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Local magnetisation of a grain-oriented electrical steel sheet

***Abstract**. In the paper, the possibility of measuring fundamental magnetic properties of punched parts of electrical steels by means of non-destructive method and requirements for the measurement area of tested object resulting from its was discussed. Also, experimental results of local magnetisation distribution of the grain-oriented electrical steel sheets area with different width magnetised asymmetrically from one of its surfaces were shown.*

Streszczenie.**W artykule przedstawiono możliwości pomiaru podstawowych wielkości magnetycznych wykrojów blach elektrotechnicznych metodą nieniszczącą oraz wynikające stąd wymagania stawiane obszarowi pomiarowemu badanego obiektu. Przedstawiono również przykładowe wyniki pomiaru rozkładu indukcji na orientowanych blachach elektrotechnicznych o różnej szerokości. **Lokalne magnesowania orientowanej blachy elektrotechnicznej

Keywords: electrical steel sheet, magnetic measurements, local magnetisationdistribution.
Słowa kluczowe: blachy elektrotechniczne, pomiary magnetyczne, lokalnyrozkład namagnesowania.

Introduction

Electrical steel sheets are basic materials used for production of magnetic cores for electromagnetic machines and devices. Commonly magnetic properties of electrical steel sheets determined in test circuits such as an Epstein frame or Single Sheet Tester (SST) differ greatly from the properties for ready-made magnetic cores. For these properties, the influence of the engineering process employed for machining electrical steel sheet, the method of stacking, the shape of the core, openworking for processing and ventilation purposes, etc. is not considered. The above processing operations substantially affect the magnetic properties of the core [1–4]. Thus, a control of local magnetic properties during key stages of the production cycle is required to obtain good technical parameters in high-efficiency electromagnetic devices.

Magnetic properties of punched parts of electrical steel sheet cannot be determined with the use of standardized test circuits. They constitute destructive test methods and assessment of magnetic properties for ready-made blanks must be performed with a non-destructive method. Economic reasons require performing a control of impact of the engineering process on magnetic properties of a product. Thus, such a control should be performed on areas that determine magnetic properties of a finished magnetic core. Usually, they are local areas where the structure of material has changed due cutting, openworking, riveting, mechanical stresses, etc.

It should be noted that the aim of local measurements of magnetic properties of the material is to determine local changes of these values due to engineering processes. In this context the measured magnetic values can describe an object, not a material. The influence of engineering can be assessed by relative changes in the measured parameters referred to the parameters of the primary material. To guarantee that the results of such assessment are accurate, magnetic values must be measured in the same conditions. This prerequisite is met for every engineering process, since individual operations are repeated on the same stations and under the same conditions. Thus, it is possible to determine changes in magnetic properties of the product on each phase of the magnetic core engineering process. It will enable for fast elimination of its abnormalities and thus competitiveness of manufactured electromagnetic devices. However, the implementation of a local control of properties of a magnetic object requires solving many complex substantive issues.

According to the authors, basic issues in measuring local magnetic properties should include a method of local magnetisation of the material, assessment of the measurement area magnetization arrangement and its definition, the possibility to measure local magnetic values, etc. In available publications the main emphasis is put in particular on the magnetic field strength. Due to the field strength gradient over the surface of the tested object, the magnetic field strength tangential component (H_T)sensors should be place as close as possible to the sample. However, design issues cause that the distance from the surface of the tested object is equal to a few millimetres, which introduces a significant field measuring error H_T. Because of that, gradient sensors are used and the magnetic field strength value on the surface of the tested object is determined using the linear extrapolation method. This method is used both in case of measuring the field strength component with a flat coil [5, 6], as well as with Hall effect sensors[7, 8]. Moreover, over the surface of the sample magnetised one-sidedly, a significant field gradient occurs, especially when used magnetising heads are small and slots at the tested object contact place occur, which introduce a significant field strength measuring error [8, 9]. This error can be greatly reduced by shielding the $H_T$sensor from influence of stray fields [10, 11].

The authors say that the basic problem when measuring local magnetic properties is to determine which factors influence the local condition of magnetisation of the electrical steel sheet and possibility to measure induction.

