Monitoring Magnetic Property Tensor Across the Weld at the Same Points where Stress Tensor was Monitored

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Abstract. The magnetic methods (Barkhausen noise and hysteresis loops) are especially suitable for ferromagnetic polycrystalline materials. They are fast, reliable, economic methods, which can be applied on-site. They are appropriate either for laboratory, or for industrial scale. The test samples require no special pre-treatment. However, it has been unknown how to establish direct connections between magnetic and mechanical features in any grade of ferromagnetic steel.

Due to the above-mentioned advantages, the magnetic methods can be rather useful in evaluating stress of welded materials. In this way, the residual stress state in each welding zone of the material may be well determined. Since stress is an extrinsic property and cannot be directly estimated, all methods applied so far take into account an intrinsic property, such as strain and then the residual stress can be therefore easily calculated. According to our proposed method, by determining the mechanical behaviour of any grade of ferromagnetic steel in either tensile or compressive loads, the magnitude and the distribution of the residual stresses can be easily evaluated.

In order to evaluate residual stresses using the magnetic techniques in the welded samples, a two-step procedure was proposed. Specifically, in the first step, the uniaxial calibration curve of the as received sample had to be obtained. In the second step, the magnetic parameters were measured on the surface and the bulk of the welded samples by taking measurements at pre-defined intervals along the length of the sample’s surface. These temporal fluctuations of the magnetic values yielded information about the spatial distribution of the residual stresses on the surface of the welded sample, with the aid of the calibration curve.

1. Introduction

The Non-Destructive Evaluation techniques include many methods, which can be used to test the ferromagnetic materials. The Barkhausen effect and the hysteresis loop can be manipulated, in order to provide us with useful information about the structure, the existence of lattice imperfections and deformations of the ferromagnetic materials.
The above mentioned measurements require the development of proper magnetic sensors, which can be used, in order to capture the desired data, followed by the processing of them, in order to retrieve the required information.

2. Theoretical Background

2.1 The Barkhausen Effect

The Barkhausen effect was discovered in 1919, by the German physicist Heinrich Barkhausen. He had wrapped a wire around a ferromagnetic material, which was then connected to a speaker. He noticed that, under the influence of a varying magnetic field, a sound was heard from the connected speaker. The sound was similar to static noise, which led to the name “Barkhausen noise” [1].

The existence of this “noise” is related to the inner structure of the ferromagnetic materials. Each of the magnetic materials, consists of magnetic regions, which are called magnetic domains. The boundaries of those regions are known as domain walls. Under the influence of an external magnetic field, the domain walls start to move. If an obstacle is present, which can be an imperfection of the structure of the material, such as an inclusion, the domain walls begin to surround it. At some point, the domain walls become capable of overcoming this obstacle, in an abrupt way. This effect is called “Barkhausen jump”.

As a result, a simple device, which can capture the above mentioned effect, includes a ferromagnetic core with an excitation and a pickup coil and the appropriate electronic circuits for the signal measurement and processing. The acquired signal is similar to the signal of an ambient noise, but it can provide us with useful information about the material, which is examined. The most important information, is related to the large spikes, which can be observed at the Barkhausen Noise signal, indicating the Barkhausen jumps that occurred during the evaluation of the specific material.

The information which can be acquired using the above mentioned Non-Destructive technique, can be used in order to determine the properties and the imperfections of the tested sample. This information can be obtained not only from the surface of the sample, but also from a certain depth, which is affected by the eddy currents and the excitation signal [2-9].

2.2 Hysteresis Loop

The hysteresis loop is a schematic description of the relation between the external magnetic field and the magnetization of a magnetic material under test. This loop is the result of the movement of the domain walls and the nucleation of the magnetic domains. A typical hysteresis loop which was acquired can be seen in Fig. 1. The horizontal axis refers to the magnetizing force (H), while the vertical axis can express either the induced magnetic flux density (B), or the magnetization (M).

When starting from positive saturation, the hysteresis loop can be read starting from the 1st quadrant and moving counter-clockwise. The information that can be acquired from the study of the hysteresis loop is valuable for the knowledge of the properties of a tested material.
The first important parameter acquired by the study of the hysteresis loop of a material is the remnant magnetization ($M_r$), which refers to the amount of the magnetization, remaining in the material even after the removal of the external magnetic field. The second parameter is the coercive field ($H_c$), which corresponds to the value of the excitation field, necessary to drive the material’s magnetization to zero. Another important pair of values, which can be extracted from the hysteresis loop, is the value of the saturation of the magnetization and the corresponding value of the magnetic field. Finally, the general observation of the hysteresis loop can help to determine if the material is a soft or a hard magnetic material, which reflects the energy storage capability of the material.

