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Distortion Analysis of Magnetic Excitation - A novel method for non-destructive evaluation of depth of surface-hardening in ferritic steels

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Abstract

The influence of ferritic steel samples with different case-depths on the distortion behaviour of magnetic excitation voltage has been investigated. The systematic changes in the height and position of the peak and the trough on the $((dV_E/dt) \text{ vs } V_T)$ profile (DAME profile) reflect the difference in the magnetisation process and hence the effect of distortion of V_E in samples with different case-depths. This study shows the good potential of this simple DAME method for materials evaluation of ferromagnetic steel components.

Key words: nondestructive testing, microstructure, ferritic steels, magnetic properties, distortion analysis

1. Introduction

The depth of surface hardening, known as “case-depth”, is normally determined from the hardness-depth profile obtained by the destructive method of hardness measurements in the cross-section of a surface hardened sample. Electromagnetic non-destructive evaluation (NDE) methods such as magnetic hysteresis loop [1,2], magnetic Barkhausen noise (MBN) [3-6] and eddy current [7-8] have also been shown to detect variations in case-depth. The low frequency MBN technique has been shown to reveal systematic changes in the two-peak MBN profile caused by the magnetisation process of softer and harder microstructural regions in different ranges of magnetic field strength [6]. It can clearly detect variations in case-depth less than ~1 mm. Recently, the maximum slope of variation in high frequency MBN signal level with magnetising sweep voltage has been correlated to case-depth variation up to ~ 4 mm [9]. However, this study [9] does not clearly support the fact that the detected MBN signals are subjected to limitation of skin-depth due to electromagnetic attenuation similar to eddy current method. In addition, these NDE techniques are relatively cumbersome for application on components. The hysteresis loop measurement requires a flux coil for measuring magnetic induction and a Hall sensor for measuring field. The MBN technique also requires meticulous optimisation of maximum applied magnetic field strength and sensitivity and frequency response of MBN pick-up coil for maximising the MBN profile for appropriate detection of different case-depths [10].

Commonly in magnetic measurements, the cyclic magnetic field is generated by applying an alternating bi-polar voltage to a coil wound around an electromagnetic (EM) yoke with suitable soft magnetic core material such as pure iron and Fe-Si steel to achieve higher magnetic field strength with lower current. Under quasi-static excitation condition, the voltage applied to an excitation coil is linearly related to the applied magnetic field strength measured at the centre of air gap between the poles in an EM yoke (in open magnetic flux path circuit). However,

when the magnetic field is measured on the surface of a ferromagnetic material placed in between the pole faces of the EM yoke (in closed magnetic flux path circuit), the tangential surface magnetic field shows non-linear behaviour. This is considered as an influence of micro-magnetisation process of the ferritic steel introduced between the poles of the EM yoke and is observed to vary with ferritic steel samples having different microstructures [11]. Hence, it is expected that the voltage applied across the excitation coil around the EM yoke will also be distorted reflecting the magnetisation behaviour of ferromagnetic steel sample placed in the magnetic flux loop. Since the magnetisation behaviour strongly depends on the microstructure of the ferritic steel, it is expected that the distortion analysis of the magnetic excitation (DAME) voltage could distinguish different surface hardened ferritic steels with gradient in microstructures consisting of harder near-surface layer and gradually softer subsurface layers.

The new approach of distortion analysis of magnetic excitation (DAME) has been explored by the author recently for microstructural evaluation of ferritic steel [12]. The DAME approach could overcome the skin-depth limitation of other electromagnetic methods as the distortion profile is expected to be influenced by the magnetisation process within the full depth of penetration of magnetic field. In addition, this is a much simpler NDE method as compared to hysteresis loop and magnetic Barkhausen noise measurements as it requires just the measurement of voltage across the coil around the EM yoke.

The principle of distortion of magnetic excitation voltage is explained in detail elsewhere [12]. The phenomenon of magnetic induction will affect the voltage (V_E) across the excitation coil which consists of resistive component due to coil resistance and inductive component as shown below in equation (1).

$$V_E = R_c * i + L * (di/dt) + i * (dL/dt) \quad (1)$$

where ' R_c ' is the coil resistance, ' i ' is the current and ' L ' is the inductance of the coil around the EM yoke. Incorporating the effect of inductance, the V_E becomes

$$V_E = R_c * i + (N^2 \mu A / l) * (di/dt) + (i N^2 A / l) * (d\mu/dt) \quad (2)$$

where ' N ' is the number of turns in the coil, ' A ' is cross-section area of coil, ' l ' is the length of the coil and ' μ ' is the permeability of the magnetic flux path.

