**Slawomir TUMAŃSKI**

Warsaw University of Technology

doi:10.15199/48.2021.03.31

# Modern methods of electrical steel testing – a review

*Abstract: The paper present the review of modern methods of testing of electrical steel. There are described two methods – indirect basing of Faraday's and Ampere's laws and direct methods basing on sensors of H or B (H-coil and needle sensor). Paper present main standard methods using: ring core, Epstein frame, single strip and single sheet testers. In next part are presented two-dimensional measurement including measurement of rotational losses. Paper is finished with typical data of electrical stell and examples of measurements.*

*Streszczenie: Przedstawiono współczesne metody pomiaru parametrów blach elektrotechnicznych. Opisano metodę pośredniego pomiaru z wykorzystaniem prawa Ampera i Faradaya oraz metodę bezpośredniego pomiaru z wykorzystaniem czujników B i H. Omówiono czujniki H-coil i igłowy. .Opisano metody i próbki znormalizowane: toroid, aparat Epsteina, tester próbek paskowych i arkuszowych. Przedstawiono też pomiary dwu- i trzywymiarowe, w tym pomiar strat rotacyjnych. Nas zakończenie przedstawiono typowe parametry blach elektrotechnicznych i przykłady badań. (**Współczesne metody pomiaru parametrów blach elektrotechnicznych**)*

Keywords: electrical steel, testing methods, H-coil, needle sensor, ring core, Epstein frame, SST, rotational losses
Słowa kluczoweL blachy elektrotechniczne, badania blach, czujnik H-coil, metoda igłowa, toroid, aparat Epsteina, SST, straty rotacyjne

**Introduction**

Testing of electrical steel is an important and also complex problem [1,2,3]. Important because quality of this steel directly influences quality of many electrical devices. Losses of power in this devices strongly influences the pollution.

The complexity of measurements results from following factors:

1. Dependence of the shape

Results of the measurement can be different for various shape of the investigated sample and moreover can be different from the parameters of device made from this steel. The reason is that sample is magnetised non-uniformly due to demagnetising field depending on the shape of the sample. The best case is if the tested sample has the same shape as the device. Many devices have a shape of toroid what is one of the most frequency tested sample. If the sample is other than device often the designers introduce roughly estimated building factor.,

In other cases solution is the selection of the standard sample. An example of such standard sample is the Epstein frame - in this case all: sample, windings, testing methods are precisely described by standard. In such a way every who use this method performs measurements in the same way. It enables comparison of obtained results and not important is if the measurements are exact for the physical point of view.

2. Nonlinearity

The basic dependence $B=f(H)$ is nonlinear ($B$ – flux density, $H$ – magnetic field strength). It means that both values $B(t)$ and $H(t)$ are usually non- sinusoidal – hjave higher harmonics. Because steel parameters depends on frequency Thus we obtain various testing results for the same flusx density.

The solution is that standards require testing the steel only for pure sinusoidal flux density. For low flux density it is relatively easy to fulfill this conditions but for high flux density it is really challenge.

3. Materioasl nonuniformity

After manufacturing of steel different parts of the same rolle or sheet can have very various performances due to different process of crystallisations or different chemical composition. Most of steel testing methods are destroying the material therefor it is not possible to test material which is planned to use to construct the device.

The solution is that usually tested are initial and final parts of the material and it is assumed that the whole part has the same parameters.

**Indirect measurements of steel parameters**

Electrical steel is usually classified according to specific power loss $P_w$:

$$P_w = \frac{P}{m} = \frac{V}{mT}\int_0^T H\frac{dB}{dt}dt = \frac{1}{\gamma T}\int_0^T H\frac{dB}{dt}dt \quad (1)$$

where P is a power loss in volume $V$:

$$P = \frac{V}{T}\int_0^T H\frac{dB}{dt}dt$$

and $\gamma$ is density of the material.

Of course other parameters can be also important. For example permeability $\mu$

$$\mu = \frac{B}{H} \quad (2)$$

can be important for design of shield and high saturation flux density $B_s$ means that the designed device can be smaller. But to determine all these parameters it is sufficient to determine two basic steel values: magnetic field strength $H$ and flux density $B$.

The typical circuit used to testing of electrical steel is presented in Fig.1.

