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Characterisation of in-depth stress state by magnetic Barkhausen noise on machined steel acquiring different frequency bands

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Abstract. The use of magnetic Barkhausen noise (MBN) signal to non-destructively characterize the in-depth residual stress state of machined steel was investigated. The effect of the frequency of the magnetic field applied and of analysing the resulting MBN signal in different frequency bands for an in-depth residual stress characterisation is discussed. The effect of the residual stress on each of the parameters derived from the MBN signal is analysed comparing with the result of the XRD method.

Introduction

To accurately predict the fatigue behaviour of a steel piece (e.g. bearings, gears, screw shafts) in standard operating conditions it is important to know its surface condition. One of the key characteristics on this knowledge is the residual stress (RS) state of the surface of the piece. If the RS at the surface is compressive the life time of a piece can be highly increased while with tensile RS an early failure may occur [1, 2]. Thus, in order to control the RS at the surface in all the production pieces a non destructive testing (NDT) technique is needed. First results of a study on the possibility of using the magnetic Barkhausen noise (MBN) NDT technique for this purpose are presented here.

The MBN results from the magnetization of a ferromagnetic material. A ferromagnetic material contains magnetic domains oriented in different directions. When a continuous magnetic field is applied to the material the domain walls oriented in the same direction of the magnetic field grow while the other domains are reduced. This growth is done irreversibly and the main mechanism is the movement of 180º walls. The 180º domain walls are pinned by obstacles such as defects of the microstructure, grain boundaries, dislocations or precipitates, and need energy to move from these pinning sites. When the field is high enough they can move from these pinning sites and produce a magnetic pulse which is the MBN and advance until other obstacles pin them. The amplitude and the number of MBN pulses depend on the number and morphology of the obstacles and on the derivative of the magnetic field applied. Moreover, there is a known effect on the MBN produced by the stress state on steel samples due to the magnetostriction energy [3-7].

The relationship between the MBN signal and the RS has been extensively studied in the last years [5-9]. However, there are only a few studies on the RS measurements at different depths due to the difficulty of separating the information coming from the different layers of the material [8, 9]. In this paper the relationship between RS profile and MBN at different frequencies is studied and the possibility of characterising qualitatively the RS profile by MBN signal is analysed.

Background

Stress. The MBN is influenced by the stress state due to the magnetostriction energy. In materials with a positive magnetostriction, such as ferritic - pearlitic steel, the magnetic domains oriented in the same direction as a tensile stress or perpendicular to a compressive stress need less energy to grow. On the one hand, when magnetic field is applied parallel to tensile stress direction or perpendicular to compressive stress direction, the amplitude of the MBN signal is increased. On the contrary, when it is applied perpendicular to the tensile stress direction or parallel to compressive stress direction the amplitude of the MBN signal decreases [3-7]. Both cases are represented in Fig. 1 [10].

In addition, several authors have reported that the MBN amplitude saturates for a certain compressive RS threshold, so the amplitude of MBN does not decrease when the compressive RS exceeds a certain value. Furthermore, for high tensile RS the MBN amplitude can also saturate and in some cases it can be reduced due to the fact that the magnetostriction value of the material changes its sign and it becomes negative. However, these two phenomena depend on the composition of the material and on the experimental set up used [6, 7, 11].

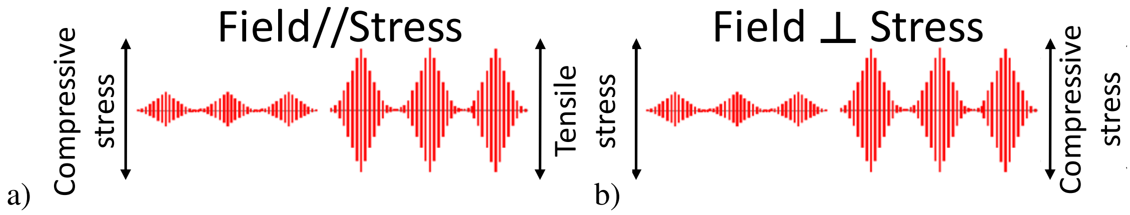


Fig. 1. Schematic representation of the effect of stress on MBN amplitude with the magnetic field a) parallel to the stress direction and b) perpendicular to the stress direction [10].

