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RECENT DEVELOPMENTS AND TRENDS IN MEASUREMENTS OF TWO-DIMENSIONAL MAGNETIC PROPERTIES

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During the past years, many efforts have been made to investigate two-dimensional magnetic properties of soft magnetic electrical steel sheets [1]. Therefore various *Rotational Single Sheet Testers* (RSSTs) were developed. The aim of this paper is to give an overview of the recent developments of RSSTs and to point out still unsolved problems in sample magnetization and measurement processes. Further, it shall give an outlook on trends in academic research and demands of industry.

Keywords: rotational single sheet testers, magnetic measurement, two-dimensional magnetic properties, soft magnetic sheets

1 INTRODUCTION

Electrical steel sheets of soft magnetic materials are used in various types of magnetic cores like in transformers, motors and generators. Since their invention, a main focus was set on the investigation of power losses in the used materials. Thus, the properties of these materials were investigated since the beginning, but usually restricted to one-dimensional magnetization. The phenomenon of *rotational magnetization* (rm), *ie* the rotation of the magnetization vector within the sample plane, has been known for about 100 years [2]. Just about 1970, the investigation of two-dimensional magnetic properties was forced by finding, that rm in magnetic cores can be harmful to energy efficiency [3, 4, 5].

Early experiences of investigating two-dimensional magnetic properties were made, *eg*, by means of torque magnetometers, where sample discs are rotated in a magnetic dc-field. It was found that hysteresis loss under a rotational magnetic field first reaches a maximum and then decreases with increasing field, whereas loss under alternating field increases steadily [2].

First RSSTs were built of cross-shaped sheets in combination with a cross shaped yoke, which carries the excitation coils [6, 7, 14]. Later the design changed to square-shaped samples and yokes [8] and to round-shaped disc samples, excited by the stator of a three phase motor [9]. But also investigations with the magnetization of Epstein strips in connection with additional perpendicular magnetization yokes [10] or the extension of the Single Sheet Tester (SST) for two-dimensions were made [11]. To support the hard direction in highly grain oriented (HGO) materials, hexagonal designs were also developed [12, 13]. Nowadays, square, round and hexagonal designs in various modifications are used concurrently.

2 MAGNETIZING SETUPS

A main demand on all RSSTs is to provide a magnetic field which magnetizes the sample uniformly over the measuring region. It should be noticed that an exactly homogeneously magnetized sample is not always possible, since the field strength **H**(t) or the flux density **B**(t), respectively, can have different directions in different grains at the same time t [15, 42].—The topic of uniform field is tackled in many publications, *eg* [8, 16, 17, 18, 19, 20, 21, 22, 23], and has also to be taken into account with respect to the measuring accuracy, since it is a precondition, that the magnetization state over the entire measuring area is representative for the type of material.

Independent of the shape of the design, the size of the sample is usually about 80 mm to 100 mm. There are laminated pole pieces with yokes, carrying the excitation coils for samples of square (*Square Rotational Single Sheet Tester*—SRSST) [22, 23, 24, 25], hexagonal (*Hexagonal Rotational Single Sheet Tester*—HRSST) [12] and round shape. For round samples an apparatus with hexagonal laminated yoke was designed [13]. Alternatively, round samples are also magnetized by a stator of a motor (*Round Rotational Single Sheet Tester*—RRSST) [26]. In all of these designs, an air gap of about 1 mm length shall balance tolerances of the geometry of sample and yokes, as well as favoring homogeneous magnetization conditions [27]. Another magnetizing setup uses two round vertical yokes [28] for samples of arbitrary shape. Thereby sample and yoke are in connection, without air gap.

Earlier **B**(t) was controlled and measured by analog techniques, *eg* [29], in order to get defined, elliptical loci of **B**(t) (also called B-patterns). Nowadays the control is done by digital feedback methods, which are predestined to control arbitrary B-patterns [18, 25, 30]. Although the digital method has sometimes the problem that it cannot control some jumps of **B**(t), because of a low sample frequency of the a/d-converter, it has become favored over the analog technique, which can have problems with phase shift from integral elements and cannot control arbitrary patterns.

Measurements [20] and calculations [22] show that, concerning uniform magnetization, round samples seem to be better suitable than square ones, if they are magnetized in an RRSST. This may be because the path of the eddy currents is the same in round samples for all magnetization directions, but not in square samples. In [22] it is also

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shown that highest values of **B** are in the center of the round sample. In the square sample, for some directions, the highest values of **B** are found in the corners of it. However, [27] concludes that square samples yield better uniform fields, but here, the basis for this investigation is an orthogonal two-phase RSST for round samples and not a stator core RRSST. Unfortunately there are no direct comparisons to hexagonal sample shapes. But from their symmetry it can be concluded, that the behavior is between square and round designs.