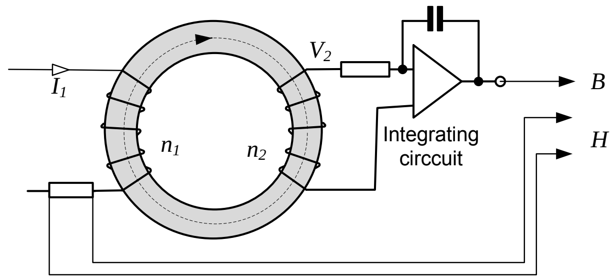


Fig. 1. Circuit with indirect measurement of $B$ and $H$

Usually to determine magnetic field strength we apply Ampere's law:

$$Hl = n_1 I_1 \quad (3)$$

where $I_1$ is magnetising current (current in primary winding), $n_1$ is number of turns in primary winding and $l$ is the length of means path of magnetic flux.

The flux density can be determine by applying Faraday's law:

(4) $$V_2 = n_2 A \frac{dB}{dt}$$

where $V_2$ is induced in secondary winding with number of turns $n_2$ and $A$ is a means cross section area of ,magnetic yoke. Because induced voltage is proportional to $dB/dt$ additionally integrating circuit is necessary.

The advantage of indirect method is simplicity and relative large signals, Drawback is that we never know exactly length $l$ and area $A$. Moreover this method is difficult to use in two-dimensional measurements. In such a case we usually is used dircet method.

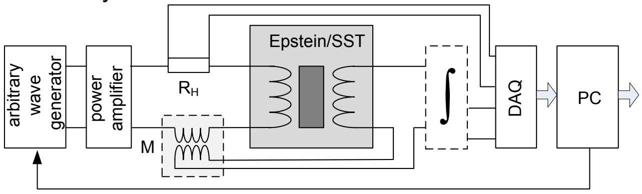


Fig. 2. Typical circuit for testing of electrical steel.

Fig. 2 presents typical circuit used to tests. The Arbitrary Wave Generator (and Pc or microcontroller) are necessary to ensure sinusoidal shape of flux density. Often in primary circuit is included mutually inductance M to compensation of the airt flux. Fig. 3 present typical results of measurement.

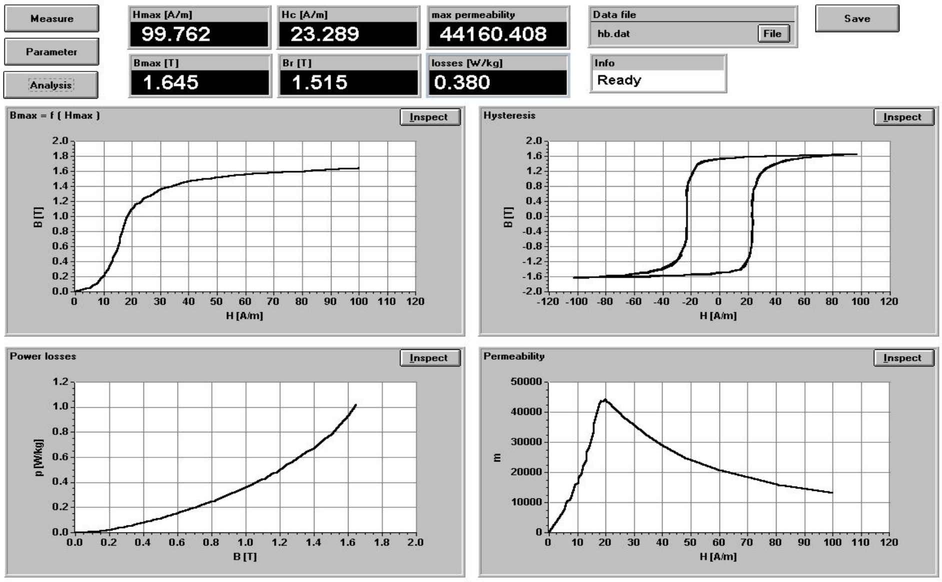


Fig. 3. Typical results of steel testing: magnetising curve, hysteresis loop, power loss versus flux density, permeability versus magnetic fierld strength

Indirect method requires closed sample – toroid or Epstein frame. In the case of open sample we do not know the length *l*. But also in a case of open sample – strip or sheet it is possible to use this method. An example of strop tester using RCP (Rogowski Chattock Potentiometer) is presented in Fig. 4.

