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On the shape of the magnetic Barkhausen noise profile for better revelation of the effect of microstructures on the magnetisation process in ferritic steels

M. Vashista [a,b], V. Moorthy [a,*]

[a] Design Unit, School of Mechanical and Systems Engineering, Newcastle University, UK
[b] Department of Mechanical Engineering, Indian Institute of Technology, BHU, Varanasi, India

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ABSTRACT

The shape of the Magnetic Barkhausen Noise (MBN) profiles has been compared for two different methods of MBN measurements in order to reveal the true extent of the influence of different carbon-content related microstructures on the magnetisation process. The MBN profiles were measured using high frequency and low frequency MBN measurement systems on samples from low carbon 18CrNiMo5 steel and high carbon 42CrMo4 steel heat treated by isothermal annealing, spheroidising annealing and quenching and tempering processes. The high frequency MBN (HFMBN) profile shows only a single peak for all the samples due to insufficient applied magnetic field strength and shallow skin-depth of detection of HFMBN signals. The low frequency MBN (LFMBN) profile shows two peaks for all the samples due to larger magnetisation range revealing the difference in the interaction of domain walls with different microstructural features such as ferrite, pearlite, martensite and carbides. The shape of the LFMBN profile shows systematic and distinct variation in the magnetisation process with respect to carbon content and different microstructures. This study shows that the LFMBN profile reveals distinct changes in shape which could be successfully used for characterisation of different microstructural phases in ferritic steels.

1. Introduction

Microstructural characterisation of materials by non-destructive evaluation (NDE) techniques is considered as important for quality assessment of initial heat treatment induced microstructure and subsequent degradation during service in various industrial components. Conventional techniques like in-situ metallographic inspection is more time consuming and also limited to surface inspection. Magnetic NDE methods such as magnetic hysteresis [1–3], Magnetic Barkhausen Noise (MBN) [3–20] and Acoustic Barkhausen Noise (ABN) [4–13] have been shown to have great potential for characterisation of microstructure and stresses in ferromagnetic steels. As a NDE method, the MBN technique is considered for several applications due to its high sensitivity and relative easiness for industrial application directly on mechanical components. MBN signal is the voltage pulses induced in the pick-up coil by the micro-magnetic flux changes due to irreversible movement of magnetic domain walls during cyclic magnetisation process. Magnetic domain wall movement is strongly influenced by microstructural features such as grain boundaries, precipitates and dislocations etc. and hence, the MBN signal is sensitive to composition, microstructure, texture and stresses in the ferromagnetic material. Previous studies [3–19] have demonstrated the applicability of MBN technique for assessment of several material properties in a number of ferromagnetic alloys. It has been observed that the MBN signal strongly depends on the measurement parameters such as maximum magnetic field strength, sensitivity and frequency response of pick-up coil, analysing frequency range of the MBN signal etc., which widely vary for different MBN measurement systems used by various researchers. Some studies [9–12] used low frequency magnetic excitation whilst others have used high frequency magnetic excitation for MBN measurements [14–20]. Also, some researchers [5,6,12,14–16,19,20] have studied the changes in material properties using only a single measurement parameter such as root mean square (rms) voltage, energy, pulse height etc. while some researchers [3,9–11,13] measured the envelope or rms voltage profile of the MBN signal for analysis. This

* Corresponding author at: Design Unit, School of Mechanical and Systems Engineering, Newcastle University, UK
E-mail addresses: mvashista.mec@iitbhu.ac.in (M. Vashista), v.moorthy@ncl.ac.uk (V. Moorthy).

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results in different analysis and an inconsistent correlation to microstructural variations using the MBN technique.

It is expected that the measurement and analysis of envelope or rms voltage profile of the MBN signal would give more information on the magnetisation process and the influence of different microstructural phases on it. The effect of variations in carbon content and its related microstructural evolution during similar heat treatment on the shape of the MBN profile have not been discussed in detail in the literature. The present study is aimed at revealing the combined effects of maximum applied magnetic field strength and frequency response of MBN pick-up coils, typically used in high frequency and low frequency MBN measurements, on the shape of the MBN profile in ferritic steel samples with two different carbon content and related microstructural features.

2. Experimental

The chemical composition of the gear steels used in this study is given in Table 1. The low carbon steel is 18CrNiMo5 grade and the high carbon steel is 42CrMo4 grade.

Disc samples of 5 mm thickness were cut from 70 mm diameter as-received bars of both steel grades and subjected to solutionising treatment. The low carbon steel grade samples were solutionised at 925 °C for 0.5 h and the high carbon steel samples were solutionised at 850 °C for 0.5 h. After solutionising, one set of the samples were cooled to 650 °C and isothermally annealed (IA) for 3 h and then air cooled to obtain a ferrite and pearlite structure. Another set of samples were cooled to 700 °C and held for 24 h to obtain a spheroidising annealed (SPA) structure and then air cooled. The remaining solutionised samples were oil quenched and tempered (QT) at 650 °C for 1 h and 5 h. Rectangular bar samples of size $70^{L} \times 20^{W} \times 5^{T}$ mm^3 were prepared from the discs for MBN measurements. Another set of heat treated samples were sectioned, resin mounted, metallographically polished to a 1 μm diamond finish and etched with 2% Nital for microstructural examination under optical microscope.

High frequency MBN (HFMBN) measurements were made using the Microscan system and flat surface MBN sensor (consisting of ferrite core EM yoke and ferrite core (~2 mm width × 1 mm thickness)) pick-up coil supplied by Stresstech, Finland with an excitation voltage of ±5 V at a frequency of 125 Hz which generates a maximum applied magnetic field strength (H_{amax}) of ~ ±3 kA/m. The HFMBN signals were acquired at 5 MHz sampling rate and analysed in the frequency range of 10–1000 kHz (70–200 kHz dominant frequency range) using the dedicated software for the Microscan system. The HFMBN signal is averaged over 20 cycles of magnetisation and the average MBN level is plotted as a function of percentage of excitation voltage applied to the EM yoke has been used for analysis of the HFMBN profile.

Low frequency MBN (LFMBN) measurements were made with a laboratory system using an iron-cored electromagnetic yoke excited with a quasi-static frequency of 0.4 Hz triangular waveform with a maximum excitation voltage of ±10 V/±0.5 A which generates a maximum applied magnetic field strength (H_{amax}) of ~ ±15 kA/m. The LFMBN signals were acquired using a ferrite cored (~1 mm diameter) pick-up coil after filtering with a 1 kHz high pass filter and amplification to 60 dB. The LFMBN signals were acquired at 200 kHz sampling rate using a NI-PCI-6111 DAQ card with dedicated LabView software and averaged over 4 cycles of magnetisation.

It has been observed that the applied magnetic field strength (H_a) measured, at the centre of the air gap in the absence of any test sample between the poles of the electromagnetic yoke, is directly proportional to the total excitation voltage applied to the electromagnet. Hence, a direct relationship between total excitation voltage and the applied magnetic field strength (H_a) has been established initially for correlation. However, it is also known that, only the tangential magnetic field can be measured, in the presence of any test sample between the poles of the electromagnetic yoke, which also shows non-linear behaviour influenced by the material properties of the test samples. Hence, in this study, the RMS voltage of the average MBN signal plotted as a function of total voltage applied to the electromagnet (a material independent *X*-axis variable) has been used for analysis of the LFMBN profile.

Typical frequency spectra of the HFMBN pick-up coil and the LFMBN pick-up coil used in this study are shown in Fig. 1(a, b). The HFMBN pick-up has high sensitivity in the frequency range of 20–200 kHz whilst the LFMBN pick-up has good sensitivity in the frequency range of 2–25 kHz with peak response at ~16 kHz. The HFMBN signals are expected to come from a shallow skin-depth of < 20 μm whereas the LFMBN signals will come from a much larger skin-depth ~200 μm in soft ferritic steels depending on the conductivity and the permeability of the steel.

Before MBN measurements, the samples were polished with 600 grit silicon carbide paper to remove oxide scale formed during heat treatment. For both high and low frequency MBN measurements, the cyclic magnetising field was applied along the length on the wide face of the samples. The MBN profiles for both HFMBN and LFMBN measurements are shown only for half the magnetisation cycle (from $-H_{amax}$ to $+H_{amax}$), since the MBN profile for the other half of the magnetisation cycle is symmetrical in shape.

3. Result and discussions

3.1. Effect of high frequency magnetic excitation

It is known that, at high frequency of magnetic excitation, there is a strong formation of eddy currents in the test material combined with other effects such as magnetic viscosity and magnetic damping etc. These electromagnetic effects strongly oppose the effective magnetising field strength and hence reduce the magnetisation range in the test material [21]. In addition, at high frequency of magnetic excitation, the test material undergoes non-steady state magnetisation process due to drag effect on the movement of magnetic domain walls where it could be difficult to resolve the interaction of magnetic domain walls with different microstructural features. At high frequency (125 Hz) of magnetic excitation, the depth of penetration of magnetic field inside the material will be lower due to eddy current opposition. Hence, the magnetisation process is mainly confined to the near-surface of the material. In addition, with weak applied magnetising field strength (~ ±3 kA/m), the effective field strength inside the

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

Steel grade	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al	Sn	Ti
18CrNiMo5	0.20	0.73	0.30	0.01	0.03	0.91	1.27	0.17	0.005	0.18	0.024	0.014	0.002
42CrMo4	0.41	0.87	0.28	0.015	0.027	1.08	0.2	0.18	0.008	0.20	0.030	0.016	0.003