Advantages of Direct Field Approach in Application to Magnetic Hysteresis Measurements

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Abstract. *Advantages of method of direct field determination were illustrated for two industrial cases of magnetic hysteresis measurements: a standard single sheet tester and an attached single-yoke coercimeter. A vertical array of three Hall sensors was used to measure the tangential field profile above the sample surface. The sample surface field was determined by a linear extrapolation of this measured field profile to the sample face. The direct field parameters were compared with the corresponding data obtained classically using the magnetization current. It was shown that the direct field approach gives more realistic data with excellent correlation to the reference values. Moreover, the method provides stable magnetic output even in the case of magnetically open circuits, which affords new opportunities for practical applications.*

Keywords: Direct Field Measurements, Magnetically Open Samples, Magnetic Hysteresis

1. Introduction

Magnetic measurements are based on determination of the ferromagnetic material magnetization as a function of the sample magnetic field. Inductive measurement method uses a time varied magnetic field to magnetize the sample (varied magnetization current/voltage is applied to the magnetization winding). At this condition, it is not a problem to detect the magnetization waveform precisely: according to the Faraday's law, the induced voltage in a search (induction/pick-up) coil wound around the sample cross-section is proportional to the time rate of change of the magnetic flux, $U_{ind} = -n \cdot d\Phi/dt = -nS \cdot dB/dt$, where n is number of the induction windings, Φ is magnetic flux, S is sample cross-section, and B is magnetic induction [1]. The complications can only arise for the dc measurements of tiny samples. In such a case, a modern fluxmeter is needed for accurate analog integration of the weak induction signal and elimination of a floating zero offset.

However, it is not a trivial task to determine the sample magnetic field precisely, which is probably the main actual problem in the field of magnetic measurements. The difficulties are connected with small sample sizes and huge field gradients at the sample surface. The problem was historically solved by a technical way: the sample magnetic field H_i was evaluated to be proportional to the magnetization current I, $H_i = NI/l$, where N is number of the magnetizing windings, and l is effective magnetic path. This requires the robust pseudo-closed magnetic circuits, such as a standard Epstein frame and a single sheet tester (SST), which minimizes the error of current field approach to a reasonable extent of 3-5 % [1].

Therefore, our attention was focused on the method of direct field determination. Measurements of tangential surface fields with a sensor, which can be usually placed at minimal distance to the sample face of about 1-2 mm, are not stable due to the huge gradients of subsurface field. This problem was solved by application of an extrapolation technique and a special shielding approach as shown in the following section [2], [3]. This work illustrates the advantages of our measurement approach in application to two industrial setups: the standard double-yoke SST and the mobile single-yoke coercimeter. The direct field data expectedly provide excellent result repeatability and reasonable values of magnetic parameter.

2. Single sheet tester

Magnetic property of electrical steels determines their industrial quality. The classical SST setup A was slightly modified for direct field measurements (see setup B in Fig. 1). A vertical array of three Hall sensors was used to measure the sample tangential surface fields. Temperature-stable and 5 mV/G sensitive chips A1321ELHLT-T from Allegro MicroSystems Inc were used. A recently introduced "shielding" approach was used for suppression of the field gradient: two soft magnetic sheets from laminated FeSi steel force the magnetic leakage flux to flow through the sample [3]. The sample surface field was determined by a linear extrapolation of the measured field profile to the sample face [2]. Setup C presents the same Helmholtz type solenoid without the closing yokes (fully open magnetic circuit). The measurements were performed with 50 Hz sinusoidal driving voltage.

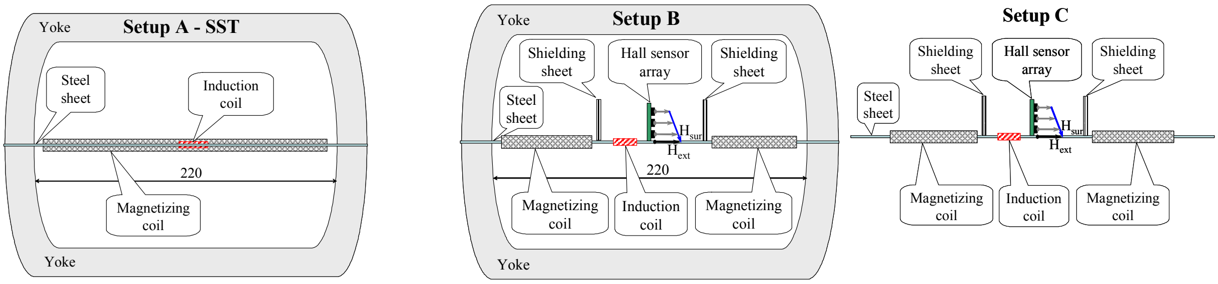

Fig. 1. Schemes of the used measurement setups.

