Simulating the change of magnetic properties of electrical steel sheets due to punching

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Abstract— Electrical machines are, especially in combination with modern power electronics, the driving horse in industry, traction and automotive applications. So there is a lot of research ongoing in the fields of new or improved topologies, better performance and increased efficiency. Latter one requires a better knowledge of the loss mechanisms in the machine in order to find solutions to reduce them. The iron losses, resulting from a varying magnetization in the ferromagnetic lamination sheets, are the most complex loss component in an electrical machine. One factor influencing the iron losses significantly is the manufacturing process. Among the different production steps, punching of the machines lamination can be considered to have a very high impact on the magnetic properties. If there is knowledge on how these properties depend on the mechanical and the process parameters there is considerable potential to optimize the process or the machine design to increase the machines efficiency. This paper will present simulation models trying to forecast the losses of punched lamination sheets. Therefore, the punching process was simulated with Finite-Element software. The resulting distribution of stress and strain in the lamination sheet can be used for the magnetic simulations. Hysteresis measurements were made on a punched lamination sheet made of the same material which comes from the same supplier as the reference probe. It will be shown that with this model it is possible to reproduce the measurements on the punched lamination sheet.

In the first section of this work the Jiles-Atherton model is briefly introduced. The parameters are being identified with measurements on a reference probe of a machines lamination. This reference probe is assumed to have no mechanical disturbances.

The mechanical simulation of a punching process is presented in the sequence and a resulting distribution of stress and strain is shown with which the Jiles-Atherton model can be used for the magnetic simulations. Hysteresis measurements were made on a punched lamination sheet made of the same material which comes from the same supplier as the reference probe. It will be shown that with this model it is possible to reproduce the measurements on the punched lamination sheet.

In the future and with given material properties, the developed
methodology should therefore be capable to forecast the iron losses of the lamination in dependence of punching parameters.

II. MAGNETIC MODEL AND SIMULATION

The magnetic calculations were done with the widely known Jiles-Atherton model of hysteresis [1].

Ferromagnetic material consists of areas, the so-called domains, where the magnetization has the same orientation. If an external field $H$ is applied, the distribution of the domains changes by domain wall movements and/or domain rotations in such a way that the total energy of the material is a minimum. The Jiles-Atherton model describes the domains behavior in dependence of the applied field $H$ globally with statistical means resulting in the modified Langevin expression (1)

$$M_a(H) = M \left[ \coth \left( \frac{H_c}{a_0} \right) - \frac{a_0}{H_e} \right]$$

where $M_a$ is the anhysteretic magnetization not considering energy loss and, hence, hysteresis and $M_S$ is the saturation magnetization. The parameter $a_0$ can be related to the domain density. $H_e$ is the effective field acting on a domain and which is calculated by (2). The parameter $\alpha$ is representing inter-domain coupling.

$$H_e = H + \alpha M$$

Also presented in [1] is an approach to include hysteresis effects with an energy loss caused by pinning. This results in (3) where $M$ is now the magnetization of the material including hysteresis; $k_0$ is the energy loss coefficient due to pinning and $\kappa$ is considering the direction of the magnetization change. For increasing applied field $dH/dt > 0$, $\kappa$ is +1 for increasing and it is -1 for decreasing magnetic field $H$.

$$M = M_{an} - k_0 \frac{dM}{dB}$$

What is left to be included in the model is the reversible bending of domain walls before it comes to an irreversible Barkhausen jump of the wall from one pinning site to the next one. This is expressed by (4) where the total magnetization $M$ is the sum of the reversible magnetization $M_{rev}$ due reversible wall bending and the irreversible component $M_{irr}$ from wall displacement.

$$M = M_{rev} + M_{irr}$$

The reversible magnetization is calculated with (5)

$$M_{rev} = c(M_{an} - M)$$

where $c$ is the irreversibility constant which can be determined experimentally using the initial susceptibility.

From (3), where now the irreversible magnetization $M_{irr}$ has to be used instead of $M$, a convenient differential equation (6) is derived which is used for simulations in this work with a given course of the field $H$.

$$\frac{dM_{irr}}{dH} = \frac{1}{\mu_0 k_0 - \alpha (M_{an} - M_{irr})}$$

A. Parameter identification of undisturbed lamination sheet

The parameters necessary to describe the magnetic hysteresis with the Jiles-Atherton model need to be identified.

This was done with magnetic measurements on an Epstein-frame test stand. It would be necessary to identify these material properties on a lamination sheet which is mechanically totally undisturbed. Since such a probe is not available, water-jet cut lamination stripes were used for the Epstein-frame test. It is assumed that water-jet cut lamination is mechanically much less disturbed than punched one, what is also stated in [4], so that this probe can serve as a reference for stress and strain equal to zero. The parameter identification was done with a standard optimization routine (Direct.m / Matlab) minimizing the error square of the measured and simulated magnetization for a given field strength $H$. The so-obtained parameter values are given in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
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<tbody>
<tr>
<td>Saturation Magnetization</td>
<td>$M_S = 1.2 \times 10^6$ A/m</td>
</tr>
<tr>
<td>Coupling constant</td>
<td>$\alpha = 5.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Factor related to domain density</td>
<td>$a_0 = 14.61$ A/m</td>
</tr>
<tr>
<td>Loss coefficient</td>
<td>$k_0 = 233.1$ Vs/m²</td>
</tr>
<tr>
<td>Irreversibility constant</td>
<td>$c = 0.805$</td>
</tr>
</tbody>
</table>

Measured and simulated hysteresis loops are shown in Fig. 1.

![Fig. 1. Measured (red) and simulated (black) hysteresis of water-jet cut lamination, reference probe.](image-url)
B. Extension to describe the effects of stress

Approaches to include the effect of stress and strain on the hysteresis were developed in [6] and [7]. The magnetic effects of internal stress acting on the domains is considered by introducing an additional magnetic field $H_{\sigma}$ originating from that stress. The magnetic field $H_{\sigma}$, which is acting on the domain, then becomes

$$H_{\sigma} = H + \alpha M + H_{\sigma}$$  \hspace{1cm} (7)

This field component $H_{\sigma}$ depends via the magnetostriction $\lambda(M, \sigma)$ on the magnetization $M$ and the internal residual stress $\sigma$ as given in (4),

$$H_{\sigma} = \frac{3\sigma}{2\mu_0} \frac{d\lambda(M, \sigma)}{dM}$$  \hspace{1cm} (8)

A Taylor series expansion for $\lambda(M, \sigma)$ with respect to magnetization as well as stress is given in [7]. Using this we obtain for the stress dependent field

$$H_{\sigma} = \frac{3\sigma}{2\mu_0} \left[ M(l_1 + \sigma l_1^0) + 2M'(l_2 + \sigma l_2^0) \right]$$  \hspace{1cm} (9)

where $l_1$, $l_2$, $l_1^0$ and $l_2^0$ are the Taylor series coefficients.

C. Extension to describe the effects of strain

The plastic strain in a ferromagnetic material has two effects which have a major impact on the magnetic properties: First, the dislocations density in the crystal will increase what will impede the movement of the domain walls and, second, the size of the domains reduces due to the deformations. Both effects result in higher hysteresis losses. This is considered in the Jiles-Atherton model by adapting the parameters $k_0$ in (2), and $a_0$ in (1) and calculated in the following way.

The output of the mechanical simulation is, beside the residual stress, the plastic strain $\varepsilon$ defined by the ratio of the change in length $\Delta l$ and the original length $L_0$ by

$$\varepsilon = \frac{\Delta l}{L_0}$$  \hspace{1cm} (10)

The deformation now introduces a strain hardening stress $\sigma_f$ in crystal lattice for which the empirical formula (11) was found in [9]. In (11), $\gamma$ and $n$ are proportional factors.

$$\sigma_f = \gamma \varepsilon^n$$  \hspace{1cm} (11)

The dislocation density $\delta$, increased from the original dislocation density $\delta_0$, is determined with the constant $C$ by (12)

$$\delta = \left( C \sigma_f + \sqrt{\delta_0} \right)^3$$  \hspace{1cm} (12)

This relationship for the dislocation density is also given in [10].

The parameter $k$ directly represents the average energy loss from pinning and is proportional to the coercivity. Relationships for $k$ and $a$ are given in [10] where their dependence on strain is similar for both parameters. Different to [10] we chose to adapt the parameters $k$ and $a$ according to equations (13) and (14).

$$k = k_0 \sqrt[\delta_0]{}$$  \hspace{1cm} (13)

$$a = a_0 \sqrt[\delta_0]{}$$  \hspace{1cm} (14)

These simpler relationships have the advantage of a better convergence of the optimization routine and it is inherently satisfied that $k=k_0$ and $a=a_0$ if there is no plastic deformation.

III. MECHANICAL SIMULATION

The mechanical simulation was done with the Finite-Element software DEFORM™. One important feature of DEFORM™ is an automatic re-meshing algorithm which maintains convergence even if the geometry is deformed. The mechanical flow curves are necessary for these simulations which were known for common metals but not for the specific iron-silicium alloy of the lamination. What was known from that alloy was the mechanical strength so that a flow curve of high-tensile aluminum with comparable mechanical strength was used.

The punching tool is shown in Fig. 2 and the area where the lamination sheet is trapped between the matrix and blank holder. The die is moving downwards to cut the sheet. The thickness of lamination sheet was 0.5mm.

![Fig. 2. Punching tool and process to cut the lamination sheet.](image)
The resulting residual stress in the material after is shown in Fig. 3. That is the distribution of stress after the sheet has been cut completely at the end of 600 simulation steps.

The mechanical Finite-Element model consists of approximately 5000 elements. The mechanical simulations showed that the lamination is considerably disturbed with internal stress in an area from the outer edge at \( x=0 \) mm to \( x=4 \) mm. For keeping the calculation effort low, this area will be discretized into a number of slices along the horizontal x-axis. In these slices, representative values for stress and strain are determined for which the magnetic model is evaluated. The number of slices is chosen to be ten, each with a width of \( \Delta x=0.4 \) mm.

Fig. 4 shows the course of the so-obtained internal, residual stress and plastic strain.

Magnetic simulations of a punched lamination were done using the Jiles-Atherton model with the parameters for the undisturbed material identified in section II.A. These parameters are \( M_s, a_0, k_0 \) and \( \alpha \) in the equations (1) and (2). With the course of an applied magnetic field \( H \), which is obtained from measurements, the Jiles-Atherton model was calculated in every region of the lamination considering the discrete values of the residual stress and plastic strain. These regions with equal cross-sections are magnetically parallel and the mean value of the simulated magnetizations have to correspond to the one measured on the Epstein-frame. The parameters necessary to extend the model for considering stress and strain, section II.B. and II.C., are identified so that these simulations match the measurements.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
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<tbody>
<tr>
<td>( l_1 )</td>
<td>( 4.738 \times 10^{-19} )</td>
</tr>
<tr>
<td>( l_2 = l_3 = l_4 = 0 )</td>
<td></td>
</tr>
<tr>
<td>( \gamma = 3.439 \times 10^5 )</td>
<td></td>
</tr>
<tr>
<td>( n=5.167 )</td>
<td></td>
</tr>
<tr>
<td>( \delta_0=1 \times 10^{10} )</td>
<td></td>
</tr>
<tr>
<td>( C=1 )</td>
<td></td>
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</table>

The results of the measured and simulated hysteresis curves are shown in Fig. 5. If compared with the hysteresis of the water-jet cut lamination in Fig. 1, which serves as an undisturbed reference probe, it can be noticed that the permeability of a magnetization curve approximating the hysteresis is considerably smaller for the punched lamination. The hysteresis losses, which correspond to the area of the hysteresis, increase by 30% for the punched lamination compared to the water-jet cut probe.
Fig. 6 compares the simulated hysteresis curves of the region at the outer edge \((x=0\) to \(0.4\)mm\) and the hysteresis of the region inside the lamination \((x=3.6\) to \(4\)mm\). As expected, the hysteresis at the outer edge is wider resulting in a much higher coercivity (=the field strength where the magnetization \(M=0\)). That also means considerably higher hysteresis losses in this region which are proportional to the area of the hysteresis.

![Simulated hysteresis curve in the region at the outer edge (black) and the hysteresis curve of the inner region (red).](image)

The aim for future work is that with such a verified calculation method, the dependence of magnetic properties on punching parameters can be forecasted enabling optimizations for the punching process as well as the machine design.

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REFERENCES