique relative, that is, changes in the inspected material are always evaluated relatively to the material in a standard reference condition. Besides that, the technique is, in essence, a surface analyser to depths up to one millimetre, depending on the excitation frequency and on the spectral frequency band considered in the MBN signal analyses. In this context, care should be taken concerning the surface condition.

Examples of applications of MBN techniques as a non-destructive test for characterization of changes in the microstructure of carbon steels are described in some of the authors' previous publications [3,4,14]. In the present work, results of MBN measurements in commercial rolled steel sheets subjected to elastic and plastic uniaxial tensile stress are presented. This study also shows the MBN mapping around a machined hole, as well as the influence of surface condition (oxide layer and roughness) on the MBN reading.

## 2. MBN measurement system

The authors have developed a complete, versatile MBN measuring system for laboratory investigations. A small, portable version of the equipment is currently being finished for field inspection applications.

The MBN measuring system used for laboratory investigations is composed by a current generator (Kepco bipolar source) for the magnetic excitation, a conditioning circuit for the MBN signal and programmable software, for controlling the frequency and the magnitude of magnetic excitation, and the parameters of acquisition, visualization and recording of the MBN data. The inspection probe contains a magnetic exciter ("U" ferrite core magnet) and an MBN pick-up sensor composed by a magnetic head. This system is schematically shown in Figure 1. In the tests, digital acquisition was performed with a sampling frequency of 200 kHz. The MBN signal contains 50,000 data points with excitation frequency of 1 Hz. The signal can be quantitatively analysed in terms of its rms value ($V_{rms}$, the root mean square), peak value ($V_p$) or energy ($MBN_{energy}$, the integral of voltage square of all MBN events).

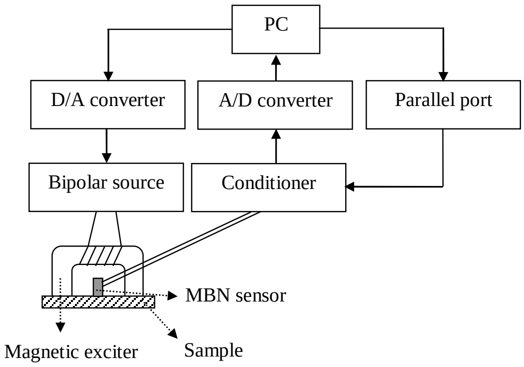



Figure 1. Schematic configuration of the MBN measuring system used in laboratory investigations.

In the experimental measurements, the samples were made of ASTM 36, commercially acquired. Next section presents some results of MBN measurements conducted on these samples to identify the material changes under elastically and plastically deformed conditions, as well as measurements around a machined hole.

## 3. Results of MBN measurements

Figure 2 illustrates a software output, with four MBN signals produced in the ascending and descending ranges of two magnetizing cycles. For MBN quantitative calculations, one considers at least five consecutive MBN signals, generated in the ascending or in the descending range of the magnetizing cycle.

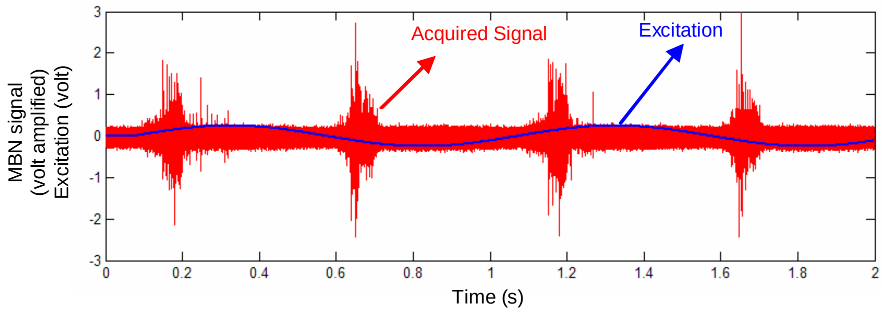



Figure 2. Illustrative example of a sequence of MBN signals acquired in two magnetizing cycles of 1 Hz.