The magnetic field strength $H_{mCD}$ (between points C-D) measured from the magnetizing current $I_m$ can be determined from the relation

(5) $$H_{mCD} l_{CD} + 2H_a l_a + H_j l_j = I_m \left( n_{mo} + n_{m1a} + n_{m1b} \right) = I_m n_m$$

Thus the measured magnetic field strength $H_{mCD}$ is strongly affected by the unknown magnetic field in the air gaps $H_a$ and magnetic field in the yoke $H_j$. By using of the compensation circuit the signal from the RCP is connected as a feedback current $I_c$ to the compensation coils $n_{c1}$ and $n_{c2}$. The condition of the feedback is the magnetic field between point A-B is equal to zero $H_{mAB}$ = 0 which means that we compensate magnetic fields in the yoke and air gaps. Therefore we obtain the following relationship

(6) $$H_{mAB} l_{AB} = I_m n_m$$

and we can determine the magnetic field between points A-B practically without errors. Of course the length of magnetic path $l_{AB}$ is known or can be easily measured with an appropriate precision.

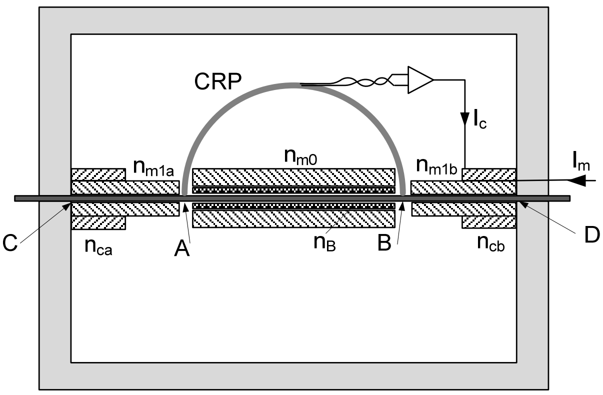


Fig. 4. The single strip tester with compensation circuit to determine magnetic path length

**Direct measurements of steel parameters**

It is possible to measure directly $B$ and $H$ using sensors of flux density or magnetic field strength. Of course we measure these values locally (in area of the sensor) but results do not depend on other factors – as magnetic path length or cross section area.

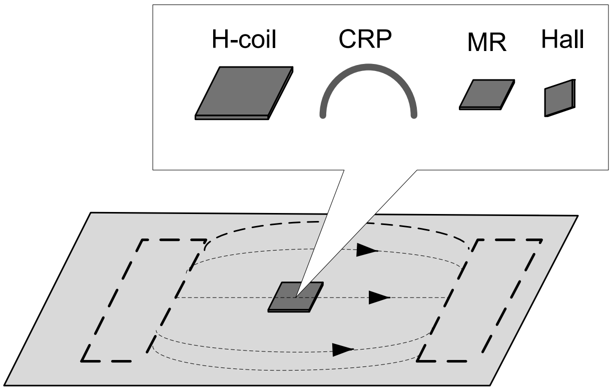


Fig. 5. Direct measurements of magnetic field strength

Easier is to detect the local value of magnetic field strength. We profit the rule that the tangential component of H in the sample is the same as field above the sample. Thus we can use very thin flat coil sensor or Chattock-Rogowski coil (de facto bended flat coil). Useful is magnetoresitive sensor because it detects the magnetic field in the film plane.

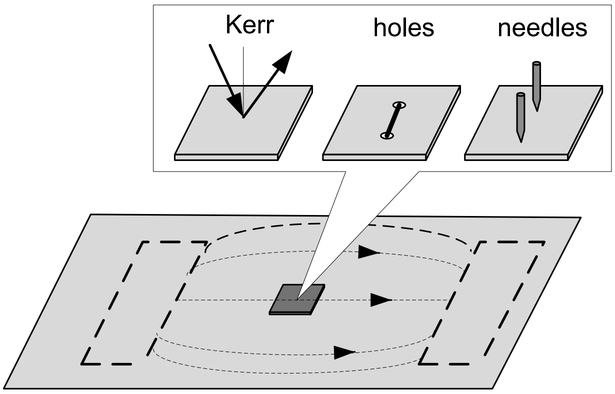


Fig. 6. Direct measurements of flux density

More difficult is to measure the flux density. We can use Kerr method but this method is rather difficult to use and not accurate. Accurate is to drill holes and apply Faraday's law but we destroy the material. Therefore recently is used thye needle method where we create half-loop and als can use Faraday's law.