The main advantage of the direct field method is that it provides the same stable results even with the open magnetic circuit, which is not possible with the current field method due to the huge demagnetization factor (see Fig. 2a). This is a very important funding, which gives new opportunities for practical application in on-line magnetic testing systems. Moreover, the direct field data have good linear correlation with the standard SST values (see Fig. 2b) [4].

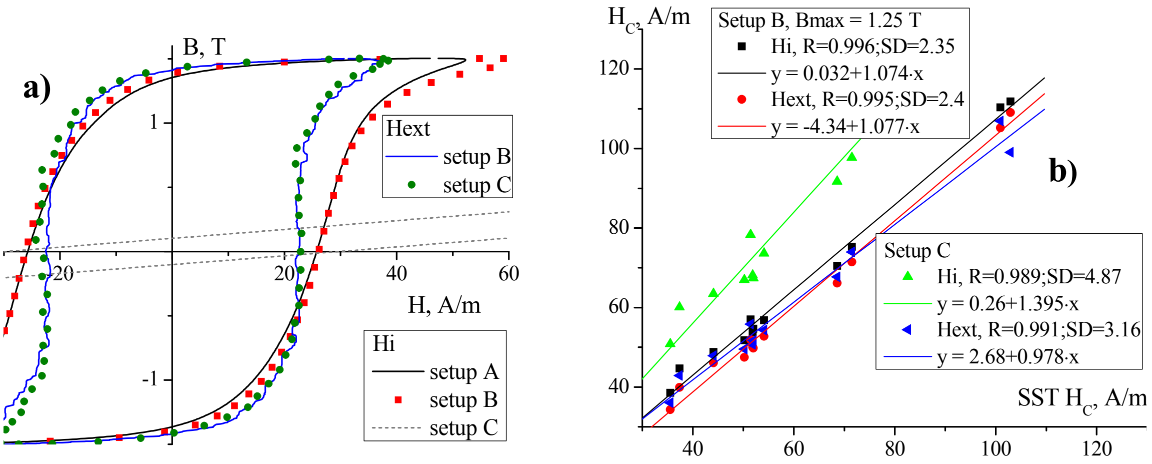

Fig. 2. (a) Typical hysteresis loops of oriented steel, measured at *Bmax* = 1.5 T by the different setups with the current *Hi* and the extrapolation *Hext* methods of field determination. (b) Correlations of the hysteresis coercive force *Hc*, obtained with the same field approaches at the magnetically closed and open setups B and C, with the standard SST data for the series of non-oriented steels measured at *Bmax* = 1.25 T. The correlation factor *R* and the standard deviation *SD* of the linear fits are shown in the graph labels.

3. Coercimeter

This mobile single-yoke device has been utilized in former USSR since the end of 1930s for coercimetric local control. Magnetization winding is placed on the small attached yoke; and the main drawback of this device is instability of the magnetization conditions with respect to uncontrollable yoke-sample contact [2]. Therefore, it can provide the stable result only for the coercive force value, which is independent of the demagnetization factor induced by the gap between the yoke and the sample [5].

For further improvement, we equipped the single yoke carrying the magnetization coil with the Hall sensor array and the two shielding plates as shown in Fig. 1 [3]. For precise measurement, the induction coil should be wound around homogeneously magnetized sample cross-section, which limits its application potential [2]. For the contactless measurement, a Barkhausen noise technique with a surface-mounting coil can be utilized [6].

Differences between the current and the extrapolation field methods are illustrated for the coercive field and the remanent induction values in Figs. 3 and 4. The measurements were done for plastically pre-deformed low-carbon steel [6]. Fig. 3 presents the data for the samples of 70x70x3 mm measured in a relatively stable configuration by a single Fe–Si yoke of 70 mm width with inner and outer pole distances of 40 and 90 mm. The samples were quasi-statically magnetized with frequency of 0.2 Hz and induction amplitude of 1.7 T. All magnetic parameters have large scattering in a Lüders band region up to 5 % of strain, where the sample microstructure is not settled. Fig. 4 presents the magnetic anisotropy data with respect to the strain direction. Before these measurements with induction amplitude of 1.35 T, the samples were machined to discs of 60 mm diameter to minimize a shape-induced measurement error [2]. The data were fitted well by a cosine square function, which is the simplest form of anisotropy energy [1], [6]. The error bars present the standard error of four identical tests.

