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Important Factors Influencing the Magnetic Barkhausen Noise Profile

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Abstract

The systematic effects of applied current amplitude to the magnetising coil, distance between the poles of the EM yoke, magnetic excitation frequency, sensitivity and frequency response of MBN pick-up coil and the geometry of the test sample on the applied magnetic field strength, tangential magnetic field strength and the Magnetic Barkhausen Noise (MBN) signal profile are presented in this study. The influence of different parameters is discussed with measurement results obtained from a harder case-carburised steel and a softer spheroidised annealed steel samples. This study shows the importance of maximising the shape of the MBN profile for appropriate evaluation of ferritic steels.

Keywords: Barkhausen noise profile, excitation current, excitation frequency, applied magnetic field, tangential magnetic field, frequency response of pick-up coil

1. Introduction

Several studies in the literature [1-9] show that the Magnetic Barkhausen Noise (MBN) (also known as Magnetic Barkhausen Emission (MBE)) technique is a potential non-destructive testing (NDT) method for evaluation of material properties such as microstructure, hardness, stresses, fatigue damage, creep damage etc. in ferritic steels. On comparison, it is clear that these studies were made with different magnetising set-up (solenoid or electromagnetic (EM) yoke), different sample geometry, different range of applied magnetic field strength, different magnetising frequencies and non-optimised MBN pick-up coils. Hence it is difficult to find a consistent behaviour of the MBN signals obtained from these studies. The changes in material properties are generally related to changes in single measurement parameter such as total root mean square (rms) voltage, energy, pulse height etc. of the detected MBN signals. The measurement and analysis of the full MBN signal profile would provide much more information about different material features and gradient in properties and their influence on the magnetisation process. However, the MBN profile strongly depends on the measurement method. In addition, since the MBN signals are picked-up on the outside surface of the test material, it is subjected to electromagnetic attenuation. Hence, it will not be possible to detect variations in material properties beyond certain skin-depth. The high frequency MBN signal analysis approach followed in some studies can detect changes in material properties only very near the surface [10-11]. Their capability for resolving different (softer and harder) microstructural phases is also limited mainly because of their limitation of insufficient applied magnetic field strength and non-optimised sensitivity of MBN signal pick-up coils for different applications. Such non-optimised measurement approach limits the range of magnetisation process and the detection of MBN signals and hence, does not utilise the full potential of the MBN technique. The acquisition and analysis of maximum MBN signal profile obtained over larger magnetisation range could provide more detailed information about changes in different microstructural features / phases present in the test material, through distinct peaks at different...
field strengths. It is expected that, through-hardened or surface hardened steel requires higher maximum applied magnetic field strength ($H_{\text{amax}}$) than softer annealed or normalised steel to achieve larger magnetisation range involving the interaction of magnetic domain walls with both weaker and stronger obstacles present in the test material. The $H_{\text{amax}}$ is decided by the number of turns in the coil, the current and the geometry and the core material of the electromagnetic (EM) yoke. In addition, the response of different EM core materials, for example Iron, Fe-Si, Permendur, Ferrites etc., will also differ, depending on the frequency of magnetic excitation and inductance / impedance effect, resulting in variation in amplitude and phase of the cyclic magnetic field strength.

Previous research studies in the literature [4,5,12-22] have shown the influence of different measurement parameters such as excitation frequency, magnetising voltage, field strength, flux densities, characteristics of pick-up coil on the MBN envelope, rms voltage, energy and pulse height distribution etc. For any magnetic method, it is also known that the distribution of magnetic field strength is also strongly influenced by the geometry of the test sample / component and the type of magnetising device (open-loop solenoid or closed-loop EM yoke). Buttke et al. [4,5], Ranjan et al. [13] and Hwang et al. [15] studied the effect of magnetising frequency on Barkhausen emission, rate of change of flux density and the dependence of power spectra of MBN signal with magnetisation using solenoid. The magnetisation with solenoid has strong demagnetisation factor, due to open magnetic flux path, which broadens the shape of the MBN profile [4,5,15,16]. On the other hand, the magnetisation using U-shaped EM yoke will have reduced effect of demagnetisation due to closed magnetic flux path [16] and also EM yoke is more appropriate for practical applications on industrial components.

Mandache et al. [17] investigated the effect of optimum magnetic field amplitude on the stress dependence of MBN energy with an excitation frequency of 12 Hz and a 360 turns pick-up coil. The single parameter, MBN energy, alone does not indicate variations in magnetisation process caused by interactions of domain walls with different microstructural features (hard and soft phases). Stupakov et al. [18] compared the MBN profile with that of differential permeability at two different magnetising frequencies. It can be realised that, in some material condition, particularly where there is sharp gradient in material properties, the direct comparison of MBN signal with the parameters derived from hysteresis loop (bulk measurement) may not very appropriate mainly due to skin-depth limitation of high frequency MBN signals. However, through proper optimisation of MBN measurement parameters, it could be possible to detect variations in the material properties in the deeper subsurface (< 1 mm) [23]. Stupakov et al. [19] also studied the effect of magnetising frequency on the MBN signal profile and frequency spectrum using encircling coil and surface pick-up coil. It is expected that the encircling coil would show average effect of the sample circumference while surface pick-up coil will show the localised effect at the point of contact on the sample surface. In addition, Stupakov et al. [19] used the surface pick-up coil on the sample surface which is outside the magnetising surface in a flat bar sample. Such measurement is influenced by the distribution of magnetic field strength in thick (>5mm) samples [20]. The effect of frequency characteristics of MBN pick-up coils on the resonance peak of the MBN signal frequency power spectrum had been studied by Capo-Shanchez et al. [21].

Even though some studies in the literature show effects of various measurement factors on the MBN signal, their combined effect on maximising the shape of the whole MBN signal profile has not been systematically studied and compared for harder and softer ferritic steels. It is known that higher MBN signal level can be achieved by increasing the magnetising frequency.
But, maximising the shape of MBN profile truly refers to achieving all possible MBN peaks reflecting the interaction of domain walls with different dominant microstructural features at different magnetic field ranges. Also, commonly, the tangential magnetic field is measured on the sample surface just for plotting the MBN signal profile. However, the effects of excitation frequency, distance between poles of the EM yoke and the sample geometry on the non-linear behaviour of tangential magnetic field ($H_T$) and its consequence on the MBN profile have not been discussed in detail in the literature.

