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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

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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 of the 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 & 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.

Keywords: magnetic Barkhausen noise; domain walls; magnetisation process; ferrite; pearlite; martensite; carbides;

1. Introduction

Microstructural characterization 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 characterization 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 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.

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

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 hrs and then air cooled to obtain a ferrite and pearlite structure. Another set of samples were cooled to 700°C and held for 24 hrs 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 hr and 5 hrs. Rectangular bar samples of size $70^L \times 20^W \times 5^T$ mm³ 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 x 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 $\sim \pm 3$ 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 $\sim \pm 15$ 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.

Fig.1. Typical frequency spectra of MBN signals acquired using (a) Stresstech's HFMBN coil in 10 – 1000 kHz range and (b) LFMBN pick-up coil in 1 - 50 kHz range.

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 $-H_{\text{amax}}$ to $+H_{\text{amax}}$), since the MBN profile for the other half of the magnetisation cycle is symmetrical in shape.

3.0 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 ($\sim \pm 3\text{kA/m}$), the effective field strength inside the sample and hence the magnetisation range are also smaller. It has been considered that the surface of a ferromagnetic material undergoes faster demagnetisation than the subsurface and bulk due to the dominant effect of surface magnetic free poles and that a material with a higher magnetisation will have a larger demagnetisation effect than the material with a lower magnetisation [22,23]. Due to high frequency of the acquired HFMBN signals (predominantly in the 70 – 200 kHz range), the skin-depth of the HFMBN signal is also very shallow ($<20\text{ }\mu\text{m}$), limited by the strong electromagnetic attenuation.

During application of cyclic magnetic field for MBN measurements, it is difficult to determine these electromagnetic effects individually due to their synergy and complex nature. However, it is known that these effects contribute to the suppression of the range of magnetisation in the material and hence affect the MBN signal generation. Hence, it can be expected that, during the HFMBN measurements, the shape of the HFMBN signal profile will be limited by the combined effect of eddy current opposition, shallow skin-depth, narrow magnetisation range, non-steady state magnetisation process, magnetic viscosity, magnetic damping, faster demagnetisation of the surface etc. in a complex manner.

3.2 Effect of quasi-static magnetic excitation

It is known that, in quasi-static magnetic excitation condition, there are no dominant effects of eddy current opposition, magnetic viscosity etc. It is considered that the test material undergoes steady state magnetisation process with systematic interaction of magnetic domain walls with weaker and stronger pinning by different microstructural features with increasing magnetising field strength.

At quasi-static (0.4 Hz) magnetic excitation, the depth of penetration of magnetic field inside the material will be much greater. Hence, the magnetisation occurs effectively in the bulk of

the test material. In addition, with strong applied magnetising field strength ($\sim \pm 15$ kA/m), the effective field strength inside the sample and hence the magnetisation range are also greater. Since the LFMBN measurements were performed with closed-loop magnetisation using a U-shaped electromagnetic yoke, the external demagnetisation effect will also be greatly reduced [23]. Due to low frequency of the acquired LFMBN signals (predominantly in the 1 – 25 kHz range), the skin-depth of the LFMBN signal will be quite large (up to ~ 200 μ m in softer steels), but, still limited by the electromagnetic attenuation inside the material.

3.3 Comparison of HFMBN and LFMBN signal profiles

The HFMBN and LFMBN profiles obtained from both low carbon and high carbon alloy steels in isothermally annealed (IA), spheroidising annealed (SPA) and quenched and tempered (QT) conditions are compared and discussed below separately. Since, these samples were subjected to softening heat-treatments, the internal residual stress fields will not be significant to influence the MBN signals in this study.

3.3.1 Effect of isothermally annealed microstructures on the MBN profile

The HFMBN and LFMBN profiles measured on IA samples are shown in Figs. 2(a-b) respectively. In a half cycle of magnetisation (from $-H_{\text{amax}}$ to $+H_{\text{amax}}$), the test material undergoes demagnetisation and then magnetisation in the opposite direction. This mainly involves irreversible movement of reverse domain walls overcoming weaker and stronger obstacles posed by different microstructural phases. This is reflected in the shape of the MBN profile depending on the extent of magnetisation range (and the slope of magnetisation curve) involved in the MBN measurement. It can be observed that the HFMBN profiles show a single peak (Fig.2(a)) for both steels whereas the LFMBN profiles show two peaks indicated by sharp slope changes (Fig.2(b)) for both steels. Optical micrographs of IA samples are shown in Fig. 3(a-b). The light regions consist of ferrite (α -iron) which is a solid solution of carbon in iron and is magnetically very soft. The dark regions consisting of alternate layers of iron carbide and ferrite is pearlite, which is relatively magnetically harder. Based on the carbon content, the low carbon steel sample is expected to have $\sim 75\%$ of ferrite and 25% of pearlite whilst the high carbon steel sample is expected to have $\sim 40\%$ ferrite and 60% pearlite after IA treatment. The pearlite lamellar structure is considered as stronger pinning sites for magnetic domain walls as compared to the ferrite structure [6,24,25].

The ascending part of HFMBN profile starts well before the zero transition of magnetising field ($H_a \ll 0$) for both steels and almost half the profile occurs before the zero transition, consistent with observations by others [26,27]. This indicates that the HFMBN signal is significantly contributed to by the demagnetisation part rather than the magnetisation part which occurs

after the zero field transition beyond coercive force. Hence, the single peak HFMBN profiles with dominant section before zero transition reflect the combined influence of faster demagnetisation of the surface, minor magnetisation range and shallow skin-depth due to the electromagnetic effects discussed above in section 3.1. The HFMBN profile mainly indicates the demagnetisation of softer microstructure near the surface. It is unable to detect further magnetisation in the deep subsurface and that involving the effect of harder microstructural features due to weak magnetising field strength. The low carbon steel will tend to demagnetise faster due to higher magnetisation than the high carbon steel [22]. Hence, the ascending part of the HFMBN profile starts increasing earlier in the low carbon steel than that in the high carbon steel. The HFMBN profile shows a lower peak height for low carbon steel than that for high carbon steel which is opposite to the expected behaviour. However, the low carbon steel shows a broader HFMBN profile. This indicates some difference in high frequency magnetisation behaviour of these two steels, possibly due to a difference in ferrite grain size distribution near the surface, which is not yet understood.

The LFMBN profiles (Fig.2(b)) have the major part after zero transition ($H_a > 0$) indicating a larger extent of magnetisation (major magnetic hysteresis loop) of the steels. The LFMBN profiles show clear merging of two peaks indicated by the sharp slope changes. As explained previously [10], the MBN profile occurs over a range of magnetic field strengths depending on the distribution of pinning strength of microstructural obstacles to domain walls in response to a given range of magnetisation. Depending on whether there is a single distribution or overlapping of two different distributions or widely separated distributions of pinning strength of microstructural obstacles, the MBN profile will show a single peak or slope changes or well-defined two or more peaks. However, the shape of the MBN profile depends on other factors such as maximum applied magnetic field strength, frequency response and sensitivity of the MBN pick-up coil and time constant used for averaging of the profile etc. Since the LFMBN measurement involves a higher magnetic field strength, it takes the ferromagnetic steel over the major magnetisation loop with the possibility of interaction of magnetic domain walls with different types of microstructural features. Hence, the LFMBN profile can show single peak or two peaks indicating the presence of different distributions of pinning strength of microstructural obstacles. The height of the LFMBN peak is decided by the maximum number of moving domain walls and their displacement within a distribution range of pinning strength of microstructural feature. The peak position is decided by the dominant pinning strength of obstacle type and the ease with which the reverse domain walls can overcome the obstacle type.

The LFMBN profiles (Fig.2(b)) clearly indicate the presence of two different metallurgical phases, softer ferrite and harder pearlite in isothermally annealed samples. The sharp slope changes in the LFMBN profile indicate the overlapping distribution of pinning strength of ferrite and pearlite phases. The larger peak 1 indicates the movement of reverse domain walls from the grain boundaries sweeping across the ferrite grains. The smaller peak 2 indicates the movement of domain walls in the harder pearlite phase which will restrict the displacement due to different orientation of lamellar structure within the pearlite phase. The difference in LFMBN profiles between these two steels makes clear distinction to variations in the volume fractions of ferrite and pearlite in relation to their carbon content. The high carbon 42CrMo4 steel shows lower LFMBN peak 1 height indicating lower % volume fraction ferrite as compared to that in low carbon 18CrNiMo5 steel. The peak 1 position also shifts to higher excitation voltage (applied magnetic field) in 42CrMo4 steel due to higher carbon content. This could be attributed to the effect of larger number of ferrite / pearlite interface grain boundaries which could offer stronger resistance to the movement of reverse domain walls from the phase boundaries in the high carbon 42CrMo4 steel. The peak 2 height is greater in 42CrMo4 steel indicating higher % of pearlite as compared to that in the 18CrNiMo5 steel. The slope change in the descending profile indicates the formation of a second peak at a similar excitation voltage range (~ 4 - 6 V) in both steels (Fig.2(b)). This may be due to a similar pearlite lamellae structure. However, further studies are required to understand the effect of variations in pearlite structure (thickness and spacing of lamellae) on the LFMBN profile.

Fig.2. (a) HFMBN profiles and (b) LFMBN profiles for isothermally annealed samples of low carbon 18CrNiMo5 and high carbon 42CrMo4 steels.

Fig.3. Optical micrographs of isothermally annealed (a) low carbon 18CrNiMo5 steel and (b) high carbon 42CrMo4 steel.

3.3.2 Effect of spheroidising annealed microstructure on the MBN profile

The HFMBN and LFMBN profiles measured on SPA samples are shown in Figs. 4(a-b) respectively. Optical micrographs of SPA samples are shown in Fig. 5(a-b). It can be observed that, similar to IA samples, the HFMBN profile show a single peak (Fig.4(a)) whereas the LFMBN profiles show two peaks (Fig.4(b)) for both steels.

The HFMBN profiles (Fig.4(a)) show dominant portion before the zero transition indicating the main contribution due to demagnetisation of near-surface layers and the HFMBN peak occurs at slightly earlier position as compared to IA samples (Fig.2(a)) indicating softer microstructural condition after SPA treatment. However, the high carbon steel shows a higher peak height against the expectation whilst the low carbon steel shows a broader profile (Fig.4(a)). This could be attributed to variations in the near-surface microstructure.

Peak 1 and peak 2 of the LFMBN profile (Fig.4(b)) are attributed to the movement of domain walls overcoming grain boundaries and carbide precipitates respectively at different magnetic field ranges as explained elsewhere [10,24]. The peak 1 height for SPA samples is higher than

that for IA samples (Fig.2(b)) which is attributed to an additional contribution from a larger volume fraction of ferrite grain structure after SPA treatment. With higher carbon content in 42CrMo4 steel, the height of both peak 1 and peak 2 decreases which is attributed to the reduction in displacement of domain walls due to the presence of a larger number of inter-granular and intra-granular carbide precipitates as evident from microstructures shown in Fig. 5(a-b). Similar to the isothermally annealed samples, the high carbon 42CrMo4 steel shows peak 1 position at higher excitation voltage (applied magnetic field) as compared to low carbon 18CrNiMo5 steel. This indicates the stronger barriers posed by grain-boundaries in high carbon steel possibly due to the presence of large number of carbides along the grain boundaries which might hinder the movement of reverse domains from the boundaries. The peak 2 position is more or less the same for both steels. The spheroidisation of carbides may result in a similar distribution of domain wall pinning strengths in both low carbon and high carbon steels, since both steels are subjected to spheroidising annealing at the same temperature and time. The main difference is the number density of spheroidised carbides which affect the mean free path of the displacement of domain walls and hence the peak 2 height as observed (Fig.4(b)).