As H-sensor the most popular is thin coil, known as H-coil or Rogowski Coil known as RCP. The main problem in this case is that to obtain sufficient accuracy the coil should be as thin as possible. But as thinner coil as lower sensitivity. For example coil with area 25 x 25 mm, thickness 05. Mm with 400 turns wound with wire of diameter 0.05 mm has sensitivity only 3 μV:A/m. Therefore sometimes are used two thicker coils and the result is extrapolated to surface of steel (Fig.7a).

The output signal of H-coil is:

(7) $$V = \mu_0 An \frac{l_{AB}}{L} \frac{dH_{AB}}{dt}$$

where $A$ is area of the coil, $n$ is number of turns and $l_{AB}$ length of Rogowski coil (for $l_{AB}=l$ we have flat coil)/ We see that the output signal depends on $dH/dt$ thus the integrating circuit is necessary.

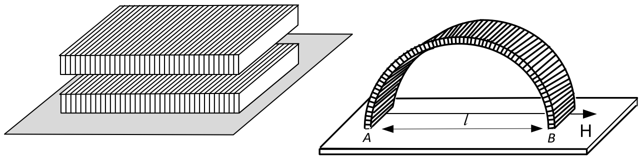


Fig. 7. H-coils or RCP used to measure magnetic fierld strenth

For local flux density measurement recently the most popular is use the needle method [4]. The method is relatively simple but sometimes problem is with overcome of insulation from the steel surface. The output signal of the sensor (Fig. 8) is:

(8) $$V == \frac{1}{2} t l_{AB} \frac{dB}{dt}$$

thus also in this case integrating circuit is necessary.

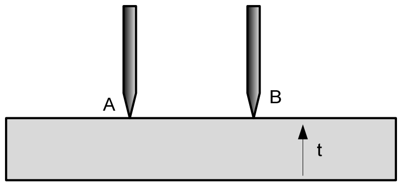


Fig. 8. Needle senor of local value of flux dfensity

**The standard shapes of the tested sample**

1. Ring core [5]

Ring core (toroid) (Fig. 1 and Fig 9).seems to be most natural and perfect sample. It is almost ideal shape for easy uniform magnetization with little stray field. Relative easy and accurate is to determine cross section and means magnetic path length as:

(9) $$l = 2\pi\left(\frac{r_e + r_i}{2}\right)$$

This condition is only fulfilled if re/ri < 1.25.

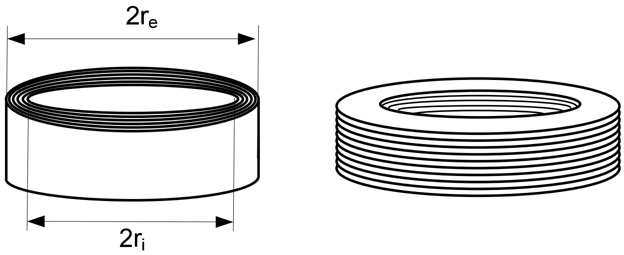


Fig. 9, Ring core sample

The main problem with toroid sample is difficult and tedious preparation – to uniform magnetization the primary winding should be uniformly wound on the whole ring. Moreover often sample should be annealed to remove stress effects. Therefor this sample is usuaslly used only if the future device is also a toroid.

2. Epstein frame [6]

The Epstein frame (Fig. 10 and Fig. 11) is commonly criticized as nonsense from the physical point of view – nobody know what happens in the corners. But the same time it is most frequently used due its advantages. It is rather easy to assembly. And the most important – it is very exactly described by the standard , therefore practically all measuring stands are the same and repeatability of obtained results is perfect.

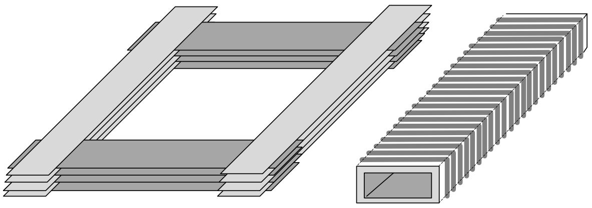

Fig. 11. The sample and one of four coils of the Epstein frame

Thus it is not important that the measurement is not exact from physical point of view (because we do not know exactly magnetic path length). Important is that all obtain the same result.