It is also reported, that shielding above and beneath the RSST sample, consisting of the same material as the sample, can improve the field homogeneity in the sample [18].

3 MEASURING SETUPS

The measuring setup has to be divided into an acquisition and a sensor part. Regarding the acquisition part, early analog equipment, *eg* [29], which has been automatized or computerized, respectively, has been replaced step-by-step by digital data acquisition and processing units during the last two decades. Thus, the measuring signal is usually converted right behind the analog sensor units. Concerning the sensors, in connection with the precondition of uniform magnetized samples, it is also necessary to measure the loss and magnetic properties over a large area to get characteristic values of the material and not only for a few grains. In RSST measurements the quantities of interest are $\mathbf{B}(t)$, $\mathbf{H}(t)$ (or their corresponding measuring voltages) and the *specific power loss P*.

3.1 Flux density

The time depending two-dimensional vector $\mathbf{B}(t)$ is measured by means of two perpendicular *search coils* or *needle pairs* [31], which detect the corresponding voltages. The detected two components of $\mathbf{B}(t)$ are not spot quantities, but averaged over the sample's cross section limited by the positions of the needles or holes, respectively [32]. Thus, the two components are average values over different regions.

Especially the needle method was disputed and tackled [33, 34, 35]. Finally, it was shown that it does yield accurate results, but only under special conditions [36]. The accuracy of RSST measurements with the needle method is not the only doubtful one. The *search coil* method yields controversial results, too, concerning different alignments and positions of the *search coils* on the sample [20]. This phenomenon, by which the needle method is also affected, may be caused by grain structures and inhomogeneous field and has not been clarified yet.

3.2 Field strength

The time depending two-dimensional vector $\mathbf{H}(t)$ on the surface of the sample is measured by means of crossed tangential air coils or *Rogowski-Chattock potential* (RCP) coils, *eg* [38], which detect the corresponding voltages. Each component of $\mathbf{H}(t)$, is averaged over the line between the end points of the corresponding coil. The tangential air coil cannot detect the field on the surface of the sample, because of its thickness, whereas the RCP coil can. An alternative to the RCP coil is the double tangential field coil or an arrangement of multiple coils connected in series [39]. With these arrangements the measured values can be extrapolated towards the sample surface. Nowadays most designs use two crossed tangential coils—or double tangential field coils—with a size compromising between errors from inhomogeneity (arising from sample grain structure) and uniform sample magnetization.

3.3 Power loss

Earlier, P was detected by means of thermal methods [6, 9]. Nowadays, most laboratories replaced this rise-of-temperature method by the field sensing method (also called field-metric method) in connection with the Poynting law [32] deriving P from the electrical field strength $\mathbf{E}(t)$—yielded by B-measurement—and $\mathbf{H}(t)$:

$$P = \frac{1}{\sigma T}\int_T p(t)\,\mathrm{d}t \qquad (P)=\mathrm{W/kg} \qquad (1)$$

$$p(t) = \frac{2}{d\,A}\int_{\mathcal{A}} (\mathbf{E}\times\mathbf{H})\,\mathbf{n}\,\mathrm{d}A \qquad (p)=\mathrm{W/m^3} \qquad (2)$$

(σ – mass density, T – periodic time, d – sample thickness, A – considered sample area, $\mathbf{n}$ – surface vector.) Therefore no additional sensor for P is needed anymore. A systematic problem is, that values for $\mathbf{E}(t)$ and $\mathbf{H}(t)$ have to be acquired at the same position, according to (2), which is not possible with the used measurement techniques. *Ie*, supposing a two-dimensional xy-model of the sample, B_x and H_x, (B_y and H_y respectively) are averaged over two different lines perpendicular to each other. A further problem may be, that—depending on grain structure—$\mathbf{B}(t)$ and $\mathbf{H}(t)$ do not have the same direction and magnitude over the measuring region for each instant of time [15,42]. Thus, the order of the integral over the measuring area $\mathcal{A}$ in (2) and the cross product is switched, but they are not commutative. The influence on the power loss seams to be untreated until now. This may also explain why results from thermal methods, as reported [37], are not in good agreement with the field sensing method. Further, unpublished results are known, where "negative power loss" values were obtained by means of the field sensing method. This phenomenon has been viewed in our laboratory while investigating thin samples of less than 0.1 mm thickness under *clockwise* (cw) and *anti-clockwise* (acw) rotating magnetization.

