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The magnetovision method as a tool to investigate the quality of electrical steel

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Abstract. This paper presents a new method for testing electrical steel sheet, based on measurements of the magnetic field distribution over the sheet surface. The tangential field value is measured with the aid of a permalloy magnetoresistive sensor. The field distribution is displayed in the form of a colour map, hence the method is called 'magnetovision'. The repeatability of the maps is excellent. The most interesting new results of electrical steel investigations are presented. The system provides a versatile tool for non-destructive quality control and for the determination of the structural uniformity of electrical steel. Magnetovision, compared with other methods, seems to be especially useful for detecting the causes of steel quality deterioration.

1. Introduction

Most methods for testing electrical steel sheets use an Epstein frame. Recently various single-sheet or single-strip testers have also been used. However, all these methods have several limitations and disadvantages [1–4]. First of all, these methods are destructive and preparation of the Epstein frame sample is rather difficult. The Epstein method is preferred for comparison purposes, but for rapid quality control of electrical steel (e.g. in computerized on-line control systems) the Epstein method is often replaced by a single-sheet tester (SST). All these methods use averaging which is often desirable because in practice magnetic circuits also average. Using standard methods the quality (specific power loss) of the sample can be precisely determined but an analysis of sheet heterogeneity is impossible due to the averaging nature of the measurements. Analysis of material heterogeneity is useful in determining the causes of eventual quality deterioration. In the case of grain oriented (GO) electrical steel the sheet is magnetized non-uniformly. It is the authors' opinion that one of the most important ways to improve steel quality is to decrease the sheet heterogeneity. This can be achieved by the elimination of defects in the crystal structure and most of all by improvements in the texture. In contrast to standard techniques, the method presented in this paper enables analysis of material heterogeneity.

There are also other reasons for the development of new steel sheet testing methods. Modern numerical methods of magnetic circuit design require more detailed data on steel sheet parameters. At present two-dimensional parameters are sometimes necessary, especially for the determination of rotational loss [5, 6]. Classical testing methods, particularly the Epstein frame, lack these capabilities. Use of a magnetoresistive sensor enables determination of magnetic field strength in the sheet for arbitrary directions of excitation [7].

In the case of the tests of the samples of arbitrary shape (i.e. differing from the sample shapes used in standard methods) it is often very useful to take into account the magnetic field non-uniformity caused by demagnetizing fields. The magnetic properties of a real magnetic circuit may differ distinctly from the properties of standard shapes (ring, frame or sheet).

We have developed a measurement system for the determination of the magnetic field distribution over the surface of a steel sheet [8, 9]. A miniature magnetoresistive permalloy sensor scans the magnetic field. The scanning results are processed numerically and presented in the form of a colour map on a VDU. This map can be printed in colour or stored in a graphic or numeric file. Because of some similarities with the thermovision method, we call this approach 'magnetovision'.

The use of magnetovision for electrical steel sheet quality assessment is based on the following assumptions.

(1) The tangential component of the magnetic field over the sheet surface is a good approximation of the magnetic field inside a sheet (the sensor should be located close to the sheet surface).

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(2) The magnetic field distribution over the sheet surface is a constant and repeatable characteristic of a sheet for given magnetizing conditions.

(3) Analysis of sheet heterogeneity [10] may be based on the determination of field non-uniformity for a given constant flux density.

A closer look at the methods of measuring the magnetic field on the surface of GO electrical steels seems to be appropriate here. The manufacture of smaller and more sensitive hallotrons has created new possibilities in the measurement of stray fields above steel sheet surfaces. Mohri and Fujimoto [11] proved in 1977 that application of miniature hallotrons enables one to detect grain boundaries in GO coated SiFe steel. The analysis of grain structure with the aid of stray field measurements was also presented in 1980 by Normann and Mende [12] who used a vibrating pick-up magnetometer for magnetic field measurements.

Pfützner and co-workers [13–19] have carried out comprehensive measurements of stray fields over steel sheet surfaces using miniature hallotrons and proved that hallotron sensors can be used successfully for the analysis of grain and domain structure of GO steel sheets with coatings. In 1992 Pfützner *et al* presented a scanning apparatus for automatic mapping of stray fields using miniature halotrons [20].

Permalloy magnetoresistive sensors are more sensitive than hallotron sensors and field measurements can be carried out over the sheet surface without resorting to sophisticated circuits. Moses and co-workers have applied permalloy magnetoresistors for SiFe steel in several investigations [21]: they developed the methods of grain structure analysis [22–24], domain structure analysis [25] and localized power losses [26] using magnetoresistive sensors.