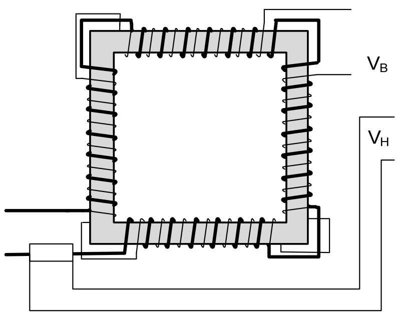


Fig. 11. The Epstein frame

3. Single strip and single sheet testers [7]

The idea of single strip or sheet tester (Fig. 4 and Fig. 12) has many supporters. Measurement is easy and fast – it is sufficient to put the sample between two yokes (although in the case of commonly used sheet 50 x 50 cm the yoke is quite heavy).

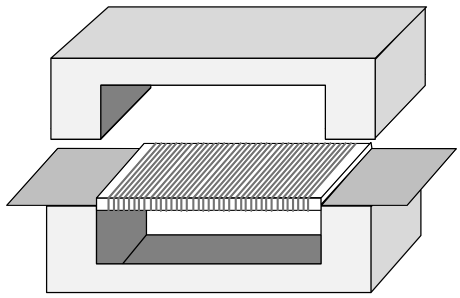

Fig. 12. The single strip tester SST

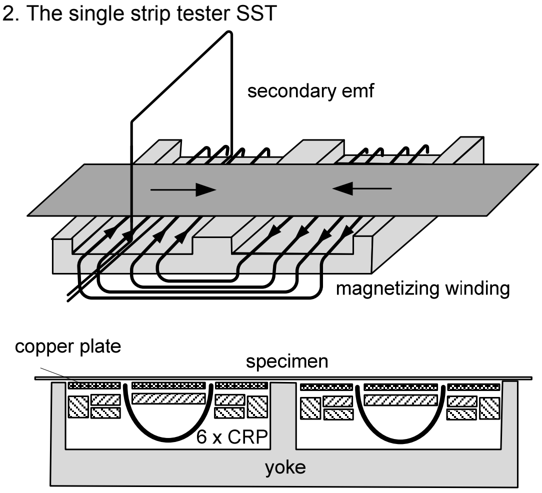


Fig. 13. The single strip tester SST for on-line steel testing [8]

But the measuring device is not so simple as in Fig. 12 – to obtain better accuracy the use of compensation coils is necessary with quite complex electronics. Thus more realistic is the device presented in Fig. 4.

If is so easy to put the sample we can consider also the case of moving sample to realise on-line testing methods. Fig. 13 present the example on-line testing device.

**Two- and three-dimensional measurements [3]**

Electrical steel is anisotropic what - the best performances are along the rolling direction. The poor performances are for the angle 90° with respect to the rolling direction.

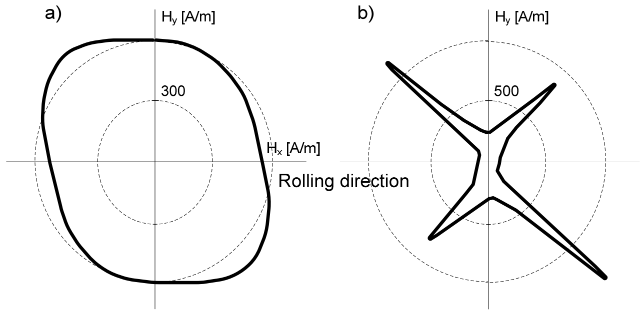


Fig. 14. The dependence of the magnetic field strength on the angler of magnetisation (for constant flux density) for non-oriented (a) and grain-oriented (b) steel [9]

In the case of non-oriented steel (Fig. 14a) these differences are not so large – of about 10%. More complex is anisotropy of grain-oriented steel (Fig. 14b) – beside 90° exist also critical angle 55°. Thus it is recommended to use GO steel for rolling direction and for rotating fields to use NO steel/

Rotating magnetic field causes additional losses known as rotational losses:

$$P_r = \frac{1}{T\gamma}\int_0^T \left( H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} \right) dt \qquad (10)$$

Rotational losses are quite important factor for designers of electrical machines and measurement of $P_r$ is also today very important.