Depth measurement. The electromagnetic signals are attenuated when they have to pass through a material. The MBN signal coming from inside the material is exponentially attenuated due to eddy current damping [8, 9, 12]. This attenuation is governed by the following equation:

$$MBN(x) = MBN_0 \exp^{-x/\delta} \quad , \tag{1}$$

where MBN_0 is the amplitude of the MBN signal at its origin, x is the distance to the surface from the origin of the signal, MBN(x) is the value of the MBN coming from the distance x from the surface and δ is the skin depth of the MBN signal calculated as:

$$\delta = \sqrt{\frac{1}{\pi\sigma\mu f}} \quad , \tag{2}$$

where σ is the conductivity of the material, μ is the permeability of the material and f is the frequency of the MBN signal emitted [8, 9]. It can be seen in Eq. 2 that the attenuation is related with the frequency emission, i.e. when high frequency of the MBN signal is analyzed the information coming from large distance is highly attenuated and the information is mainly coming from the surface.

Experimental procedure

In order to study the influence of RS state on the MBN signal, three ferritic - pearlitic steel samples were chosen. They were processed with different heat treatments and machining processes in order to obtain different RS profiles. The hardness and the microstructure did not suffer any significant variation with these processes as was observed by optical microscopy and microhardness measurements at the cross-section of samples. For reasons of confidentiality we cannot specify the composition of the materials and the processes used to obtain these RS profiles.

The RS profiles were measured by means of X-ray diffraction using the $\text{sen}^2\psi$ method. A Bruker D8 Advance diffractometer with parallel beam pollycap, PSD detector and Cr radiation (wavelength λ = 2.291 Å) were employed for these measurements. In order to measure the depth profile it is necessary to successively remove layers of material without further changing the RS state of the material. The best way to do this is by electrolytic polishing [13]. This method introduces the smallest modification in the stress state, although obviously it produces a slight stress relaxation. To take into account this relaxation, the layer removal correction proposed by Moore and Evans [14] can be applied. Nevertheless, in the present study this correction is practically zero, because it is necessary to eliminate layers of millimetres of thickness to obtain a noticeable correction and in this work the maximum depth reached after the removal of several layers is below 250 µm.

In Fig. 2 the block diagram of the experimental set-up for the MBN measurements is shown, which is explained in more detail in [15]. In order to measure RS at the surface, high frequency excitation signal is applied usually because the penetration depth of the magnetic field decreases with the frequency [12, 16]. As in this work we wanted to obtain both the information from the surface and from the subsurface two different excitation frequencies were used: 100 Hz for the surface and 10 Hz for also the subsurface.

For both excitation frequencies the tangential magnetic field (H) is acquired by a Honeywell solid-state SS495A1 Hall sensor placed next to the MBN sensor, amplified and sent to the PC. At the same time, the output electromotive force signal (EMF) coming from the MBN sensor is conditioned with an analogue band-pass filter between 8 kHz – 500 kHz and is sent to the PC with an acquisition rate of 1M samples per second. There, with a customized script of Matlab software, additional numerical band-pass filtering was carried out; the width of the band-pass of each filter implemented is of 20 kHz. A set of filters ranging from the band-pass filter with its low cut-off frequency at 20 kHz to the band-pass filter with its high cut-off frequency at 500 kHz was implemented. Afterwards, the envelope of the MBN (RMS) is calculated for each band-passed signal. Then 16 half cycles of the RMS are averaged to smooth the peak. As parameters, the RMS_{max}, the position in H of the RMS_{max} (H_{peak}) and the area of the RMS peak (A_{peak}) are obtained as shown in Fig. 2 b).

