Non-Destructive Characterization of Subsurface Plastic Deformation in Case Carburized Steel Using Magnetic Barkhausen Noise Technique

Mohamed M. Blaow, Mohamed Ali Ballem, and Brian Andrew Shaw

Abstract—The effect of extreme loading in bending was investigated by magnetic Barkhausen Noise (MBN) and X-ray diffraction (XRD) in two types of inhomogeneous steels that widely used in gear industry. EN 36 and H8620 steels in the carburized, tempered and ground condition were investigated after unloading from high stress levels. The inhomogeneity arising from the variation in carbon content showed up clearly by double peaks MBN profiles before loading. The first MBN peak at low field revealed the soft subsurface region and the second peak at higher field revealed the hard surface layer. Residual stresses profiles were produced by XRD before and after loading to probe plasticity in the cross sections of both specimens. Barkhausen noise measurements showed a considerable change in the first peak height in both steels as a response to plastic deformation in tension and compression in the subsurface material. The height of the second peak remained unchanged in EN 36 specimen but increased slightly in the H8620 specimen. The residual stress measurements after unloading indicated that the subsurface materials after a depth of 0.4 mm in both specimens were yielded. The surface layer of the H8620 steel was also affected slightly by bending as revealed by an increase in the second MBN peak height and confirmed by XRD as indication of yielding. The experiment confirmed that the magnetic Barkhausen noise can be used to characterize yielding in inhomogeneous steels non-destructively.

Index Terms—Case-Carburised Steels, Magnetic Barkhausen Noise, Residual Stress, X-Ray Diffraction.

I. INTRODUCTION

Steel components are often subjected to hardening processes in which the surface is hardened in order to improve its wear and fatigue resistance, these processes introduce a case-hardened layer; the hardness of this layer is higher than that of the bulk material, and its depth is varying depending on the different requirements and applications. Case hardening process is often used for the manufacture of machine parts such as gears that need to have externally hard surface to endure wear and tear, but soft internally to withstand shock. During the manufacturing process of case-hardened steel gears, residual stresses are developed [1], [2]. The presence of residual stresses in materials affecting their behavior during the service life, for instance crack initiation and propagation, stress corrosion cracking, and cycle fatigue performance are strongly influenced by residual stresses. Tensile residual stresses are generally harmful since they are the major cause of stress corrosion cracking, and fatigue failure. On the other hand, compressive residual stresses are usually beneficial because they increase wear and corrosion resistance and prevent propagation of fatigue cracks [3], [4].

Various methods have been developed for measuring residual stresses, and for determining case depth in case-hardened materials. Usually, case depth is determined by measuring microhardness profile in randomly selected samples. Sample preparation includes cutting and polishing in the areas of measurements. This method is time consuming, expensive, and considered as a destructive method. Residual stresses measurements broadly can be classified into destructive and non-destructive methods. The use of destructive methods e.g., hole drilling method, ring-core technique, bending deflection methods, and sectioning methods is limited mostly to laboratory samples, also tests are not made on the structures or components directly, therefore the correlation of behavior between objects and the used spacemen need to be proved [3], [5].

Non-destructive measurements of residual stresses can be done by variety of methods, including x-ray diffraction, ultrasonic, and electromagnetic techniques. Non-destructive methods do not promote changes in the material characteristics under examination and do not interfere in its later application; thus the use of these techniques has been increasing in the last years. X-ray diffraction can be used for quantitative analysis of surface residual stresses; however it is time consuming when investigating components with relatively large surface areas, also it has some limitations since it is expansive and destructive if used to measure residual stresses in the subsurface regions [6]–[9].

The non-destructive testing tool which is finding wide application in stress analysis is the magneto elasticity method, based on the Barkhausen noise principle. The advantages of using the Barkhausen noise technique for stress measurements are that it is fast, reliable, requires no surface preparation, and can be used for components having complex geometries. The main advantage is that an absolute value of stress is obtained if instrument properly calibrated [3], [10]–[12]. The case hardening process produces changes in the microstructure, and as a result the electrical conductivity and magnetic permeability in the case-hardened region are different from those in the substrate.
[13]. Since the magnetic properties are very sensitive to material structural changes, magnetic measurements like magnetic Barkhausen noise (MBN) method is a potential technique and may be applied as non-destructive inspection method for the detection of material changes and stress status in inhomogeneous cross sections [14].

