Moorthy V.

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Distortion Analysis of Magnetic Excitation - A novel approach for non-destructive microstructural evaluation of ferromagnetic steel

V. Moorthy

Design Unit, School of Mechanical and Systems Engineering, Newcastle University, UK, v.moorthy@ncl.ac.uk

Abstract

The presence of a different ferromagnetic material, between the poles of a U-shaped iron cored electromagnetic (EM) yoke, has been observed to introduce a distortion in the alternating excitation voltage (V_E) across the coil around the EM yoke. The influence of four different microstructural conditions of a ferromagnetic 18CrNiMo5 gear steel on the distortion behaviour of magnetic excitation voltage has been investigated. The time derivative of the excitation voltage (dV_E/dt) plotted as a function of total applied voltage (V_T) has been found to show unique shape for each sample with different microstructural conditions. The systematic changes in the height and position of the peak and the trough on the voltage-time derivative profile reflect the difference in the magnetisation process for each microstructural condition. This study reveals the good potential of this simple method of distortion analysis of magnetic excitation for variety of applications related to materials evaluation of ferromagnetic steel components.

Key words: Distortion, magnetic excitation voltage, microstructures, ferritic steel.

1. Introduction

Magnetic methods such as hysteresis loop and magnetic Barkhausen noise are potential non-destructive testing methods for evaluation of ferromagnetic materials [1-5]. Magnetic hysteresis loop is obtained by plotting the magnetic induction as a function of applied cyclic magnetic field strength. The magnetic Barkhausen noise profile is measured by plotting the average of voltage pulses induced in the pick-up coil as a function of applied cyclic magnetic field strength. Commonly in several applications, the cyclic magnetic field is generated by applying an alternating bi-polar voltage to an electromagnetic 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 a slow varying DC excitation condition, the applied excitation voltage is linearly related to the applied magnetic field strength measured at the centre of air gap in a U-shaped electromagnetic yoke (open magnetic flux path circuit). However, when the magnetic field is measured on the surface of a ferromagnetic material placed between the poles of the U-shaped electromagnetic yoke (closed the magnetic flux path circuit), the tangential surface magnetic field shows non-linear behaviour. This is considered as an influence of magnetisation behaviour of the ferritic steel introduced between the poles of the electromagnetic yoke [5]. It is expected that the voltage applied across the excitation coil around the electromagnetic yoke will also be distorted reflecting the magnetisation behaviour of ferromagnetic steel sample placed in the loop. Since the magnetisation behaviour strongly depends on the microstructure of the ferritic steel, it is expected that the analysis of distortion of excitation voltage could distinguish different microstructural grades of a ferritic steel.

The distortion analysis of magnetic excitation has been not studied previously for microstructural evaluation of ferritic steels to the best knowledge of the author in the literature. This is a simpler method as compared to hysteresis loop and magnetic Barkhausen noise measurements. This paper attempts to distinguish four different microstructural grades of a ferritic steel commonly used in gear industries using this new approach.

2. Principle of distortion analysis of magnetic excitation

The total voltage (V_T) applied is divided into the voltage across the excitation coil (V_E) and that across any current limiting resistor (V_{RCL}) in series in the circuit. It is known that the magnetic induction will affect only V_E which consists of resistive component due to coil resistance and inductive component. Then,

$$V_E = R i + L \frac{di}{dt} + i \frac{dL}{dt} , \quad (1)$$

Where 'R' is the coil resistance and 'i' is the current through the circuit and 'L' is the inductance of the coil. For a simple solenoid, $dL/dt = 0$.

In an electromagnet with a soft magnetic core material, the inductance 'L' becomes

$$L = N^2 \mu A / l , \quad (2)$$

Where 'N' is the number of turns in the coil, 'A' is the area of lux path, ' μ ' is the permeability of the flux path and 'l' is the length of the flux path.

The inductance of the excitation circuit is a strong function of the permeability of the flux path. Rewriting equation (1),

$$V_E = R i + (N^2 \mu A / l) (di/dt) + (i N^2 A / l) (d\mu/dt) , \quad (3)$$

When an electromagnetic yoke (EM), with a finite air gap between the poles, is excited with a slow varying (<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 resulting in second and third terms on the right side of the equation (3) become zero. There will be small hysteresis loss depending on the magnetic characteristics of the core material. However, in the presence of another ferromagnetic material introduced in the 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.