Recently, it has been clearly shown that the shape of the MBN signal profile strongly depends on the maximum applied magnetic field strength and the frequency response of the MBN pick-up coil [22]. This present study is an extension of that research to compile the influence of various factors affecting the shape of the MBN profile in a more comprehensive way using two steel samples with widely different material conditions, with an aim to provide researchers further insight into the MBN measurement approach.

2. Experimental

The experimental measurements were carried out on case-carburised En36 steel samples and spheroidised annealed 18CrNiMo5 steel samples to understand the behaviour of harder surface-hardened sample with gradient in material properties and that of softer sample with uniform microstructure (ferrite grains and spheroidised carbides) in response to different measurement factors. The alternating magnetic field excitations were produced with a U-shaped commercially pure iron solid core electromagnetic (EM) yokes having same cross section area (30 mm x 15 mm) and number of turns (~ 600 turns to achieve a coil resistance of ~ 5 Ω), but with different distance between pole faces (25 mm and 45 mm). Some researchers use laminated Fe-Si core in EM yoke which is good for inspection of flat samples. The solid core EM yoke is more appropriate for practical applications of the inspection of test samples with complex geometry. For example, a solid iron core can be easily designed and manufactured perfectly to form effective magnetic surface contact with involute profile geometry of a gear tooth. This will be very difficult with laminated core material and also laminated core could introduce large air-gap between the sample and the pole faces of the EM yoke and reduce the effective field strength, if the magnetic contact is not perfectly smooth. The magnetic field strength was measured using a semiconductor based Hall-effect sensor which is calibrated to give an output voltage of 20 mV for a field strength of 79.58 A/m (1 Oe). The low frequency MBN (LFMBN) measurements were made similar to the procedure discussed in detail elsewhere [23]. The schematic of the experimental set-up for MBN measurement used in this study is shown in Fig.1. The MBN signals were acquired with an amplification of 72 dB for harder carburised samples and 60 dB for softer annealed samples. The MBN signals were acquired using ferrite cored surface pick-up coils having a different number of turns of coil (made with ~30μm thin copper wire) so that each pick-up has different characteristic frequency response. The ferrite core of the MBN pick-up coil has ~ 1 mm diameter. The number of turns in the MBN pick-up coils range from ~ 8500 to 1500 turns so that pick-up coil resistance vary from ~ 5 kΩ to 0.6 kΩ. The geometry of the MBN pick-up coil such as length and diameter will also affect the frequency response, which has not been evaluated in this study. Both the magnetic field strength and the MBN signals have been measured at the centre of the distance between the poles of the EM yoke, but as two separate measurements in order to measure both at the same position. The applied magnetic field ($H_{applied}$) is measured at the centre of distance between the poles of the EM yoke without any test sample (open magnetic circuit). The tangential magnetic field ($H_T$) is measured at the same position on the surface of the test sample in between the poles.
of the EM yoke (closed magnetic circuit). The time constant of data acquisition / averaging has been optimised from 5ms to 1ms for different excitation frequencies to obtain the best shape of the MBN profile in this study.

2.1 Distinction between applied magnetic field and tangential magnetic field

Typically in a magnetic measurement, the variation in magnetic properties such as magnetic flux density, permeability, MBN signal level etc. are shown as a function of magnetic field strength. Ideally, the magnetic hysteresis is measured in a ring sample with magnetising coil wound all around the sample and the applied magnetic field \( H_a \) is determined using the relation, \( H_a = N \times i / l \), where \( i \) is current, \( N \) is the number of turns in the coil and \( l \) is length of the coil. The applied magnetic field \( H_a \) has the value of unambiguously designating the driving magnetic influence from external currents in a material, independent of the material's magnetic response. But, this is possible only with solenoid type air core magnetising coil. However in practice, for magnetic measurements with electromagnetic (EM) yoke, the magnetic flux of the core material also contributes to the magnetic field, in addition to the current driven field from the magnetising coil around the core of the yoke. The geometry of the EM core will also affect the actual magnetic field strength due to the changes in magnetic flux from the core material. In such EM yoke type magnetic measurements, it is conventional to measure the magnetic field strength on the surface of the test sample at the centre distance between the poles of the EM yoke using a magnetic field sensor. Commonly, this tangential
field is simply termed as "magnetic field" and used by most researchers as a representative of the magnetic field inside the test sample for plotting the variation in magnetic induction ($B$) and MBN signal etc. However, this magnetic field measured tangential to the surface of the test sample is strongly affected by the geometry and the material properties of the test sample through their influence on the external and internal demagnetising fields [16]. Generally, the tangential magnetic field ($H_T$) is considered as the difference between the applied field ($H_a$) and the demagnetising field ($H_d$) [24]. The external demagnetising field ($H_{ed}$) refers to the opposing magnetic field generated by the magnetic free poles at the boundaries of the test sample with finite dimension and the internal demagnetising field ($H_{id}$) refers to the opposing magnetic field generated by the local magnetic free poles at the crystallographic imperfections (dislocations network, grain boundaries, matrix-precipitate interface etc.) present inside the test sample [24]. The tangential field (particularly in the knee region of the hysteresis where the test sample undergoes steep changes in the magnetisation) is quite different from the actual applied magnetic field (measured in open circuit without any test sample between the poles of the EM yoke) and hence a clear distinction would be useful for better understanding.