### *3.1 Elastically deformed samples*

The evaluation of the ASTM 36 sample under uniaxial elastic deformation was conducted using the procedure for MBN angular measurement. This was made by a proper device for positioning the MBN probe at a specific point of the sample and then rotating it radially along 360$^o$, with increments of 15$^o$, as shown in Figure 3. Measurements prior to stress application indicated a magnetic easy axis parallel to the rolling direction (RD). It was attributed to the rolling texture. The tensile elastic stress was applied transversely to the RD axis, using a conventional tensile machine. Figure 4 shows the polar graphs obtained for the sample without stress application and under five levels of elastic tensile stressing. The values in the graphs refer to the $MBN_{energy}$ values.

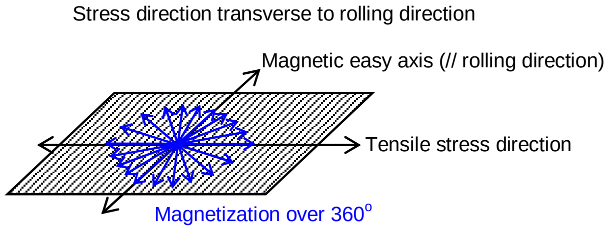



Figure 3. Radial axes taken for MBN angular measurements in the sheet samples.

Figure 4 shows that a continuous change of magnetic easy axis occurs when the sample is elastically strained. At 0 MPa, the magnetic easy axis is related to the crystallographic texture of the material due to rolling process (previous metallographic observation did not show any plastic deformation caused by mechanical rolling). It is clearly revealed that the tensile stress changes the internal structure of the material, destroying the original magnetic easy axis and creating a new distribution of magnetic domain walls, now sensitive to a magnetic axis parallel to the direction of the applied stress. This means that the elastic strain changed the material anisotropy towards the stressing direction. In addition, it is interesting to note that there is a level of elastic strain that makes the material isotropic. The rearrangements in the interatomic spacing, caused by elastic deformation, are the probable cause of the change in the behaviour of the magnetic domain walls [11].