Much of the literature concerns the study of sheet microstructure. Deviating from this research direction, in 1988 Tumanski reported on the possibility of applying permalloy magnetoresistive sensors to the investigation of steel sheet parameters not only on the microscale, but also on a macroscale [8]. In order to reach this goal, somewhat larger and more sensitive sensors must be used. It has been proved, during subsequent work, that the mapping of the tangential component of magnetic stray field over a relatively large area (e.g. 10 cm^2) of the sheet enables an estimation of the quality of GO electrical steel. We have constructed a scanning apparatus for automatic mapping of magnetic stray fields [9]. Using this apparatus we have tested several hundred assorted samples of GO electrical steels. This paper presents the most interesting results of these investigations and an assessment of the actual capabilities of the magnetovision method.

2. The basic principle of the measurement system

Figure 1 presents the basic principle of the magnetovision system. The steel sheet under test is magnetized with the aid of double-C yoke. In lower accuracy measurements it is acceptable to use only a single-sided yoke system (thus the influence of additional eddy currents [27] is ignored). Two computer-controlled stepper motors move the permalloy magnetoresistive (MR) sensor to follow a meandering path over the sheet. The primary signal from the sensor is

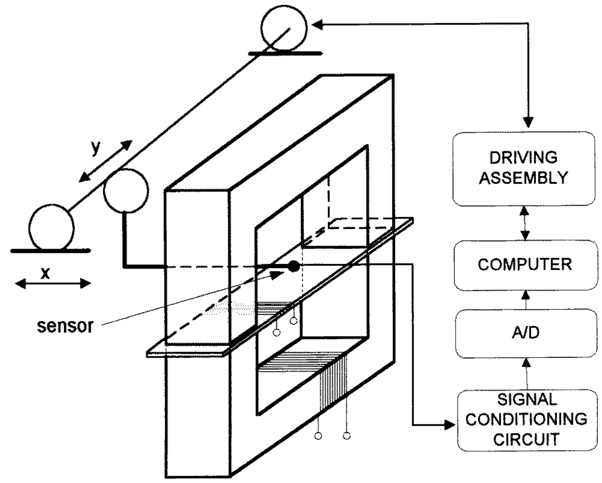


Figure 1. The principle of magnetovision system operation.

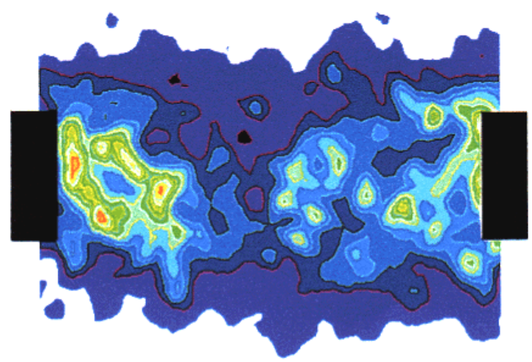


Figure 2. The map of magnetic field distribution for a sheet placed over the yoke. The yoke poles dimensions are 3 cm by 2.5 cm, and they are situated 8 cm apart.

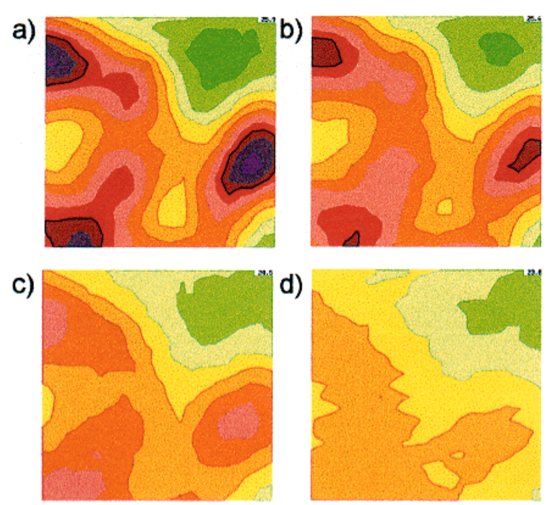


Figure 3. The maps of magnetic field for various distances between the sensor and the sheet surface. (a) 0.3 mm, (b) 0.5 mm, (c) 1 mm and (d) 2 mm.

