PULSED MAGNETO-ACOUSTIC EMISSION SENSOR ARRAY FOR STRESS MEASUREMENT AND MATERIAL CHARACTERISATION

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ABSTRACT

This paper introduces a new method of pulsed magnetic acoustic emission (MAE) for stress detection and material characterisation and investigates the viability of implementing an acoustic emission sensor array for enhanced location information and noise suppression. Pulsed excitation can provide wide spectral components for non-destructive evaluation and material characterisation and lead to greater sensitivity over a range of depths and the extraction of depth information through time/frequency analysis. After introducing the system set-up, several experiments including stress variation and residual stress orientation are outlined, in comparison with magnetic Barkhausen noise (MBN) and magnetic field intensity measurement. Due to differences in the generation of MAE and MBN the techniques are sensitive to different properties at different depths, so fusion of data from the two techniques is investigated. The work concludes with an investigation into the implementation of an acoustic emission sensor for MAE measurements. Possible signal processing techniques are investigated, including time delay calculations for location information and addition of sensor signals for noise suppression.

Keywords: Barkhausen noise, magneto-acoustic emission, NDT, NDE, pulsed excitation, stress.

1 INTRODUCTION

Non-destructive testing (NDT) is a defined as a method of testing equipment and materials which does not destroy them or effect their future performance or properties. Demands from manufacturing in recent years has led to an expansion of NDT from simple defect detection to the provision of qualitative information about a range of material properties including hardness measurement, stress detection and characterisation of microstructural properties such as rolling direction and grain size. One way in which these properties can be measured is through electromagnetic inspection. The magnetic properties of a material have been proven to be dependant on stress and microstructure and can be measured using a number of techniques, including hysteresis loop measurement (Sipeky et al (2006)) and magnetic adaptive testing (Tomáš et al (2006)).

In this paper, an inspection technique measuring magnetic Barkhausen noise induced in a material through electromagnetic excitation is used to quantify the magnetic properties of materials and draw conclusions about active and residual stresses. Two techniques are used to measure the Barkhausen noise; direct measurement using a magnetic field sensor (MBN) and measurement of acoustic pulse generated by the phenomena using a piezoelectric sensor (MAE). Although the two techniques are generated by the same phenomena, they are detected by different sensors at different locations, have different measurement depths and are sensitive to different stress ranges so offer complementary information and show great potential for enhanced stress measurement with the help of data fusion. After a description of the test probe design and signal processing techniques, experimental results using both applied and residual stresses are outlined. The work concludes with a discussion of the development of an MAE sensor array for enhanced location information and noise cancellation purposes.

2 BACKGROUND AND THEORY

In a magnetic Barkhausen noise (MBN) system as shown in figure 1a, a time varying magnetic field is induced in the test sample using an electromagnet fed with a time-varying signal via a power amplifier. The induced magnetism is measured using a pick-up coil or magnetic field sensor placed above the surface of the material. When a magnetic field is induced in a ferromagnetic material, the change in magnetism is not continual; rather, it is made up of discreet steps corresponding to discontinuous magnetic domain wall movement in the material, as illustrated in the figure 1b. This discontinuous domain wall movement also causes a release of elastic energy which manifests itself as an acoustic pulse and is referred to as magneto-acoustic emission (MAE). Using a high frequency (typically 50 – 200 kHz) acoustic emission sensor, these emissions can be recorded and quantified.

As magnetic domain movement is intrinsically linked to the microstructure of the material, which is modified when stress is applied, BN and MAE are stress sensitive and therefore can be used for stress detection, include the development of techniques to measure fatigue damage due to cyclic loading (Vincent et al (2005)), characterisation of BN due to bending stresses (Blaow et al (2005)), characterisation of plastic deformation due to tensile stresses (Kleber et al (2004)) and studies using samples exposed to both residual and active tensile and compressive stresses (Moorthy et al (2006)). Studies have also shown that MAE exhibits a strong correlation with both elastic and plastic stresses in ferromagnetic materials (Augustyniak (1999)). Advantages of BN over other stress detection techniques include higher depth of information, faster measurement, portable equipment, no need for surface preparation and the capability to inspect components with complex geometries like gears etc.