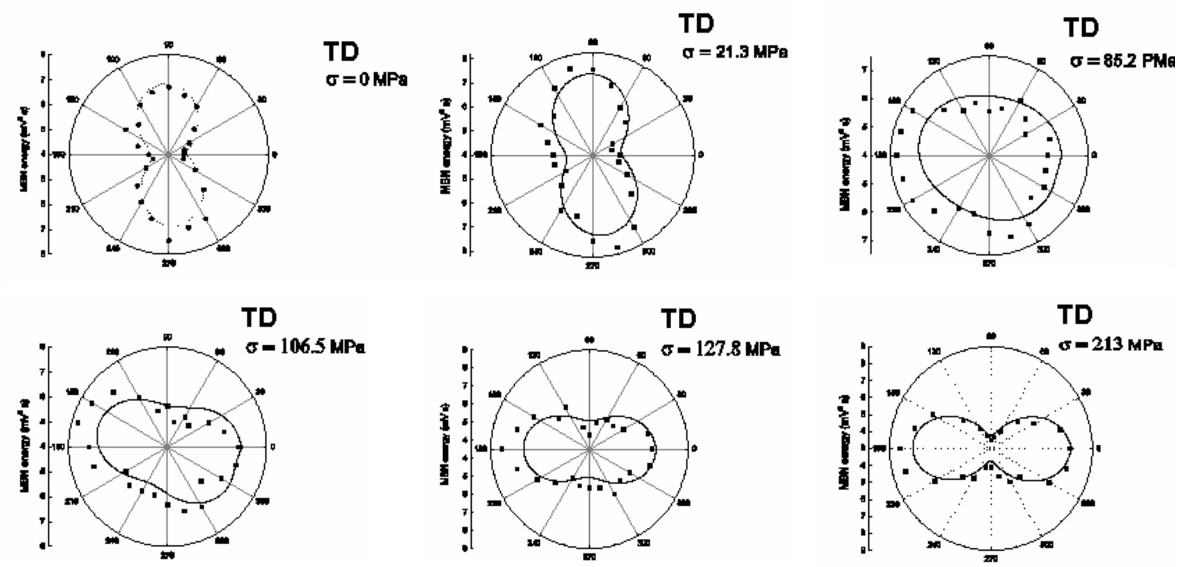



Figure 4. Changes in the magnetic anisotropy of ASTM A36 steel sheet caused by successive elastic straining. Initial rolling direction: vertical (TD). Tensile stress direction: horizontal.

The results in Figure 4 suggest a possible MBN technique application for characterization of rolled materials subjected to elastic deformations, in addition to the simple identification of anisotropy in rolled materials.

*3.2 Plastically deformed samples*

*3.2.1 Uniaxial tensile deformation*

Plastic deformation creates a significant increase in the dislocation density as well as in the movement of dislocations. The structures of dislocations act as pinning sites to domain wall movements [11]. On the other hand, the consequences of permanent lattice distortions, introduced by plastic deformation, are different for each particular magnetic domain wall configuration [13]. This fact indicates that the plastic deformation state can be evaluated by an MBN technique. Nevertheless, it is worth mentioning that, despite several studies on the effect of plastic deformation on the MBN behaviour, the understanding of the interaction of magnetic domains with the diversity of the types of pinning sites (each one having specific coercitive field) originated by plastic deformation is still unclear.

A useful parameter for describing the angular behaviour of the MBN energy is [12]:

$k = MBN_{energy}(0^o)/MBN_{energy}(90^o)$

Where $MBN_{energy}$ $(0^o)$ is the energy of MBN signal in the direction of the magnetic easy axis (maximum $MBN_{energy}$) and $MBN_{energy}$ $(90^o)$ is the energy of MBN signal in a direction perpendicular to the magnetic easy axis direction (minimum $MBN_{energy}$).

The k parameter was used to characterize the changes in the magnetic anisotropy produced in the sample when it is plastically deformed at different rates.

Figure 5 shows the trends in k parameter, calculated from the MBN data measured in ASTM A36 steel sheet samples after plastically deformed in a uniaxial tensile machine at 1%, 3% and 5%, when subjected to several levels of elastic tensile stresses. Each k value is related to an average of the MBN measurements in samples with different orientations of initial magnetic easy axis.

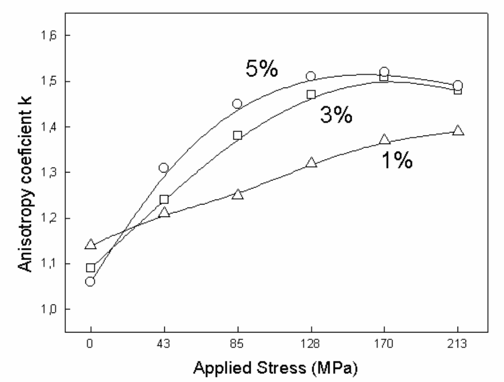



Figure 5. Dependence of the average anisotropy parameter k as a function of applied elastic tensile stress of ASTM A36 samples, with previous plastic deformation of 1%, 3% and 5% rates.

Figure 5 shows that k increases continuously with the elastic strain, for the samples with 1% plastic deformation while, for higher plastic deformation (3% and 5%), it appears first to grow and then to reduce. It is reasonable to consider the following three aspects:

- The number of defects (pinning sites for domain walls) in the material structure increases if plastic deformation level increases. Depending on the type, number and distribution of pinning sites, they can cause MBN increase or not.