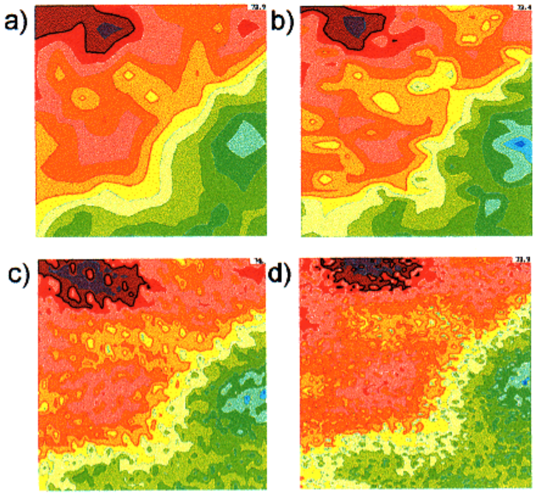


Figure 4. The maps of field distribution for various measurement points densities. (a) 1 mm, (b) 0.5 mm, (c) 0.25 mm, and (d) 0.125 mm.

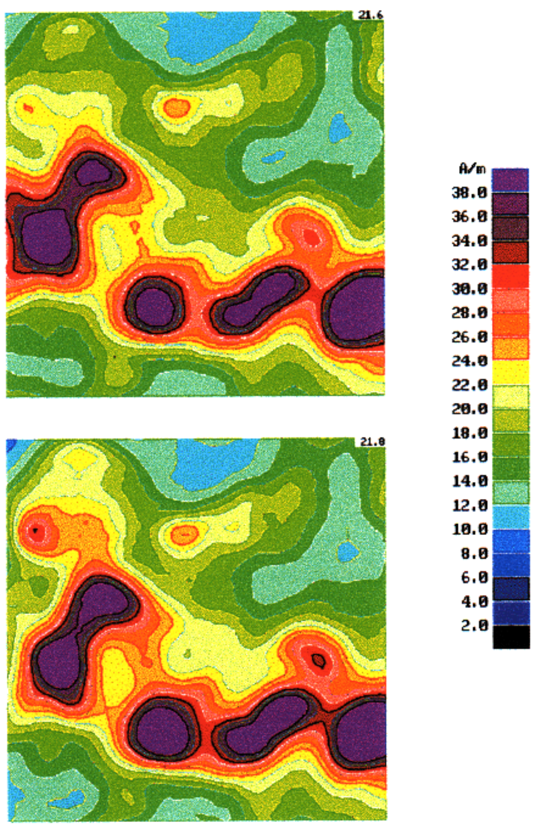


Figure 5. The maps of the same sheet area determined in two different measurement runs.

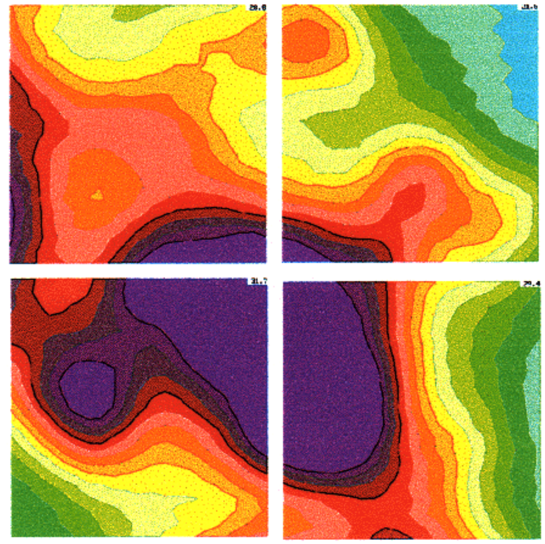


Figure 6. The maps of field distribution for neighbouring sheet areas.

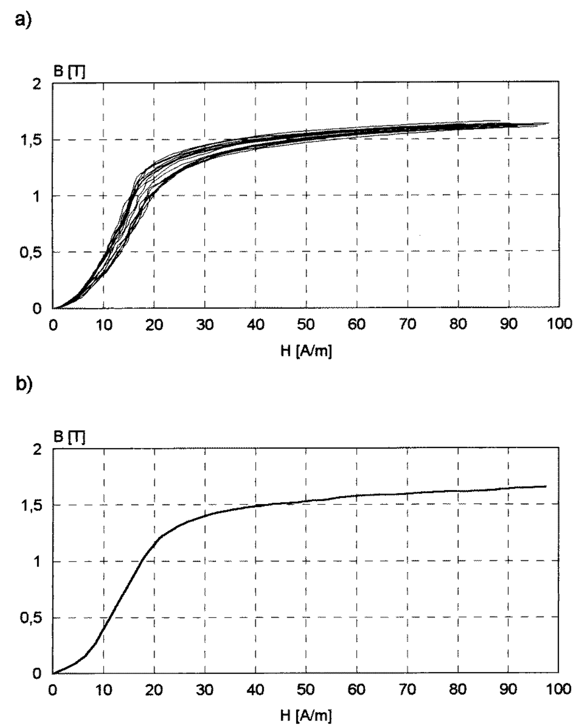


Figure 7. Comparison of the toroid steel sample investigations. (a) Magnetizing curve for H determined by remote sensors in 16 randomly selected points; (b) magnetizing curve for H determined from magnetizing current.

converted into a digital voltage signal. The signal from the sensor is sampled at a fixed rate related to the exciting field frequency. Every measurement point is characterized by a series of digitized readings.

