CHANGES IN ELECTRICAL STEEL SHEETS INDUCED BY HEAT TREATMENT

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Abstract

Surface coating of electrical steel sheets is very important due to minimizing eddy current losses in electrical machines. The quality of coating can differ according to the composition. The coating layer has limited heat stability and after crossing of the guaranteed temperature it can be significantly degraded and its insulation properties may change importantly. The aim of this study is to describe changes in parameters of magnetic behavior of the non-oriented Si electrical steel sheet due to degradation of the coating by annealing in air. The parameters were acquired from the measuring of magnetic hysteresis loops on two types of samples with different excitation. The basic information on structure was obtained by optical microscopy. Acquired data are compared between samples with the damaged coating layer by annealing and the original coating layer. The results are discussed from the point of view of the possibility of using sheets with damaged insulation in electrical machines.

Keywords: Surface coating, magnetic properties, annealing, degradation

1. INTRODUCTION

Non-oriented Si steel sheets are essential for the construction of rotary electrical machines [1]. Every sheet of this steel is coated with a thin layer of resistive insulation. This surface coating minimizes eddy current losses in electrical machines. By damages of the coatings, eddy currents are closed between adjacent sheets and in consequence, it causes heating of the sheets and deteriorates magnetic properties of the material [2-4]. Electrical machines then have worse efficiency or they cannot be used at all. Damages can appear after mechanical impacts or by heating at high temperatures in air. On the other hand, a focused annealing of the sheets can be very beneficial for magnetic properties because of releasing of stresses after manufacturing [5, 6]. The coating layer has limited heat stability for a different kind of atmosphere. Electrical insulation can be significantly degraded after crossing of the guaranteed temperature without a protective atmosphere [7]. Besides magnetic and electrical properties, change in the colour of the coating also occurs.

The goal of this paper is to describe changes in parameters of magnetic properties sheets due to heat treatment without a protective atmosphere. The main attention will be given to increase magnetic losses in dependence on the deterioration of the dielectric strength.

2. EXPERIMENTAL

The investigated samples are commercially produced from non-oriented Si steel. The coating insulation layer is called C-5 according to AISI Designation ASTM A976. The thermal class is H of this coating and it means that the heat resistance is 180 °C in air long time and 850 °C in a protective atmosphere (as stress-relief annealing). The organic elements are supplemented by some inorganic filler for increasing interlamination resistance. The thickness of a layer on each side of the sheet is usually from 0.5 to 3 μm and the coating is colorless [7]. The main properties of insulation are resistance, punchability and corrosion resistance.

Secondary properties are for example heat resistance, stacking factor, resistance to chemicals or compression and scratch resistance [4].

Toroid-shaped samples were prepared by laser and erosion spark cutting. Laminations were pulled together by insulation tape. Geometrical dimensions and other parameters of samples can be seen in **Table 1**. Samples labeled as 1 were cut by spark cutting from originally stator sheets. Index a means that this sample was additionally annealed at 500 °C without a protective atmosphere for 5 hours. Coating layer changes its color from gray to brass or dark brown. Index d means that the insulation coating was mechanically damaged and significantly removed by abrasive paper. Samples labeled as 2 were specially prepared for this testing. Their diameter was similar to original stator sheet and it was cut by laser. Index 2.1 means that only 1 sheet was measured and the magnetic circuit cross-section is not square.

Table 1 Parameters of tested samples

Sample	1	1a	1ad	2	2a	2.1	2.1a	
Outer diameter	30	30	30	365	365	365	365	mm
Inner diameter	26	26	26	334	334	334	334	mm
Thickness	2.6	2.6	2.6	4.7	4.7	0.5	0.5	mm
Mass	3.33	3.35	3.35	653	653	72.5	72.6	g
Primary windings	60	60	64	442	448	540	584	Turns
Secondary windings	40	40	40	50	50	50	50	Turns

The magnetic parameters were acquired by hysteresis graph called RemaGRAPH - RemaCOMP C-710 (Magnet-Physik Dr.Steingroever GmbH). This device measures hysteresis loops in dependence on saturation fields and frequencies. Several additional modules can be connected to the device and device's measuring capabilities can be extended. It is based on the principle of Faraday's law. Toroid-shaped samples were measured quasi-statically and with frequency. Assuming the insulation coating is damaged and does not fulfill its function, there will be an increase of eddy currents, because they are not restricted to individual laminations.