- In the case of 1% plastic deformation, the dislocations are in a small number and the number of pinning sites is also low. Then, when the applied elastic tensile stress is increased, the MBN increases continuously due to the change in the domain walls motion, caused by the atomic rearrangement in the material during elastic straining.

- In the cases of 3% and 5% plastic deformation, the number of dislocations increases and the structure changes, changing the type and distribution of pinning sites. When the applied elastic tensile stress is increased, the MBN also increases continuously due to the change in the domain walls motion, caused by the atomic rearrangement during elastic straining, but at a lower rate, because now the strong pinning sites become obstacles for the domain movement. Additionally, as the elastic deformation reaches higher levels, the MBN in the transversal direction also increases significantly (see Figure 6). A probable cause for such behaviour can be a raise of residual elastic tensile stresses in the transversal direction due to the high plastic deformation, since it is known that residual tensile stress can cause an increase in the MBN emission.

In order to illustrate the differences in the trends of the magnetic anisotropy during elastic straining of different plastically deformed samples, Figure 6 shows the polar graphs of angular MBN data, measured in samples plastically deformed at 1% and 3% deformation rates. Each curve in the graph corresponds to a different level of applied elastic tensile stress (stress levels were equal to those of Figure 4). It is possible to observed in Figure 6 that the range of $MBN_{energy}$, measured in the 1% deformed sample along the direction transversal to that of the applied stress, is broader than that observed in the range of $MBN_{energy}$ , measured in the 3% deformed sample.

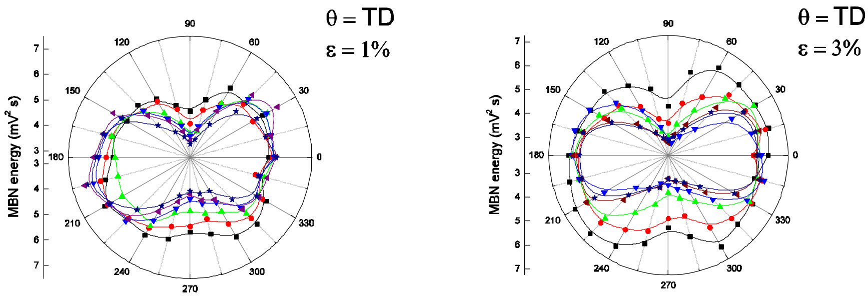


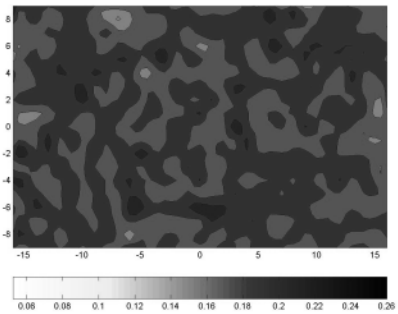

Figure 6. Curves of magnetic anisotropy of ASTM A36 steel sheet with previous plastic deformation of 1% and 3% rate, under several levels of elastic straining. Each colour corresponds to a straining level. Initial rolling direction: vertical (TD). Tensile stressing direction: horizontal.

*3.2.2 MBN mapping next to a drilled hole*

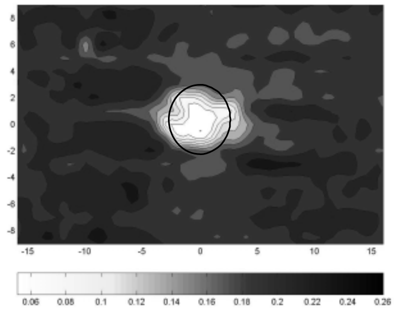
Figure 7 presents MBN ($V_{rms}$) mapping results of ASTM A36 sheet samples. The measurements were taken at each 1 mm x 1 mm, using a PC controlled XY coordinates system. Map (A) corresponds to a sample that had been heat treated for stress relief (700$^{o}$ C for 1 h, cooled in furnace), protected against oxide formation. The grades in grey colour are related to the $V_{rms}$ deviations in the sample.

