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Approach for Improving the Sensitivity of Barkhausen Noise Sensors with Applications to Magnetic Nondestructive Testing

by Neelam Prabhu Gaunkar*, Ikenna Nlebedim†, and David Jiles‡

ABSTRACT

Barkhausen noise emissions occur in ferromagnetic materials on application of a time varying external magnetic field. These emissions primarily occur because of the movement of domain walls in the presence of pinning sites or discontinuities, which act as inhibitors to domain wall motion within the material. The emissions can be sensed using an induction coil placed close to the sample surface. The coil can sense the variations in magnetic flux, which translates to the induced electromagnetic field. This study optimizes the design of the barkhausen noise sensor via finite element simulations. The different parameters involved in improvement of the design of the barkhausen noise sensor are discussed.

KEYWORDS: barkhausen effect, sensitivity, induction sensor, finite element analysis, optimization.

Introduction

There are many nondestructive testing (NDT) techniques including ultrasonic testing, eddy current testing, acoustic emission testing, magnetic flux leakage testing, magnetic particle testing, dye penetrant testing, and so on, which are employed to detect and characterize surface and subsurface discontinuities in materials; most of these techniques are complementary and can be used in suitable combination with others (Jiles, 1988). Among the surface inspection techniques based on electromagnetics, magnetic barkhausen noise (MBN) measurement has emerged as an efficient and cost-effective NDT technique that is vital for several industrial applications in integrity assessment of installations. Often, surface treatments such as grinding, carburization, and shot-peening are needed to prolong the service lifetime of components. Such surface modification treatments usually result in changes in microstructure and surface stress conditions in the components. Surface chemistry, microstructure, and stresses can also evolve during service exposure, sometimes compromising the durability of components and structures. Reliable techniques are therefore needed to evaluate the surface and near-surface conditions of components and structures both during pre-service or in-service periods. MBN measurement is one such inspection technique that permits detection and evaluation of surface degradation in ferromagnetic materials and can be used to determine the onset of failure of the component.

MBN measurement tools use the interaction between the magnetization, microstructural characteristics, and stress-states of ferromagnetic materials to provide vital information about the state of the materials. The magnetic properties of ferromagnetic materials, such as steels, are strongly coupled to their microstructure. Therefore, changes in microstructure can be readily detected using changes in the magnetic behavior of the material. This relationship between the microstructure and magnetic properties has been proven to be very useful and is being increasingly used for NDT of load bearing parts exposed to aggressive environments and complex service stress patterns, where the failure of parts can have catastrophic consequences.

Among the magnetic NDT techniques, MBN monitoring and measurement offers a unique capability for evaluating the health of structures by enabling detection of anomalies in surface microstructure, residual stresses, or even microcracks. Ferromagnetic and ferrimagnetic materials contain regions of uniform magnetization called magnetic domains. Under an applied magnetic field, the domains that are favorably...
oriented in the direction of the applied magnetic field tend to grow at the expense of the others. This results in the movement of the walls separating adjacent domains. Because this movement of domain walls is impeded by pinning sites that influence their movement in the materials, the magnetization process is discontinuous. Therefore, the MBN emission process consists of discontinuous changes in magnetic flux density due to sudden irreversible and discontinuous changes in magnetization inside the material as the applied magnetic field, $H$, changes continuously (Jiles, 1998).

Magnetic barkhausen emission can be measured by application of an alternating magnetic field to a test specimen. The barkhausen emissions in the sample are then detected and measured as voltage pulses induced in a sense coil positioned close to the component surface (Wilson, 2004). The amplitude and profile of the voltage pulses have been shown to depend on the microstructure and residual stress condition of the test specimen (Kypris et al., 2012; Kypris et al., 2014). Bandpass filtering is usually employed to remove the high frequency noise while processing the signals. The filtered signal is further amplified. A representation of the measurement procedure is shown in Figure 1.

Previous work has shown that the reciprocal of the peak barkhausen noise voltage is proportional to the stress level within a test specimen, other parameters remaining identical (Kypris et al., 2013; Mierczak et al., 2011). This implies that, using a suitable sensor, measured barkhausen noise signals can be used to assess the stress condition in test specimens. Hence, it is essential to effectively capture and analyze the signal generated and for this purpose it is important to optimize the design of the sensor for its sensitivity and resolution.

In this work the design considerations for a typical barkhausen noise detection sensor are presented. Previous works have highlighted the importance of improving the design of the magnetization unit and selection of an appropriate core material (Meyendorf et al., 2014; Prabhu Gaunkar et al., 2014; Tumanski, 2007). In this study, it was observed that, besides the magnetization unit, the performance of the sensing unit should be optimized. Finite element simulations were used to evaluate and optimize the performance of a sensing unit. Extending the work from the previous studies, the simulations were conducted under an alternating current magnetization field (Prabhu Gaunkar et al., 2014).