The quality of surface insulation was measured by multimeter Agilent U1252B. Continuity measurements were made and annealed sample showed a greater number of continuous contacts than samples without additional annealing. The exact value of the resistance could not be measured by this device due to the lack of contact of the measuring spikes with the substrate through the tested insulation. More accurate results could be achieved by Franklin tester which is used for the classical evaluation of insulation quality.

The chemical composition and depth profile of coating were tested using Glow Discharge Optical Emission Spectrometry (GDOES). The basic information of structure was obtained by optical microscopy (OM). Changes in local structure and magnetism were checked using ^{57}Fe Mössbauer spectroscopy and took at room temperature using detection of conversion electrons (penetration depth < 0.3 micrometers) and by detection gamma radiation in scattering geometry (penetration depth ~30 micrometers).

3. RESULTS

Structure information was obtained by OM and it can be seen in **Figures 1, 2**. There are compared two samples before (Sample 1) and after additional annealing (Sample 1a). The annealed sample shows signs of surface layer oxidation and the change of color. Since the applied coating is not of uniform thickness, there has also been an uneven change in the color of coating after annealing without a protective atmosphere.

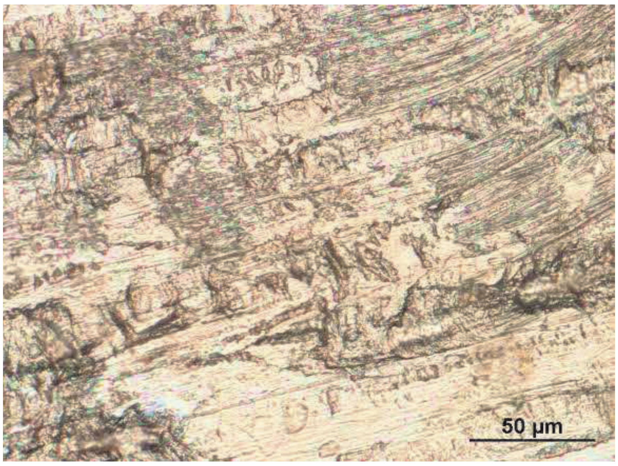

Figure 1 OM 500x magnification, Sample 1

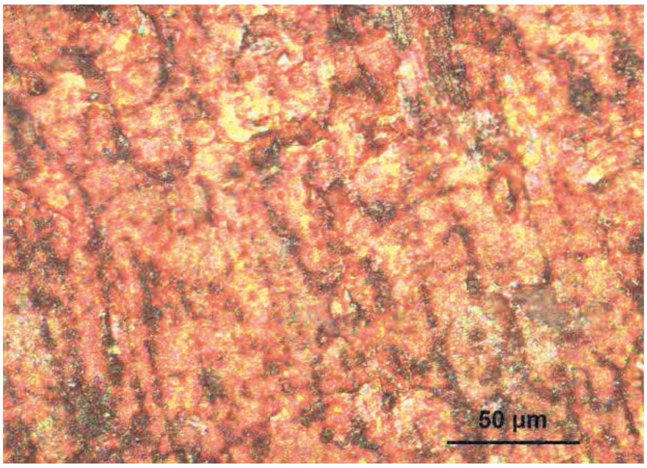

Figure 2 OM 500x magnification, Sample 1a

The coating layer is very thin (1 µm) according to results from GDOES in **Figures 3, 4**. It also showed that coating layer after annealing was changed and probably iron oxides appeared. Only several main elements are showed in **Figures 3, 4**. Among the other elements that were detected belong hydrogen, nitrogen, zinc and magnesium but their percentage weight were under 0.5 % or these elements are not detected with great reliability. Oxygen and carbon were added into graph due to a better resolution between samples and because of oxidized layer.