Map (B) refers to a sample that had been 3% plastically deformed in a tensile machine and then had a hole (5 mm diameter) drilled on, as indicated by the black line circle. The horizontal grey coloured boundaries indicate the modification in the structure caused by plastic deformation. The drilled hole is put in evidence by the white colour (absence of MBN) in the map. It is interesting to see that the MBN intensity reduces near the hole, when compared to that in the whole plastically deformed area. This means that the plastic deformation induced by the drilling process leaded to the reduction of domain walls movements. The reduction of MBN activity is comprehensible from the point of view that high level of plastic deformation increases the density of structure defects, also increasing the number of the pinning sites, which makes domain wall movements difficult.

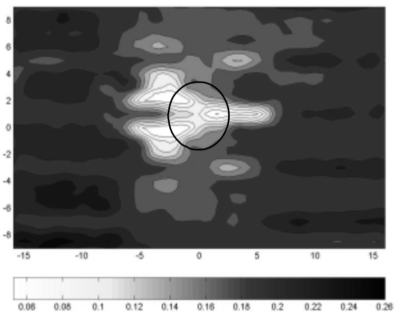
Map (C) is from a sample with higher plastic deformation (5%), also presenting a drilled hole. In this case, the grey area near the hole gets larger, that is, the area with reduction in the MBN activity is broadened. The asymmetric geometry of this area is in accordance with computational simulation, by finite element method, of the plastic deformation field near the hole, seen in Map (D). Near the hole, the larger area of plastic deformation is in the vertical direction and the lower in the horizontal one.



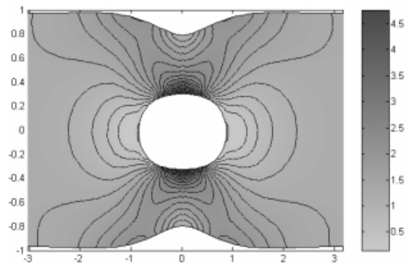
(A) After stress relieved



(B) After 3% plastically deformed, drilled



(C) After 5% plastically deformed, drilled



(D) Computational simulation of (C)

Figure 7. MBN mapping ($V_{rms}$ values) for evaluation of plastic deformation of ASTM A36 sheet sample.

The MBN mapping results strongly indicates the potentiality of the technique for inspecting material structural alterations produced in components under mechanical solicitations.

Although both characterizations shown here, anisotropy of rolled steel sheets and structural alterations caused by local mechanical process such as drilling machining, may be performed through other classical methods, the MBN technique represents a simpler, fast and low cost, non-destructive alternative.

### *3.3 Influence of surface condition of the sample*

Surface condition is one of the important factors influencing the reproducibility of MBN signals. In particular, the presence of an oxide layer is common on heat treated samples. The influence of this factor on the MBN signal has not been clearly reported.

The MBN is usually measured in samples with ideal surface condition. However, the use of the MBN as a non-destructive method frequently deals with materials with oxide layers, which may modify the dependence of the MBN signal on the microstructural or stress parameters.

#### *3.3.1 Oxide layer*

ASTM A36 sheet samples were plastically deformed to several rates and heat treated for stress relieving (700$^o$ for 1 h, cooled in furnace). The treatment created an oxide layer on the surfaces. A set of these samples had the surface oxide removed by sandpaper. Figure 8 shows the results of MBN ($V_{rms}$) measurements. Type I samples correspond to those with oxide layer and Type II samples, to those without oxide layer. Background noise corresponds to the information picked up by the MBN sensor that does not contain the domain wall jumps (see Figure 2).