In order to plot the hysteresis loop of a tested material, a device similar to the Barkhausen Noise sensor is required, including two ferromagnetic cores with an excitation coil and a pickup coil. The developed devices, which were used in order to measure the Barkhausen Noise signal and the hysteresis loop will be described in the following paragraph.

3. Development of the Measuring Devices

3.1 Magnetic Barkhausen Noise Sensor

The basic concept of the Barkhausen noise signal acquisition, is based on the transfer of an alternating electrical signal to an excitation coil, which is wrapped around a ferromagnetic core. The core is usually U-shaped [10-24] and is placed on surface of the tested sample. The excitation coil converts the electrical signal to magnetic flux, which flows through the closed magnetic circuit of the core and the sample. A second coil, the pickup coil, is either placed between the parallel sides of the yoke, or it is wrapped around one of them. This coil reconverts the magnetic flux to an electrical signal, which is modulated by the properties and the imperfections of the tested material.

The value of the magnetic permeability of the core and the material is different. According to Ampere’s Law:

$$H_1(t) \cdot L_1 + H_2(t) \cdot L_2 = N \cdot I(t)$$

(3.1)

where $H_1$ and $H_2$ are the excitation fields in the coil and the sample, $L_1$ and $L_2$ are the lengths of the coil and the sample, N is the count of the windings of the excitation coil an I is the current flowing through the coil.

The magnetic flux can be calculated as:

$$\Phi = B_1(t) \cdot S_1 = B_2(t) \cdot S_2 = \mu_1(t) \cdot H_1(t) \cdot S_1 = \mu_2(t) \cdot H_2(t) \cdot S_2$$

(3.2)
where \( B_1 \) and \( B_2 \) are the induced magnetic flux densities on the coil and the sample, \( S_1 \) and \( S_2 \) are the cross sectional areas of the coil and the sample and finally, \( \mu_1 \) and \( \mu_2 \) are the values of the magnetic permeability of the coil and the sample.

The external field \( H_1 \) can be calculated by solving the equation (3.2):

\[
H_1 = \frac{\mu_2(t) \cdot H_2(t) \cdot S_2}{\mu_1(t) \cdot S_1}
\]  

(3.3)

The value of the field \( H_2 \) can be calculated by the equations (3.1) and (3.3):

\[
\begin{align*}
H_2(t) \cdot \frac{\mu_2(t) \cdot S_2}{\mu_1(t) \cdot S_1} \cdot L_1 + H_2(t) \cdot L_2 &= N \cdot I(t) \\
\iff H_2(t) \cdot \left[ \frac{\mu_2(t) \cdot S_2}{\mu_1(t) \cdot S_1} \cdot L_1 + L_2 \right] &= N \cdot I(t) \\
\iff H_2(t) &= \frac{N}{\frac{\mu_2(t) \cdot S_2}{\mu_1(t) \cdot S_1} \cdot L_1 + L_2} \cdot I(t)
\end{align*}
\]  

(3.4)

As a result, the value of the magnetic field on the sample depends on the excitation current and the characteristics of the magnetic circuit. In order to consider a linear relation between the value of the field and the current, the cross sectional area of the electromagnet should be larger than the area of the sample. Additionally, the value of saturation of the electromagnet should be larger than the value of saturation of the sample.

Finally, it is possible to calculate the maximum penetration depth, \( \delta \), of the measurement, according to the equation (3.5):

\[
\delta = \frac{1}{\sqrt{\pi \cdot \mu \cdot f \cdot \rho}}
\]  

(3.5)

where \( \mu \) is the magnetic permeability of the material, \( \rho \) is the electrical resistivity of the material and \( f \) is the excitation frequency. It is obvious that the penetration depth can be increased by decreasing the excitation frequency.

The above mentioned results were used to develop the specific magnetic sensor. The design which was selected includes a U-shaped core made of layers of electrical steel. This arrangement is also known as “single yoke”. An excitation coil of 400 windings made of Ø0.5mm copper wire was wrapped around the yoke, while a pickup coil of 600 windings made of Ø0.1mm copper wire was placed between the parallel sides of the yoke. The sensor can be seen in Fig. 2.
The arrangement also includes a function generator, in order to provide the excitation coil with the proper alternating signal, electronic amplification and filtering circuits, a DC power supply for the operation of the electronic components and an oscilloscope to display the output signal.