Fig.4. (a) HFMBN profiles and (b) LFMBN profiles for spheroidising annealed samples of low carbon 18CrNiMo5 and high carbon 42CrMo4 steels.

Fig.5. Optical micrographs of spheroidising annealed (a) low carbon 18CrNiMo5 steel and (b) high carbon 42CrMo4 steel.

3.3.3 Effect of quenched and tempered microstructure on the MBN profile

The HFMBN and LFMBN profiles measured on samples quenched and tempered (QT) for 1 hr and 5 hrs are shown in Figs. 6(a-b) and 7(a-b) respectively. Optical micrographs of samples quenched and tempered for 1 hr and 5 hrs are shown in Figs. 8(a-b) and 9(a-b) respectively. Again, the HFMBN signals show single peak MBN profiles (Fig.6(a-b)) while the LFMBN signals show two-peak MBN profiles (Fig.7(a-b)) for both steels.

From Fig. 6(a-b), it can be observed that the major portion of the HFMBN profile is still below the zero transition in 18CrNiMo5 steel. For 42CrMo4 steel, the HFMBN profile is more or less equally split on both sides of zero transition. Only, the peak position of the HFMBN profile shows a clear distinction between the two steels, which reflects the difference in the magnetisation level due to the different carbon content of the steels and hence the delay in demagnetisation of near-surface layers in high carbon 42CrMo4 steel due to lower magnetisation and permeability.

The LFMBN shows very high peak 1 with narrow profile for 18CrNiMo5 steel as compared to 42CrMo4 steel (Fig.7(a)) after tempering for 1 hr. This indicates the difference between low carbon lath martensite and high carbon plate martensite (Fig.8(a-b)). The narrow and very large peak 1 indicates that the low carbon lath martensite is associated with movement of very large number of reverse domain walls in a narrow magnetic field range over a shorter displacement within the martensite laths. In high carbon 42CrMo4 steel with plate martensite structure, the height of both peak 1 and peak 2 are decreased and their positions are also shifted to higher excitation voltage (magnetic field) as compared to low carbon 18CrNiMo5 steel. This could be due to restricted displacement of domain walls in the plate martensite structure and stronger pinning of carbide precipitates in 42CrMo4 steel. After 5 hrs of tempering (Fig.7(a-b)), the peak 1 has reduced significantly in 18CrNiMo5 steel. This may be attributed to the precipitation of more carbides along the lath boundaries which reduces the displacement of domain walls from lath boundaries. The plate martensite boundaries in high carbon steel are considered to be a more stable structure when compared to lath boundaries due to precipitation of large numbers of carbides along the plate boundaries in high carbon 42CrMo4 steel (Fig.9(a-b)). This is also supported by insignificant change in peak 1 height for 42CrMo4 steel with tempering time. It can be observed by comparing Fig. 7(a-b) that the peak 2 in 42CrMo4 steel is shifted to lower excitation voltage after tempering for 5 hrs as compared to that after tempering for 1 hr. This is attributed to the growth of carbides in high carbon steel. The large size carbides are expected to be associated with 90° closure domains which reduce the local magneto-static energy and hence the magnetic field strength required for the domains walls to overcome such large size carbides [10,28].

Fig.6. HFMBN profiles of 18CrNiMo5 and 42CrMo4 steel samples quenched and tempered for (a) 1hr and (b) 5hrs.

Fig.7. LFMBN profiles of 18CrNiMo5 and 42CrMo4 steel samples quenched and tempered for (a) 1hr and (b) 5hrs.

Fig.8. Optical micrographs of samples quenched and tempered for 1hr (a) low carbon 18CrNiMo5 steel and (b) high carbon 42CrMo4 steel.

