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Published in:
IEEE Transactions on Industry Applications

DOI:
[10.1109/TIA.2016.2638405](https://doi.org/10.1109/TIA.2016.2638405)

Published: 01/03/2017

Document Version
Peer reviewed version

Please cite the original version:
Holopainen, T. P., Rasilo, P., & Arkkio, A. (2017). Identification of Magnetic Properties for Cutting Edge of Electrical Steel Sheets. *IEEE Transactions on Industry Applications*, 53(2), 1049 - 1053.
<https://doi.org/10.1109/TIA.2016.2638405>

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Identification of Magnetic Properties for Cutting Edge of Electrical Steel Sheets

Timo P. Holopainen, Paavo Rasilo, Antero Arkkio

Abstract – Electrical steel sheets of motors and generators are usually shaped to the final form by punching. The punching and other cutting processes generate large plastic deformations and residual stresses. These are known to deteriorate the magnetic properties of the edge region. However, the characterization of this deterioration in the form of magnetic properties is missing. The main aim of this paper is to a method to identify the magnetic properties of the edge region based on experimental results. This approach is demonstrated by using previously presented test results for magnetic properties of rectangular strips. The width of these strips is varied, and thus, the share of the edge region to the whole can be used as a variable. Based on this variation a simple model is developed and the model parameters fitted to the experimental results. The correspondence between the calculated and experimental results is good.

Index Terms--Electric machines, magnetic losses, magnetic materials, magnetic properties, punching, sheet materials, sheet metal processing.

I. INTRODUCTION

NON-ORIENTED electrical steel sheets are used to assemble rotor and stator cores of electric machines. The final forming of these sheets is carried usually out by punching. It is well known that the punching and other cutting techniques deteriorate the magnetic properties of electrical steels [1], [2]. The punching generates large plastic deformations and residual stresses in the cut-edge region [3] - [5]. These cutting effects influence the power loss and flux density distribution in electrical steel sheets. The phenomenon is well-documented by experimental results [6]-[8]. Gmyrek et al. [9] presented a simple model for the cut-edge region and identified the model parameters from the experimental results for concentric rings with punched edges. Bali et al. [10] identified the non-degraded and fully degraded material characteristics using the Epstein frame measurements with sample strips of two different widths.

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The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement n°339380.

The main aim of this paper is to propose a method to identify the magnetic properties of the edge region based on experimental results. This approach is demonstrated by using previously presented test results for magnetic properties of rectangular strips of variable widths [6].

A previous version of this paper has been presented at the ICEM 2016 conference [11].

II. METHODS

A. Experimental Results

The experimental set-up and results are presented by Schoppa, Schneider and Roth [6]. The testing method and cutting process are described in detail in [3]. Particularly, the cutting process has been controlled by a special punching tool with two guide-bars to get purely translational motion. This tool enables the use of 20-60 mm gap between the cutting edges [3], but the exact value applied for the current experimental results [6] has not been given.

The size of the original strip is 160 x 30 mm. The magnetic properties of this strip are measured using a single-sheet testing device. Next, this strip is cut into two strips with width 15 mm and measured in the same way. This procedure is repeated several times to increase the characteristic parameter: cutting length per mass of the sample. However, to avoid the influence of the geometrical shape of the strips on the magnetic properties, the samples are put together into the testing device and measured simultaneously.

In this paper we use the experimental results obtained for an FeSi 3.2-alloy. The thickness of the strips is 0.5 mm and the applied frequency 50 Hz. Table I shows the dimensions of the strips. The original publication [6] applies the characteristic parameter: cutting length per mass of the sample. Using the assumption that the mass of strips is 18.0 g the parameters given in [6] are consistent.

TABLE I
CHARACTERISTICS OF TEST SAMPLES.

Strips	Width of One Strip	Strip Length	Cutting length	Mass of Strips ¹	Cutting Length/Mass
	[mm]	[mm]	[mm]	[g]	[m/kg]
1	30	160	380	18.0	21.11
2	15	160	700	18.0	38.89
3	10	160	1020	18.0	56.67
4	7.5	160	1340	18.0	74.44
5	6	160	1660	18.0	92.22
6	5	160	1980	18.0	110.00

¹Assumed mass of strips

The experimental data points were digitized from the enlarged original figures of [6]. Fig. 1 shows the magnetic polarization as the function of magnetic field strength and Fig. 2 shows the specific core loss as the function of magnetic polarization.