The measurements both with XRD and MBN were done on the longitudinal direction of the samples.

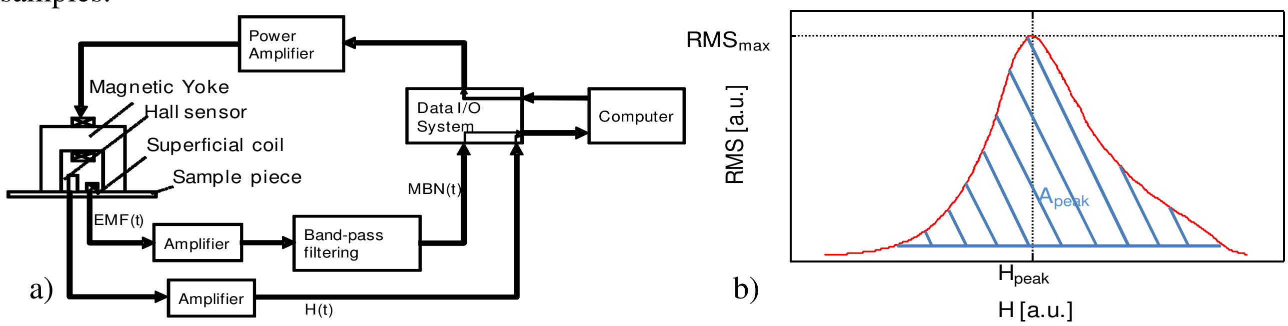


Fig. 2. Schematic representation of a) the experimental setup of the system for MBN measurements b) the parameters used to characterize de RMS of the MBN signal.

Results and discussion

The stress profiles obtained by XRD in the longitudinal direction of the samples are shown in Fig. 3. The data has been subdivided in different layers for their comparison with the MBN results. It can be seen that the stresses at the first 10 µm (layer 1) in all the pieces are highly compressive. Sample 3 and sample 1 are the samples with the highest and the lowest compressive stress levels respectively.

In the layer between 10 µm and 50 µm (layer 2) sample 2 has a great increase toward tensile stress and then from 50 µm to 100 µm (layer 3) drops to low compressive stress. Sample 1 shows the lowest compressive stress state at the surface, then the RS increases up to the same compressive stress level as sample 2 at 100 µm, and rises in layer 2 more than in layer 3. Sample 3 shows the most compressive state in these layers. Finally, in the depth between 100 µm and 200/300 µm (layer 4) samples 1 and 2 have a similar compressive stress value of -50 MPa and sample 3 keeps the high compressive stress value larger than -400 MPa shown in the above layers.

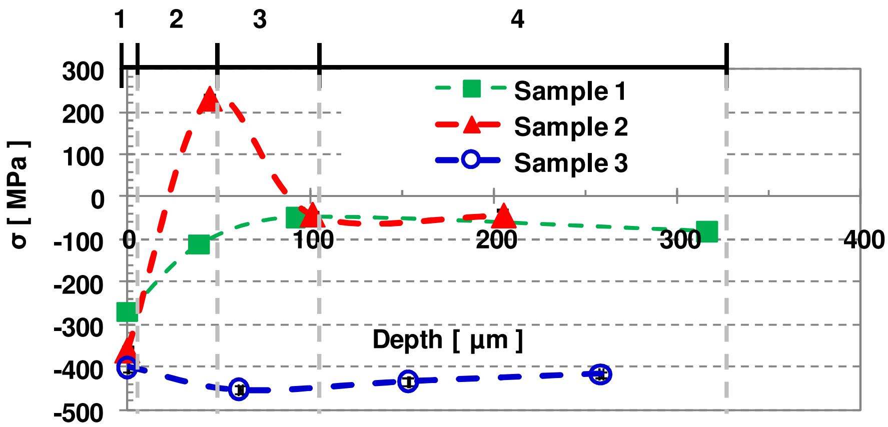


Fig. 3. RS measurements by XRD and electrolytic polishing.

