Journal of Magnetism and Magnetic Materials 398 (2016) 101–108

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Unique correlation between non-linear distortion of tangential magnetic field and magnetic excitation voltage – Unexplored ferromagnetic phenomena and their application for ferromagnetic materials evaluation

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form
28 August 2015
Accepted 7 September 2015
Available online 11 September 2015

Keywords:
Non-linear distortion
Tangential magnetic field
Magnetic excitation voltage
Ferromagnetism
Microstructures
Ferritic steel

ABSTRACT

Unexplored ferromagnetic phenomena of non-linear distortion of tangential magnetic field (H_T) and that of excitation voltage (V_E) across the electromagnetic (EM) yoke, in the presence of a ferromagnetic material between the poles of the EM yoke, have been uniquely correlated in this study. Both the H_T and V_E show similar distortion behaviour, but in the opposite direction, with unique shape for each ferromagnetic sample with different microstructural conditions. Interestingly unique correlation between (dV_E/dt) and (dH_T/dt) profiles and their ability to distinguish different magnetisation behaviour of ferromagnetic material with different microstructures have also been discussed in this study. One to one correlation between the distortion of H_T and V_E shown in this study is clear evidence that both these parameters are strongly influenced by the same mechanism of magnetisation process, but in different ways. The systematic changes in the height and position of the peak and the trough on the time derivative profiles of V_E and H_T reflect the subtle differences in the magnetisation process for each microstructural condition of the steel. This study reveals the new scientific insight and good potential of this novel as well as very simple approach of distortion analysis of H_T and V_E for understanding the influence of material properties on the mechanism of magnetisation process and also their suitability for variety of applications related to materials evaluation of ferromagnetic components and structures.

1. Introduction

Magnetic methods such as hysteresis loop (B–H loop) and magnetic Barkhausen noise (MBN) measurements are well known in the history of ferromagnetism and have been applied for the assessment of variations in the properties of ferromagnetic materials [1–8]. Several magnetic parameters such as coercive force, residual induction, permeability, MBN signal level etc. have been correlated to various material properties in ferritic steels. However, a common feature in all these magnetic measurements is the generation of cyclic applied magnetic field (H_a) by applying an alternating bi-polar excitation voltage (V_E) to a solenoid or a coil around an electromagnetic (EM) yoke. Generally in a quasi-static frequency triangular waveform magnetic excitation condition, the excitation voltage (V_E) applied across the coil around the EM yoke is linearly related to the applied magnetic field strength (H_a) measured at the centre of the air gap between the poles of an EM yoke (in open magnetic flux path circuit). But, in the presence of a different ferromagnetic material placed between the poles of the EM yoke (to achieve closed magnetic flux path circuit), both the V_E and the tangential surface magnetic field (H_T) measured on the surface of the ferromagnetic material show non-linear distortion which is considered as an influence of magnetisation of the ferromagnetic sample introduced between the poles of the EM yoke [7–13]. Since the magnetisation process is strongly influenced by the microstructure and stresses in ferromagnetic materials, the non-linear distortion behaviour of V_E and H_T is expected to have some relationship and could distinguish subtle differences in the magnetisation process between different ferromagnetic materials.

Only recently, the non-linear distortion behaviour of V_E has been explored by the author based on the time derivative analysis (dV_E/dt). The Distortion Analysis of Magnetic Excitation (DAME) voltage profile ((dV_E/dt) vs V_T) has been shown to uniquely identify different microstructural grades of a ferromagnetic material [9,10]. The non-linear distortion behaviour of H_T had been shown earlier [7,8,11–13] and the harmonic distortion factor derived from upper harmonics of H_T has been correlated to magnetic properties [11,12]. However, the influence of material properties of the

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http://dx.doi.org/10.1016/j.jmmm.2015.09.029
0304-8853/

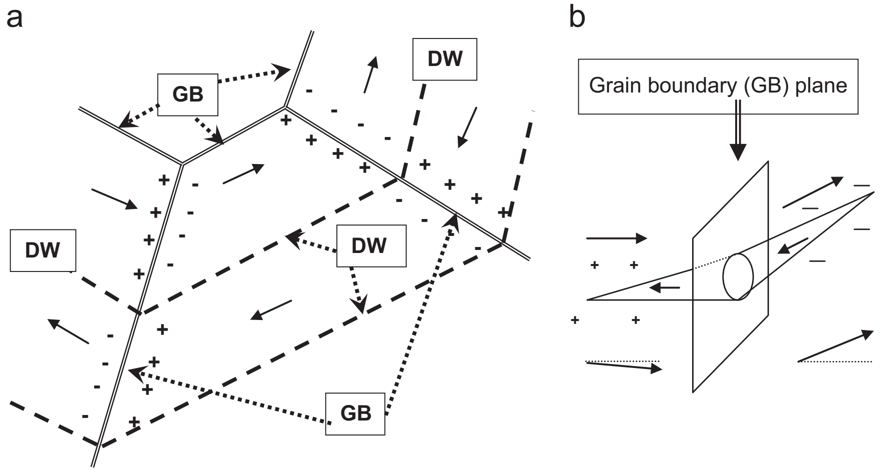

Fig. 1. (a) Multi-domain structure in a thermally demagnetized polycrystalline material with magnetic free poles at the grain boundary (GB) interface and (b) Schematic of formation of reverse spike domain structure at a grain boundary (GB) to reduce the boundary surface magnetic free pole density. (DW refers to Domain Wall).