Although MAE and BN are generated by the same mechanisms, there are important differences between the two methods. The main difference in the application of the two techniques is the measurement depth, due to the difference in the nature of the measured signals. In a BN system, sensitivity to the magnetic field decreases with depth, leading to a maximum measurement depth of around 1mm (near surface measurement), depending on material properties. The measured signal in an MAE system is an acoustic pulse, which propagates through the whole test piece, so the maximum measurement depth is only limited by excitation frequency and material properties and is around 10mm (bulk measurement) (O'Sullivan et al (2004)). The nature of the acoustic signal also allows remote sensing of the signal, where BN sensing needs to be in the immediate proximity of the source, leading to recent investigations into the feasibility of using AE sensor arrays with advanced signal processing techniques such as Wavelet analysis to provide enhanced defect and stress location and characterisation capabilities (Axinte et al (2005)).

Another difference between the two measurement systems is that BN results from reversible and irreversible displacement of 180° and non-180° domain walls, or by abrupt rotation of domain magnetisation vectors at higher magnetic fields. In contrast MAE is only caused by discontinuous motion of non-180° walls, or the irreversible rotation of domains through angles other than 180°, leading to variations in sensitivity for BN and MAE at different points along the stress/strain curve (O'Sullivan et al (2004)).

The penetration depth of a magnetic field in a material is governed by the skin effect. The skin depth or penetration depth (δ) is defined as the distance at which the wave amplitude decreases by a factor of e^{-1} (about 37%). The skin depth in a conductive material is given by:

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

Where f is the frequency of the electromagnetic wave in Hz, μ is magnetic permeability (H/mm) and σ is electrical conductivity (% IACS). It can be seen from equation 1 that δ decreases as f increases, so the skin depth reduces as the frequency of the applied wave increases. Most inspection systems employ single frequency (sine wave) excitation, where selection of high frequency excitation means that the magnetic field is concentrated at the surface of the material and low frequency excitation equates to a greater penetration depth but a decrease in sensitivity, especially for surface and near surface measurements.

An alternative to single frequency excitation is pulsed excitation. Pulsed excitation provides the opportunity to apply an excitation signal with a string of frequency components, with the depth of penetration of low frequency excitation and the sensitivity to surface and near surface measurements of high frequency excitation, using a relatively simple driver circuit. Pulsed excitation also opens up opportunities to extract depth information from the induced signal. The frequency components of a pulsed signal vary with time; high frequency field components at the start of the waveform, reducing in frequency as time continues. From equation 1 it can be seen that signals induced from excitation delivered at the beginning of the pulse will correspond to surface material properties, whereas signals induced towards the end of the excitation pulse will correspond to material properties deeper in the material. This opens up opportunities for the extraction of depth related data from test results using time/frequency analysis of the induced signal.

3 PROBE DESIGN AND SIGNAL PROCESSING FOR EXPERIMENTAL RESULTS

Figure 2a shows the developed probe. The probe consists of a ferrite core wound with an excitation coil, fed with 5Hz square wave by a square wave generator via a power amplifier. A GMR magnetic field sensor is used for Barkhausen noise sensing and is interfaced to a PC data acquisition card (DAQ) via signal processing electronics. A PAC R15I-AST piezoelectric acoustic emission sensor, coupled to the material surface with petroleum jelly and interfaced to the DAQ via signal processing electronics is used for MAE sensing. A pickup coil wound onto one of the legs of the ferrite core is used to measure the field around the magnetic circuit formed by the ferrite core and the material under inspection. Data acquisition is performed at sample rate of 2MHz in LabView and signal processing is performed in Matlab.

Figure 2b shows a zoomed section of the AE signal; every time the envelope of the signal crosses a preset threshold, this is classed as an AE event. Several parameters used to characterise each AE event are shown on the plot, these include:

- Signal energy; computed from the area of the signal for each event.
- Count for each AE Event, number of times signal crosses the threshold for each event
- RMS signal power.

The signal acquired from the GMR sensor is bandpass filtered between 0.3 kHz and 38 kHz at the software stage to reject the low frequency envelope of the signal and select the higher frequency Barkhausen noise and RMS measurements of the filtered signal are used to quantify the Barkhausen noise. Two methods are used to characterise the signal from the pickup coil; RMS amplitude measurement of the acquired signal and because the voltage drop over the pickup coil is proportional to the rate of change of the field through the coil, the integral of the coil signal is also used.