In general, when measuring magnetic properties of electrical steel sheets induction is determined based on rotation of the electrical field strength across the surface of the sample containing a defined and homogenous cross-section, usually covered by the induction sensor. The situation changes dramatically when the dimensions of the circuit that induces magnetisation of the object are smaller than the dimensions of the tested object. There is no expressly determined magnetic flux path and local cross-section. The measurement of the basic magnetic values becomes problematic. It is not possible to determine induction or estimate the cross-section of a local area if the propagation of the magnetic flux for the tested object is unknown. To estimate the uniformity of the H_T distribution within the tested object is very hard. In case of a locally magnetised object, it is virtually impossible to achieve and assess a uniform distribution of the H_T in the measurement area. It is defined by boundary conditions dependent on, for example, dimensions, shape, magnetic properties and magnetisation of the tested object and magnetising circuit. Assessing the influence of the indicated factors requires conducting an empirical reconnaissance of the magnetisation distribution of the tested area using the method for local measurement of induction and magnetic field strength.

In the paper, experimental results of local magnetisation distribution of the grain oriented electrical steel sheet area magnetised asymmetrically from one of its surfaces were shown.

Experiment

The tests of local magnetization were performed on samples in the form of strips cut from grain oriented steel sheet (grade M140-27S). Samples with a length of 500 mm and width 9 mm, 30 mm and 125 mm were cut mechanically along the rolling direction. The width of the individual test areas was the width of magnetizing poles - 9 mm. On the border of separated areas in the middle of the samples, holes with a diameter of 0.7 mm distant from each other by 9 mm were drilled. Four induction coils were wound through each adjacent hole. Therefore there was one measurement area for a sample with a width of 9 mm and two and seven measurement areas for samples with a width of 30 mm and 125 mm, respectively. The centre of the sample was the first area (1). Next, indicated by consecutive numbers (Fig. 1).

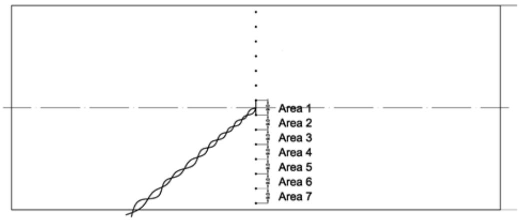


Fig. 1.Arrangement of measurement areas for 125 mmsample

Measurements were carried out forcing the required state of magnetization of the first test area of the sample. The magnetizing U-shape magnetic core with a square cross-section (9 x 9) mm with 9 mm spacing between magnetizing poles was put on the surface of the sample area so that the coil for the measurement of the induction in this area was located in the central zone of magnetizing poles. Magnetic induction was measured by two ways: induction sensors wound directly on the object and induction sensor placed on the magnetizing yoke pole. Magnetic field strength was measured by means of flat coil (Fig.2).

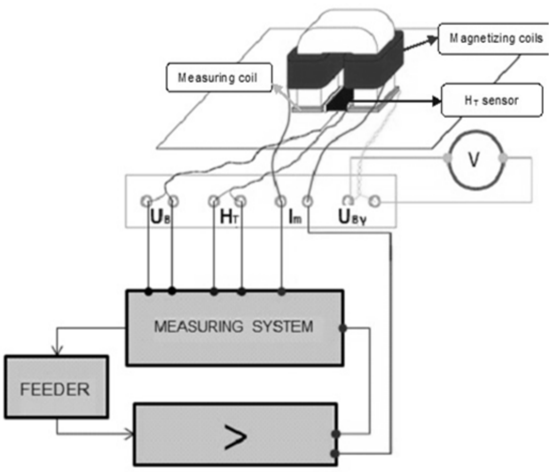


Fig. 2.Magnetising and measuring head – demonstrative drawing of coils' arrangement

Magnetising winding connected in series with the primary winding of the mutual inductance M, was supplied from the power amplifier of the MAG-3.0 computer system manufactured by R & J Measurement. Magnetizing flux sensor was push-pull connected to the secondary winding of the mutual inductance with such number of coils as to enable to reach the resultant value of the voltage of this circuit equal to zero in the absence of the tested object. Measurement of magnetizing current, the magnetic field strength and induction in the cross-section covered by the width of the magnetizing poles, was implemented by means of a MAG 3.0 computerized system. Other signals from the sensors of magnetic induction in separate sections of the electrical steel sheet sample were measured using universal measuring instruments with average value transducers.