Fig.9. Optical micrographs of samples quenched and tempered for 5hrs (a) low carbon 18CrNiMo5 steel and (b) high carbon 42CrMo4 steel.

3.4 Analysis of LFMBN profile for distinguishing different microstructures

The LFMBN profiles have been fitted using 1st order Gaussian curve fitting over the two peaks separately and peak parameters such as peak height, peak position and full width at half maximum (FWHM) were determined, using a MATLAB script, as shown typically in Fig.10(a-b). Table 2 shows peak parameters for both 18CrNiMo5 and 42CrMo4 steel samples. A comparison of height and position of LFMBN peaks for different samples is shown in Fig.11.

It can be observed from Table 2 and Fig.11 that, by using a combination of parameters of both LFMBN peaks, it is possible to uniquely distinguish each of these heat-treated microstructures. It can be observed from Fig.11 that for each heat-treated condition, the peak 1 height decreases and the peak 1 position increases for 42CrMo4 steel as compared to that for 18CrNiMo5 steel. The FWHM of peak 1 is also consistently broader for 42CrMo4 steel when compared to 18CrNiMo5 steel for all microstructural conditions, indicating the broader distribution of domain wall pinning strength of phase boundaries in the high carbon steel. The peak 2 height increases for 42CrMo4 steel in the isothermal annealed condition due to increased pearlite content whilst it decreases for all other conditions due to the effect of a larger number density of carbide precipitates which restrict the displacement of domain walls. The peak 1 position shows systematic shift to higher excitation voltage (higher applied field) for high carbon 42CrMo4 steel as compared to low carbon 18CrNiMo5 steel for all four groups of microstructural conditions (Table 2). Since, the LFMBN peak 1 is attributed to the movement of reverse domain walls from the grain boundaries [10], the presence of relatively larger number of ferrite / pearlite interface boundaries in IA samples and larger number density of inter-granular carbide precipitates in SPA and QT samples in high carbon 42CrMo4 steel could offer more resistance to movement of domain walls from such boundaries. This could result in shifting of peak 1 position to higher magnetic field in high carbon steel as compared to low carbon steel. The position of LFMBN peak 2 seems to be strongly influenced by the average size of pearlite lamellae and carbide precipitates which are affected by the heat-treatment.

The changes in the LFMBN peak parameters clearly reflect the influence of carbon content related variations in microstructural features on the domain wall movement. These peak parameters could also be correlated to volume fractions of ferrite and pearlite and average size of grains and carbide precipitates for each microstructural condition. It would be very useful to correlate the LFMBN with different characteristics of pearlite phase such as lamellae thickness and spacing between the lamellae in isothermally annealed condition in different carbon steels. Similarly, it would be useful to correlate the LFMBN with average size grains / laths and carbide precipitates in SPA and QT conditions in different steel samples. However, this requires further detailed study using more number (> 3 or 4) of samples in each

microstructural category with systematic variations in the size of different microstructural constituents, which will be pursued in the future studies.

Fig.10. Typical 1st order Gaussian fitting of peak 1 and peak 2 of LFMBN profiles for 18CrNiMo5 steel samples (a) isothermally annealed and (b) quenched and tempered for 1 h.

Table 2 LFMBN peak parameters for different heat-treated samples of 18CrNiMo5 and 42CrMo4 steels.

Steel	Heat-treated condition	Peak 1 parameters			Peak 2 parameters		
		Height	Position	FWHM	Height	Position	FWHM
18CrNiMo5	IA	2.43	1.28	1.14	1.20	3.51	3.74
42CrMo4	IA	1.87	2.55	1.77	1.31	4.76	2.52
18CrNiMo5	SPA	2.78	0.61	0.88	1.27	4.41	0.93
42CrMo4	SPA	2.66	1.53	0.93	1.05	3.99	1.36
18CrNiMo5	QT-1hr	6.74	0.74	0.39	1.01	5.15	1.27
42CrMo4	QT-1hr	2.81	1.94	0.82	0.77	5.91	2.06
18CrNiMo5	QT-5hrs	6.19	0.65	0.41	1.16	5.16	1.05
42CrMo4	QT-5hrs	2.72	1.53	1.12	0.94	5.12	1.26

Fig.11. A comparison of height and position of MBN peaks for different samples of 18CrNiMo5 and 42CrMo4 steels.