The present study is aimed at demonstrating this effect of non-linear distortion of magnetic excitation experimentally and attempt to distinguish different microstructural grades of ferromagnetic steel.

3. Experimental

The schematic of the experimental set-up used to demonstrate the distortion of magnetic excitation is shown in Fig.1. A bi-polar triangular waveform at a frequency of 0.4 Hz is generated through the NI-PCI-6111 DAQ card using LabVIEW software which is fed to a bi-polar power amplifier. The alternating voltage output ($\pm 20V$) of the power amplifier is used to

excite the electromagnetic (EM) yoke (Fig.1) made with commercially pure iron as core material. The excitation coil around the EM yoke is connected to a current limiting resistor (R_{CL}) in series. The EM yoke has an air gap of 25 mm between its poles. The voltage signal across the excitation coil wound around the EM yoke (V_E) is passed through a 100 Hz low pass frequency filter to remove any high frequency noise in the signal. The total excitation voltage (V_T) and the voltage across the excitation coil (V_E) are acquired over 4 cycles of magnetisation with a period of 10s at a sampling frequency of 100 kHz. The data is smoothened further by averaging over 4 magnetisation cycles. The average voltage across the excitation coil (V_E) is plotted as a function of total voltage (V_T). The average voltage across the excitation coil (V_E) is differentiated with time and plotted as a function of total voltage (V_T) for further analysis.

Fig.1. Schematic of the experimental set-up used for acquiring and analysing distortion of magnetic excitation voltage

Gear steel, commonly designated as 18CrNiMo5 steel, is received in as-rolled (AR) condition. Rectangular bar samples of 70 mm x 20 mm x 5 mm were made from the AR steel bar. The bar samples were subjected to different heat treatment to obtain different microstructures. The sample in AR condition is expected to be harder due to high dislocation density generated by the rolling process. An isothermal annealing (IA) process is carried out to obtain two-phase microstructure with ~75% volume fraction of ferrite and ~25% volume fraction of pearlite phases. A spheroidising annealing (SPA) process is carried out to obtain microstructure with more volume fraction of ferrite phase and spheroidised carbides. Another

quenched and tempered (QT) process is carried out to obtain microstructure with tempered lath martensite and fine carbide precipitates. The distinct microstructural variation is expected to cause difference in magnetisation process due to different interaction of magnetic domain walls with microstructural features. The variation in micro-magnetisation process will result in variation in rate of change of permeability. This is expected to cause different extent of distortion in excitation coil voltage (V_E).

4. Results and Discussion

Typical variations in voltage across coil around the EM yoke (V_E) measured without any sample (only air gap) and with an isothermally annealed (IA) 18CrNiMo5 steel sample is shown for 10s period over 4 cycles of magnetisation in Fig.2. The variation in average V_E as a function of total applied voltage (V_T) is shown in Fig.3 for half the magnetisation cycle ($-V_{Tmax}$ to $+V_{Tmax}$) for better clarity, since it will be symmetrical in the other half of the magnetisation cycle.

It is obvious from Figs. 2 and 3 that the variation in V_E is linear without any sample between the EM yoke poles (only air gap of $\sim 25\text{mm}$), but it varies non-linearly when a ferritic steel bar sample is placed between the EM yoke poles (as shown in Fig.1) resulting in distortion to V_E . It can also be noticed from Fig.3 that the shape of distortion in V_E is different for each microstructural condition. The difference in the distortion of V_E between samples with different heat-treated microstructures is more clearly revealed in Fig.4 in which the variation in time derivative of voltage across coil around the EM yoke (dV_E / dt) is plotted as a function of total applied excitation voltage (V_T) for half the magnetisation cycle ($-V_{Tmax}$ to $+V_{Tmax}$). The other half is symmetrical, but is in the negative side which is not shown here for better clarity.

Fig.2. Typical variations in voltage across the EM yoke (V_E) measured without any sample and with an isothermally annealed (IA) 18CrNiMo5 steel bar sample is shown for 10s period over 4 cycles of magnetisation. The distortion in excitation coil voltage (V_E) with IA sample can be noticed clearly.