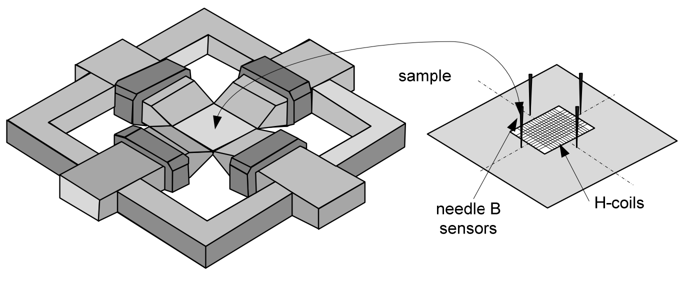


Fig. 12. The testing device for two-dimensional measurements

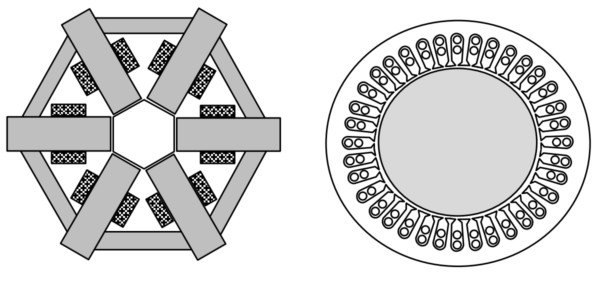

Fig. 13. The testing device with hexagonal or circular sample

Figure 12 presents devices to two-dimensional measurement. In this case to determine magnetic field strength and flux density the sensors are used, most often two H-coils and two pairs of needles. Rotating magnetic field can be also generated in hexagonal or circular sample (Fig. 13). Figure 14 presents device for three-dimensional measurements.

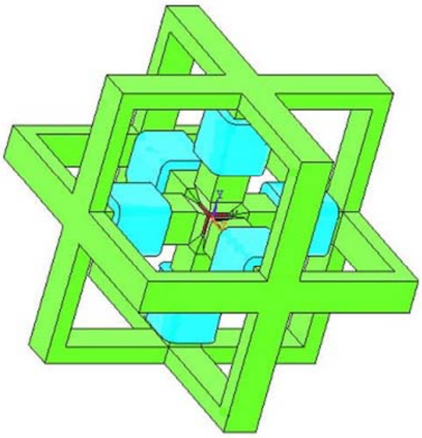

Fig. 14. The device for three-dimensional measurements [10]

**Results of measurements**

Tables 1 and 2 present performances and classification of typical grain-oriented and non-oriented electrical steel. Note that instead flux density $B$ the polarization $J$ is used ($J=B-\mu_o H$ – for soft magnetic materials the second component is negligible small and we can assume that $J \cong B$).

In tables 3 and 4 are presented typical results of testing of No and GO steel – usually are measured: polarization $J_{max}$ and magnetic field strength $H_{max}$, remanence $B_r$ and coercivity $H_c$, losses $P$ and permeability $\mu$.

Table 1. Performances of typical grain-oriented steel samples [11]

| Name | Thickness [mm] | Loss at 1.7 T, 50 Hz [W/kg] | Polarization for 800 A/m [T] |
|---|---|---|---|
| M080-23N | 0.23 | 1.27 | 1.75 |
| M089-27N | 0.27 | 1.40 | 1.75 |
| M097-30N | 0.30 | 1.50 | 1.75 |
| M111-35N | 0.35 | 1.65 | 1.75 |
| M120-23S | 0.23 | 1.20 | 1.78 |
| M130-27S | 0.27 | 1.30 | 1.78 |
| M140-30S | 0.30 | 1.40 | 1.78 |
| M150-35S | 0.35 | 1.50 | 1.78 |
| M100-23P | 0.23 | 1.00 | 1.85 |
| M103-27P | 0.27 | 1.03 | 1.88 |
| M105-30P | 0.30 | 1.05 | 1.88 |
| M111-30P | 0.30 | 1.11 | 1.88 |
| M117-30P | 0.30 | 1.17 | 1.85 |