The possibility of measuring the case depth of an induction-hardened steel using MBN technique was investigated by Vaidyanathan et al. [15]. They concluded that the effective depth is reflected in the MBN profile is in the range below 0.7 mm by showing a small peak in a low field strength reflecting the core material (pearlite) and larger peak at higher field strength, indicating the martensitic layer. This is due to the microstructural change through the depth with the result that two major domain walls populations contribute to the magnetization process independently. Bach et al. [16], using a different experimental arrangement, showed that a case depth of 5 mm could be detected in the MBN profile with double peaks. They used the ratio of peak heights as an indicator of the case depth. Dubois and Fiset [17] correlated case depth in case carburized steel with the frequency spectrum of the MBN signal integrated over a range of frequencies specific to the steel type. Vaidyanathan et al. [18] used the MBN technique to evaluate the carburization depth in ferritic steels. They showed that the variation of carbon content affects the magnetic properties and consequently the MBN signal level. They indicated that as the carbon content increases, the intensity of MBN emission was found to decrease. In carburized and decarburized steels, hardness gradients are present [14], [16], [19], [20] and that can cause two MBN intensity peaks to appear at different field strengths. The reason is that each peak originates in a material layer of different hardness. The variation in ferromagnetic material properties can be correlated to different parameters derived from the MBN signal generated during the magnetization cycle. The MBN profile is a plot of the root-mean-square voltage (rms) of the MBN voltage pulses as a function of applied current to the electromagnet [21].

The aim of this paper is to examine the applicability of magnetic Barkhausen noise technique to evaluate the residual stresses at the subsurface region, and to explore the possibility of detecting plastic deformation non-destructively across the section of case carburized steels. The obtained results were discussed and correlated with X-ray measurement.

II. MATERIALS AND METHOD

The composition of the EN36 and H8620 alloy steels prior to carburization is given in Table 1. Bars (12×12×150) mm³ were case-carburized to produce a surface carbon content of 0.85 wt % in a case-depth of 0.5 mm. The specimens were then oil quenched from 900°C in oil. The specimens were then tempered at 190°C for 2 h (standard tempering used for gears) before testing. The carburized batches were subsequently ground gently to take off a layer of 50 microns to eliminate the effect of any decarburization might have taken place during the heat treatment.

<table>
<thead>
<tr>
<th>Steel</th>
<th>Elements, % weight (Balance Fe)</th>
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<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>EN 36</td>
<td>0.14</td>
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<tr>
<td>H8620</td>
<td>0.2</td>
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Microhardness measurements were performed in the specimens’ cross sections to determine the effective hardening depth of the carburization process (Fig. 1). The heat treated and ground specimens consist of martensite layer of approximately 0.4 mm and ferrite-pearlite structures in the subsurface regions as revealed by optical micrographs (Fig. 2).

![Fig. 1 Microhardness profiles of case carburized steels H8620 and EN36](image1)

![Fig. 2 Microstructure of the case (a) and the bulk material (b) of H8620 steel](image2)

Specimens were mounted in a cantilever rig with one end...
anchored en-castre in a rigid fixture and the other end attached to the cantilever arm. The length of the specimen exposed to deformation was set at 75 mm. The applied moment was increased incrementally by applying masses to the free end of the cantilever up to fracture in the first step. After determining the fracture bending load, another specimen was loaded in the same way but to a lower load that is high enough to produce a plastic deformation in the bulk material of the specimens (1578 MPa). The yield strength of the as received EN36 and H8620 before carburization found by uniaxial loading machine was 381 MPa and 370 MPa respectively.

The MBN measurements were made using equipment developed in the authors’ laboratory. The testing procedure was developed to give a high degree of reproducibility, i.e. to produce minimum variations in a run of tests on the same specimen. A schematic illustration of the equipment is shown in Fig. 3. To produce a constant rate of magnetic induction in the specimen, the U-shape electromagnetic yoke is fed by a triangular waveform from a bipolar amplifier to take the specimen to near saturation at maximum current. The amplitude of the driving current to produce a maximum magnetic field strength of 4.5 kA m\(^{-1}\) at a frequency of 0.2Hz was 1A. A relatively low excitation frequency was used to minimise eddy current opposition to the applied magnetic field and to ensure a relatively slow magnetisation rate in the sample.