4.0 Conclusions

This experimental study clearly shows the difference between the MBN signal profiles obtained at high frequency and quasi-static frequency magnetic excitation conditions. The LFMBN measurements at quasi-static magnetic excitation frequency shows more systematic variations in the shape of the LFMBN profile in response to the variations in microstructural features as compared to the HFMBN measurements with high frequency magnetic excitation. The HFMBN profile is strongly affected by the complex electromagnetic effects such as eddy currents, magnetic viscosity, damping, faster surface demagnetisation etc. limiting the variations in the shape of the HFMBN profile.

The HFMBN profile always shows single peak with major part of the profile occurring before and near the zero transition. This clearly indicates that the HFMBN signal is mainly contributed to by the faster demagnetisation of near-surface of the softer ferromagnetic material. The difference between low carbon and high carbon steels is indicated only by the higher peak position of the HFMBN profile in high carbon steel. The peak height of HFMBN profile does not reflect the effect of carbon content as expected. This is mainly attributed to the electromagnetic effects of higher excitation frequency and lower magnetising field strength used with the HFMBN system. Even though, the HFMBN measurements are used for assessment of near-surface grinding damage, this study shows that, further optimisation of HFMBN measurement parameters is required for enhancing its potential for detection of subsurface damage.

The variations in the two peaks of the LFMBN profile clearly reflect the systematic changes in the magnetisation process caused by variation in microstructural features such as ferrite, pearlite, martensite and second phase carbides depending on the carbon content of the steel.

- In isothermally annealed condition, the peak 1 of LFMBN profile decreases with decrease in volume fraction of ferrite and the peak 2 increases with increase in volume fraction of pearlite in response increases carbon content of steel.
- In spheroidising annealed condition, both peak 1 and peak 2 of LFMBN profile decreased with increase in carbon content of the steel reflecting the precipitation of large number of inter-granular and intra-granular carbides.
- In quenched and tempered condition, the low carbon lath martensite shows large increase in peak 1 of LFMBN profile after short time tempering. The tempering of high carbon steel shows only small changes in peak 1 indicating the better stability of plate martensite structure. However, the peak 2 position shifts to lower magnetic field indicating the significant coarsening of carbide precipitates.

The analysis of LFMBN peaks differentiates various microstructural conditions of both low carbon and high carbon steels more effectively than the HFMBN profiles. Further detailed study is needed to develop a quantitative correlation of microstructural features with LFMBN peak parameters.

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Figures in colour for online publication

Fig.1. Typical frequency spectra of MBN signals acquired using (a) Stresstech's HFMBN coil in 10 – 1000 kHz range and (b) LFMBN pick-up coil in 1 – 50 kHz range.

Fig.2(a)

Fig.2(b)

Fig.3(a)

Fig.3(b)

Fig.4(a)

Fig.4(b)

Fig.5(a)

Fig.5(b)

Fig.6(a)

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Fig.7(a)

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Fig.8(a)

Fig.8(b)

Fig.9(a)

Fig.9(b)

Fig.10(a)

Fig.10(b)

Fig.11. A comparison of height and position of MBN peaks for different samples of 18CrNiMo5 and 42CrMo4 steels.

Figures in black and white

Fig.1. Typical frequency spectra of MBN signals acquired using (a) Stresstech's HFMBN coil in 10 – 1000 kHz range and (b) LFMBN pick-up coil in 1 – 50 kHz range.

Fig.2(a)

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