Commonly, the distinction between the applied magnetic field strength ($H_a$) and the tangential surface magnetic field strength ($H_T$) is not clearly mentioned in several studies. Typical variations in the $H_a$ and $H_T$ are shown as function of $V_T$ in the Fig. 2. In this study, the applied magnetic field strength ($H_a$) refers to the measurement of magnetic field strength at the centre of air gap between the poles of the EM yoke in the absence of any ferromagnetic test sample (open magnetic circuit with only air gap between the poles of the yoke). The tangential magnetic field strength ($H_T$) refers to the measurement of field strength on the surface of the ferromagnetic test sample at the centre of poles of the EM yoke (closed magnetic circuit with test sample between the poles of the yoke). In case of quasi-static triangular waveform magnetic excitation, the $H_a$ varies almost linearly with total excitation voltage ($V_T$) applied to the open magnetic circuit. The linearity is extended over a large part of the magnetisation cycle, except near the maximums ($\pm H_{amax}$). However, the variation in $H_a$ over a full cycle would show small hysteresis depending on the magnetic response of the core material of the EM yoke (increase in loss with increase in excitation frequency). During actual measurement with test sample between the poles, only the $H_T$ can be measured. Even in measurements with U-shaped EM yoke having insignificant external demagnetising field due to the effective contact between the test sample and the poles of the yoke ensuring closed circuit magnetic flux path [16], the $H_T$ varies non-linearly which is mainly attributed to the internal demagnetising effect generated during the magnetisation process [24]. The internal demagnetising field is originated from the local magnetic free poles at the crystallographic imperfections such as dislocations network, grain boundaries and second phase precipitates present inside the test sample [24]. The non-linearity of $H_T$ is also strongly influenced by various measurement factors including the material properties [24] and geometry of test sample as discussed in the next section. It can be observed from the Fig.2 that, corresponding to the steep change in the magnetisation (knee region of the hysteresis curve) in the test material, the $H_T$ distorts severely with very small change in the $H_T$ as compared to that in the $H_a$. As a result, the plotting of MBN signal profile as a function of $H_T$ would result in narrow MBN profile resulting in poor discrimination of peaks and subtle slope changes in the MBN profile. Simply, the $H_a$ can’t be measured in the presence of a test sample between the poles of the yoke.

As a simple approach, once from the initial Hall sensor measurements without any test sample, the linear relationship between $\pm H_a$ and $\pm V_T$ can be established. Then, the variation
in $V_T$ can be used as material independent X-axis variable for plotting MBN signal profiles for different samples for comparison with respect to applied field strength ($H_a$). Hence, in this paper, the variations in magnetic field strength and average rms voltage of the MBN signal profile are shown as a function of total voltage ($V_T$) applied to the excitation circuit ($\pm 20V$). In this study, it is very important to note that, for the same range of $V_T$ ($\pm 20V$), the maximum current will vary with value of the current limiting power resistor ($R_{CL}$) used in series with magnetising coil. Hence, both $\pm H_{amax}$ and $\pm H_{Tmax}$ will vary and it is important to establish the correlation between $\pm V_{Tmax}$ and $\pm H_{amax}$ for each current level, which varies from 0.31 A to 1.33 A and the corresponding $\pm H_{amax}$ varies from $\approx 6700$ kA/m to $\approx 25800$ kA/m for EM yoke with 25mm pole-gap and the $\pm H_{amax}$ varies from $\approx 3800$ kA/m to $\approx 12700$ kA/m (obtained from the minimum and maximum values of the calibrated Hall sensor voltage) for EM yoke with 45mm pole-gap used in this study. Since the existing data acquisition system involves only measurement of analog voltages, the current signal has not been acquired (only maximum current levels have been calculated and verified from the power supply).

Also, it is very important to note the difference between the total applied excitation voltage ($V_T$) and the individual voltages across the magnetising coil ($V_E$) and that across the current limiting resistor ($V_{RCL}$). It has been recently shown by the author that, both the $V_E$ and the $V_{RCL}$ will be subjected to non-linear distortion in the presence of a ferromagnetic sample between the poles of the EM yoke and will vary depending on the magnetisation behaviour of the test sample [25]. Even though the total applied voltage $V_T$ is equal to the sum of $V_E$ and $V_{RCL}$, individually both the $V_E$ and $V_{RCL}$ will undergo non-linear distortion in the opposite direction (to support the linear variation in $V_T$) in the presence of a test sample between the poles of the yoke, due to the magnetisation of the test sample [25]. Only the total applied excitation voltage ($V_T$) obtained at the output of the power amplifier (as indicated in Fig.1) is linear and independent of the test sample in the magnetic circuit. Hence the $V_T$ is used as material independent parameter on the X-axis for all the plots in this study for uniform comparison of different samples. However, the $V_T$ can be linearly related to the $H_a$ for half the cycle of magnetisation for any quantitative correlation with the magnetic field. The variations in $H_a$, $H_T$ and MBN profile are shown only for half the excitation cycle (from $-V_{Tmax}$ to $+V_{Tmax}$), i.e. from -20V to +20V for simplification and better clarity to readers, since their variations in the other half cycle will be symmetrical.
3. Results and Discussion

3.1 Effect of current and the distance between the poles in the EM yoke

The effect of current applied to the EM yoke on the applied magnetic field strength \( H_a \) measured at the centre of air gap between the poles is shown in Fig.3(a-b) for EM yokes with 25 mm and 45 mm distance between poles. The variation in \( H_a \) is shown for half the excitation cycle (- \( V_{T_{\text{max}}} \) to + \( V_{T_{\text{max}}} \)) for different levels of maximum current applied at 0.4 Hz excitation. The applied current and hence the applied magnetic field strength were varied by connecting different current limiting resistors in series with the magnetising coil.