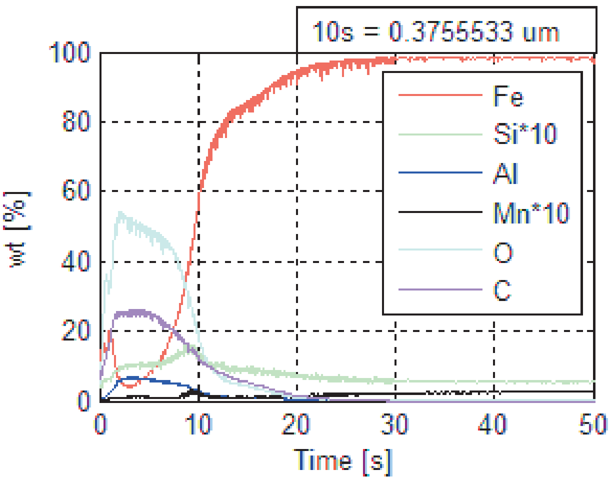

Figure 3 GDOES sample 1

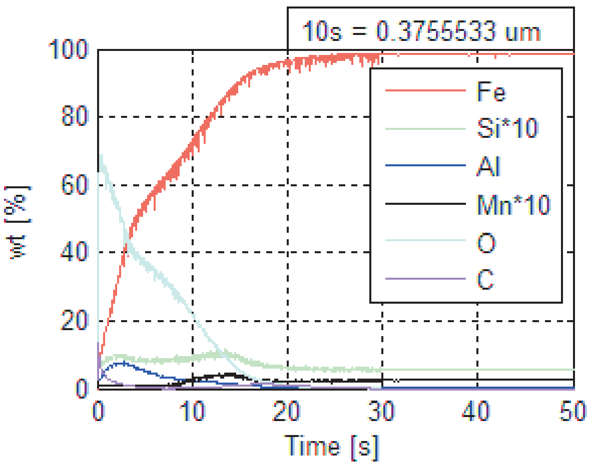

Figure 4 GDOES sample 1a

Mössbauer spectra of the sheet samples are shown in **Figure 5**. The spectrum was taken from the surface layer < 0.3 micrometers exhibit the presence of iron Fe^{3+} oxides. In the sample annealed in air is increased a number of magnetic domains with moment orientations perpendicular to the surface. It is in agreement with high probable formation of closing domains at the surface due to some products of the surface oxidation.

Magnetic measurements showed the best results for quasi-static measurements. There should be no eddy currents, but the differences between samples 1 and 1ad due to the removed insulation should occur. Small samples (**Figure 6**) were measured for original, annealed and removed coating. The most suitable parameter for comparison is permeability. Samples with coating are almost the same. However, permeability of the sample with removed coating dropped. Similar results can be seen in **Figure 7**, where larger samples are displayed. Annealed samples exhibit better properties than samples without additional annealing. This difference can be caused by stress relief after manufacturing of samples.