The amplification and filtering were necessary, because of the extremely small amplitude of the received signal. The developed electronic circuit includes a preamplifier, which amplifies the received signal by 200 times, a high pass filter, which blocks the frequencies which are lower than 2 kHz and amplifies the signal by 10 times and finally, a low pass filter, which blocks the frequencies which are higher than 100 kHz and amplifies the signal by 10 more times (Fig. 3). As a result, the output signal is limited in the range of 2-100 kHz in order to eliminate the ambient noise [25, 26] and it is amplified by a total of 20,000 times.

In order to plot the hysteresis loop of a specific material under test, an arrangement similar to the above mentioned is required.

According to Faraday’s and Lenz’s laws, the output signal of a coil is given by the following equation:
\[ V(t) = -N \frac{d\Phi}{dt} \]  \hspace{1cm} (3.6)

where \( V \) is the output voltage, \( N \) is the number of the windings of the coil and \( \Phi \) is the magnetic flux.

Moreover, we can calculate the correlation between the output voltage and the induced field:

\[ V(t) = -N \frac{d\Phi}{dt} \iff V(t) = -N \frac{d(B \cdot S)}{dt} \iff \]

\[ \iff V(t) = -N \cdot S \frac{dB}{dt} \iff V(t) = -N \cdot S \frac{dB}{dH} \cdot \frac{dH}{dt} \iff \]

\[ \iff V(t) = -N \cdot S \cdot \mu(H) \frac{dH}{dt} \iff V(t) = -N \cdot S \cdot \mu(H) \cdot \omega \cdot \cos(\omega t) \Rightarrow \]

\[ \Rightarrow V(t) \propto A \cdot \mu(H) \cdot \cos(\omega t) \]  \hspace{1cm} (3.7)

As a result, it can be observed that the output signal is proportional to the differential magnetic permeability of the sample.

The arrangement which was used includes two identical U-shaped cores made of electrical steel, similar to the yoke that was previously described. On the horizontal side of the yokes, two coils were wrapped: an excitation coil, made of Ø0.5 mm copper wire and a pickup coil, made of Ø0.2 mm copper wire. The sample was placed between the two yokes, in order to form a magnetic circuit, as it is shown in Fig. 4.

The processing of the signal was possible by the use of a MATLAB script, which was capable of filtering the signal, analysing it and plotting the hysteresis loop [8].

![Fig. 4. The hysteresis loop arrangement: (1) Core, (2) Excitation coil, (3) Pickup coil, (4) Sample [8].](image)

4. **Experimental Results**

A low carbon steel plate was used as a sample, in order to test the developed magnetic sensors. The Barkhausen noise signal was captured using the developed sensor. A triangular 6.5 V, 2 Hz waveform was used as an excitation signal. The received signal was then amplified and filtered, using the appropriate electronic circuits. The final signal is shown in Fig. 5.
The large spikes, which are present on the output signal, indicate the Barkhausen jumps, which occurred during the magnetization of the sample. Finally, the correlation between the voltage and the magnetic permeability was plotted, using a sinusoidal 1 V, 0.1 Hz waveform as an excitation signal. The loop is shown in Fig. 6.

Fig. 6. Correlation between the magnetic permeability and the induced magnetic field.

5. Conclusions

The results indicate that both the Barkhausen noise sensor and the hysteresis loop sensor, which were developed, can be used effectively, in order to acquire information about the properties and the imperfections of a tested material.

The acquired signal is too weak to be processed properly. As a result, it is necessary to develop and use the appropriate electronic circuits for the filtering and amplification of the signal. If this is not possible, the digital filtering of the signal may be sufficient, using the proper software. In any case, the cost of the development of the sensors and the electronic circuits is low, making possible the production of similar sensors.

The improvement of the sensors is mainly based on the improvement of the electronic components. The selection of these components and the design of the electronic circuit was based on the elimination of the ambient noise and the best possible signal amplification, without adding extra noise to the processed signal, through the components. As a result, the implementation of higher cost components, will lead to the maximization of the sensor’s performance.

As it was mentioned before, the penetration depth of the sensors is related to the frequency. Thus, it is encouraged to conduct measurements using various amplitude and frequency ranges of the excitation signal, as well as different types of samples of ferromagnetic materials, in order to improve the results.
Finally, the portability of a sensing device, like the one constructed, is an important aspect. The developed sensors were part of a laboratory arrangement, which includes a function generator, a computer, a DC power supply and an oscilloscope. Certainly, a laboratory arrangement reduces the errors during the measurements, but it is not always practical. As a result, a portable device, which can include most of the devices mentioned above, can be very useful, in order to conduct field measurements.

6. References

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