In Fig. 4a) the results for the three samples of the peak amplitude of the MBN envelope (RMSmax) after applying a low frequency magnetic field (10 Hz) and filtering the resulting signal by the set of 20 kHz width band-pass filters are shown. It can be seen that when the information is coming from the maximum depth (band-pass filtering at low frequencies) the sample 2 shows the largest RMS_{max}, while the sample 3 shows the lowest RMS_{max} and the sample 1 shows intermediate values. According to results obtained by several authors [3-7], it can be deduced that the sample 2 should have the highest tensile RS, the sample 3 the most compressive RS and the sample 1 RS between the other two samples. This corresponds to the RS profile in layers 2 and 3 in Fig. 3, i.e. sample 2 has the highest tensile RS and the highest RMS_{max}, while the sample 3 has the most compressive RS and the lowest RMS_{max} and the sample 1 has intermediate RS values and intermediate values in the RMS_{max}. However, when band-pass filtering is carried out in the highest frequency range, and therefore the information is coming from a more superficial depth, it is harder to find a relationship between the RS and the RMS_{max} because the differences in the RMS_{max} between samples are smaller. This effect can be attributed to the attenuation occurring at high frequencies as Eq. 1 and Eq. 2 show. This attenuation does not exactly fit to an exponential function as these samples are not homogeneous in their RS profile.

In order to understand this variation, a model of the effect of having a heterogeneous RS profile on the RMS_{max} is presented in the following. For this purpose in Fig. 5 the effect on the RMS_{max} of having different model RS profiles on a sample are represented schematically. In Fig. 5 a) four model RS profiles are represented: one with homogeneous tensile RS (PR1), other with homogeneous compressive RS (PR2), another with compressive RS on the surface and tensile RS on the subsurface (PR3) and the last with tensile RS on the surface and compressive RS on the subsurface (PR4). In Fig. 5 b) the expected RMS_{max} values of these samples for the set of band-pass filters are plotted considering the relationship between stress and RMS_{max} [3-7] and the attenuation according to Eq. 1 and Eq. 2. It can be seen that the four model RS profiles have different behaviours for the set of band-pass filters. But this is not easy to interpret due to the attenuation, therefore a normalization of the RMS_{max} is proposed and shown in Fig 5c) in order to obtain a better representation and to see the relative changes of RS respect to the reference RS profile (in this case PR2 with an homogeneous compressive RS). It is observed that if the band-pass filtering is done at low frequencies the information comes both from the surface and from the subsurface, but when the cut-off frequencies of the band-pass filters are increased the information from the subsurface is attenuated and its impact on the normalized RMS_{max} is reduced until the cut-off frequencies are high enough to give information only from the most superficial layers.