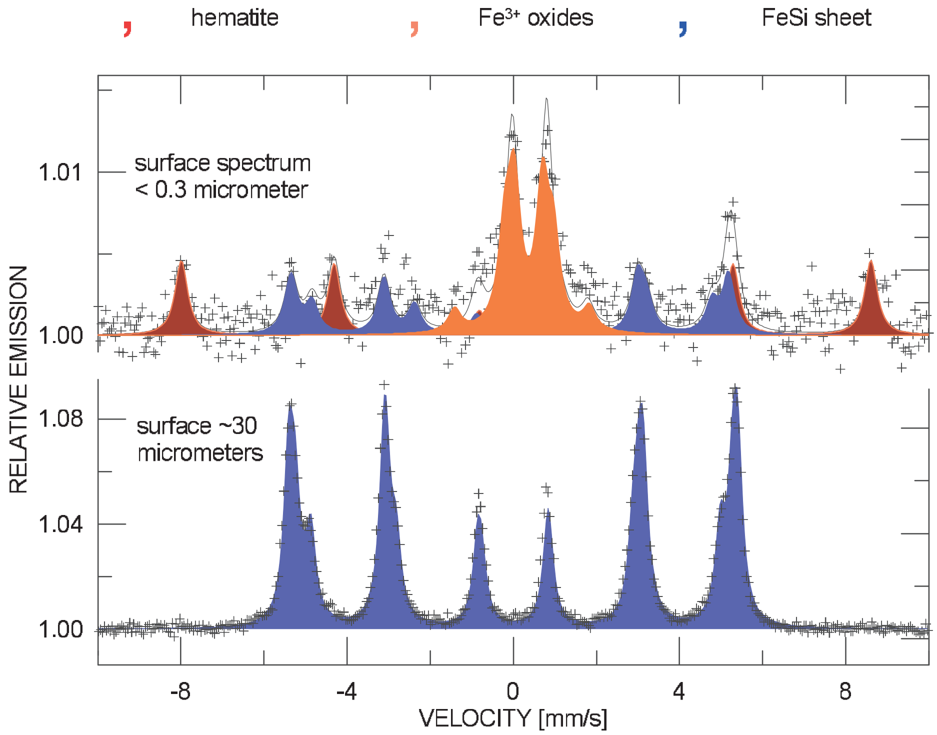

Figure 5 Mössbauer spectra of the sample annealed at 500 °C for 5 hours in air

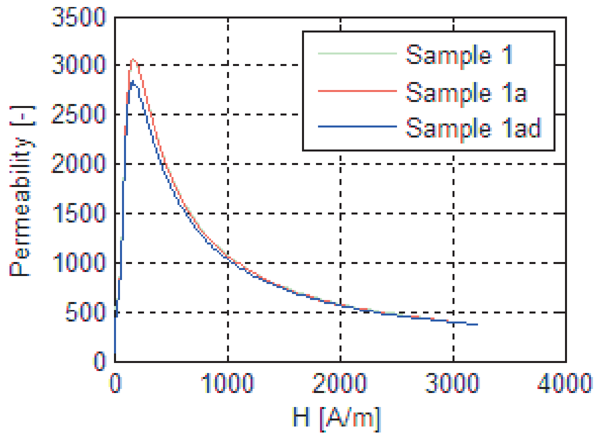

Figure 6 Quasi-static measurement, permeability for small samples

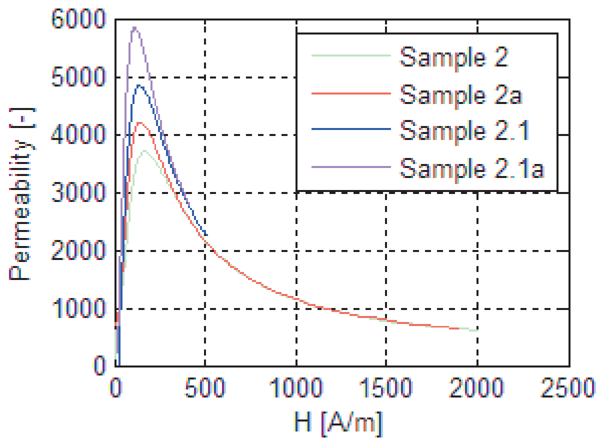

Figure 7 Quasi-static measurement permeability for large samples

The same differences are in **Figure 8** where permeability is showed at 50 Hz. The difference between large and small samples is due to the greater distance of machined edges of toroid samples. Permeability belongs among the most sensitive magnetic parameters but as the input parameter for simulation is more suitable initialization magnetization curve. These curves are showed in **Figures 9, 10** and correspond to permeability value. Better permeability means a greater slope of the magnetization curve so the annealed samples have a greater slope.