With increase in maximum current, the \( \pm H_{\text{amax}} \) also increases as expected, which is well known. But, the important observation is the difference between Fig. 3(a) and (b) for the same level of current. This shows significant difference in \( \pm H_{\text{amax}} \) obtained with 25 mm pole gap and 45 mm pole gap distance in the EM yoke. In the EM yoke with 25 mm pole-gap distance, the \( \pm H_{\text{amax}} \) is \( \sim 7200, 9600, 17100 \) and 25800 A/m for current amplitude level of 0.31, 0.44, 0.87 and 1.33 A at \( V_T \) of 20 V respectively. In the EM yoke with 45 mm pole-gap distance, the \( \pm H_{\text{amax}} \) is \( \sim 3800, 4800, 8000 \) and 12700 A/m for current amplitude level of 0.31, 0.44, 0.87 and 1.33 A at \( V_T \) of 20V respectively. The increase in distance between poles drastically decreases the \( H_{\text{amax}} \). For the same level of applied current amplitude, the \( H_{\text{amax}} \) is reduced...
approximately to half the value in the EM yoke with 45 mm pole gap as compared to that in
the EM yoke with 25 mm pole gap. This is attributed to increasing dilution of magnetic flux
distribution between the poles of the yoke over longer flux path with increase in distance
between the poles of the EM yoke. It can be realised that the distributions of both the magnetic
field and magnetic flux between the poles of the EM yoke vary continuously in a complex
manner, particularly in the presence of a test sample. Apart from the effect of increase in the
length of the magnetic flux path between the poles of the yoke, the magnetic field distribution
inside the sample will also depend on the geometry of the test sample. For a finite amount of
magnetic flux generated by the EM yoke, the flux output will tend to confine to a specific
volume within the test sample around the region of contact with EM yoke. Hence the overall
size and cross section area of the sample will also affect the magnetic field distribution and
hence the magnetisation inside the test sample. This mainly arises from the effect of
geometrical influence on the external demagnetising field which will decrease the depth of
penetration of magnetic field. Even though, the $H_{\text{amax}}$ also depends on factors such as core
material, size and shape of the EM yoke etc., generally, it can be expected that the increase
in pole-gap distance will distribute the magnetic field over larger area and hence decrease the
field strength and also the depth of penetration of magnetic field. The effects of current and
the distance between the poles in EM yoke on the distribution and depth of penetration of
magnetic field will in-turn influence the magnetisation range and hence the MBN profile.

The effect of current (and $H_{\text{amax}}$) on the MBN profiles measured on the case-carburised bar
sample is shown in Fig.4(a-b) with EM yokes having 25 mm and 45 mm pole gap. Similar MBN
profiles measured on the spheroidising annealed bar sample are shown in Fig.5(a-b). It can
be observed from Figs.4(a-b) and 5(a-b) that the height of MBN peaks increases with increase
in maximum current as expected. Since the MBN profile is plotted as a function of the total
applied voltage ($V_T$), the MBN peak position will occur at lower $V_T$ at a higher current which
will correspond to higher magnetic field strength ($H_a$) as compared to that at a lower current.
Hence, the position of MBN peaks appear to shift towards lower applied voltage ($V_T$) with the
increase in maximum current level (in Figs.4(a-b) and 5(a-b)). In effect, it indicates the
increase in the maximum applied magnetic field strength ($\pm H_{\text{amax}}$) with increase in current level.
The increase in MBN peak height shows the effect of increase in rate of change of
magnetisation due to increase in $H_{\text{amax}}$ associated with increased level of maximum current.
The decrease in peak position shows the effect of enlarged range of magnetisation associated
with increased maximum current (for the same $\pm V_{\text{tmax}}$ of $\pm 20V$). If the MBN profile is plotted
as a function of applied field ($H_a$) or tangential field ($H_T$), which will have different range of X-
axis values depending on the current level, it would be difficult to compare such changes in
the MBN profile with different current levels.
Fig. 3. Effect of distance between poles of EM yoke and the current on the applied magnetic field strength ($H_a$) measured as Hall sensor voltage at the centre of air gap between the poles for EM yokes with (a) 25 mm and (b) 45 mm distance between poles.
Fig. 4. Effect of distance between poles of EM yoke and the current on the MBN profiles measured on the case-carburised bar sample with EM yokes having (a) 25 mm and (b) 45 mm distance between poles.
Fig. 5. Effect of distance between poles of EM yoke and the current on the MBN profiles measured on the spheroidising annealed bar sample with EM yokes having (a) 25 mm and (b) 45 mm distance between poles.
It can be observed from Figs. 4(a-b) and 5(a-b) that the MBN profiles show two peaks for both case-carburised and spheroidising annealed samples, but with very different shape. The two-peak MBN profile may not occur in all samples. For example, the quenched or short time tempered samples will show only single peak MBN profile [7]. As discussed previously [22,23], in case-carburised sample with gradient in microstructures along the depth, the peak 1 is attributed to magnetisation in the softer subsurface region and peak 2 is attributed to that in the harder near-surface region. The peak 2 is dominating at higher current (H<sub>amax</sub>) indicating sufficient magnetic field strength to magnetise harder carburised near-surface region. The MBN signals from the deeper subsurface are subjected to electromagnetic attenuation resulting in smaller peak 1 as compared to peak 2 in case-carburised sample. In spheroidising annealed sample, the dominant peak 1 is attributed to magnetisation involving movement of reverse domain walls from dominant ferrite phase grain boundaries while the smaller peak 2 is attributed to magnetisation involving interaction of magnetic domain walls overcoming the pinning by carbides [7].

The effect of current and hence the H<sub>a</sub> can be clearly observed from Figs.4(a-b) and 5(a-b). In case-carburised sample (Fig.4(a-b)), the reduction in height of MBN peak 2 is much faster than peak 1 and almost disappears at lowest current. This clearly shows that, below certain current (≪0.44A) (or H<sub>amax</sub> < 4000 A/m), the magnetic field near the surface is not sufficient enough to magnetise the hardened case layer and generate detectable MBN signals.