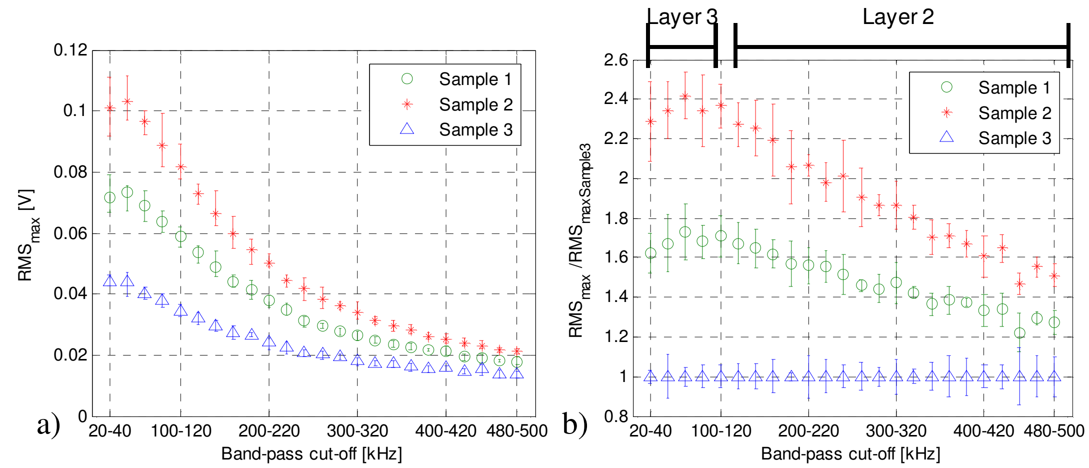
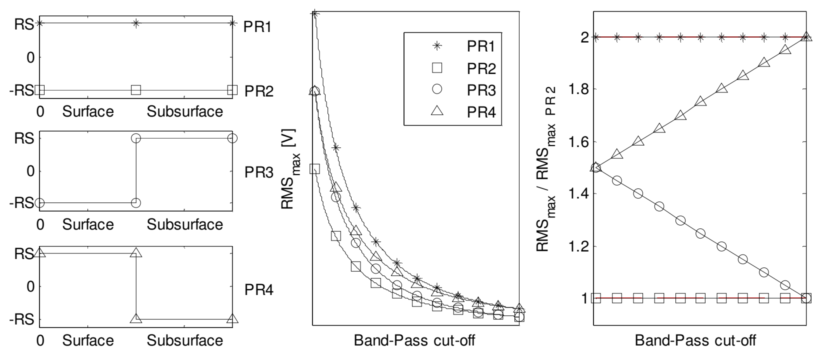


Fig. 4.Results of experiment carried out at 10 Hz. a) RMS_{max} of each sample for the set of band-pass filters and b) normalized RMS_{max} of each sample for the set of band-pass filters. The bars represent the dispersion of the measurements on each sample.



a) b) c)

Fig. 5. Schematic representation of a) RS profiles, b) expected RMS_{max} for the set of band-pass filters, c) normalized RMS_{max} for the set of band-pass filter.

As a consequence, for low cut-off frequencies of the band-pass filters the relative values of PR3 and PR4 are between the values of PR2 and PR1, as their average RS on all the depth are also between them. For higher cut-off frequencies the relative values of PR3 tend to values of PR2 and those of PR4 to values of PR1 as their RS have the same values at the surface. In real samples the observation of these trends would not be so clear, as the material is always heterogeneous and the variation in stress could change the penetration depth slightly.

The RS profile taken as reference in this work is the RS profile of sample 3. This sample is selected because it shows the RS profile with a homogeneous desired level of compressive stress and the objective of the present work is to detect non-destructively by the MBN measurements differences with respect to this reference state. Therefore, the RMS_{max} of the rest of the samples were normalized with respect to the RMS_{max} values of sample 3. In Fig. 4b these normalized RMS_{max} values obtained when applying low frequency (10 Hz) are shown for the set of band-pass filters. Sample 2 shows the largest values for the whole set of band-pass filters analysed. A noticeable increase on its amplitude with respect to sample 3 is observed as the cut-off frequencies of the filters tend to 100 kHz, and then a continuous decrease of the amplitude occurs for the rest of the set of filters, as their cut-off frequencies increase. According to Eq. 2 and the σ and μ of iron [12], the analysed depth at 20 kHz is around 80 μm, at 100 kHz the depth is around 40 μm -50 μm, the same depth of the RS peak, and the minimum analysed depth is of 20 μm at 500 kHz.