Table 1. Performances of typical non-oriented steel samples [12]

| Name | Thick-ness [mm] | Loss at 1.5 T, 50 Hz [W/kg] | Polarization for 5000 A/m [T] | Anizo-tropy of loss % |
|---|---|---|---|---|
| M235-35A | 0.35 | 2.35 | 1.6o | 17 |
| M250-35A | | 2.50 | | |
| M270-35A | | 2.70 | | |
| M300-35A | | 3.00 | | |
| M330-35A | | 3.30 | | |
| | | | | |
| M250-50A | 0.50 | 2.50 | 1…60 | 17 |
| M270-50A | | 2.70 | 1.60 | 17 |
| M290-50A | | 2.90 | 1.60 | 17 |
| M310-50A | | 3.10 | 1.60 | 14 |
| M330-50A | | 3.30 | 1.60 | 14 |
| M350-50A | | 3.50 | 1.60 | 12 |
| M400-50A | | 4.00 | 1.63 | 12 |
| M470-50A | | 4.70 | 1.64 | 10 |
| M530-50A | | 5.30 | 1.65 | 10 |
| M600-50A | | 6.00 | 1.66 | 10 |
| M700-50A | | 7.00 | 1.69 | 10 |
| M800-50A | | 8.00 | 1.70 | 10 |
| M940-50A | | 9.40 | 1.72 | 8 |

Table 3. Results of testing of typical GO steel – M089-27/N

| $J_{max}$ [T] | $B_r$ [T] | $H_{max}$ [A/m] | $H_c$ [A/m] | P [W/kg] | μ |
|---|---|---|---|---|---|
| 0.1 | 0.048 | 4.2 | 2 | | 18 800 |
| 0.2 | 0.136 | 6.7 | 4 | 0.016 | 23 600 |
| 0.3 | 0.189 | 8.9 | 6 | 0.034 | 26 700 |
| 0.4 | 0.262 | 10.7 | 8 | 0.060 | 29 500 |
| 0.5 | 0.343 | 12.4 | 9 | 0.091 | 31 900 |
| 0.6 | 0.433 | 14.1 | 11 | 0.129 | 33 700 |
| 0.7 | 0.530 | 15.6 | 12 | 0.174 | 35 700 |
| 0.8 | 0.629 | 17.0 | 13 | 0.224 | 37 400 |
| 0.9 | 0.735 | 18.4 | 15 | 0.281 | 38 900 |
| 1.0 | 0.846 | 19.6 | 16 | 0.345 | 40 500 |
| 1.1 | 0.959 | 21.3 | 17 | 0.417 | 41 000 |
| 1.2 | 1.076 | 23.0 | 18 | 0.495 | 41 400 |
| 1.3 | 1.180 | 25.8 | 19 | 0.582 | 40 000 |
| 1.4 | 1.302 | 31.1 | 20 | 0.684 | 35 800 |
| **1.5** | **1.407** | **40.4** | **21** | **0.802** | **29 500** |
| 1.6 | 1.511 | 62.0 | 22 | 0.952 | 20 500 |
| **1.7** | **1.620** | **132.8** | **24** | **1.189** | **10 200** |
| 1.8 | 1.685 | 455.8 | 27 | 1.590 | 3 100 |
| 1.9 | 1.726 | 1767.3 | 33 | 2.026 | 900 |

Table 3. Results of testing of typical NO steel – M400-50AP

| $J_{max}$ [T] | $B_r$ [T] | $H_{max}$ [A/m] | $H_c$ [A/m] | P [W/kg] | μ |
|---|---|---|---|---|---|
| 0.1 | 0.039 | 35.24 | 14.2 | 0.026 | 2 280 |
| 0.2 | 0.106 | 48.00 | 27.2 | 0.102 | 3 310 |
| 0.3 | 0.188 | 56.55 | 36.3 | 0.210 | 4 220 |
| 0.4 | 0.275 | 64.00 | 43.8 | 0.345 | 4 980 |
| 0.5 | 0.360 | 70.34 | 49.1 | 0.495 | 5 650 |
| 0.6 | 0.443 | 77.27 | 53.8 | 0.664 | 6 180 |
| 0.7 | 0.529 | 84.35 | 57.7 | 0.850 | 6 600 |
| 0.8 | 0.617 | 92.78 | 61.3 | 1.055 | 6 860 |
| 0.9 | 0.709 | 103.23 | 65.7 | 1.279 | 6 940 |
| 1.0 | 0.790 | 116.80 | 69.4 | 1.530 | 6 820 |
| 1.1 | 0.878 | 134.64 | 72.0 | 1.810 | 6 500 |
| 1.2 | 0.962 | 165.32 | 75.9 | 2.122 | 5 780 |
| 1.3 | 1.043 | 224.16 | 80.3 | 2.479 | 4 610 |
| 1.4 | 1.123 | 363.38 | 83.6 | 2.910 | 3 070 |
| **1.5** | **1.157** | **782.52** | **86.7** | **3.427** | **1 530** |
| 1.6 | 1.210 | 1990.36 | 91.5 | 4.002 | 640 |
| **1.7** | **1.230** | **4413.73** | **98.2** | **4.485** | **310** |