Inductions in the cross-sections of the selected areas covered by the inductive sensors were determined by measuring the induced electromotive force, as follows

(1) $$B_{mk} = \frac{U_{Bk}}{4.44 f z_k s_k}$$

where: k – number of measurement area (k = 1 …7), B_{mk} – magnetic induction in the k-area, U_{Bk}– voltage measured at the inductive sensor in the k-area, f – magnetizing field frequency, z_k – number of turns of an inductive sensor, s_k– cross-section of the k-measuring area.

In contrast, B_{mYk} induction in the k-area of the sample from the condition of continuity of the magnetic flux at the border of magnetizing yoke and tested object was determined from the relationship:

(2) $$B_{mY} = \frac{U_{BY}}{4.44 f z_Y s_k}$$

where: z_Y– number of turns of the coil at the yoke pole (170 coils), U_{BY} – voltage measured at the inductive sensor placed on the magnetizing yoke pole.

The procedure for enforcing the required conditions for the magnetization of the first area of the tested object was carried out using a computer system. Induction measurement sensor of the first measurement area of the sample and the tangential component of the magnetic field strength sensor (flat coil) were connected to the system. The distance of the $H_T$sensor from the sample surface was approximately 1 mm.Negative feedback of the measurement system automatically provided the required and repeatable state of magnetization of the distinguished measurement area of each sample.

Measurements results

Figures 3-6 show the magnetization characteristics and relative magnetic amplitude permeability as a function of magnetic field strength for different areas of the samples. The measured magnetization characteristics of specific areas were designated with numbers from 1 to k (k = 1 ... 7), and the ones determined on the basis of measurement of magnetizing yoke magnetic flux were marked with "Y" index. The determined magnetization characteristics show a strong dependence of the magnetic flux propagation conditioned by the width of the sample and its magnetic properties. They decide about the local magnetization of the areas of the tested objects. The most favourable case occurs for a tested object with a width equal to the width of the magnetizing poles (Fig. 3).

For the actual magnetization characteristics coincide with the characteristics determined from of the continuity of the magnetic flux in the range of up to 1.3 T. Above these values, the differences between the actual induction values in the sample and the values determined from the continuity of the magnetic flux increase quickly. This case, however, concerns a defined cross-section of the tested object.

Propagation of magnetic flux beyond the physical dimensions of the sample may in fact take place exclusively by air, whose reluctance is very high in relation to the reluctance of electrical steel sheet. The convergence of the two characteristics only in a certain range of induction indicates that not symmetrical magnetization of the object does not allow to determine its magnetic properties in the state of deep saturation even for an object with a width equal to the width of the magnetizing poles. The reason is the strong scattering of the magnetic flux in the air gaps: magnetizing circuit - tested object. Moreover, the presence of the tested object also changes the original conditions of the compensation of the magnetic flux in the air. As a result, lack of compensation increases the measured induction (B_m> 1.4 T) in the states of deep saturation of the object.