ferromagnetic samples on the non-linear distortion behaviour of tangential magnetic field (H_T) based on its time derivative analysis (dH_T/dt) has not been widely explored previously to the best knowledge of the author in the literature. Stupakov [13] also showed only the effect of air gap on the distortion behaviour of H_T. This study is an extension of author's recent research to present the non-linear distortion behaviour of H_T and the direct correlation between the distortion behaviour of V_E and H_T. This paper attempts to show the unique correlation between the profiles of (dV_E/dt) and (dH_T/dt) and their potential to distinguish different microstructural grades of a ferritic steel using this novel and simple approach.

2. Principle of distortion of tangential magnetic field

It is known that the applied magnetic field (H_a) at the centre of the U shaped EM yoke can be measured only without any test sample between the poles of the yoke. In case of a triangular waveform magnetic excitation, the H_a varies linearly with respect to the total voltage (V_T) applied to the EM yoke in a half cycle of magnetisation (from $-V_{Tmax}$ to $+V_{Tmax}$), that is from $-H_{amax}$ to $+H_{amax}$. However, in a full cycle, the plot of H_a vs V_T will show a small hysteresis loss depending on the characteristics of the core material of the EM yoke.

In the presence of any ferromagnetic sample between the poles of EM yoke, only tangential magnetic field (H_T) can be measured on the surface of sample. The variation in H_T is non-linear and it strongly depends on the geometry and also on the properties of ferromagnetic material [7,8]. The H_T can be considered as the effective magnetic field strength seen by the ferromagnetic test sample. Hence,

$$H_T = H_a – H_d \tag{1}$$

where "H_d" is the demagnetising field which is related to the magnetisation of the sample by

$$H_d = N_d{*}M \tag{2}$$

where "N_d" is the demagnetising factor and "M" is the magnetisation of the ferromagnetic sample.

In a solenoid type open loop magnetising circuit, the demagnetising effect will be quite large due to open magnetic flux path which will lead to reduced effective magnetising field strength in the sample resulting in shearing of the magnetic hysteresis loop. In case of electromagnetic yoke type closed loop magnetising circuit, the demagnetising effect will be smaller due to closed magnetic flux path. In addition, it is also known that the demagnetising factor, N_d, is a strong function of geometry and magnetisation of the ferromagnetic sample [14,15]. For example, ferromagnetic sample with smaller length (l) to diameter (d) ratio will have larger demagnetising field which will reduce the effective magnetic field strength in the sample as compared to a sample with larger (l/d) ratio. The geometrical influence of external demagnetising field (H_{ed}) is represented through the external demagnetising factor (N_{ed}).

It has also been considered that the localised demagnetising field varies with interaction of magnetic domain walls with microstructural features in the ferromagnetic material [16–19]. Since the microstructural features such as grain boundaries, inclusions, second phase precipitates etc. are regions of discontinuity in the magnetisation vector and therefore associated with magnetic free poles. The distribution and density of magnetic free poles and hence the local magnetic energy are altered by the formation of new domains and the interaction of moving domain walls with these microstructural features. For example, the nucleation and growth of 180°-reverse spike domains or 90°-closure spike domains at the planar grain boundary interface reduce the surface magnetic pole density due to redistribution of magnetic free poles over larger area as shown in Fig. 1 and hence the reduction in localised magnetic free pole energy. Similarly, when the domain wall bi-sects an inclusion or second phase precipitate with or without closure domains, the localised magnetic energy is reduced due to redistribution of magnetic free poles of alternating sign on both sides of the domain wall as typically shown in Fig. 2. Such variations in localised magnetic free pole energy would result in variation in the internal demagnetising field (H_{id}) during the course of magnetisation process through the internal demagnetising factor (N_{id}).

Hence, the total demagnetising field, H_d can be written as

$$H_d = H_{ed} + H_{id} \tag{3}$$

Incorporating the influence of both external ($H_{ed}=N_{ed}{*}M_e$) and internal ($H_{id}=N_{id}{*}M_i$) demagnetising effects in Eq. (1), the H_T becomes

$$H_T = H_a – N_{ed}{*}M_e – N_{id}{*}M_i \tag{4}$$

where M_e is the net magnetisation in the sample and M_i is the localised spontaneous magnetisation near the microstructural features.

Considering the fact that the external demagnetising effect is