Barkhausen noise was detected by an inductive search coil with 1000 turns wound around a ferrite core. The signal was amplified in two stages. In the first stage, the gain was fixed at 40 dB. The amplified signal is filtered using a 1-100 kHz band pass filter. After filtering, the signal was passed through an additional amplifier with a variable gain of up to 60 dB. The MBN signals were then acquired using a 20 Ms/s Pico Tech 12-bit DAC oscilloscope and stored in a PC. As described below, MBN emission, to a first approximation, was correlated with the differential permeability of the material. It follows that in a homogeneous material the emission is a maximum twice in each hysteresis loop. The intensity of the MBN emission is anticipated to peak at a positive field with increasing energising current and peak again at a negative field as the state of magnetisation of the sample moves around the BH loop. This was observed in our experiments, but only profiles obtained with a rising current are used unless otherwise stated. An indication of the amplified and filtered output from the search coil is shown in the inset in Fig. 3.

As appropriate for the skin depth relationship with the excitation frequency (0.2Hz) and the analysing frequency range (1–100kHz), the broadband MBN signal containing multiple frequencies samples the specimen to a depth of about 0.6 mm below the surface [22]. An important requirement in the MBN measurements was to produce data that is reproducible across a large number of magnetic cycles and was insensitive to any variations in the location of the energising electromagnet and search coil. Very good reproducibility was achieved in the experiment. To avoid mechanical damage, the specimens were chemically etched followed by electropolishing according to standard procedure. The time of chemical etching is varied to achieve the desired depth of layer removal to make XRD measurements following extreme bending.

III. RESULTS AND DISCUSSION

It is convenient to smooth emissions to produce a measure of the amplitude of the envelope enclosing the signal. This was done numerically using a Matlab script. The signal was rectified by calculating the local root mean square using a running average of fifteen points. Examples of the resulted type of MBN profiles are shown in Fig. 4 for one magnetization cycle for both steels before loading. The case carburized specimens have two different microstructures: martensite layer at the surface of 0.4 mm effective depth and ferrite-pearlite in the bulk.

![Fig. 3. Schematic layout of the MBE measurement apparatus.](image)

![Fig. 4. MBN profiles of one magnetization cycle for both steels (before loading).](image)

Obviously the associated Magnetic properties and their organization under the applied field are independent and
hence, the MBN activities are characteristic of both microstructures. Each microstructure is represented by a peak at a particular magnetic field as seen in Fig. 4. The first peak at low field represent the soft magnetic material at the bulk and the second peak at higher field represent the hard magnetic material at the case. It is assumed that both structures would have a different response to applied stress because both materials at the surface and the subsurface yield at different stress levels. Based on microhardness measurements, the yield stress of the case is about 2 GPa whereas the yield stress of the bulk is about 0.375 GPa approximately for both steels. Consequently, it is anticipated that the MBN output would be affected by the application of an extreme bending load. This makes the basis of the investigation by MBN and followed by XRD.

Bending load of 1578 MPa was gradually applied to the cantilever arm and then gradually removed too, after that the specimens were dismounted from the bending rig. Barkhausen noise measurements in both specimens (EN36 and H8620) on the tension side and the compression sides were performed and compared with the MBN output before loading as shown in Fig. 5 and Fig. 6 respectively.

The MBN result shows that the first peak representing the subsurface material height has been modified by plastic deformation in tension and compression. The residual compressive stresses in the tension side are characterized by a diminishing of the first peak and the residual tensile stresses in the compression side are characterized by an increase in the first peak height for both types of steels. The height of the second peak representing the martensite layer has also changed but to a much less extent. Moreover, the change in the height of the second peak in the H8620 steel is more than that of the EN 36 steel.

In order to correlate the result of MBN, XRD measurements at the specimens centre have been conducted to both surfaces of the specimens. The variation in residual stresses after unloading the specimen from ≈1578 MPa is shown in Figs. 7 and 8. In the as ground specimens before loading, the residual stresses were compressive through the depth of 1 mm in both steels. After loading and unloading of the specimens, progressive changes in the surface residual stresses values and the irrede distribution through the depth have been determined by XRD. These changes in the residual stresses can be relatively compared and correlated with MBN profiles peaks.