**Theory**

Capturing and analyzing the response of ferromagnetic materials to applied magnetic fields offers a potentially powerful tool to obtain insight into the nature of the material's microstructural characteristics in a nondestructive manner. MBN measurement is one such technique that is well suited for monitoring metallurgical processes that induce surface residual stresses and produce changes in microstructure of materials and is increasingly being used in manufacturing as well as in-service inspection of industrial equipment. This section examines some of the essential principles of the barkhausen effect and certain concepts related to the design of the barkhausen noise sensor.

![Figure 1. Schematic of barkhausen noise measurement setup. A time varying sinusoidal voltage was applied to the magnetizing coil, and the signal response was recorded using a pickup coil placed near the sample, processed, and displayed.](image1)

![Figure 2. Barkhausen noise: (a) schematic showing how the barkhausen noise signal travels as an electromagnetic wave to the surface of the test specimen; and (b) a typical barkhausen noise signal.](image2)
The Barkhausen Effect

Barkhausen emissions occur in response to sudden changes in magnetization within a ferromagnetic material and can be generated by the application of a continuously varying magnetic field (Dhar and Atherton, 1992). The Barkhausen emissions that occur within a ferromagnetic material travel outwards as electromagnetic waves and can be sensed on the material surface using inductive sensors. A schematic representation is shown in Figure 2.

The electromagnetic field (EMF) induced in the pickup coil can be described by Faraday’s law of electromagnetic induction. The induced EMF, \( V_{\text{emf}} \), is directly proportional to the changing magnetic flux, \( d\Phi / dt \), and can be further related to the magnetic induction, \( B \), within the coil and the area, \( A \), of the sensing coil. Mathematically, the induced voltage can be described as follows.

\[
V_{\text{emf}} = -N \frac{d\Phi}{dt} = -N B \frac{dA}{dt} = -N \mu_0 A \frac{dH}{dt}
\]

From this relationship it is well understood that the Barkhausen voltage is dependent on the magnetic induction and is thus also related to the magnetic permeability, \( \mu_0 \mu_r \). Hence, the recorded signal may be enhanced by using a high magnetic permeability core material within the pickup coil. Nevertheless, care should be taken not to saturate the core material under operation.

Mutual Inductance Effects

It is required that the change in magnetic flux detected by the sensing coil be shielded from the magnetization within the magnetizing core. This is often controlled by adjusting the proximity of the magnetization and sense coil. However, if the two coils are positioned relatively close to each other, the mutual inductance, \( M_m \), may be described as follows:

\[
M_m = \frac{\mu_0 \mu_r N_1 N_2 A}{l}
\]

where
- \( \mu_0 \) is the permeability of free space,
- \( \mu_r \) is the relative permeability of the core,
- \( N_1 \) and \( N_2 \) represent the number of coil turns in the primary and the secondary coil, respectively,
- \( A \) is the cross-sectional area of the core pole,
- \( l \) is the length of the coil.

The mutual inductance is a measure of the EMF generated in the secondary/pickup coil due to the change in current in the primary/magnetization coil. Thus, the measured EMF is affected because of the mutual inductance effects between the primary and the secondary coils.

Signal Sensitivity of the Sensor

The sensitivity of a sensor is defined as the relationship between the applied input and the output signal of interest. For Barkhausen noise signals, the sensitivity is the ratio of the measured signal voltage to the magnetizing field intensity or magnetizing current. High sensor sensitivity is desirable for obtaining an accurate record of the actual Barkhausen noise signal.

Simulation Setup

Figure 3 is a representation of the geometry of the magnetizing unit (Prabhu Gaukdar et al., 2014). C-core geometry was selected, being a typical geometry for Barkhausen noise sensors. The properties and dimensions of the core and the coil are listed in Table 1. The finite element simulations were performed using the alternating current/direct current module of commercial software.