Processing of the measurement data is performed off-line. In the very first step the raw measurement data are converted into a more easily readable floating number format. The next step may include various forms of mathematical manipulation, e.g. computations of rms values, determination of peak (maximum) value, FFT analysis. The results of this stage are stored in a numeric file and at this stage every measurement point corresponds to single numerical value. The results from the numeric file may be transformed (2D interpolation) into a colour map or graphic file map.

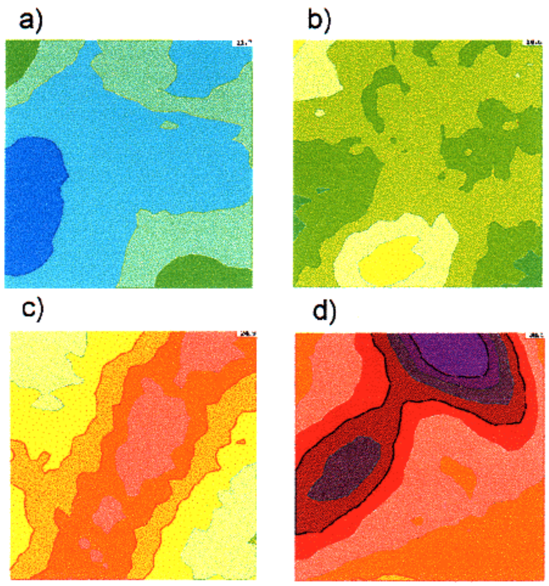


Figure 8. The maps of four materials with different power loss. (a) $P_1 = 0.31$ W kg^{-1}, (b) $P_1 = 0.37$ W kg^{-1}, (c) $P_1 = 0.45$ W kg^{-1}, and (d) $P_1 = 0.51$ W kg^{-1}.

A basic prerequisite of correct and meaningful measurements is uniformity of the sheet magnetization. Because of this condition, only a small central area of the sheet located between the C yokes is scanned. Figure 2 presents an experimentally determined map of the field distribution over a steel sheet placed between the C yokes†. It follows from this figure that the magnetized area is concentrated only in the line between the poles. The size of the tested area is closely related to the size of the yoke. The yoke used here had poles of dimensions 3 cm by 9 cm situated 8 cm apart. The area under test was usually a 3 cm by 3 cm square midway between the poles. The sample used in the tests was either an entire sheet or a single strip.

As stated previously, a permalloy magnetoresistor [28] was used as a sensor. The most important advantages of this sensor with respect to an H-coil sensor (standard sensor in SST) may be summarized as follows.

(1) Small dimensions (a 1 mm by 1 mm sensor was used in these experiments). Smaller sensors are commercially available, for example a sensor of dimensions 1 mm by 0.04 mm with a sensitivity of 1 μV A^{-1} m^{-1}.

(2) Both direct and alternating magnetic fields can be measured (typical commercial sensors measure alternating magnetic fields up to a frequency of several megahertz).

(3) The output signal is proportional to H, not to $\mathrm{d}H/\mathrm{d}t$.

(4) Relatively high sensitivity (we used a sensor of sensitivity 20 μV A^{-1} m^{-1}).

(5) The sensor can be placed close to the steel sheet as it senses field components in the plane of a thin film. A thin film permalloy sensor detects only the field component in the film plane.

It is recommended that the sensor is placed as close to the sheet surface as possible. The only limitation is the sensor case construction. A distance of 0.3 mm is practically attainable. The influence of the distance between the sheet and the sensor on the output signal value and on the field map coarseness has been investigated (figure 3). The sensor output signal decreases by approximately 5% if the sheet–sensor separation increases by 1 mm. For a distance greater than 1 mm the resolution of the map is distinctly impaired (figures 3(c) and 3(d)).

The time taken for a complete set of measurements depends on the density of measurement points (nodes), i.e. on the scanning parameters. Figure 4 presents the magnetovision pictures of the same sheet area (dimensions 1 cm by 1 cm) for various node densities. It seems that for a sensor of dimensions 1 mm by 1 mm the lower limit of measurement node distance is about 0.5 mm. Further reduction of the node distance (e.g. to 0.125 mm) only increases the measurement time and blurs the information on the field distribution. It follows from figure 4 that a spatial resolution of 1 mm leads to a satisfactory assessment of magnetization non-uniformity.