The effect of distance between poles in the EM yoke is also evident from Figs.4(a-b) and 5(a-b). For the same level of applied current, in case-carburised steel sample, the MBN peak 1 height is drastically reduced in EM yoke with 45 mm pole gap as compared to that with 25 mm pole gap even with the highest current level of 1.33 A (Fig.4(a-b)). The MBN peak 1 at lower applied voltage for case-carburised sample is attributed to the magnetisation from the deeper subsurface region with softer microstructure. The large reduction in MBN peak 1 height (from 2.28 V to 1.27 V), with increase in pole gap distance, clearly indicates the drastic reduction in magnetic field strength below the surface and hence the depth of penetration of magnetic field with larger distance between poles of the EM yoke. For the same case-carburised sample (Fig.4(a-b)), the reduction in the peak 1 of the MBN profile with larger pole gap distance in the EM yoke, is a clear indication of the suppression of the MBN activity in the deep subsurface region, which is in-turn should be due to lower magnetising field in the subsurface. This can be considered as a direct evidence for reduction in the depth of penetration of magnetic field with wider pole gap distance in the EM yoke. In spheroidised annealed sample, the two-peak MBN profile can be observed even at lowest current level (Fig.3(a-b)) in both EM yokes. This indicates the ease of magnetisation of softer steel sample even with lower current (or H<sub>amax</sub>). It can also be observed, by comparing Fig. 4(a) and 4(b) that, for a given level of current, the position of both MBN peaks shifts to higher applied voltage (V<sub>T</sub>) for EM yoke with 45 mm pole gap as compared to 25 mm pole gap. In case-carburised steel, for the same current level of 1.33 A, the MBN peak 1 position shifts from 3.95 to 4.11 V and the peak 2 position shifts from 7.16 to 8.3 V when the pole-gap distance increases from 25 mm to 45 mm. This shift in MBN peak position to higher applied voltage (V<sub>T</sub>) is a clear indication of the effect of reduction in applied magnetic field strength (H<sub>a</sub>) and hence the effective field inside the sample with increase in pole gap distance in the EM yoke. Here, it is very important to consider the corresponding difference in the maximum applied field strength (H<sub>amax</sub>) for EM yokes with 25 mm and 45 mm pole-gap distance whilst comparing the shift in the peak positions of the corresponding MBN profiles. The H<sub>amax</sub> for 25 mm pole-gap EM yoke
is \(\sim 25800\ \text{A/m}\) corresponding to a \(V_{\text{Tmax}}\) of 20 V. The \(H_{\text{amax}}\) for 45 mm pole-gap EM yoke is \(\sim 12700\ \text{A/m}\) corresponding to the same \(V_{\text{Tmax}}\) of 20 V. Correspondingly in terms of the applied magnetic field (\(H_a\)), the MBN peak 1 position shifts from \(\sim 5100\) to \(\sim 2600\ \text{A/m}\) and the peak 2 position shifts from \(\sim 9200\) to \(\sim 5300\ \text{A/m}\). It can also be noticed from the above that the shift in the peak 2 position (by 3900 A/m) is larger than that of peak 1 position (by 2500 A/m). This is another indication that the peak 1 is generated by the softer microstructure in the inner layers and the peak 2 is generated by the harder microstructures near the surface which is much more sensitive to reduction in the applied magnetic field strength. This is also supported by the similar peak positions in much softer annealed sample, where domain walls can move more easily even with lower field range resulting in broader MBN profile, for lower \(H_{\text{amax}}\) in EM yoke with 45 mm pole-gap distance as shown in Fig. 5(a) and (b).

The shift in peak position and the broadening of the profile indicate the decreasing range of magnetisation with decrease in current and increase in distance between poles of EM yoke. This study shows that, it is important to keep the distance between the poles of EM yoke as small as possible (typically < 25 mm), with minimum background noise level from other surrounding stray field electromagnetic interference, for detecting appropriate MBN signals showing two-peak profiles. Also, maximum applied magnetic field strength (\(H_{\text{amax}}\)) significantly greater 4000 A/m is required for case-carburised samples to reveal two-peak MBN profile indicating the variations in near-surface case-hardness and subsurface core hardness for appropriate determination of depth of case-hardening. However, it is also important to note that the MBN profile also depends on other factors as discussed below.

### 3.2 Effect of excitation frequency

Several studies in literature show the use of different magnetic excitation frequencies, typically ranging from 0.05 Hz to 125 Hz for MBN measurements [4-7,9-11,17-19]. Buttle et al. [4,5] and Lo et al. [6] studied the effect of excitation frequency on the MBN profile using solenoid type magnetisation. Dhar et al. [12] studied the effect of excitation frequency on total rms voltage value and pulse height distribution of MBN signals for relatively high frequencies ranging from 12 Hz to 135 Hz which will have dominating effect of eddy current damping. At high excitation frequencies, the surface tends to undergo demagnetisation faster than the subsurface of the ferromagnetic test material [26]. However, the effect of excitation frequency on the \(H_a\) and \(H_T\) has not been discussed in detail in the literature. It is known that the \(H_a\) is strongly influenced by the excitation frequency depending on the response of core of the EM yoke to the electromagnetic effects of eddy current, inductance, impedance etc. As a result, the \(H_T\) will also be influenced by this effect, in addition to the effect of demagnetisation [7,16], which is expected to affect the shape of the MBN profile.

The effect of excitation frequency of the voltage applied to the EM yoke on the \(H_a\) measured at the centre of air gap between the poles is shown in Fig.6 for EM yoke with 25 mm distance between poles. The variation in \(H_a\) is shown for full excitation cycle for different excitation frequencies (up to 6 Hz) with a maximum current of 1.33 A. It is obvious from Fig.6 that the solid iron core EM yoke shows increasing amount of hysteresis loss with increase in frequency of magnetic excitation voltage (\(V_T\)). The decreasing slope of \(H_a\) vs \(V_T\) and significant drop in \(H_{\text{amax}}\), particularly at higher excitation frequencies (>1.6 Hz), indicates the weakening response of the solid iron core EM yoke to increasing excitation frequency due to electromagnetic effects of the magnetic circuit. At higher excitation frequencies (> 3Hz), there appears to be some effect of phase shift between the applied voltage and measured applied...
field which could be due to the opposing emf from the influence of inductance and impedance of the magnetising coil of the EM yoke. It is known that ferrites cores will have better response at high excitation frequencies, but will generate only weak magnetic field strength as compared to metallic core used in this study. In addition to the effect of excitation frequency on the rate of change of magnetisation of the material, the variation in $H_a$ with excitation frequency is expected to influence the $H_T$ and the shape of the MBN profile, particularly at higher frequencies (> 3 Hz).

Fig. 6. Effect of excitation frequency on the applied magnetic field strength ($H_a$) measured as Hall sensor voltage at the centre of air gap between the poles of EM yoke with 25 mm pole gap distance with a maximum current of 1.33 A.