4 MEASUREMENT EXPERIENCES

In the last decades especially data for low anisotropic, *non-oriented* (NO) materials were accumulated. Small amounts of data have been collected for *grain oriented* (GO) or even *highly grain oriented* (HGO) materials. This may be caused by increasing difficulties to magnetize a sample with a circular rotating flux, if the grade of anisotropy increases. *Ie*, materials with higher anisotropy also exhibit higher loss under the same rotational B-pattern. On the other hand, concerning practical applications, the appearance of rotating flux is larger in cores of low anisotropy, *eg* in stator cores, which may favor the interest in this type of materials.

The fact of magnetizing difficulties depends not only on possible insufficiencies of the power supplies, but also on the various magnetizing setup designs, which have not been sufficiently investigated and optimized, yet. *Eg*, it is shown, that with NO materials these various designs yield results, which are in good agreement with each other, but with GO materials they yield different results [46].

Indeed, there exist some finite element method (FEM) calculations to analyze this problem [16, 17, 18, 22, 23], but because of the complexity of the magnetic problem, they have some simplifications like two-dimensional approximation, and neglected eddy currents or anisotropy or nonlinearity or hysteresis.

5 CLOCKWISE/ANTI-CLOCKWISE MAGNETIZATION

One of the biggest unsolved phenomena is that cw and acw rotating magnetization in a sample can yield different results in loss characteristic and magnetic field patterns. This fact was measured by the field sensing method [26, 37 ,38]. But different behaviors of Barkhausen noise, concerning cw/acw rotating magnetization, have been reported, too.

First, it was assumed that this may only be caused by an error of the sensor alignment. Therefore it was suggested to average cw and acw results [40, 41]. But systematic investigations show, that imperfections of the sensor system cannot solely account for the differences found [26, 37]. Further, the loss characteristic depends on the cw or acw rotating magnetization referring to a coordinate system fixed to the sample. Thus the asymmetry may be caused by different behavior of domain reconfiguration in combination with local anisotropy effects.

6 TRENDS IN INDUSTRY AND RESEARCH

Industry is interested in quick and easy test methods for new developed materials and for semi-finished products, *eg* stator cores [43, 44]. In-line-tests are demanded to reduce their costs in the production of electrical steels. Time consuming procedures like the Epstein measurement have to be avoided. But also two-dimensional measurement techniques, like RSSTs, are time consuming and very tricky to perform. Thus industry is not interested in using them frequently, yet. Especially because of the lack of reproducibility, depending on the grade of anisotropy, results cannot be compared very well. Thus a standardization of developed RSSTs is not their primer need. Industry uses either empirical formulas to calculate the increase of loss caused by rotational magnetization, or FEM analysis to show flux distributions in their devices. They look for physical data obtained from RSST measurements as input values or for validation of their mathematical calculations. Especially the use of FEM calculations has increased. Therefore rm data are desired.

A trend in academic research is to find the better RSST with higher possible flux density and a more uniform field, *eg* [45]. Comparisons of measurement and FEM calculation of $\mathbf{B}(t)$ and $\mathbf{H}(t)$ distribution in RSSTs and the samples have been started, but an effective model of the physical mechanism is missing. Generally, the knowledge about the physical mechanism is very restricted. A focus is set on digital feedback control [18, 25, 30], which enables the possibility to generate arbitrary shapes of B- or H-patterns, but systematic errors of the sensor systems—on which the control is based—are not sufficiently investigated.

7 SUMMARY AND CONCLUSIONS

In the last two decades, several versions of RSSTs and also various kinds of sensor systems were built. Generally, the digital procedure, in connection with the field sensing method detecting $\mathbf{B}(t)$ and $\mathbf{H}(t)$ in combination with the Poynting law, is favored. The RSST systems proof to be effective tools for the investigation of the two-dimensional magnetic properties of electrical sheets. But not all problems in repeatability and reproducibility have been solved yet.

Now, physical interpretations of the magnetic processes in the samples are required. Investigations on domains, hysteresis and grains at a closer look have to clarify which mechanisms are included. The systematic errors have to be detected and eliminated. Especially, the questions about cw and acw rotating magnetization and the "negative loss problem" have to be clarified.

Years ago a standardization of RSST seemed to be near. However, because of the mentioned problems, a universally usable RSST standard for all grades of anisotropic materials is not probable in the near future.

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