3. Repeatability of the measurements

Figure 5 presents two maps of the same sheet area (dimensions 3 cm by 3 cm) determined for two different measurement runs. The maps are almost identical. This leads to two conclusions. First, the measuring equipment is robust and reliable, as disassembly and assembly of the second yoke–sheet–sensor set-up does not impair the results. Second, it proves experimentally that the map of stray magnetic field over the sheet surface, for the same magnetizing conditions, is an invariant and specific parameter of the sheet. Figure 5 also shows the colour scale used for various field strengths in all the figures presented in this paper (except figure 13).

Figure 6 presents four maps of neighbouring sheet areas. Also in this case the measurements were taken in four separate runs over an interval of several days. Coincidence of the separate map patterns along the boundaries is excellent. The time and space repeatability of the measurements led to the idea of whole-area map construction by pasting neighbouring maps. The results for elementary subregions can be merged and then processed numerically as a whole. Thus maps for very large areas can be constructed.

Calibration of the system was carried out using a toroid core made of GO SiFe steel. The field strength in the core was measured in several tens of randomly selected places. The results in the form of magnetization curves are presented in figure 7(a). The magnetization curve was then determined using the classical magnetizing current method (figure 7(b)). Comparison of this curve with the averaged results of figure 7(a) of the remote MR sensor reveals differences of less than 3%.

† The software system constructs the field maps using a scale of 20 colours. The user may freely select the values of scale start H_{xo} and scale increment ΔH_x. All maps presented in this paper (except the map in figure 13) use the scale shown in figure 5, i.e. $Hxo = 0$ and $\Delta H_x = 2$ A m^{-1}. The mean value of field strength is shown in the upper right-hand corner of each map.

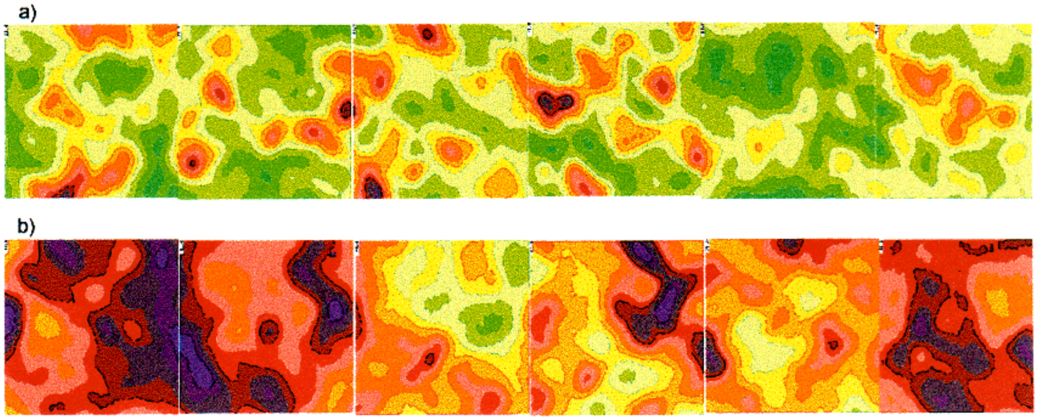


Figure 9. The maps of two stripes (dimensions 18 cm by 3 cm) with different specific loss measured by the Epstein method. (a) $P_1 = 0.35$ W kg^{-1}, and (b) $P_1 = 0.45$ W kg^{-1}.

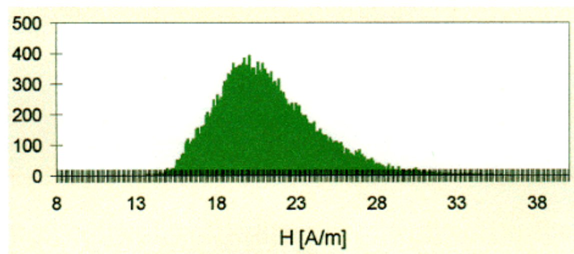
4. Assessment of steel sheet quality using the magnetovision method

Figure 8 presents maps of an area 1 cm by 1 cm for a set of assorted sheets which had been previously tested using the SST method. In the full colour picture the areas of low magnetic field strength (below 20 A m^{-1}) are represented by cool colours—various shades of blue and green. The areas of higher field strength (above 20 A m^{-1}) are indicated by the warmer colours of yellow and red. This colour scale (see figure 5) quite closely resembles that used for temperature in geographical maps. We have carefully analysed several hundred sheet samples and have observed a correlation between the 'colour temperature' of the map and the sheet quality (determined by specific power loss) in all cases. A map of magnetic field strength thus enables a quick visual assessment of steel quality.