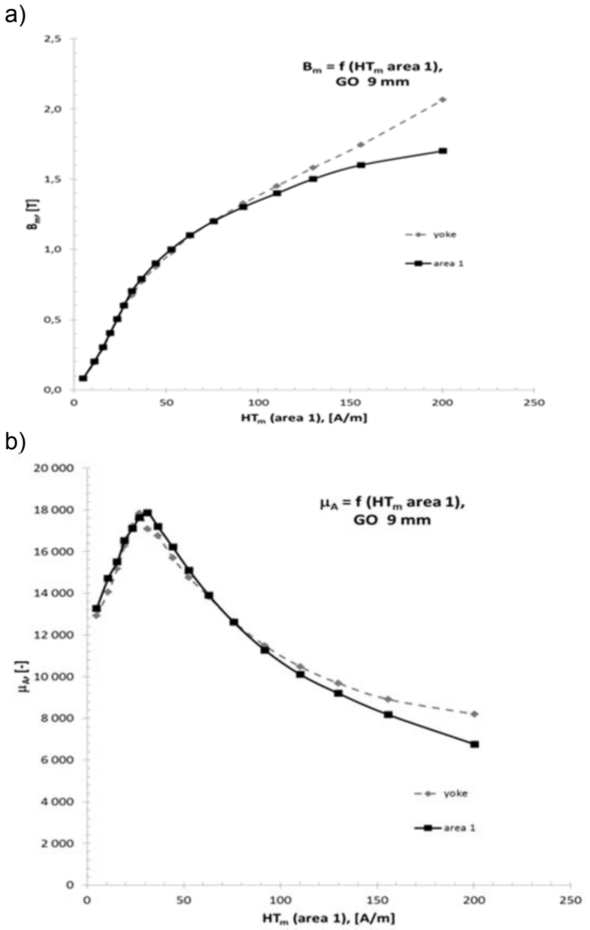


Fig. 3. Magnetization characteristics of the 9 mm wide grain-oriented steel sheet sample (a) and the relative magnetic permeability (b) as a function of magnetic field strength

For 30 and 125 mm wide samples (Figs. 4 and 5) the magnetic flux propagates over the base measurement area k=1, determined by the dimensions of the magnetizing poles. However, it is noticeable that the propagation of flux across the width of the sample is hindered by a very high reluctance in the direction opposite to the sheet rolling direction, which is in accordance with the width of the tested samples. Due to the anisotropy of the magnetic properties, the second measurement area does not reach the magnetization level equal to first area, even in a state of high saturation of sample with a width of 30 mm.It should be emphasized that in the case of sample with a width of 125 mm, propagation of the magnetic flux does not change significantly compared to the 30 mm wide one. The maximum magnetic permeability is reduced and its extremum is blurred as compared to the sample with a width of 30 mm. Moreover, for samples with a width of 125 mm, the actual induction values over the third measurement area are practically non-measurable. The measured induction values in the area 3 are very small (about 10 mT) even with deep saturation (about 1 000 A/m) of the first sample area (Figs. 5 and 6). Only the second measurementarea has the substantial influence on the propagation of the magneticflux.

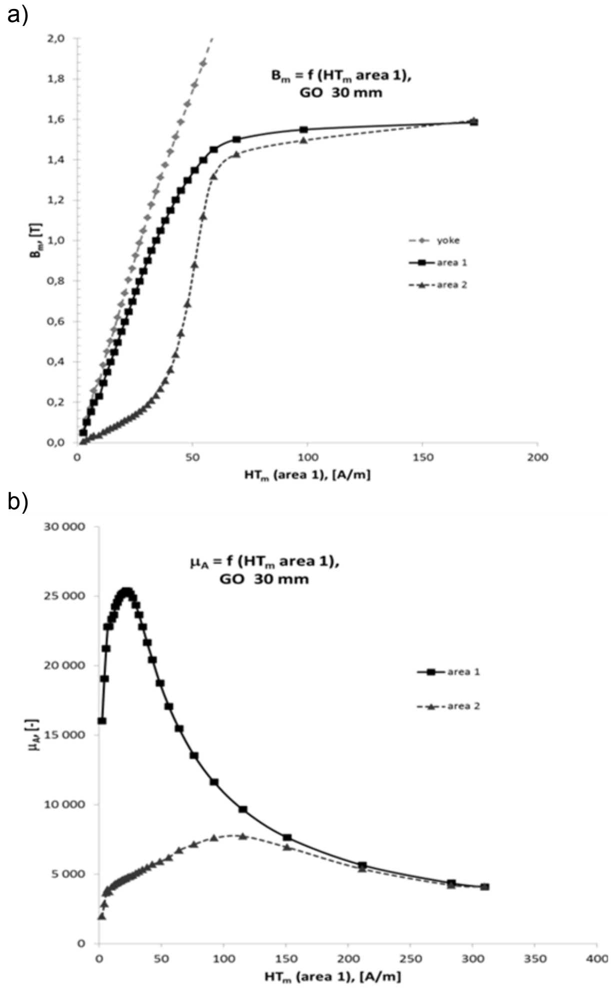
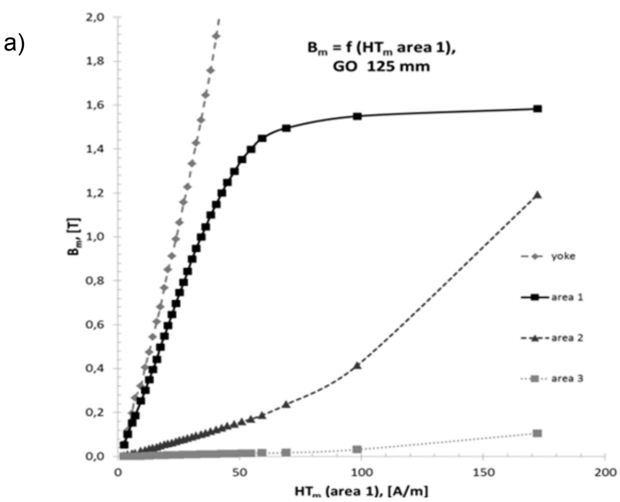