The variation in tangential magnetic field strength ($H_T$) in response to the variation in magnetic excitation frequency is shown in Fig. 7(a-b) for case-carburised and spheroidised annealed samples for half the cycle (-$V_{\text{max}}$ to +$V_{\text{max}}$). As discussed in the previous study [7,24], at low excitation frequencies, even though, the applied magnetic field ($H_a$) shows linear variation in a half cycle, the tangential magnetic field ($H_T$) shows non-linear variation which is attributed to the influence of both external and internal demagnetisation effects on the magnetisation process. The $H_T$ is influenced by the effects of demagnetising fields as

$$H_T = H_a - N_{\text{ed}} \cdot M - N_{\text{id}} \cdot M \quad (1)$$

Where $N_{\text{id}}$ is internal demagnetisation factor and $N_{\text{ed}}$ is the external demagnetisation factor and $M$ is magnetisation in the sample. The external demagnetisation is due to the effect of sample geometry on the demagnetisation factor ($N_{\text{ed}}$) and the internal demagnetising ($N_{\text{id}}$) effect is attributed to the localised variation in magnetostatic energy caused by the domain nucleation, annihilation and interaction of domain walls with microstructural features [27-29].
For example, a free matrix-precipitate interface has larger localised magnetostatic energy than that when precipitate is intersected by a domain wall, which halves the local magnetostatic energy due to redistribution of magnetic free poles on both sides of domain wall [24]. Such variation in local magnetostatic energy contributed to internal demagnetising ($N_{id}$) effect during the entire magnetisation process resulting in non-linear variation in $H_T$ as observed in earlier studies [7, 24, 30-31].

When considering the fact that the external demagnetising effect is minimum in a closed loop circuit with EM yoke as compared to that in open loop solenoid, the external demagnetising effect can be assumed to be constant for test specimens having same geometry. In such case, the $H_T$ is mainly considered to be influenced by the effect of changing internal demagnetising ($N_{id}$) effect during the magnetisation process [7,24]. Hence, the $H_T$ is expected to be influenced by the material condition and geometry of the sample. In addition, the excitation frequency also affects both the amplitude and non-linearity of $H_T$ as evident from Fig.7(a-b). It can be observed by comparing Fig.6 and Fig.7(a-b) that the variation in $H_T$ is much larger than that in $H_a$ with increase in excitation frequency. The non-linear distortion of $H_T$ increases with larger reduction in $H_T$ for a given value of $V_T$ with increase in excitation frequency. This is attributed to the additional effect of demagnetisation on $H_T$. The reduction in $H_T$ occurs to larger extent in softer spheroidised annealed sample than in harder steel. This is attributed to the higher magnetisation (M) level in softer steel sample and hence higher demagnetisation effect [7,24]. The tangential magnetic field strength ($H_T$) can be considered as the effective magnetic field strength seen by the surface of the test material due to the combined influence of excitation frequency, geometry, material condition and demagnetisation effect on $H_T$. The lower $H_T$ is expected to reduce the magnetisation range, particularly more significantly in harder steel sample and affect the MBN profile. As explained earlier, the non-distortion of $H_T$ is mainly affected by the internal demagnetising field ($H_{id}$) which depends on the magnetisation (M) of the test sample.

The effect of magnetic excitation frequency on the MBN profile is shown in Fig.8(a-b) for case-carburised and spheroidised annealed samples for half the magnetisation cycle. It is known that the MBN signal level depends on the number of magnetic domain walls as well as their extent of displacement at a given instant of magnetising field [7]. Dhar et al. [12] attributed the increase in MBN with excitation frequency to increase in number of domain walls. It has been shown by Haller and Kramer [32] that the dynamic spacing of domains is inversely proportional to square root of excitation frequency whilst the number of dynamic domain walls is proportional to square root of excitation frequency. However, such dynamic effect of domain walls will be more pronounced when the excitation frequency varies to a larger extent (for example 10 - 100 Hz) than that used in this study (0.2 – 6 Hz). Even at lower excitation frequencies, it is obvious that rate of change of magnetisation of the material increases with excitation frequency.
Fig. 7. Effect of excitation frequency of the voltage applied to the EM yoke on the tangential magnetic field strength ($H_T$) measured as Hall sensor voltage, on the surface of (a) case-carburised sample and (b) spheroidised annealed sample, at the centre of pole gap with a maximum current of 1.33 A applied to the EM yoke with 25 mm pole gap distance.
Fig. 8. Effect of excitation frequency on the MBN profile measured on the surface of (a) case-carburised sample and (b) spheroidised annealed sample, at the centre of pole gap with a maximum current of 1.33 A applied to the EM yoke with 25 mm pole gap distance.
Since the MBN profile is obtained by averaging over suitable time constant to obtain the best possible shape of the MBN profile, the overall increase in average MBN voltage profile with excitation frequency (Fig.8(a-b)) can be generally related to the increase in domain wall activity due to increase in the rate of change of magnetisation in the material. However, the MBN profile will be influenced by the two different effects in synergy in this case, one is the rate of change of magnetisation and the other is its effect on the distortion of $H_T$. The increase in rate of magnetisation with increase in excitation frequency will tend to increase the peak height in the MBN profile. But, at the same time, the magnetisation level of the sample will affect the effective magnetic field inside the sample through its effect on the demagnetising field. It can be observed from Fig.7(a-b) that the distortion in $H_T$ is much sharper (very small change in the knee region of magnetisation) in softer annealed steel with higher magnetisation level than that in harder carburised steel with lower magnetisation level. That is the higher magnetisation in softer steel will suppress the effective magnetic field inside the sample (lower $H_T$) much more than that of the harder steel with lower magnetisation level. This results in smaller increase in MBN peak height with excitation frequency in softer annealed sample (~1.5 time) than that of harder carburised sample (~3 times) (Fig. 8(a-b)). Hence, the increase in MBN peak with increase in excitation frequency could not be related to rate of change of magnetisation alone for all the steels. It can be stated that the effect of excitation frequency on MBN peak is directly proportional to the rate of magnetisation and inversely proportional to the magnetisation of the test sample.