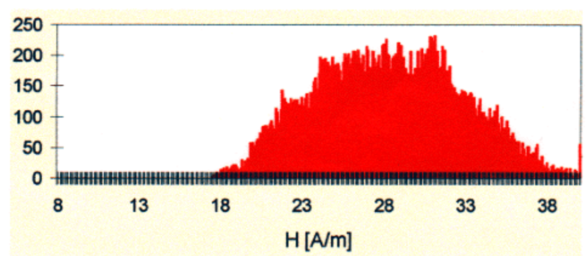
This conclusion was also confirmed by the maps of the whole strip, tested previously with the Epstein frame (figure 9). Figure 9 also illustrates the experimental observation that the sheets with higher power losses exhibit a higher mean value of field strength and a wider spread of these values at the same peak induction values.

Specific power loss of the steel is a very important parameter for the majority of users. For this reason a map of specific power loss would be more useful than the magnetic field strength map. In order to construct such a map measurement of the local flux density is necessary. This is not an easy task and another approach using miniature thermistors may be alternatively used [20].

We are currently working on the problem of local measurements of power losses using magnetic quantities [29]. It is quite obvious that local power loss (for constant flux density) depends not only on the magnetic field strength, but also on the phase shift between B and H. Preliminary results have led to the observation that this phase shift may differ significantly at different points of the sheet [30]. Therefore a precise assessment of steel power loss cannot be based exclusively on magnetovision measurements. However, it has been shown that there is quite a good correlation between the specific power loss and magnetic field strength for the whole investigated area. It follows therefore that a simple assessment of steel quality is possible. For example, in the design stage of any equipment it is usually assumed that the parameters of a steel sheet are the same as the typical values for the steel type used. But in practice it may be that a real magnetic circuit is manufactured from a portion of the sheet which is of a lower quality. By testing specific selected fragments of the sheet the user can be sure of material of the desired quality.



(a)



(b)

Figure 10. The histograms of magnetic field strength distribution above two different sheets.
(a) $P_1 = 0.35$ W kg^{-1}, (b) $P_1 = 0.51$ W kg^{-1}.

The results may be processed statistically in order to obtain a mean value, standard deviation or a histogram of magnetic field strength. These parameters enable automatic assessment of sheet quality without having to construct a complete map. Figure 10 presents two histograms of magnetic field strength obtained after numerical processing of 25 000 test points from the map shown in figure 9.

The field map of a sheet with diversified grain structure is presented in figure 11. An inclusion consisting of small grains with dimensions less than 1 mm can be observed.

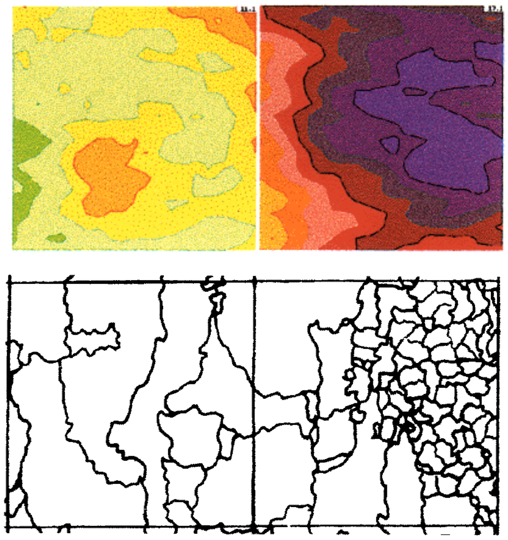


Figure 11. The grain structure of a sheet with corresponding magnetovision map.

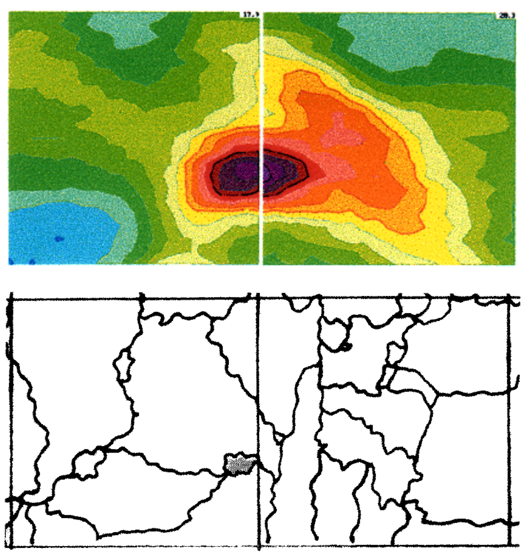


Figure 12. Identification of a grain causing local sheet quality deterioration.