The distortion of V_E is expected in response to the effect of Faraday's law and Lenz's law of magnetic induction according to equation (2). When an electromagnetic (EM) yoke, with a finite air gap between the poles, is excited with a quasi-static (<1 Hz) triangular waveform voltage source, it is expected to have linear change in V_E (and applied magnetic field strength) due to open loop and hence incomplete flux path. However, there will be small hysteresis loss in the cyclic process depending on the magnetic characteristics of the core material of the EM yoke. But, in the presence of another ferromagnetic material introduced to close the magnetic flux path, the change in V_E is expected to behave non-linearly due to the non-linear variation in rate of change of permeability of the ferromagnetic material between the poles of the EM yoke.

This study is an attempt to distinguish gear steels with different depths of surface hardening using the DAME approach. This paper shows the effect of different case-depths on the

2. Experimental

The schematic of the experimental set-up used to demonstrate the distortion of magnetic excitation and the details of distortion measurements are given elsewhere [12]. The alternating voltage output ($\pm 20\text{V}$) of the bi-polar power amplifier is used to excite the electromagnetic (EM) yoke made with commercially pure iron as core material. The EM yoke used in this study has different number of turns of coil and geometry as compared to the EM yoke used in [12]. The average of voltage across the excitation coil (V_E) over 4 magnetisation cycles is plotted as a function of total applied voltage (V_T). The V_E and V_T are acquired with a sampling rate of 100 kHz and averaged with time constant of 5 ms using NI-DAQ PCI-6111 card and LabView software. The average V_E is differentiated with (dt) of 1 ms and the (dV_E/dt) is plotted as a function of total applied voltage (V_T) to obtain the DAME profile for further analysis.

Samples from two carburising grade (EN36 and 8620H) steels and two nitriding grade (En40B and GKH) steels were made and were subjected to case-carburising and nitriding heat-treatment processes to obtain different depths of surface hardening. For comparison and analysis, the actual case-depth was determined by measuring hardness-depth profiles using Micro-Vickers's hardness measurements with a load of 300 g on a sample cross-section cut from each group after metallographic polishing. The case-depth is defined as depth from surface at which the hardness value reaches 550 HV.

3. Results and Discussion

Typical variations in average excitation voltage across the coil around the EM yoke (V_E) measured without any sample and with 0.5 mm case-depth carburised En36 steel sample between the poles are shown as a function of total applied excitation voltage (V_T) in Fig.1. The variation in V_E is shown only for half the magnetisation cycle (from $-V_{Tmax}$ to $+V_{Tmax}$) for better clarity, since it will be symmetrical in the other half of the magnetisation cycle (from $+V_{Tmax}$ to $-V_{Tmax}$), but the distortion is on the negative side of axis. It can be noticed from Figs. 1 that the variation in V_E is linear without any sample between the poles of the EM yoke (only air gap of $\sim 25\text{mm}$), but it varies non-linearly (as indicated by the deviation) when a ferritic steel sample is placed between the poles resulting in distortion of V_E .

The DAME profile, time derivative of voltage across the EM yoke (dV_E/dt) plotted as a function of total applied excitation voltage (V_T), is shown for half the magnetisation cycle (from $-V_{Tmax}$ to $+V_{Tmax}$) in Fig.2(a-b) and Fig.3(a-b) for carburised and nitrided samples with different case-depths respectively. The DAME profile in other half of magnetisation cycles (from $+V_{Tmax}$ to $-V_{Tmax}$) is also symmetrical, but is on the negative side of axis, which is not shown here for better clarity.

The variation in (dV_E/dt) is influenced by the rate of change of permeability of the ferromagnetic sample introduced in the magnetic flux path. The distortion of V_E is mainly contributed by the effects of Faraday's law and Lenz's law of magnetic induction in response to the changing magnetisation of a ferromagnetic sample in the flux path. The variation in V_E deviates with an increase corresponding to the demagnetisation of the sample and then

decreases again corresponding to the remagnetisation of the sample in a half cycle of magnetisation as can be observed in Fig.1. With respect to this, the (dV_E/dt) profile shows a peak corresponding to the demagnetisation section and a trough corresponding to the remagnetisation section during cyclic magnetisation process as can be observed in Figs.2(a-b) and 3(a-b). This satisfies the effects of Faraday's law / Lenz's law of induction and also shows the effect of different magnetisation behaviour of ferromagnetic samples with different surface hardened microstructural gradient.