4 ACTIVE AND RESIDUAL STRESS DETECTION

The test shown in figure 3a was set up to study the effect on MAE and BN of application of stress. A steel sample measuring 230mm x 30mm x 2mm was placed in a Hounsfield material test machine with the test system shown in figure 1 attached. The force applied to the sample was increased from 0kN to 16kN in 1kN steps, corresponding to a maximum stress of 267MPa and a maximum strain of 8.5%, well into the plastic region for the material. After each 1kN step, the test was paused and the probe signals recorded. Before the test was carried out, the stress / strain curve for the material (figure 3b) was calculated using an identical test sample, cut from the same piece of steel. The stress / strain curve shows that the yield point for the material is around 150MPa of stress at 0.8% strain. So stresses below this point will be referred to as elastic and stresses above this point will be referred to as plastic.

Figure 4a shows the MAE event count and figure 4b the RMS measurement of MBN for applied stresses up to 267MPa. It can be seen from the plots that although the two signals are both generated by Barkhausen noise in the sample, the signals are sensitive to different sections of the stress/strain profile. It can be seen from figure 4a that MAE is most sensitive to stresses in the elastic region, with the most linear section of the plot corresponding to stresses below 100MPa. It can be seen from figure 4b that although MBN shows a greater rate of change in the elastic region, the most linear region of the curve is in the plastic region.

After the application and release of stress to the sample, the test shown in figure 5a was carried out to determine if the orientation of previously applied stress can be determined. The AE sensor was coupled to the sample using petroleum jelly and a miniature version of the probe without the MBN sensor was rotated through 360°, with readings taken at 22.5° increments. Figures 5b and 5c show the change in peak to peak coil voltage and AE event count around the full 360° scan of the material, with the residual stress orientated horizontally. It can be seen from figure 5b that the coil voltage is at a maximum at 90° with respect to residual stress and conversely, the MAE event count is greatest parallel to residual stress.

5 INTEGRATION OF TECHNIQUES AND PROPOSED MAE SENSOR ARRAY

In order to provide a comprehensive material assessment system, integration of the Barkhausen based inspection systems as shown in figure 6a is proposed, with MBN providing surface and near surface stress and material characterisation data and MAE providing bulk stress measurement and material characterisation data. Raw data level and feature level data fusion techniques will be employed to merge the signals from the two sensors and provide mapping of stresses and material properties.

Although MAE can provide data at much greater depth than MBN, there are problems associated with the techniques, two of the major problems are:

- Location of the source of the MAE signal; unlike MBN, where measurement is localised, with the greatest sensitivity directly beneath the magnetic field sensor, the source of MAE signals could be anywhere in the path of the induced magnetic field.
- Noise; as the acoustic signal from domain movement is very low amplitude, MAE systems are prone to noise from external sources such as vibration of the test material and electrical noise introduced at the high gain signal conditioning stage prior to data acquisition.

However, the introduction of an MAE sensor array could go some way to counteracting these problems.

Figure 6b and 6c show the array and the associated signals MAE signals. It can be seen from figure 6b that excitation is provided over a wide area, with three AE sensors positioned in a triangular arrangement around the excitation core. As the acoustic signal from a particular domain wall movement will reach each of the sensors at a different time, identification of a particular acoustic event and calculation of the time delays for that particular event (figure 6c) will allow calculation of the location of the source of that event. This technique has the potential to enable mapping of signal properties outlined earlier such as the count for each AE event, signal energy and RMS signal level over the excited area, these signal properties can then be used to draw conclusions about stresses and material properties acting on the material in this area and be used for mapping these properties.

Figure 7 illustrates the potential of utilising the array for noise cancellation purposes. Three noisy signals are shown, featuring the same acoustic event buried within the noise at different points due to differing distances between the induced event and the AE sensors. Time delays are introduced to the signals to cancel out the differing distances and the signals are summed, causing the signal from the acoustic event to be increased in amplitude and the noise to be attenuated. The modified signal can then be passed on for processing.

6 CONCLUSIONS

The work shows that the pulsed MAE/MBN system can be used for the characterisation of both active and residual stresses and has the potential for the characterisation of various material properties, such as grain size and rolling direction. MBN and MAE offer differing measurement depths and are sensitive to differing stress ranges, so by combining of the two inspection methods using data fusion techniques, a comprehensive material assessment system can be realised. An investigation into the feasibility of implementing an AE sensor array for MAE measurement is investigated, and concludes that the array could be used to provide positional information through calculation of relative time delays and be used for noise suppression by combining the sensor signals to reinforce signals from actual AE events and attenuating noise.

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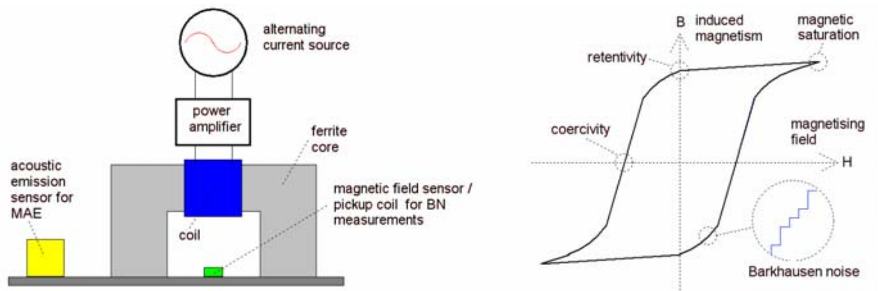
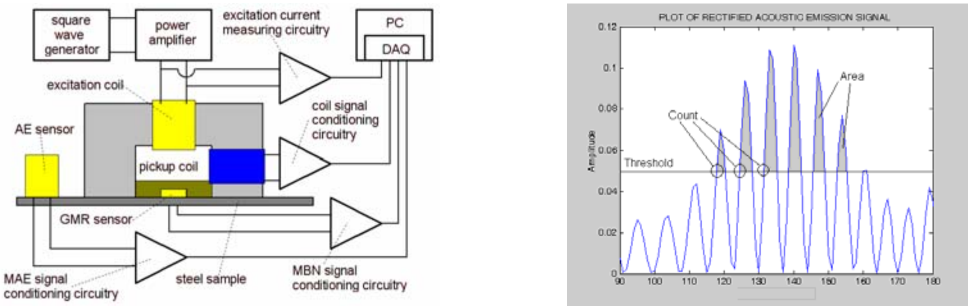


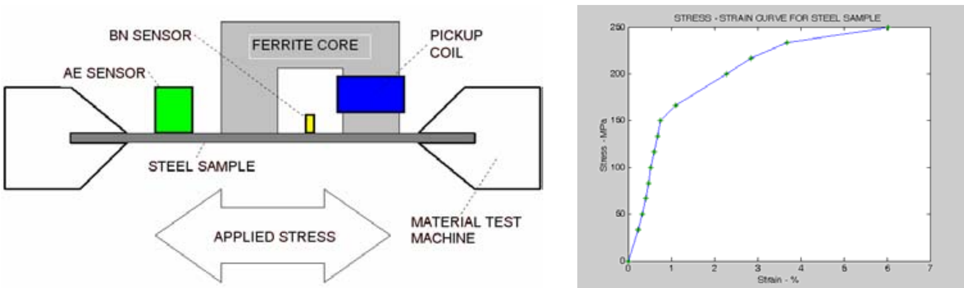
(a) (b)

Figure 1: a) Magnetic hysteresis curve and associated magnetic properties, b) Typical BN / MAE system



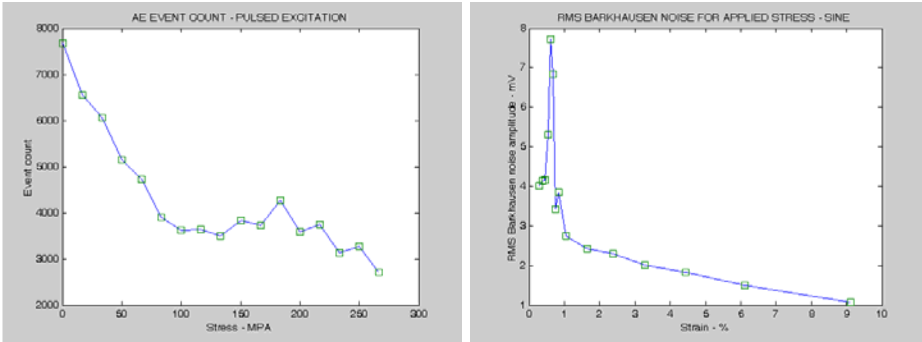
(a) (b)

Figure 2: a) MAE/MBN probe design, b) Zoomed section of induced AE signal



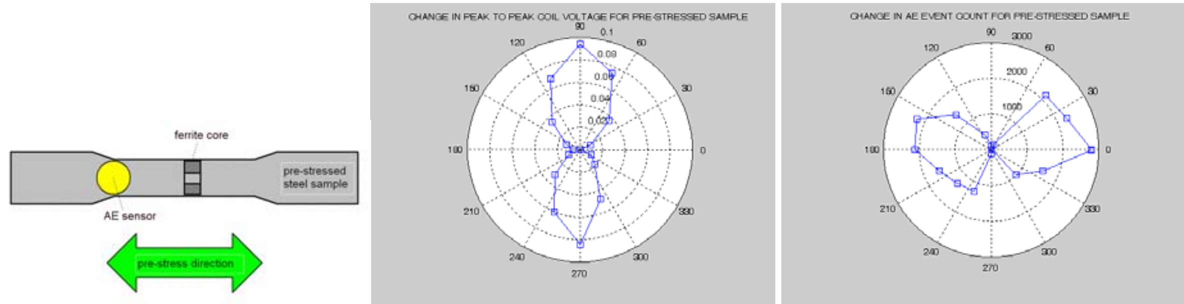
(a) (b)

Figure 3: a) Active stress test set-up, b) Stress/strain curve for material



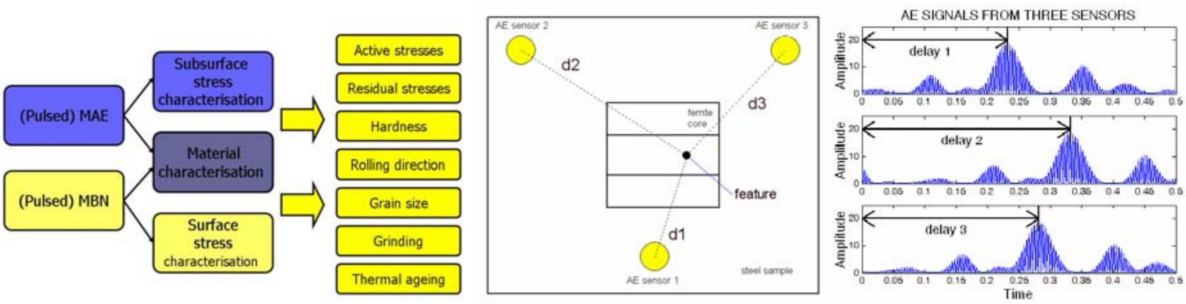
(a) (b)

Figure 4: a) MAE event count for applied stress, b) RMS MBN for applied stress



(a) (b) (c)

Figure 5: a) Residual stress orientation test set-up, b) Coil voltage test result, c) AE event count test result



(a) (b) (c)

Figure 6: a) Integration of Barkhausen inspection techniques, b) MAE sensor array, c) Extraction of location information from associated signals

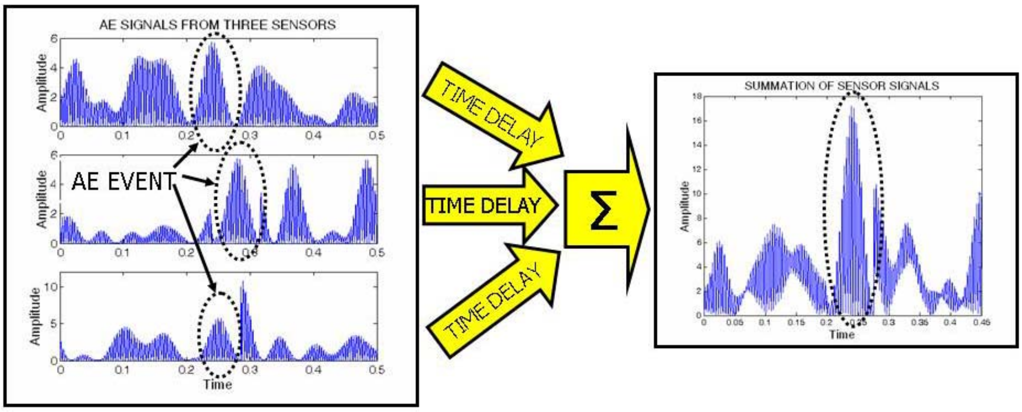


Figure 7: Noise cancellation using sensor array signals