In the absence of a calibration that would allow a quantitative calculation of the complete RS profile, a qualitative estimation of the shape of the RS profile can be done if the RS profile of the reference sample (Fig. 3) and the model presented (Fig. 5) are considered. When analysing the information obtained by the set of band-pass filters with the lowest cut-off frequencies and hence, coming from the maximum depth in the analysis, it can be deduced that the RS of sample 2 are larger (tensile) than those of sample 3. As the frequency of the band-pass filters increase, and therefore, the depth of the layer from which the information is obtained decreases, the RS becomes more tensile up to a certain depth. Then, as the most superficial layers are analysed, with the use of band-pass filters with increasing values of their cut-off frequencies, the RS become more compressive. The relative decrease of this decay is larger than the relative increase corresponding to the first part of the curve. This evolution of the RS profile is corroborated by the measurements of the RS profile performed in sample 2 (layer 3 and 2). However, in the most superficial layer (high band-pass filtering) the same value as the reference sample is not observed, as it would be expected because both samples have similar residual stress value at layer 1 (see Fig 3). In order to obtain only more superficial information, the acquisition frequency should be higher (minimum analysed depth is around 20 μm), but this is not possible with the presently available experimental set up.

Sample 1 shows intermediate normalized RMS_{max} values (see Fig. 4b) which indicates intermediate RS values as can be seen in Fig. 3.

The results of A_{peak} and H_{peak} did not show significant relationship with the RS profile.

In Fig. 6 the normalized RMS_{max} values obtained when high frequency H is applied (100 Hz) are shown for the set of band-pass filters. For low-intermediate band-pass cut-off frequencies (up to 220 kHz) the normalized RMS_{max} for samples 1 and 2 is reduced as the cut-off frequencies increase. As it is previously explained, this is due to a decrease of the tensile stress of these samples as the depth decreases. This behaviour shown in samples 1 and 2 can be compared with the behaviour observed on the stress profile, where sample 1 have a decrease in the RS from layers 3 to 1 and sample 2 have a decrease on the stress from layer 2 to 1. For the high cut-off frequencies the three samples have similar RMS_{max} values. This could be due to the fact that for high compressive stress the RMS_{max} reaches a saturation level at which there is no difference between higher compressive stresses [6, 7, 11]. Therefore, with this experimental setup (100 Hz) the compressive RS could not be distinguished below a certain value that it is reached in these samples. Moreover, as the acquisition band of the MBN has not changed between the magnetic field applied at 10 Hz (Fig 4b) and 100 Hz (Fig 5), the differences seen in these two excitation modes are due to the reduction in the penetration depth of the magnetic field applied as the frequency is increased [12, 16].

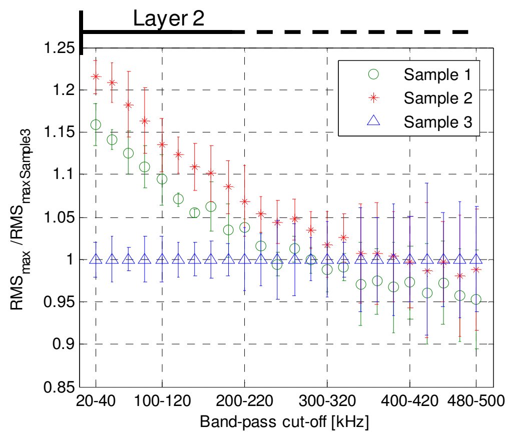


Fig. 6. Results of the experiment carried out at 100 Hz. Normalized RMS_{max} of each sample of each sample for the set of band-pass filters. The bars represent the absolute error of the measurements on each sample.

Conclusions

- The RMS_{max} obtained after applying band-pass filters with different cut-off frequencies can give information of RS profile.
- With a known RS profile of a correct manufactured sample it is possible to qualitatively estimate the relative change on the RS profile of any other sample and define criteria to accept or reject these samples. This can be done normalizing the RMS_{max} at each band-pass filter with the RMS_{max} of the correct manufactured sample.
- With an extensive calibration process it would be possible to characterize the RS profile with the RMS_{max} values.
- With the adequate excitation frequency of the H it is possible to obtain information from RS profile at different depths. With magnetic field applied at low frequency more depth can be analyzed, whereas with high frequency the analyzed depth is more superficial.

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