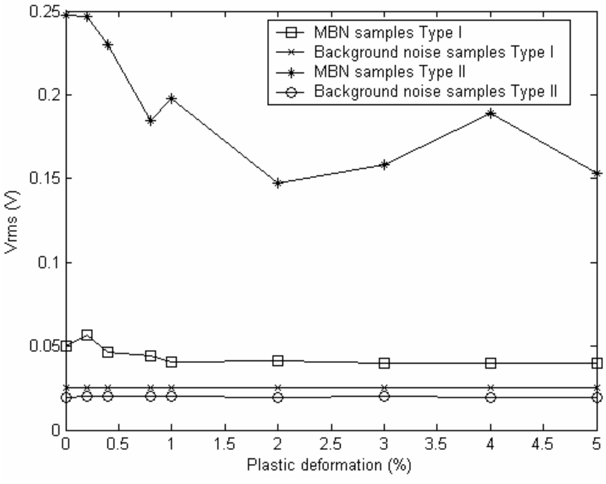



Figure 8. Dependence of $V_{rms}$ of MBN signal and background noise with plastic deformation for samples Type I (with oxide layer) and Type II (without oxide layer).

Figure 8 shows that the MBN of the samples with oxide layer (Type I) is quite low when compared to that of Type II samples. It is clear that the oxide layer "weakens" and makes unclear the MBN emission related to the material plastic deformation. Additionally, the background noise of Type I samples is higher than that of Type II samples. This fact can be due to the roughness topography of the oxide layer, which was somewhat higher than that found in the surface without oxide. The roughness effect on MBN is illustrated in next section.

*3.3.2 Surface roughness*

Figure 9 shows the finite element simulation of the magnetic flux inside the MBN sensor in two situations: when the sensor (A) fully touches or (B) partially touches the sample surface, in the last case due to the high roughness of the sample. It can be observed that, in (A), the magnetic flux inside the sensor is higher that that in (B). Then, it is clear that the high roughness of the sample reduces the sensor sensibility to pick up the MBN emission.

(A) (B)

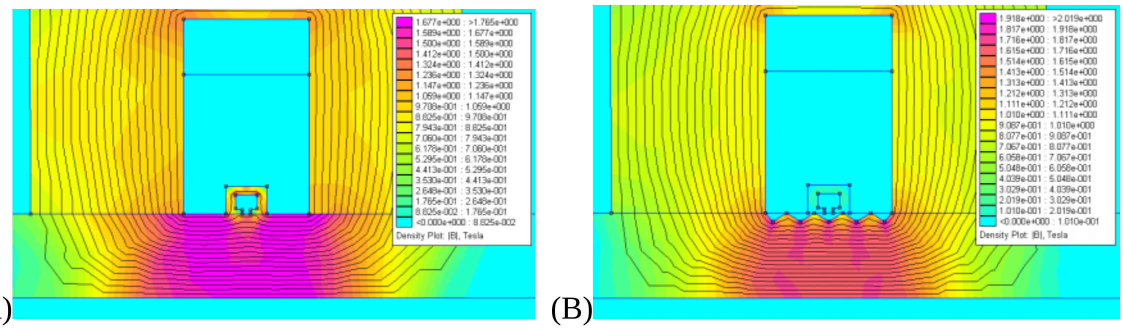


Figure 9. Finite element simulation of the magnetic flux inside the sensor a) without oxide layer and b) with oxide layer.

## 4. Concluding remarks

This work presents some results of MBN measurements for characterizing the anisotropy of steel sheet samples and its alteration when samples are subjected to mechanical tensioning.

In addition, the MBN mapping of samples subjected to drilling machining processes is also shown.

The results show the high sensitivity of the technique for detecting material structural alterations, both oriented and localized. This fact strongly indicates the MBN measurements as being a reliable technique for non-destructive inspection of materials, in both applications: processing and service. The study also shows that, during inspection, care should be taken in what concerns the surface condition, that is, the presence of oxide layers and high roughness.

Finally, the authors would like to emphasize that, although the characterizations shown here may be performed through other classical methods, the MBN technique represents a fairly simple, fast and low cost, non destructive alternative.

## 5. Acknowledgements

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