Fig.3. 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 different heat-treated 18CrNiMo5 steel bar samples for half the magnetisation cycle ($-V_{Tmax}$ to $+V_{Tmax}$).

Fig.4. Variations in time derivative of the voltage across the EM yoke (dV_E / dt) as a function of total applied excitation voltage (V_T) measured without any sample and with different heat-treated 18CrNiMo5 steel bar samples for half the magnetisation cycle ($-V_{Tmax}$ to $+V_{Tmax}$).

It can be noticed from Fig. 4 that the (dV_E / dt) is more or less constant when there is no sample between the EM yoke poles. The sharp change in (dV_E / dt) at both the ends corresponds to change in polarity of voltage (direction of applied magnetic field). The variation in (dV_E / dt) profile with steel sample shows a peak and a trough for each sample. The height and position of both peak and trough are different for each heat-treated sample.

The optical micrographs of different heat-treated samples are shown in Fig.5(a-d). The as-rolled (AR) sample shows bainitic structure (Fig.5(a)) and is expected to contain high dislocation density due to plastic deformation of the steel bar during the rolling process. However, the dislocation structure can be observed only in transmission electron microscopy (TEM). The isothermal annealed (IA) sample shows a mixture of ferrite phase (white grains) and pearlite phase (dark grains) (Fig.5(b)). The spheroidising annealed (SPA) sample shows a dominant ferrite grains with dispersion of spheroidised carbide particles (Fig.5(c)). The quenched and tempered (QT) sample shows tempered low carbon lath martensite with fine carbide precipitates (Fig.5(d)).

Fig.5. Optical micrographs of different heat-treated 18CrNiMo5 steel samples (a) as-rolled (AR), (b) Isothermally annealed (IA), (c) Spheroidising annealed (SPA) and (d) Quenched and tempered (QT).

The unique shape of the (dV_E / dt) profiles (Fig.4) 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 microstructural features. The positions of the peak and the trough for AR sample occur at highest voltages (V_T) and gradually shift to lower voltages for IA, QT and SPA samples respectively. This indicates the softening of the microstructure with heat treatment. The heights of peak and trough also vary with microstructural conditions.

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 microstructural condition. This section of the (dV_E / dt) profile shows two-slope behaviour for all samples except the AR sample. The two-slope behaviour could be an indication of different magnetisation process in different metallurgical phases at different magnetic field strengths (applied voltages) as discussed earlier to explain the two-peak behaviour of magnetic Barkhausen noise (MBN) profiles [3,5].

The interaction of magnetic domain walls with different microstructural features such as ferrite grain boundaries, pearlitic lamellar structure, martensitic lath boundaries, inter-granular and intra-granular carbide precipitates etc. will occur at different ranges of magnetic field strengths (applied voltages) and will affect the rate of change of permeability. This variation in micro-magnetisation process will affect the excitation voltage across the coil around EM yoke resulting in the distortion of V_E and hence in (dV_E / dt) profile.

The unique behaviour of the (dV_E / dt) profile depending on the microstructural condition can be used to evaluate different heat-treated material quality of ferritic steels. Further detailed analysis of the (dV_E / dt) profile could help in correlating to variation in specific microstructural features and mechanical properties of the ferritic steel. However, it is important to realise that, apart from the influence of different microstructural conditions, the distortion behaviour will also be affected by the geometry of the ferritic steel sample due to the effect of demagnetisation factor and the distribution of magnetic field strength in the sample. Further understanding of this phenomenon of distortion of magnetic excitation is in progress.

5. Conclusions

This study clearly shows that the excitation voltage (V_E) across the 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 different magnetisation process in ferromagnetic samples with different microstructures.

The different extent of distortion is uniquely and more distinctly reflected by the shape of the time derivative profile of the V_E (dV_E / dt). The systematic shift in the height and position of the peak and the trough can be used to identify different microstructural grades of a ferritic steel.

This study shows good potential of this method of distortion analysis of magnetic excitation for variety of applications related to materials evaluation of ferromagnetic steel components. Further study is required for better understanding of this phenomenon of distortion of magnetic excitation and its correlation to microstructural and mechanical properties of ferromagnetic materials / components.

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Figures in black and white

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