Fig. 4. Magnetization characteristics of the 30 mm wide grain-oriented steel sheet sample (a) and magnetic permeability (b) as a function of magnetic field strength.



b)

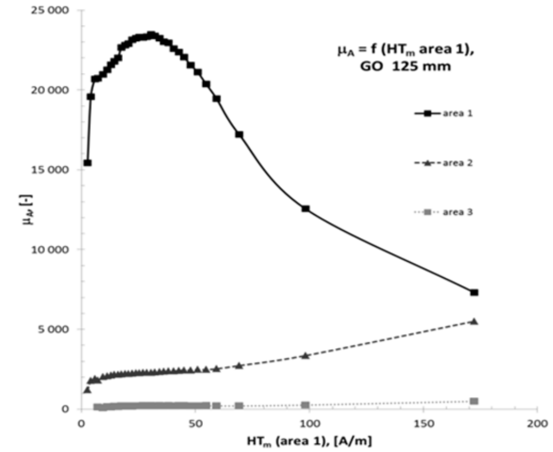


Fig. 5. Magnetization characteristics of the 125 mm wide grain-oriented steel sheet sample (a) and magnetic permeability (b) as a function of magnetic field strength.

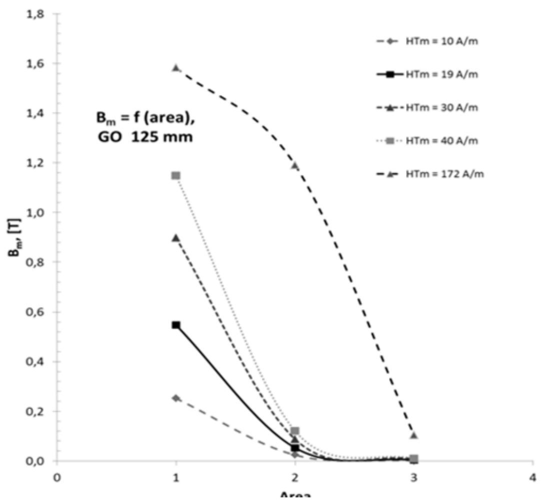


Fig.6. Distribution of magnetic induction along the width of the 125 mm samples (in particular measurement areas)

Conclusions

The results of experimental tests in the field of dependence of propagation of the magnetic flux on the width of the tested sample and its magnetic properties show the possibility for the local determination of the magnetization characteristics of the material to a limited extent of the changes of induction, even with the non-symmetrical magnetization. The width of the tested object must, however, be equal to the width of the magnetizing circuit. During the magnetization of grain-oriented materials in the preferred direction (the direction of the rolling) the areas directly adjacent to the magnetized area (second measurement area) have the primary impact on the magnetization of the measurement area. This creates the possibility of a local measurement of the dynamic magnetic properties of these materials on sheets of virtually any size. So, there is the possibility to control the impact of technology on the magnetic properties of these materials in the technological process.

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