![Figure 3. Schematic of the magnetization assembly: (a) showing the magnetizing soft iron core material, coils (N = 1000 turns each), and test specimen; and (b) the equivalent magnetic circuit for the magnetization assembly. In Figure 3a the pickup coil is placed at location C, and the ferrite core is used within the pickup coil. \( R_{\text{core}} \) corresponds to the resistance of the magnetizing core; \( R_{\text{gap}} \) corresponds to the resistance of the air gap; and \( R_{\text{specimen}} \) is the resistance of the test specimen. The coils are represented by equivalent voltage or magnetomotive force (MMF) sources.](image)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Material</th>
<th>Length</th>
<th>Width</th>
<th>Depth</th>
<th>Number of turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coll</td>
<td>Copper</td>
<td>8 mm</td>
<td>4 mm</td>
<td>4 mm</td>
<td>1000</td>
</tr>
<tr>
<td>Core</td>
<td>Variable</td>
<td>14 mm</td>
<td>3.4 mm</td>
<td>3.4 mm</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Direct current finite element simulations were performed ignoring the frequency dependent effects. This is a valid assumption considering that typical barkhausen noise excitation coils operate in the lower quasi-static limit and are thus well described by a direct current approach. The direct current magnetic flux density profile for a magnetizing current of 1 A through both coils is illustrated in Figure 4 (Prabhu Gaunkar et al., 2014). Each coil has 1000 turns, and the test sample is considered to be the same material as the magnetization core to ensure maximum coupling of signal from the magnetizing core into the test specimen. Essentially referring to Figure 3b, $R_{\text{specimen}}$ would be comparable to $R_{\text{core}}/3$, whereas in most cases the magnetizing core will not be the same material as the test specimen and there will be more losses. A curved core tip was selected to enhance coupling with different geometries. It was observed that the magnetic flux density was reduced at the edges; hence, rounded edges were used in the core design to minimize magnetic flux leakage at the edges. A higher magnetic flux concentration was also obtained at the interface between the sample and the magnetizing core. Overall, the magnetic flux density was uniform through the magnetizing core. Also, there was slight leakage of magnetic flux with the pickup core.

**Initial Measurements**

A barkhausen noise sensor was constructed using an ASTM A 36 steel core for the magnetization unit and a nickel-zinc ferrite core for the pickup unit. Figure 5 shows the signal that was captured directly from the sensing coil after passing through a single amplification stage. The signal was further amplified and filtered in the frequency range of 10 to 500 kHz, as seen in Figure 6. From these measurements it was observed that the barkhausen noise signal had low amplitude and the...
signal amplitude was close to the noise floor. Thus, it became essential to effectively sense the signal and differentiate the measured Barkhausen signal from actual noise.

Simulation Results
From Figure 5 and Figure 6 it was observed that the measured signal was relatively close to the noise floor. In order to improve the measurement accuracy, the design of the sensor was optimized. Thus, finite element simulations were conducted to replicate the actual measurement system. The soft-iron based magnetization coil was considered as a part of the load for an amplifier circuit. The input magnetization was selected to be near the quasi-static limit at a frequency of 10 kHz. A representation of the coil magnetizing voltage is found in Figure 7.

On application of a time-varying field, a variation in the magnetic flux around the pickup coil was observed. Figure 8
shows the induced current density at a particular instant in time, indicating the maximum current density at the location closest to the test sample. The peak in the induced current density may be attributed to the magnetic flux leakage at the interface of the magnetizing core and the test sample and to the mutual inductance between the magnetizing and sense coils.

Further investigations were conducted on the effect of the alternating current magnetizing field on the sensing coil. The magnetic flux density was recorded at two points, C and D, respectively (Figure 3). Point C corresponds to a point on the test sample. The relative permeability of the test-sample was varied from 2500 to 10 000. Figure 9 is a comparison of the norm of the magnetic flux densities with time for different relative permeability, \( \mu_r \), values. From this comparison, it can be inferred that the magnetic flux profile at the sensing coil had extremely small variation due to fluctuations in \( \mu_r \) of the test sample, except that it was extremely low when \( \mu_r \) was equal to 1. This implies that the sensing coil is in fact more responsive to the input magnetizing signal compared to the signals received from the test sample.

Furthermore, a comparison of the norm of the magnetic flux densities at point D, a point on the sensing coil, is found in Figure 10. In this case, on varying the relative permeability of the test sample it was found that the magnetic flux density at point D decreased. There is a reduction in the magnetic flux density with an increase in the permeability of the test sample because there is a reduction in the magnetic flux leakage and a major part of the magnetic flux penetrates through the test sample. Thus, the maximum magnetic flux density was obtained for a core material with \( \mu_r \) equal to 1 since there was high leakage at the interface of the test sample and the surrounding media.

**Conclusion**

A finite element simulation technique was developed to analyze the behavior of a magnetic sensor for barkhausen emission measurements. The simulation results highlight the presence of mutual inductance effects between the magnetizing coil and the sensing coil. The sensitivity of the sensor based on this design may be improved by using a high magnetic permeability core material within a pickup coil with a large number of turns while compensating for the interference effects between the two coils. Although higher permeability is desirable, the sensing material should also possess high saturation magnetization in order to not be saturated in operation. Alternatively, to improve the detection accuracy of the sensing unit and to compensate for the mutual inductance effects, a different sensing mechanism such as hall effect based measurements may be utilized. Further investigations are needed to improve measurement sensitivity and reproducibility for more effective application to NDT.

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**REFERENCES**