**Conclusions**

Correct tests of electrical steel is very important because differences in price of various grades are significant. Some years ago well known in Poland was a contention between reputable steel manufacturer and a factory producing electrical machines. The factory suspected that not always correct performance of manufacturing devices occurred because not always declared parameters of steel were fulfilled. Finally it was necessary to employ Accredited Laboratory to judge the controversy.

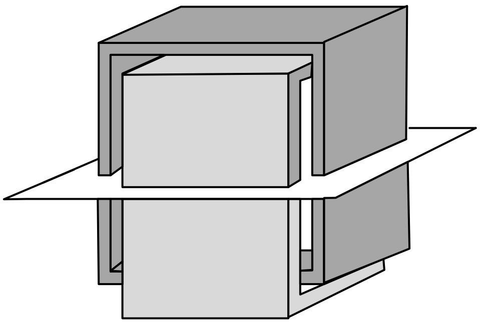

Fig. 15. Proposed device for testing of electrical steel [13]

In this paper was pointed that we never test the material but rather well defined sample of this material. Some years ago we proposed the method to solve this dilemma – demonstrated in Fig. 15 [13]. The sample was tested by using two pairs of small B and H sensors (area 20x20 mm). Magnetising yokes were significantly larger (20 x 20 cm) to avoid influence of yoke geometry on measuring results. Next the sheet of the steel was significant larger than magnetising yokes – 50x50 cm. This way influence of sample shape (influence do non-uniform demagnetising field) were negligible. To date nobody bought this idea.

***Author:*** *prof. Slawomir Tumanski, Warsaw University of Technology, Electrical Eng. Dept., , e-mail: tumanski@tumanski.pl*

REFERENCES


1. Fiorillo F., Measurement and characterization of magnetic materials, Elsevier 2004
2. Tumanski S., Handbook of magnetic measurements, CRC Press, 2011
3. Zurek S., Characterization of soft magnetic materials under rotational magnetization, CRC Press, 2018
4. Pfützner H., Krismanic G., The needle method for induction tests: sources of errors, IEEE Trans. Magn., **40**, 2004, 1610-1616
5. IEC 60404-6. "Magnetic materials. Part 6: Methods of measurement of the magnetic properties soft magnetic and powder materials at frequencies in the range 20 Hz to 200 kHz by the use of ring specimen"
6. iEC 60404-2 "Magnetic materials. Part 2: Methods of measurements of the magnetic properties of electrical steel sheet by means of an Epstein frame"
7. IEC 60404-3. "Magnetic materials. Part 3: Methods of measurement of the magnetic properties of magnetic sheet and strip by means of a single sheet tester"
8. KhanlouA., Moses A.J., Meydan T., Beckley P., Computerised on-line power loss testing system for the steel industry, based on the RCP compensation technique, IEEE Trans. Magn., 1995, 31, 3385-3387
9. Anuszczyk J., Pluta W., Soft ferromagnetics in rotating magnetic fields (in Polish), WNT, 2009
10. Zhu J.G., Lin Z.W., Guo Y.G., Huanf Y., 3D measurement and modelling of magnetic properties of soft magnetic composite, Przeg. Elektr. 2009, 85 (1), 11-15
11. EN 10107:2014, Grain-oriented electrical steel strip and sheet delivered in the fully processed state
12. EN 10106:2015, Cold rolled non-oriented electrical steel strip and sheet delivered in the fully processed state

13 Tumanski S., 2005, New design of the magnetizing circuit for 2D testing of electrical steel, Przegl;. Elektr., **81** (5), 32-34