The broadening of the MBN profile (Fig.8(a-b)) could be wrongly attributed to the enhanced sensitivity of the MBN pick-up coil with increase in excitation frequency, even though it is partially true, ignoring the effect of variation in $H_a$ and $H_T$. But, in fact, the broadening of the MBN profile with increase in excitation frequency clearly indicates the reduction in the magnetisation range in relation to the reduction in $H_a$ and $H_T$ supporting the observation in Fig.6 and Fig.7(a-b) in both softer and harder steels. This will be evident when the $V_T$ on X-axis is related to the corresponding values of $H_a$ and $H_T$.

It can be observed from Fig.8(a-b) that the double peak MBN profile enlarges with increase in excitation frequency, transforming into a single peak behaviour at excitation frequency > 3Hz. At 6 Hz, the MBN profile appears to have been influenced by some phase shift indicated by a trough near $-V_{T\text{max}}$ and higher MBN voltage level than the background level near $+V_{T\text{max}}$. Even though, the MBN voltage level increases with excitation frequency, the effect of decreasing range of $H_a$ and hence the smaller range of magnetisation can be noticed from the disappearance of MBN peak 2 (Fig.8(a-b)) at frequencies > 1.6 Hz. This effect of decreasing range of $H_a$ and $H_T$ with increase in excitation frequency can be more clearly observed from the gradual decrease in the height of MBN peak 2 and complete disappearance in spheroidised annealed sample (Fig.8(b)). In short, the increase in the height of MBN peak 1 with increase in excitation frequency indicates the effect of increasing rate of change of magnetisation of softer phase of the material whilst the decrease and disappearance of MBN peak 2 indicates the difficulty in magnetising harder phase of the material due to decreasing range of $H_a$ and hence the $H_T$ as evident from Fig.7(a-b). The two peaks in MBN profile should not be simply directly related to the non-linear behaviour of $H_T$, since even the quenched or short-time tempered steel samples show such non-linear $H_T$, but with only single peak MBN profile [5].
Overall, the effect of increasing excitation frequency will increase the MBN signal level (an effect of rate of magnetisation), but will also decrease the range of magnetisation due to reduction in $H_a$ and $H_T$. This will result in reduction in the ability to magnetise harder phases in material and the interaction of magnetic domain walls with harder obstacles such as surface hardened layer, harder metallurgical phases (martensite, pearlite, carbides) etc. may not be activated and detected in the MBN profile for appropriate correlation. It is important to realise that higher MBN level does not always mean maximum MBN profile unless it is achieved at sufficient level of $H_{a_{\text{max}}}$ and $H_{T_{\text{max}}}$ (with major hysteresis loop). Hence, it is important to optimise excitation frequency (typically < 2 Hz) for achieving sufficient level of $H_a$ and $H_T$ and minimising the effect of phase shift and hence maximise the shape of the MBN profile. However, this will depend on the response of core material of the EM yoke.

3.3 Effect of sensitivity and frequency response of MBN pick-up

It is known that the MBN profile strongly depends on the resonant frequency characteristics of the pick-up coil. Previous studies [21,22] have shown that the sensitivity and the frequency characteristics of the MBN pick-up coils vary with number of turns and size of the coil. The pick-up coil with larger number of turns will give good sensitivity and better response in the lower frequency range. The pick-up coil with smaller number of turns will shift its peak response to higher frequency range, but will give reduced sensitivity. Hence the optimisation of MBN pick-up coil is very important.

The effect of characteristics of three different ferrite core pick-up coils on the MBN profile is shown in Fig.9 (a-b) for case-carburised and spheroidised annealed samples. The characteristic frequency spectra of these three MBN pick-up coils are shown in Fig.10(a-c). It can be observed from Fig.9(a-b) that there is clear difference in MBN profiles between case-carburised sample with gradient in material properties along the depth and the spheroidised annealed sample with no gradient in material properties. In case-carburised sample, the MBN peak 1 height drastically reduced with pick-up coil S3 as compared to that for L1 with largest number of turns. The peak 1 has disappeared with pick-up coil S4 with smallest number of turns. In spheroidised annealed sample, the peak 1 height has significantly reduced for pick-up coil S4 as compared that for pick-up coils L1 and S3. The height of MBN peak 2 has not significantly reduced for different pick-up coils in both case-carburised and spheroidised samples. The significant reduction in the height of MBN peak 1 clearly indicates the effect of characteristic frequency response of pick-up coils on the depth of detection of MBN signals. The pick-up coil L1 with good sensitivity in the low frequency range < 10 kHz (Fig.10(a)) shows highest MBN peak 1 mainly due to higher depth of detection of MBN signals. The pick-up coil S3 with peak frequency response at ~ 22 kHz (Fig.10(b)) and pick-up coil S4 with peak frequency response at ~ 34 kHz (Fig.10(c)) show systematic reduction in MBN peak 1 due to decrease in their depth of detection.

The effect of characteristic frequency response of pick-up coil is more pronounced in case-carburised sample with gradient in material properties along the depth. With shift in sensitivity of the MBN pick-up coil to higher frequency, it becomes increasingly difficult to detect MBN signals generated by the magnetisation process in the deeper subsurface and hence the MBN peak 1 decreases systematically in case-carburised steel [22]. Since the spheroidised annealed sample has uniform material properties along the depth, the significant reduction in
MBN peak 1 with pick-up coil S4 is mainly attributed to reduction in sensitivity due to lower number of turns in this pick-up coil. At the same time, it is also important to realise that the depth of detection of MBN signals will be shallow in softer steel due to higher permeability than that in harder steel.