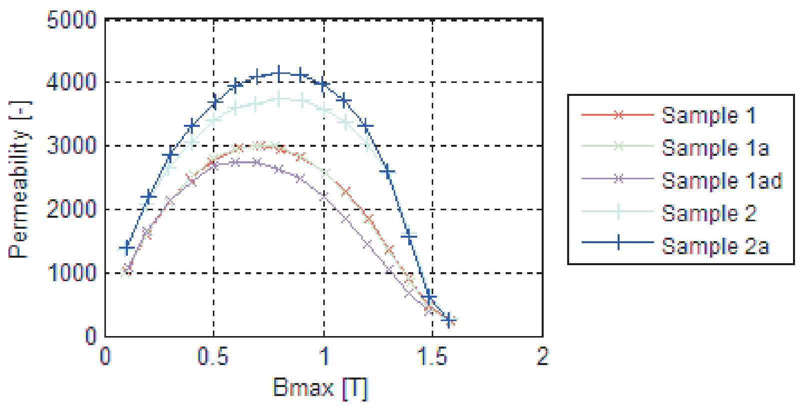

Figure 8 Permeability at 50 Hz for small and large samples

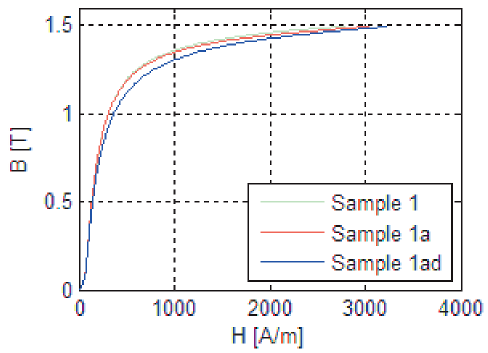

Figure 9 Quasi-static measurements for small samples

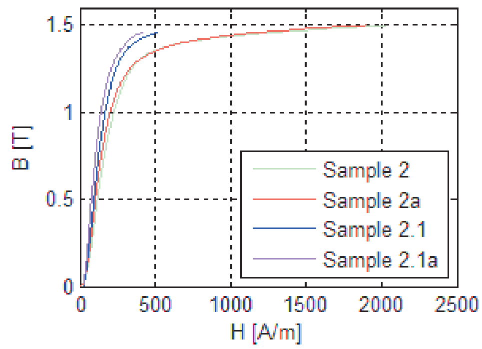

Figure 10 Quasi-static measurement for large samples

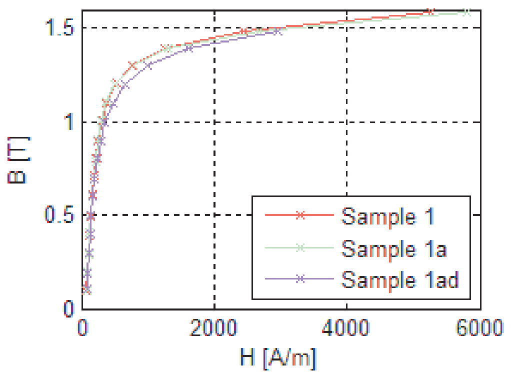

Figure 11 Commutation curves for small samples at 50 Hz

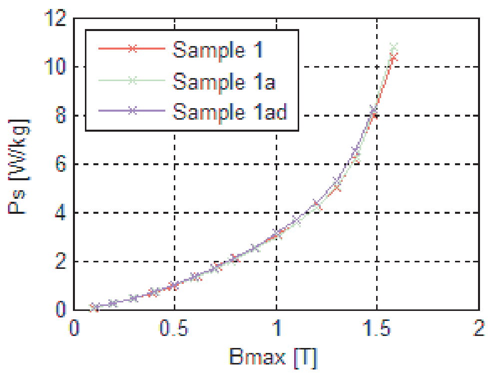

Figure 12 Losses for small samples at 50 Hz

Commutation curves (**Figure 11**) are similar to the initialization curves. Slightly different are total magnetic losses (**Figure 12**) which increased at higher excitation for annealed samples, while there is no difference in lower saturation. It looks like that insulation layer is damaged and at higher excitation does not fulfill its function. Differences are relatively small but with greater pressure which would push these laminations together, these losses would probably increase. Sample 1ad has higher total magnetic losses than only annealed Sample 1a, due to the removed of insulation coating (**Figure 12**). This sample appears to be a solid material instead of lamination.

4. CONCLUSION

Obtained results show that insulation coating C-5 can almost withstand annealing at 500 °C for 5 hours without a protective atmosphere. The quality of insulation is greatly affected and the colour is changed. It will not probably withstand excessive pressure due to occurrence of flaking insulation layer. Depth profile of coating showed a significant difference in the chemical composition between tested samples for carbon and oxygen. Annealing itself had a beneficial effect on magnetic properties because of relaxation of tested material but oxidation occurred without protective atmosphere and the mechanical strength of the coating was impaired. The quasi-static measurement showed better results of permeability and initialization magnetization curves for additionally annealed samples than rest of samples. Also, these samples had better parameters for frequency measurements however for less saturation. The eddy currents became noticeable with more saturation due to slightly higher total magnetic losses.

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