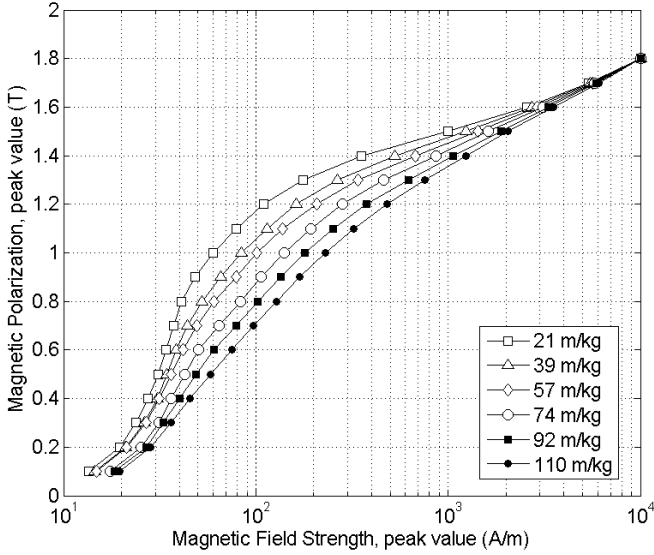


Fig. 1. Magnetic polarization as a function of magnetic field strength. The reproduction made by manually digitizing the data points of [6].

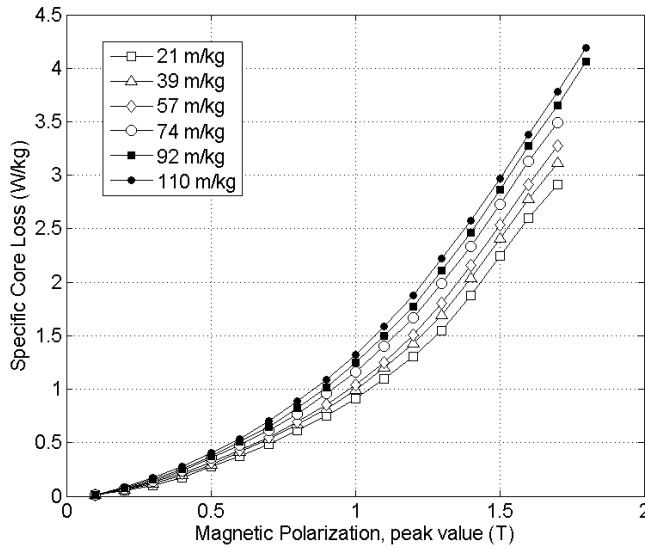


Fig. 2. Specific core loss as a function of magnetic polarization. The reproduction made by manually digitizing the data points of [6].

The experimental results are given for the peak value of magnetic polarization. The data range is from 0.1 T to 1.7 T (or 1.8 T) with the step of 0.1 T. Thus, the discrete experimental results can be presented as

$$\begin{aligned} \hat{H}_{mn} &= {}^e f_n^{-1}({}^e \hat{J}_m) \\ {}^e P_{S,mn} &= {}^e g_n({}^e \hat{J}_m) \\ {}^e \hat{J}_m &= m \times 0.1 \text{ T} \end{aligned} \quad (1)$$

where \hat{H}_{mn} is the measured peak value of the magnetic

field strength, ${}^e P_{S,mn}$ is the measured specific core loss, ${}^e \hat{J}_m$ is the applied peak value of magnetic polarization, m is the ordinal number of applied magnetic polarization, n is the number of strips, ${}^e f_n$ and ${}^e g_n$ are the discrete functions between the input and output values of the measurements.

In this paper the results obtained with the magnetic polarization 1.8 T are neglected, because the experimental data do not cover all the strip numbers. Thus, the total number of magnetic polarization points $N_m = 17$, and the maximum number of strips $N_n = 6$. Further, the total number of data points is 204 to define the magnetization and core loss curves.

B. Cutting Edge Model

The applied material model is identical with the model presented by Gmyrek et al. [9]. The main assumptions of the cutting edge model are:

1. The cutting edges of original 30 mm strip and all smaller strips are identical.
2. Width of the cutting edge is constant w_e .
3. Magnetic properties of the cutting edge are uniform.
4. Magnetic properties in the middle of the strip inside the edge regions are uniform and equal to the properties of intact material.
5. Total width of the edge regions is smaller than the width of the smallest strip, i.e. $w_e < 2.5$ mm.
6. Magnetic properties of the short sides of the strip are assumed to be those of the intact material between the edge regions of long sides, i.e. the magnetic properties are equal in all cross sections.
7. Magnetic field lines are parallel to the long sides of the strip.
8. Magnetization curves of intact material and cutting edge material are positive and monotonically increasing functions.
9. Specific core loss curves of intact material and cutting edge material are positive and monotonically increasing functions.

All the modelled strips include cutting edges and the intact material in the middle. The magnetization curve and the specific core loss of the intact material can be written in continuous form as

$$\begin{aligned} \hat{J}_0 &= f_0(\hat{H}) \\ P_{S,0} &= g_0(\hat{J}) \end{aligned} \quad (2)$$

Similarly, the magnetization curve and the specific core loss of the edge region can be written as

$$\begin{aligned} \hat{J}_e &= f_e(\hat{H}) \\ P_{S,e} &= g_e(\hat{J}) \end{aligned} \quad (3)$$

Thus, the model is described by the edge width w_e and the

magnetization curves f_0 and f_e together with specific core loss functions g_0 and g_e (Fig. 3). These monotonically increasing continuous functions can be approximatively presented by a set of increasing function values and Piecewise Cubic Hermite Interpolating Polynomial (PCHIP). If the total number of function values is N_{int} for all the functions (f_0, f_e, g_0 and g_e), the number of model parameters is

$$N_{\text{mod}} = 4N_{\text{int}} + 1 \quad (4)$$

where the additional parameter is for the edge width.

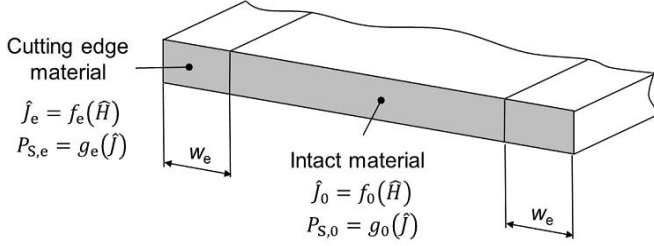


Fig. 3. Material model for the cutting edge and intact regions of a strip.

C. Identification of Model Parameters

The peak value of the magnetic polarization with n strips is

$$\hat{j}_n = \frac{(w_n - 2w_e)\hat{J}_0 + 2w_e\hat{J}_e}{w_n} \quad (5)$$

where

$$w_n = (1/n) \times 30 \text{ mm} \quad (6)$$

is the width of one strip. It was preliminary assumed that there was always a region with intact material in the middle of any strip, i.e. $w_n - 2w_e > 0$. This assumption was later on evaluated and validated by the calculated width of the edge region. This equation can be written for a chosen magnetic polarization \hat{H}_m as

$$\hat{j}_{mn} = \frac{(w_n - 2w_e)f_0(\hat{H}_m) + 2w_e f_e(\hat{H}_m)}{w_n} \quad (7)$$

Based on (1) and (7) the difference between the experimental and calculated magnetic polarization with n strips can be written as

$$D\hat{j}_{mn} = \frac{(w_n - 2w_e)f_0({}^e\hat{H}_{mn}) + 2w_e f_e({}^e\hat{H}_{mn})}{w_n} - {}^e f_n({}^e\hat{H}_{mn}) \quad (8)$$

The parameters describing the magnetization curve and the edge width can be searched by the method of least squares. If all the experimental data is used without any particular weighting function, the function for the minimization gets the form

$$D_j = \frac{1}{N_m N_n} \times \sqrt{\prod_{m=1}^{N_m} \prod_{n=1}^{N_n} (D\hat{j}_{mn})^2} \quad (9)$$

The minimum value of D_j gives the best fit between the experimental results and the model determined by the edge width and discrete values of magnetization curve.

The specific core loss for the magnetic polarization \hat{J}_m and n strips is

$$P_{S0,mn} = \frac{(w_n - 2w_e)P_{S0,m} + 2w_e P_{Se,m}}{w_n} \quad (10)$$

where the subscript m refers to the number of magnetic polarization according to (1). The edge width w_e is hold fixed based on the best fit of magnetization curve. Based on (1) and (10) the difference between the experimental and calculated specific core loss can be written as

$$DP_{S,mn} = \frac{(w_n - 2w_e)P_{S0,m} + 2w_e P_{Se,m}}{w_n} - {}^e P_{S,mn} \quad (11)$$

The model parameters can be searched similarly as above by minimizing the formula

$$D_p = \frac{1}{N_m N_n} \times \sqrt{\prod_{m=1}^{N_m} \prod_{n=1}^{N_n} (DP_{S,mn})^2} \quad (12)$$

D. Numerical Solution

The calculation algorithm was programmed with Matlab 2012. The end points of magnetic field strength curve were chosen to be 10 A/m and 11000 A/m. The additional discrete function values, i.e. parameters, were logarithmically (base 10) distributed between these two end points. The end points of the specific loss curve were 0.1 T and 1.7 T. The additional function values were evenly distributed between the end points.

The assumption of positive and monotonically increasing magnetization and loss functions were realized by using the Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) together with increasing values of consecutive data points. The requirement of increasing values was obtained by using the absolute value of parameter increments in the calculations.

The minimized function (8) is non-linear and the solution space is limited by different requirements. Thus, there is a possibility of several local minima. For this reason, the model parameters were first identified for a model with a small number of parameters, e.g. $N_{\text{int}} = 4$, and then the obtained magnetization and loss curves were used to generate the initial guess values for a model with larger number of parameters.

III. RESULTS

The numerical solution was calculated for $N_{\text{int}} = 4 \dots 13$. The differences D_j and D_p clearly decreased with

increasing number of parameters up to 9. The results of this model, $N_{int} = 9$, are presented and discussed. The identified edge width was 1.69 mm. Fig. 4 shows the identified magnetization curve and Fig. 5 the identified specific loss curve for the intact material and edge region.

As expected, the magnetization curve of intact material (Fig. 4) has higher magnetic polarization compared to the experimental curve with 1 strip (Fig. 1). The identified magnetic polarization of edge region is remarkably lower than that of the intact material with low magnetic field strength values. With high field strength values the magnetic polarization of edge region converges with the polarization of intact material. The same effect can be seen in the original experimental results (Fig. 1).

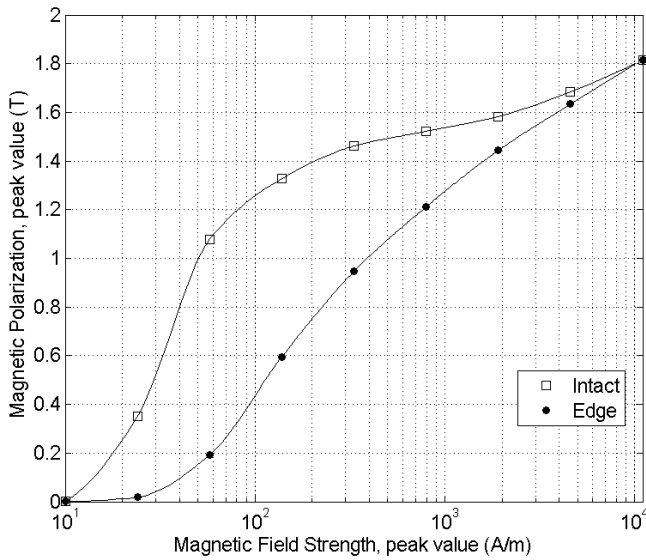


Fig. 4. Identified magnetic polarization of the intact material and end region as a function of magnetic field strength. The discrete function values are presented by the markers and the curves by PCHIP.

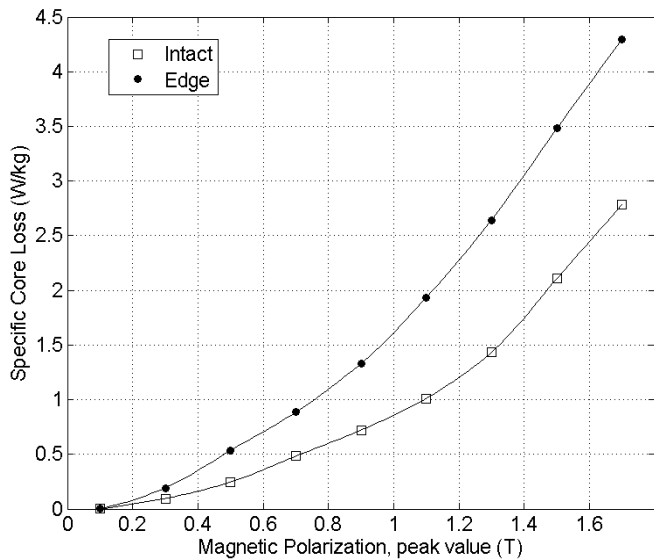


Fig. 5. Identified specific core loss of the intact material and edge region as a function of magnetic polarization. The discrete function values are presented by the markers and the curves by PCHIP.

Similarly, as expected, the specific core loss curve of

intact material (Fig. 5) is below the experimental core loss curve with 1 strip (Fig. 2). The identified specific core loss of edge region is higher than that of the intact material. The increase is largest, about 100 %, with low magnetic polarization values decreasing to about 50 % with large values of magnetic polarization.

The performance of chosen edge model and the quality of fitting can be evaluated by comparing the original experimental data to the fitted curves. Fig. 6 shows the predicted curves of magnetization and Fig. 7 the predicted curves of specific core losses together with the experimental values used for the identification of the model parameters. As can be seen the chosen model can be fitted well to the experimental data points. The average differences with the applied model $N_{int} = 9$ are $D_J = 0.0013\text{T}$ and $D_P = 0.0023\text{ W/kg}$.

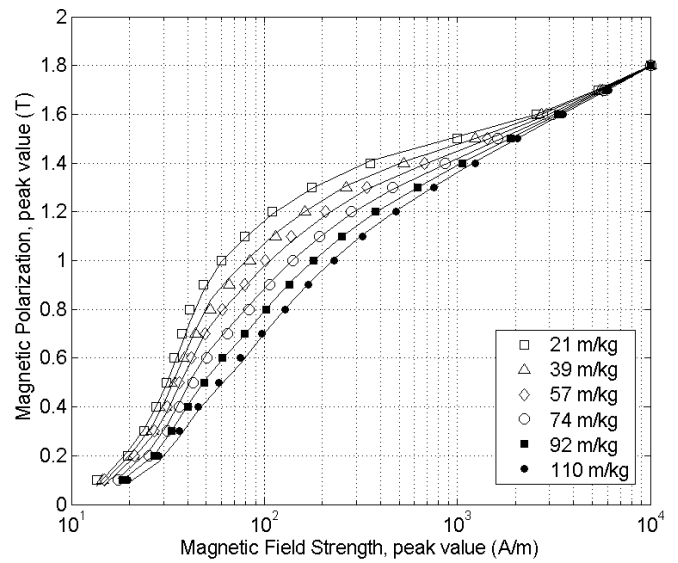


Fig. 6. Magnetic polarization as a function of magnetic field strength. The predicted curves from the optimal fit together with the experimental data points given by markers [6].

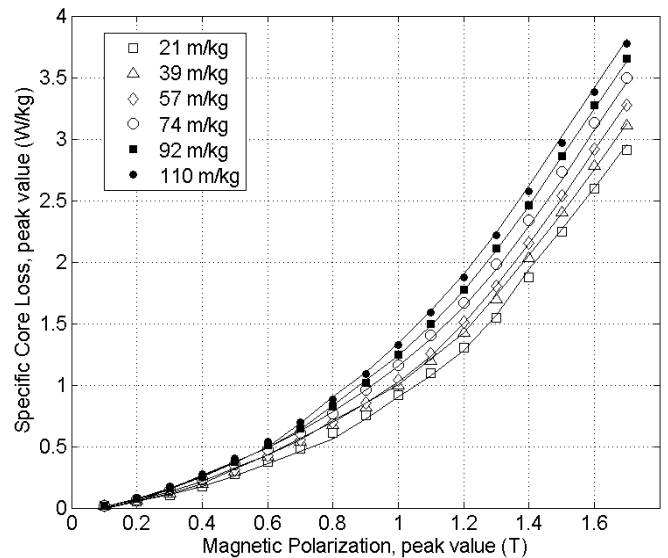


Fig. 7. Specific core loss as a function of magnetic polarization. The predicted curves from the optimal fit together with the experimental data points given by markers [6].

IV. DISCUSSION AND CONCLUSIONS

A simple magnetic material model for the cut-edge region was developed and a method to determine the model parameters from the experimental results presented. The calculated results show that the model can be fitted to the experimental magnetization and specific loss values very well.

The fitted width of the cutting edge region was 1.69 mm. This is close to the equivalent width 1.87 mm obtained by Gmyrek et al. [9] for electrical steel sheets with thickness 0.5 mm. However, the width of the equivalent edge is much larger than the width of the region where an increased hardness has been measured [3], [4]. The explanation might be the applied assumption of uniform distribution of the material properties in edge region.

The derived model parameters are based on one extensive set of experimental results [6]. In order to generalize the obtained results, the model should be applied for the available or new experimental data including different steel grades, sheet thickness, (relative) rolling directions and punching or cutting processes.

The cutting edge material model can be incorporated to numerical electromagnetic models developed for the calculation of electromagnetic fields and losses of electric machines. This kind of an approach has been presented in [4] and [5] without explicit description of the material properties of cutting edge region.

The presented cutting edge material model with the parameters identified in this paper has been applied for a 37 kW induction motor [12]. The numerical simulations show that the iron losses increase up to 38 %, but the torque and active power are only slightly affected.

V. ACKNOWLEDGEMENTS

T. P. Holopainen gratefully acknowledges the opportunity to work as visiting researcher at the Department of Electrical Engineering and Automation, Aalto University School of Electrical Engineering.

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VII. BIOGRAPHIES

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