This study clearly shows that it is important to use a MBN pick-up coil with good response in the low frequency range (<10 kHz) for effective detection of MBN signals from deep subsurface for appropriate correlation of depth of hardening in case-hardened steels. However, MBN pick-up coils having peak response in the high frequency range (>20 kHz) could be useful for detecting alterations in near-surface properties, by minimising the MBN signals from subsurface.
Fig. 9. Effect of characteristic of pick-up coil on the MBN profile measured on the surface of (a) case-carburised sample and (b) spheroidised annealed sample, at the centre of pole gap with a maximum current of 1.33 A applied to the EM yoke with 25 mm pole gap distance.
Fig. 10. Characteristic frequency response of the MBN pick-up coils with different number of turns (a) L1, (b) S3 and (c) S4. The MBN signals were obtained from the samples used in this study.
3.4 Effect of sample geometry

The effect of demagnetisation factor on the MBN signal profile has been studied in [16] for magnetisation using a U-shaped EM yoke with closed magnetic flux path and a solenoid with open magnetic flux path. Apart from the influence of magnetising device and the excitation frequency on the magnetic field distribution as discussed above in sections 3.1 and 3.2, the geometry of the test sample / component is also expected to have strong influence on demagnetisation [29] and hence on $H_T$ and the MBN profile. In this study, since the measurements were made using U-shaped EM yoke, the effect of external demagnetising factor is low due to closed magnetic flux path. Hence, the influence of sample geometry mainly arises from the effect of distribution of magnetic field strength in the sample.

Typical effect of test sample geometry on the MBN profile is shown in Fig.11(a-b) for case-carburised and spheroidised annealed samples. It can be observed from Fig.11(a-b) that the MBN profile becomes broader in samples with larger surface area. It is expected that, for a given maximum applied magnetic field strength ($H_{\text{amax}}$), the effective magnetic field strength inside the test material tends to distribute over larger surface area resulting in the dilution of magnetic field strength. This is supported by the variations in tangential magnetic field strength ($H_T$) measured on the surface of samples with different geometry as shown in Fig.12(a-b). The non-linear distortion of tangential magnetic field strength ($H_T$) is attributed to the effects of external and internal demagnetising factors [7]. The external demagnetising effect is associated with geometrical effect of demagnetisation factor. The internal demagnetising effect is associated with variation in magnetostatic energy due to redistribution of magnetic free poles upon interaction of moving magnetic domain walls with microstructural features such as grain boundaries, precipitates etc. present in the material during cyclic magnetisation process [7]. However, the decrease in maximum tangential magnetic field strength ($H_{\text{Tmax}}$) observed in Fig.12(a-b) is mainly attributed to the influence of sample geometry on the external demagnetising effect for the same set of samples.

The decrease in $H_{\text{Tmax}}$ in samples with larger surface area supports the broadening of the MBN profile due to smaller magnetisation range, but extending over larger range of applied excitation voltage ($V_T$). With increase in surface area of the sample, the dilution of magnetic field will decrease the $H_T$ and also the depth of penetration of magnetic field. This is expected to decrease the MBN signal level as observed from Fig.11(a-b). In case-carburised sample, the reduction in MBN peak 1 height in 30 mm wide sample is quite significant which could be attributed to the reduction in the depth of penetration of magnetic field strength affecting the magnetisation of deeper subsurface region. In spheroidised annealed sample, the reduction in height of MBN peaks is compensated by the peak broadening, in particular the peak 2 of the MBN profile.
Fig. 11. The MBN profiles measured on the surface of (a) case-carburised samples and (b) spheroidised annealed samples with different geometry.
Fig. 12. Variations in tangential magnetic field strength measured on the surface of samples with different geometry (a) case-carburised samples and (b) spheroidising annealed samples.
It can be expected that, with increasing surface area and/or thickness of the sample, it may not be possible to sufficiently magnetise the harder microstructural phases present in the material with limited range of $H_{\text{am}}$ resulting in decrease or disappearance of MBN peak 2 at higher field. Hence, it requires application of larger $H_{\text{am}}$ to maximise the $H_{T\text{max}}$ for appropriate detection of MBN signals corresponding to domain wall movements from both softer and harder microstructural phases present in the material. This clearly shows that optimisation of $H_{\text{am}}$ taking into account the effect of geometry of test material/component is very important for achieving maximum MBN profile and hence appropriate correlation of material properties. For some practical applications, the sample geometry may cause the limitation for achieving maximum MBN profile.

4. Conclusions

It has been clearly shown that the shape of the MBN profile strongly depends on the level of maximum current, the distance between poles on the EM yoke and excitation frequency through their synergistic effects on the applied magnetic field strength and tangential magnetic field strength. The characteristic frequency response and sensitivity of the MBN pick-up coils is also shown to influence the MBN profile through their effect on depth of detection of MBN signals. In addition, the geometry of the test sample is also shown to affect the MBN profile due to its effect on the distribution and penetration of magnetic field strength. An optimised combination of larger current amplitude, smaller distance between poles of EM yoke, smaller excitation frequency and low frequency MBN pick-up would be give better MBN profile on a test sample with low demagnetisation effect (typically with large length to diameter ratio).

It can be realised that it is difficult to pinpoint one set of measurement parameters for all applications. However, the following suggestions can be proposed for maximising the MBN profile to appropriate level even in case-hardened steels which are relatively difficult to magnetise.

- The distance between the poles of EM yoke can be as small as possible (typically < 25 mm), with minimum background noise level. The size and geometry of EM yoke should be optimised to maximise the $H_{\text{am}}$ and $H_{T\text{max}}$ for a given application.
- The maximum current amplitude should be such that the maximum applied magnetic field strength ($H_{\text{am}}$) is significantly greater 4000 A/m, which again depends on the resulting $H_{T\text{max}}$ on the test sample geometry. It is important to measure the $H_{T\text{max}}$ on a component surface which will help to understand the distribution of surface magnetic field and possibly optimise EM yoke for further enhancement.
- Low excitation frequency (typically < 2 Hz) can be used for achieving sufficient level of $H_{\text{am}}$ and $H_{T\text{max}}$. However, this will depend on the response of core material of the EM yoke.
- MBN pick-up coil with good response in the low frequency range (<10 kHz) could be used for effective detection of MBN signals from deep subsurface for appropriate correlation of depth of hardening in case-hardened steels. However, MBN pick-up coils having peak response in the high frequency range (>20 kHz) could be useful for detecting alterations in near-surface properties, by minimising the MBN signals from subsurface.
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References:


