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Influence of applied magnetic field strength and frequency response of pick-up coil on the magnetic barkhausen noise profile

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ABSTRACT

The influence of applied magnetic field strength and frequency response of the pick-up coil on the shape of Magnetic Barkhausen Noise (MBN) profile have been studied. The low frequency MBN measurements have been carried out using 5 different MBN pick-up coils at two different ranges of applied magnetic field strengths on quenched and tempered (QT) and case-carburised and tempered (CT) 18CrNiMo7 steel bar samples. The MBN pick-up coils have been designed to obtain different frequency response such that the peak frequency response varies from ~4 kHz to ~32 kHz and the amplitude of low frequency signals decreases gradually. At lower applied magnetic field strength of $\pm 14{,}000$ A/m, all the pick-up coils produced a single peak MBN profile for both QT and CT sample. However, at higher applied magnetic field strength of $\pm 22{,}000$ A/m, the MBN profile showed two peaks for both QT and CT samples for pick-up coils with peak frequency response up to ~17 kHz. Also, there is systematic reduction in peak 2 for QT sample and asymmetric reduction in the heights of peak 1 and peak 2 for CT sample with increase in peak frequency response of the pick-up coils. The decreasing sensitivity of pick-up coils with increasing peak frequency response to MBN signal generation is indicated by the gradual reduction in width of MBN profile and height of peak 2 in the QT sample. The drastic reduction in peak 1 as compared to peak 2 in the CT sample shows the effect of decreasing low frequency response of the pick-up coils on lowering skin-depth of MBN signal detection. This study clearly suggests that it is essential to optimise both maximum applied magnetic field strength and frequency response of the MBN pick-up coil for maximising the shape of the MBN profile for appropriate correlation with the magnetisation process and hence the material properties.

1. Introduction:

When a ferromagnetic material is subjected to an external varying magnetic field, a voltage signal is induced in a pick-up coil due to changes in magnetisation of material caused by the discrete movement of magnetic domain walls overcoming various pinning sites in the material [1]. This phenomenon of electromagnetic activity known as Magnetic Barkhausen noise (MBN) signal generation can have a wide frequency spectrum depending on the rate of change of magnetic flux at the micro and macro level of the magnetisation process inside the ferromagnetic material. The frequency of discrete magnetisation changes is believed to range starting from an order of the excitation frequency of the applied magnetic field and spreads beyond 1 MHz in most ferromagnetic materials. Since the MBN signals are the voltage pulses induced by the changing discrete magnetic flux on to a pick-up coil placed on the surface of a test material, it is believed that the detected MBN signal will reflect more of the characteristics of the pick-up coil than that of the actual rate of change of the micro-magnetisation process inside the material which is an unknown factor. However, the strength of induced voltage pulses is expected to decay exponentially as a function of depth under homogeneous excitation of magnetic field due to eddy current damping experienced by the propagating electromagnetic fields created by the movement of magnetic domain walls. The extent of damping determines the detection-depth (skin-depth) of MBN signals. The main factors affecting the skin-depth of electromagnetic signals are frequency of the signal, conductivity and permeability of the material [1–3]. Jiles and Suominen [3] while working on the assessment of micro-hardness and residual stress observed that the skin-depth of MBN at the same analysing frequency decreases for materials having higher specific electric conductivity and relative permeability.

The determination of skin-depth of MBN signals is more complicated than that of eddy current signals due to the generation of MBN signals in a wide frequency range. It has also been observed that the detection depth of MBN signal also depends on

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the applied magnetic field strength and its excitation frequency, sensitivity and frequency response of the MBN pick-up coil, analysing frequency range of the MBN signal [4]. Studies from literature shows that various MBN signal parameters are used for microstructural characterization [5,6], assessment of residual stress [7], plastic deformation [8,9] and fatigue [9–12]. A handful of researchers [13,14] attempted filtering of frequency spectrum of MBN signal in various band-widths to characterise case-depth of case-hardened steel. Dubois and Fiset [13] evaluated case-depth in carburised steels by using frequency spectrum obtained at various frequency ranges, each 20 kHz band-widths, from 0 to 200 kHz. It has also been shown that the low frequency MBN measurements distinctly show the MBN signals from near-surface hardened layer and that from deep subsurface softer layers as two well-defined MBN peaks [15,16].

It is realised that pick-up coil with a wide frequency bandwidth will have poor sensitivity due to less number of turns and may not help in detecting MBN signals generated from magnetisation process in the deep subsurface. This will result in shallow skin-depth for this technique.

It is known that the MBN pick-up coil can have different frequency response depending on the number of turns and coil diameter. Different pick-up coils are expected to have resonance behaviour at some characteristic frequency depending on the coil impedance. However, they will possess significant sensitivity at frequencies close to its resonant frequency. It is expected that the synergistic effect of a characteristic frequency response of the pick-up coil and a specific range of rate of change of the magnetisation process can change the shape of the MBN profile. Hence, an optimum combination of a characteristic pick-up coil and maximum magnetic field strength and its excitation frequency will help in obtaining the best possible MBN profile with maximum details about the magnetisation process in a material condition. In spite of various studies in the literature on MBN measurements, the influence of characteristic frequency response of the pick-up coils and the applied magnetic field strength on the shape of the MBN signal profile is not discussed in detail. However, it has been observed that the MBN profile can show a single peak or multiple peaks depending on the microstructural state in the material.

The present study has been aimed at understanding the influence of frequency response of different pick-up coils and maximum applied magnetic field strengths on the low frequency MBN profile in 18CrNiMo7 steel samples with two different material conditions.

2. Experimental:

Rectangular bar specimens having $12 \times 10 \times 135\ \text{mm}^3$ were prepared from the widely used 18CrNiMo7 grade gear steel for this study. The chemical composition of the steel is given below in Table 1. The bar samples were solutionised at 930 °C for 1 h followed by oil quenching and tempered at 180 °C for 2 h. Some of the samples were case-carburised at 930 °C to a case-depth of ~1 mm and tempered at 180 °C for 2 h. Specimens were carefully surface ground to remove surface oxidation and grain boundary oxidation layers. The low frequency MBN measurements were made using a laboratory based MBN system developed at Newcastle University, UK. The details of the MBN system and measurement procedure are given elsewhere [4].

The quenched and tempered (QT) and carburised and tempered (CT) bar samples were subjected to an alternating magnetic field excitation at 0.4 Hz with a triangular waveform voltage of ±20 V using two different U-shaped iron-core electromagnetic yokes having different number of turns. The yoke Y1 can generate a maximum applied magnetic field strength (H_{amax}) of ±14,000 A/m. The yoke Y2 can generate a H_{amax} of ±22,000 A/m. The MBN signals were acquired with five different ferrite cored pick-up coils identified as L2, L1, S2, S1 and S4 having different number of turns such that the number of turns in L2 > L1 > S2 > S1 > S4. The MBN signals were acquired after filtering using 1 kHz high-pass filter and amplification to 60 dB for QT sample and to 72 dB for CT sample. The MBN signal and the magnetic excitation voltage were acquired using a NI PCI-6111 data acquisition card using a LabVIEW programme. Since the MBN signals were acquired over 4 cycles of magnetisation (10 s duration) for averaging, the sampling rate of data acquisition was limited to 200 kHz per channel for optimum memory size of the card, which is sufficient for appropriate sampling of signals up to ~50 kHz. Typical magnetic excitation voltage and the MBN signal are shown in Fig. 1 over a period of 10 s (4 cycles of magnetisation). The average rms voltage profile of the MBN signal over 4 excitation cycles has been determined. Since triangular waveform excitation is used, the excitation voltage (V) can be linearly related to the applied magnetic field strength (H_a) for each yoke and hence, it can be used as an independent parameter for easy representation. It is important to note that the excitation voltage of ±20 V corresponds to ±14,000 A/m for yoke Y1 and ±22,000 A/m for yoke Y2. Hence, the yoke Y1 is expected to induce cyclic magnetisation process over a smaller range than the yoke Y2. However, since the low frequency MBN profile is shown as a plot of average rms voltage of the MBN signal as a function of excitation voltage (V) applied to the electromagnetic yoke, the MBN profiles obtained with yoke Y1 appear broader than that with yoke Y2. This is due to the lower maximum applied magnetic field strength in Y1 than in Y2 induced by the same excitation voltage of ±20 V. The frequency spectrum of the MBN signals induced as voltage pulses in the pick-up coil has been determined from the Fast Fourier Transformation (FFT) of the time-domain signals using MATLAB.

3. Results and discussion

The characteristic shape of MBN profiles obtained using different electromagnetic yokes and pick-up coils in QT and CT samples and their correlation to characteristic frequency response of each pick-up coil are shown and discussed below.

3.1. MBN profiles for different pick-up coils

The low frequency MBN profiles obtained with different pick-up coils using electromagnetic yokes Y1 and Y2 in quenched and tempered (QT) are shown in Fig. 2(a–b). It can be found from Fig. 2 (a–b) that all the MBN profiles show single peak for yoke Y1 with lower H_{amax} whereas the MBN profiles show a slope change indicating the presence of peak 2 at a higher excitation voltage (~8 V) for

Table 1
Chemical composition of the steel used in this study.

Steel	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al	Sn	Fe
18CrNiMo7-6	0.195	0.54	0.19	0.009	0.026	1.58	1.52	0.3	0.005	0.15	0.032	0.018	Bal.