Since carbon level is the major factor affecting the maximum differential permeability and hence MBN, it is wise enough to divide the depth into two averages of mechanical states; a hard material at the surface up to the effective hardness depth and a soft material below the effective case depth. The effective case depth of the two specimens after grinding was found to be about 0.4 mm and an approximation for simplicity has been proposed such that the hard depth is 0 - 0.4 mm and the soft depth below 0.4 mm. In order to make a correlation of MBN and XRD measurements, the profile peak height (Vp) for each peak have been considered in the analysis. After the completion of data mining, a summary of the results of interest is shown in Table II.
In case hardened steels a hardness gradient is present. This can cause two MBN intensity peaks to appear at different field strengths. The reason is that each peak originates in a material layer of different hardness. It is known that martensite as a hard structure is characterized by a low MBN intensity occurring at a high applied field and the ferrite-pearlite structure is a soft material which is characterized by a higher MBN activity at low applied field [14]. Accordingly, in complex MBN profile containing two peaks in inhomogeneous material, peak I refers to the magnetically soft material at the subsurface range and peak II refers to the hard one at the surface.

It follows from the result that the subsurface region below 0.4 mm has experienced plastic deformation in tension and compression as indicated by the variation in the heights of the first peak. In EN 36 steel, in the compression side, the increase in the height of the first peak refers to yield in compression and hence tensile residual stresses have been induced and vice versa in the tensile side. This has been confirmed by XRD measurements. The residual stresses in the compression side at the subsurface region have converted from compressive (−140 MPa) to tensile (+193 MPa). Furthermore, in the tensile side, the residual stresses at the subsurface (−140 MPa) have become more compression (−189 MPa). However, the result indicated also that the surface residual stresses have also been redistributed in tension and compression sides. The bending has caused the hard material at the surface to respond to severe bending by yielding as well but to a less extent and hence the residual stresses have been redistributed through the surface material (0 - 0.4 mm) especially in the compression side. The residual stresses (−200 MPa) have become less compression (-136 MPa) in the compression side but at the tensile side (−214 MPa) seems negligible (−14 MPa) as it lies within the error value. The change in peak height (Vp) of the second peak confirms the mechanical state of the surface region where Vp at the tensile surface did not change and that of the compression surface changed slightly from 211 to 229 a.u.

The results from H8620 steel are to a large extent similar to that of the EN 36 steel. However, an indication of yield has been observed by an increase in the height of peak II from 221 to 291 which has been confirmed by the XRD measurement by a change in residual stresses from (−224 MPa) to (−178 MPa). The results confirm that MBN profile analysis indicates the plastic deformation of the subsurface material by the variation of the first peak heights since residual tensile stresses increase MBN and the residual compressive stresses decrease MBN.

The reason for the variation in MBN that refers to the subsurface material as a result of yield is that residual stresses change the arrangement of the magnetic domains according to the sign of the residual stresses. Since steel is a positive magnetostriction material, residual tensile stresses increase MBN activity and residual compressive stresses decrease it [14]. In steel tensile stresses increase the number of 180° domain walls which are mainly responsible for the MBN. Therefore, in steel tensile stresses increases the intensity of the MBN when the measurements are made in the direction of the applied stresses. The opposite is true for compressive stresses that increase the number of 90° domain walls.

### IV. CONCLUSIONS

On the basis of material presented in this paper the following conclusions may be drawn:

1) The experiment confirmed that the magnetic Barkhausen noise can be used to characterize yielding in inhomogeneous steels non-destructively.

2) Changes in the residual stress profiles were correlated with MBN peaks composing the produced profiles.

3) The results confirmed that MBN profile analysis indicates the plastic deformation of the subsurface material by the modification of the first peak heights.

### REFERENCES


### TABLE II: SUMMARY OF RESULTS

<table>
<thead>
<tr>
<th>Steel and condition</th>
<th>Before loading</th>
<th>After loading</th>
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<tbody>
<tr>
<td></td>
<td>Tension side</td>
<td>Compression side</td>
</tr>
<tr>
<td>EN 36</td>
<td>Tension side</td>
<td>Compression side</td>
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<tr>
<td></td>
<td>Vp I sub</td>
<td>Vp II sub</td>
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<tr>
<td>Before loading</td>
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<td>211</td>
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<tr>
<td>After loading</td>
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<td>210</td>
</tr>
<tr>
<td>Compression side</td>
<td>242</td>
<td>229</td>
</tr>
<tr>
<td></td>
<td>77.8</td>
<td>221</td>
</tr>
</tbody>
</table>

| H8620               | Tension side | Compression side |
|                     | Vp I sub | Vp II sub | 0 - 0.4 mm surface | 0.4 - 1 mm subsurface |
| Before loading      | 40.7 | 291 | −178 | −198 |
| After loading       | 261 | 222 | −230 | 144 |

**Note:** The table above provides a summary of the results for different steels and conditions before and after loading, indicating changes in MBN profile parameters such as peak heights and surface subsurface stresses.