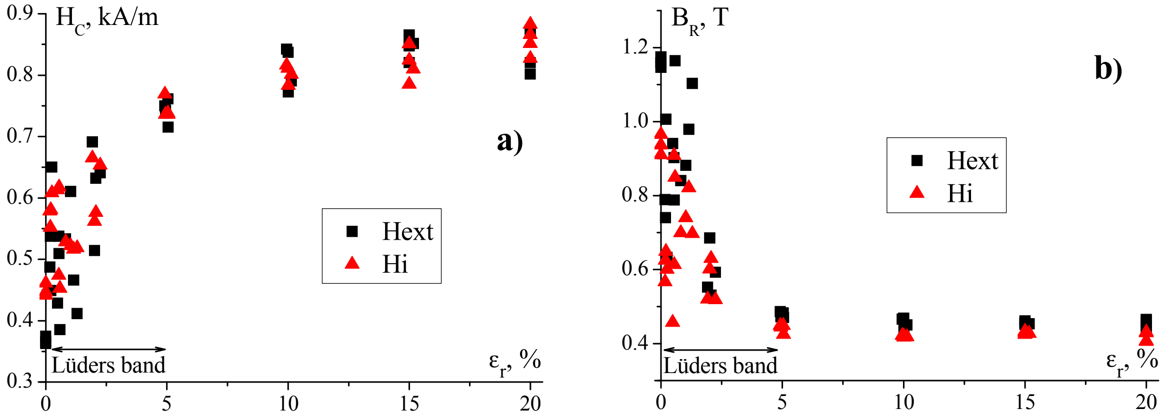

Fig. 3. Dependence of coercive force, Hc, (a) and remanent induction, Br, (b) on residual strain for the current Hi and the extrapolation $Hext$ field methods.

It is well seen that both methods of field determination provide qualitatively similar results, however, there are serious quantitative distinctions. For magnetically hard deformed samples (ε = 10-20 %) the methods give close values; but for the unstrained (ε = 0 %) and the perpendicularly magnetized samples ($\varphi \sim 90^{o}$), the difference is considerable, especially for the remanence values, due to higher demagnetization component (see Figs. 3 and 4b). Moreover, the coercive force obtained by the extrapolation field method determines the easy magnetization axis $\varphi = 90^{o}$ precisely, whereas the corresponding current field values show a shift of about six degree (see Fig. 4a). Quantitative correlation is worse for the measurements of magnetic anisotropy because of mistakes induced by the disk sample shape [6]. However, the extrapolation field data are more sensitive with the magnetization angle (see Fig. 4).

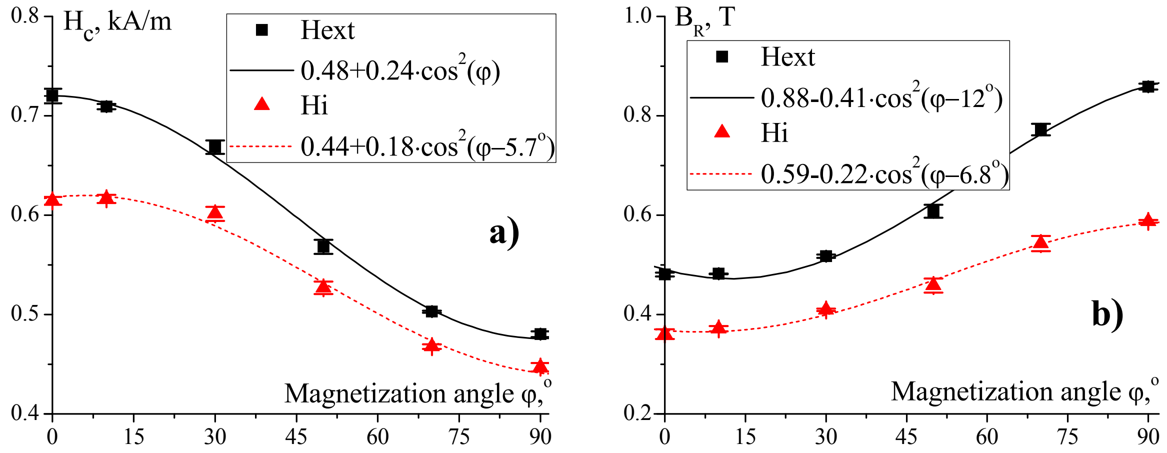

Fig. 4. Dependence of coercive force, *Hc*, (a) and remanent induction, *Br*, (b) on magnetization angle for the current *Hi* and the extrapolation *Hext* field methods measured for the 5% strained sample ($\varphi = 0$ is the stress direction).

4. Conclusions

It was experimentally proved that physically-based direct field measurements provide stable and reliable results even for the open magnetic circuits, which can not be done with the simple and standard current field method. This is the important outcome, which can change the main principles of the industrial testing techniques. The disadvantage of the proposed method is a comparative complication of the magnetic setup, especially in the case of mobile coercimeter.

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