It can be noticed from Fig.1 that the deviation of V_E in the presence of a ferromagnetic sample occurs in the range of 0 – 12 V in V_T . The dominant distortion of V_E occurs in the region where the magnetic Barkhausen noise (MBN) signal is detected from irreversible movement of magnetic domain walls [6]. The MBN signal, detected on the sample surface, is more strongly limited by the shallow skin-depth of high frequency signals as compared to the depth of magnetic field penetration. The MBN signal is more easily detected corresponding to the region where the rate of change of magnetisation is large. Hence, the MBN signal is expected between the peak and the trough of the DAME profile ((dV_E/dt) vs V_T profile). Generally, the coercive force (H_c) occurs in the middle of MBN profile corresponding to zero magnetisation in the material [11]. In the DAME profile, the coercive force (H_c) could be ideally defined as the point of intersection of (dV_E/dt) vs V_T profile of a test material with that obtained without any sample. That point of intersection lies in the region of ~ 5 – 7 V of total applied voltage as can be observed from Figs 2(a-b) and 3(a-b). This point of intersection depends on the balancing effect from the net magnetisation of the case and core regions of the surface hardened material.

The surface hardened steel is expected to show distinct ranges of magnetisation process in a half cycle due to different interaction of magnetic domain walls in harder near-surface region, case-core interface region and softer subsurface region with different hardness and microstructural features [6]. Due to this effect, the surface hardened steels show distorted magnetic hysteresis curve [2]. The variation in micro-magnetisation process will result in variation in the rate of change of permeability and is expected to cause different extent of distortion in excitation voltage (V_E) and hence in the (dV_E/dt) vs V_T profile. It can be noticed from Figs. 2(a-b) and 3(a-b) that the (dV_E/dt) is more or less constant when there is no sample between the EM yoke poles supporting the constant slope of V_E corresponding to triangular waveform excitation. The distortion of V_E with a sample between the poles of EM yoke is more evident from the non-linear variation in the (dV_E/dt) profile (named as the DAME profile) shown in Figs. 2(a-b) and 3(a-b). The sharp change in (dV_E/dt) at both the ends corresponds to change in the direction of voltage. The variation in (dV_E/dt) profile shows a peak and a trough for each sample. The height and position of both peak and trough show systematic variation for different case-depth samples. The decrease in height of both peak and trough with increase in depth of hardening could be related to the decrease in magnetisation and the permeability in hardened material condition. It is also interesting to note that the systematic shift in the DAME profile with increase in case-depth is similar for both carburised and nitrided samples. Their relationship to case-depth is shown just as a relevant material property in Figs. 2(a-b) and 3(a-b), which is defined as depth at which a hardness value of 550 HV is achieved by surface hardening process. The variations in DAME profile could actually be an indication of the gradient in the chemical composition, microstructure and hardness along the depth direction caused by the carburising and nitriding processes. The unique shape of the DAME

profile clearly indicates the difference in magnetisation process and hence the difference in rate of change of permeability ($d\mu/dt$) in these ferritic steel samples with different case-depths.

In these surface hardened samples with different case-depth, the extent of hard case region near the surface and the case-core region will vary with different gradient in composition, microstructure and hardness for samples different case-depths [6]. They also have different softer core regions depending on the time and temperature of surface hardening heat-treatment. The variation in micro-magnetisation process in each of these three distinct regions among samples with different case-depths will affect the excitation voltage across the coil around EM yoke resulting in the peak and trough of (dV_E/dt) profile at different positions as observed in Figs. 2(a-b) and 3(a-b).