This small-grain area is characterized by distinctly higher values of the mean field strength. Such magnetic field maps thus help in precisely locating regions of lower quality. We tested some sheets with rather a high spread of field strength values. A spread between 4 and 60 A m^{-1} for a flux density of 1 T was observed in an area of 2 cm^2. An example of a map with large magnetic field strength differences over a small area (1 cm by 2 cm) is presented in figure 12.

The magnetovision investigations complement standard test methods and supply additional information on sheet steel. Sheet steel manufacturers may be interested in the identification of local defects. After determining sheet areas with distinctly inferior properties, the same area may be tested with another method to yield further detail. It seems that complementing magnetovision with crystallographic analysis might lead to good results.

5. Observation of the magnetizing process

As the real magnetic state of a sheet can be easily determined, it is also possible to analyse the influence of the working conditions, i.e. the influence of flux density value, frequency, waveform of the flux, etc, on the magnetic state. Figure 13 presents the influence of flux density changes on the magnetizing process of a selected sheet area. The picture of field non-uniformity becomes almost stable above a certain value of flux density. This happens in the saturated state (field strength above 300 A m^{-1}).

In order to arrange an animated show of the magnetizing process, a sufficient number of maps should be scanned for various values of flux density B. The construction of more spectacular on-line animated magnetovision systems is possible. In order to achieve this goal the sensor positioning system should be replaced by a static array of sensors.

Using the magnetovision system we can also observe the effect of changes in sheet shape. In figure 14 maps of the same (Hi-B type) sheet fragment before and after cutting it into 3 cm wide strips are presented. It is interesting to observe that after cutting the sheet into strips, the mean value of field strength may decrease for the same value of flux density.

In general, a field strength map determined for a boundary area of a strip cut out from a larger sheet does not change significantly if the cutting device is sharp. Figure 15 presents an example of material deterioration after cutting with a bad blunt device.

6. Conclusions

The magnetovision system presented in this paper may provide a useful tool for quality control of electrical steel sheets. The key advantages of this method are its non-destructive nature and the easy localization of low-quality areas. End users may also benefit by applying the technique to select areas with desirable parameters from a whole sheet. Moreover, this method offers the possibility of testing specific magnetic circuits of different shapes. In this way one can test portions of electrical machine circuits, especially those susceptible to local overheating or magnetic saturation.

Magnetic measurements, in particular magnetic materials testing, are influenced by various external factors. Therefore comparison with standard methods is important. The magnetovision method is not considered a competitive technique to standard methods; at present it is rather a semi-quantitative measurement method. Standardization of the magnetovision assembly and measurement conditions would help to assess steel quality more unambiguously. For example, the mean field strength for fixed magnetizing conditions and the standard deviation are quite representative measures of steel sheet heteogeneity.

At present, scanning the test area takes a relatively long time. The set-up used in our experiments scans an area of 5 cm^2 in about half an hour. A fast system taking 40 000 measurement points over a 10 cm^2 area in just a couple minutes is in preparation [31]. One way of reducing the

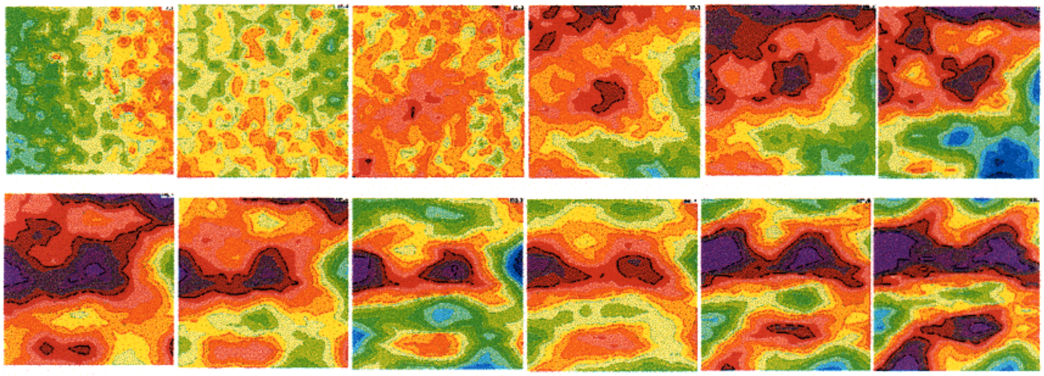


Figure 13. The maps of the same sheet area for various flux densities (every map has a different scale of magnetic field strength. Parameters of the scale (A m^{-1}) in the sequence of maps: 1, $H_{xo} = 0$, $\Delta H_x = 0.2$; 2, $H_{xo} = 5$, $\Delta H_x = 0.5$; 3, $H_{xo} - 10$, $\Delta H_x = 0.5$; 4, $H_{xo} = 25$, $\Delta H_x = 1$; 5, $H_{xo} = 80$, $\Delta H_x = 2$; 6, $H_{xo} = 120$, $\Delta H_x = 2$; 7, $H_{xo} = 150$, $\Delta H_x = 5$; 8, $H_{xo} = 180$, $\Delta H_x = 5$; 9, $H_{xo} = 280$, $\Delta H_x = 5$; 10, $H_{xo} = 320$, $\Delta H_x = 10$; 11, $H_{xo} = 500$, $\Delta H_x = 10$; 12, $H_{xo} = 700$, $\Delta H_x = 10$).

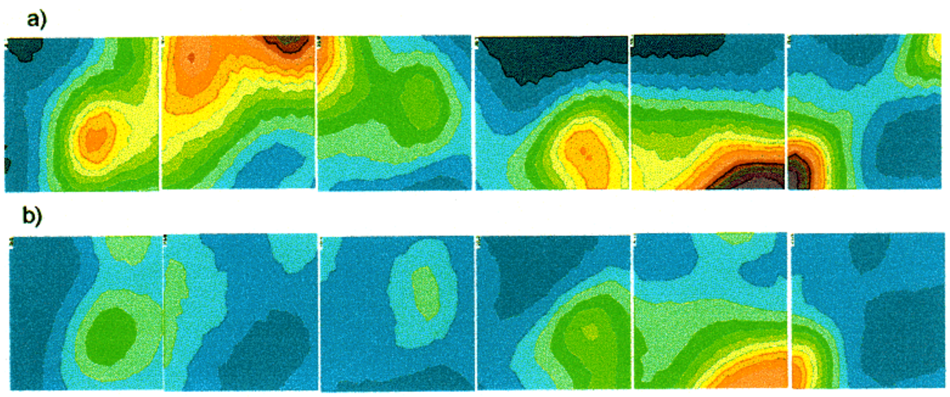


Figure 14. The map of the same strip (dimensions 1 cm by 6 cm). (a) In the central part of the sheet, 25 cm by 25 cm; (b) after cutting the sheet into 3 cm wide strips and annealing.

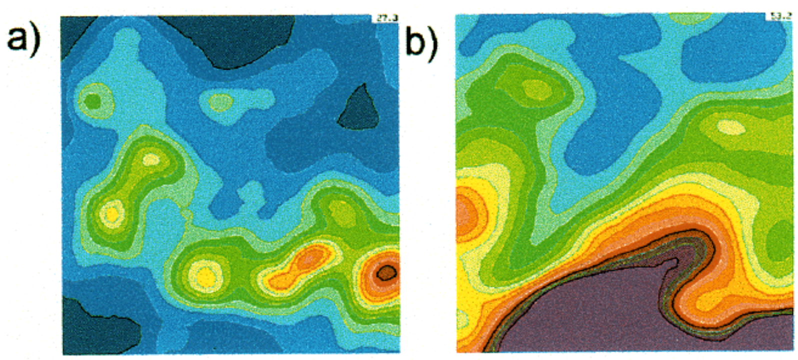


Figure 15. Materials deterioration after cutting with poor quality cutting device: the same sheet area before (a) and after (b) cutting into the strips.

measurement time would be to replace the current map scanning process with a system taking measurements in only several tens of randomly selected points. Such a tester should be capable of performing the measurements in several seconds, including statistical processing.

The presented method is quite versatile. It may be used, apart from steel quality testing, for the measurement of magnetic field distribution and non-uniformity, e.g. for determining shape anisotropy. Interesting results have been obtained through application of a similar method in the investigation of mechanical properties (fatigue processes) of ferromagnetic materials [32]. Basic parts of the system can also be used with other sensors, e.g. with a thermistor for local loss determination.

The presented examples of GO SiFe steel investigations are only a small part of many experiments carried out in recent years. It seems that extending the presented magnetovision system to yield three-dimensional measurements may be useful in more sophisticated tests on magnetized steel. Interesting results have also been obtained in the application of MR sensors for two-dimensional measurements of magnetic field strength [7] and for anisotropy and texture analysis [33].

Acknowledgment

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