It is interesting to note that the section of the (dV_E/dt) profile between the peak and the trough exhibit different slope changes for each case-depth condition with different microstructural gradient. This section of the DAME (dV_E/dt) profile shows approximately three different slopes (the descending slope of peak, ascending slope of trough and a slope in between, as marked in Fig.3(b)). Considering the positions with respect to total applied voltage (V_T) (proportional to the applied magnetic field strength), the three-slope behaviour could be an indication of deep softer core regions (slope-1), case-core interface region with gradient (slope-2) and the near-surface hard case region (slope-3) associated with different magnetisation process. This is due to interaction of magnetic domain walls with different microstructural features at different magnetic field strengths (total applied voltages) in these three different regions. The slope changes are more distinct in nitrided samples than carburised samples. This could be due to sharp gradient in material properties in shallow case-depth nitrided samples. In case-carburised samples, the extent of shift in the DAME profile for deeper case-depth sample is not very significant which could be due to very small reduction in net magnetisation level. Overall, it appears that the variation in these slopes could be an indication of different extent of these distinct microstructural zones in different case-depth samples. However, it needs further understanding of the physical significance of the DAME profile to support this argument.

It is well known that the skin-depth of electromagnetic signals depends on the permeability and conductivity of the test material and frequency of the signal. In the DAME measurement, since the frequency of magnetic excitation is low (0.4Hz), the magnetic field penetration is high and hence is expected to reflect the magnetisation behaviour over larger depth than the MBN signal measurement. However, since the distortion of V_E and the DAME profile strongly depend on the magnetisation behaviour of the test material, the extent of distortion will be small for harder material due to lower permeability and rate of change of magnetisation. However, in case-hardened steels, the softer inner core region has higher permeability than the harder case-layers. The variations in the peak and the trough of the DAME profile reflect this difference between core and case regions. Hence, the case-hardening depth sensitivity depends on the difference in the magnetic permeability of case and core regions. It is expected that, larger difference between the permeability of case and core regions could result in enhanced sensitivity for detecting variations in case-hardening depth. However, more studies are required for better understanding of this correlation.

The unique behaviour of the DAME profile depending on the microstructural condition shows that this new DAME approach can be used for variety of applications of non-destructive evaluation of ferromagnetic steels. It is expected that detailed analysis of the DAME profile could be related to variations in microstructural features and mechanical properties caused by high temperature exposure and /or mechanical loads in ferritic steel components. However, it is important to realise that, apart from the influence of different microstructural and stress conditions, the DAME profile could also be affected by the magnetising parameters, geometry of the ferritic steel sample due to the effect of demagnetisation factor and the distribution of magnetic field strength. Further understanding of this phenomenon of distortion of magnetic excitation voltage and its quantitative correlation to case-depth is in progress.

4. Conclusions

This study clearly shows that the voltage (V_E) across the excitation coil around the EM yoke is distorted in the presence of a ferromagnetic sample placed between the poles. The distortion behaviour depends on the microstructural condition of the sample supporting the influence of variation in rate of change of permeability associated with magnetisation process in ferromagnetic samples with different surface hardened case-depth. The different extent of distortion is uniquely reflected by the shape of the time derivative profile of the excitation voltage (dV_E/dt) (DAME profile). The systematic shift in the height and position of the peak and the trough can be used to identify different case-depths in surface hardened ferritic steel components. Further research is in progress for better understanding of this phenomenon of distortion of magnetic excitation and its correlation to microstructural and mechanical properties of ferromagnetic materials.

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List of figure captions:

Fig.1. Variations in average voltage across the EM yoke (V_E) as a function of total applied excitation voltage (V_T) measured without any sample and with 0.5 mm case-depth En36 steel sample for half the magnetisation cycle ($-V_{Tmax}$ to $+ V_{Tmax}$). Arrow indicates the direction of magnetisation.

Fig.2. Variations in time derivative of the voltage across the EM yoke (dV_E/dt) as a function of total applied excitation voltage (V_T) for half the magnetisation cycle ($-V_{Tmax}$ to $+ V_{Tmax}$) measured without any sample and with carburised samples with different case-depths (a) En36 steel and (b) SAE 8620H steel. Arrow indicates the direction of magnetisation.

Fig.3. Variations in time derivative of the voltage across the EM yoke (dV_E/dt) as a function of total applied excitation voltage (V_T) for half the magnetisation cycle ($-V_{Tmax}$ to $+ V_{Tmax}$) for measured without any sample and with nitrided samples with different case-depths (a) En40B steel and (b) GKH steel. Three distinct regions with different slopes are marked with arrows.

Figures in colour for online publication

Figure 1.

Figure 2(a)

Figure 2(b)

Figure 3(a)

Figure 3(b)

Figures in black and white

Figure 1.

Figure 2(a)

Figure 2(b)

Figure 3(a)

Figure 3(b)