MAGNETOCRYSTALLINE ANISOTROPY IN THIN GRAIN ORIENTED SILICON IRON ALLOY CUT THROUGH DIFFERENT TECHNOLOGIES

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Investigation of the magnetocrystalline anisotropy of the grain oriented (GO) electrical steels is important in improving the performance of the electrical devices, since they are used as magnetic cores for transformers. Due to the (110)[001] Goss texture, these alloys have a strong magnetic anisotropy with the easy axis [001] along the rolling direction (RD) and hard axis [111] at about 54° to the rolling direction. In the electrical transformers, the magnetic flux path has usually a straight direction, which follows the [001] axis. Because of the geometry of magnetic core that contains T-joint intersections and corner parts, the magnetization detours and intersects the easy axis of the steel sheet at different values of the angle between the RD and the magnetic flux direction. In the paper there were analyzed samples made of a commercial grain oriented alloy (M0H) with thickness of 0.30 mm. The 300 mm × 30 mm samples were cut through punching and laser technology at different angles (0°, 15°, 30°, 45°, 60°, 75°, 90°) with the rolling direction. For the representation of the magnetic field strength at constant magnetic polarization it was used a software program that interpolated the experimental results. A frequency analysis from 12 Hz to 100 Hz was performed, to investigate the energy loss behavior and, by applying the loss separation concept, the influence of the cutting technology and the magnetocrystalline anisotropy on the hysteresis, classical and excess losses was studied.

1. INTRODUCTION

Grain oriented steels are used in the manufacturing of the electrical transformer magnetic cores as a result of their property to enhance and conduct the magnetic flux, which is generated by an electric current [1, 2].

In the metallurgical process, the induced Goss texture determines superior magnetic properties in the rolling direction due to the high percent of grains, that have the same atomic crystalline structure, oriented to the [001] easy axis. This leads to steel with high values of the magnetic anisotropy and permeability.

The magnetic properties of electrical steels are measured with one-dimensional devices (single strip tester or Epstein frame) according to the manufacturer data sheets [3, 4], but application requirements need to investigate the magnetic behavior at an arbitrary angle different from 0° or 90°. This information is obtained from measurements carried out between the two principal [001] and [011] directions. Experimental characterizations under rotational magnetization flux (two-dimensional devices) were reported [5–10] but these systems are not standardized and many configurations of testers are used in different laboratories [11]. A more appropriate approach to the standards is to cut the samples at different angles with respect to the rolling direction and to characterize them with a unidirectional (1D) single strip tester. It is well known that the total energy losses can be split, in the case of 1D measurement into hysteresis, classical eddy current and excess losses. The same it could be applied in the case of two-dimensional characterization (2D), but it is very difficult to find a correlation between the rotational magnetization processes or losses and the physical properties and microstructure of the materials. Another important problem is the accuracy and the meaning of the loss components for 2D measurements under non-standard magnetization conditions [12].

The IEC Standards [13] for grain oriented steels present an analysis regarding the anisotropy of the losses by taking into account the energy losses, measured in the rolling direction and the losses, determined in direction perpendicular to RD [12]. Nowadays the influence of the magnetocrystalline anisotropy on the texture and on the losses could be made by estimating the magnetization at an intermediate angle to the RD.

In the electrotechnical devices a rigorous control of the anisotropy level could lead to a reduction of vibrations and noise emitted by the transformers. The electrical steel is usually cut through mechanical punching, but this classical and cheap method could conduct to mechanical stresses, which have an influence on the crystallographic texture and on the energy losses. Punching is usually linked to the apparition of burrs. It was noticed [12], that when a sheet was cut through punching crosswise and then the halves of the sheet were stacked together, there was observed a small gap, between them along the cutting profile, which was the result of the relaxation of the internal stresses, and it could be concluded that these stresses can be directly linked to the size of the gap [11].

The laser cut technology is a fast method and it leads to a perfect cut edge with any burrs. If the strips are cut through this technology the noise, due to burrs, is minimal and the control of the magnetocrystalline anisotropy could be made in a more appropriate way. The laser cut technology has unfortunately a main disadvantage, because thermal stresses are induced during the cutting process, which could affect in an unexpected way the position of the hard and easy axes.

In the electrical transformers local magnetic field detours from a direction parallel to RD in the T-joints and corner parts of the core, generating rotating energy losses, which should be higher that the ones, obtained if the magnetic field was in line with the easy axis of the grain oriented steel [14]. Therefore an analysis of the magnetic properties at intermediate angles with the single strip tester becomes an important task.

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2. EXPERIMENTAL PROCEDURE

Thin grain oriented silicon iron strips 0.30 mm-thick cut at angle $\theta = \{0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ with the rolling direction (Fig. 1) have been investigated by means of a unidirectional single strip tester (SST), which permits to measure the total energy losses up to high magnetic polarizations (1 T in this paper). Nowadays the single strip tester is the most suitable instrument for observing important variations in the magnetic properties of the industrial steel.

The samples were placed between the pole faces of a double C-shaped vertical yoke. The form factor was kept within 1.111 ± 1 %. The test frequencies varies between 12 Hz and 100 Hz at a constant value for the peak magnetic polarization ($J_p = \{250, 500, 1000\}$ mT) and the hysteresis loss component $W_h$ was determined according to [15, 16] by extrapolating the results to $f = 0$. The classical losses are given, for a sinusoidal magnetic polarization, by eq. (1), in which $\sigma = \frac{1}{49 \times 10^{-8}}$ S/m is the electrical conductivity, $\rho = \frac{7386 \text{ kg/m}^3}{\text{s}}$ is the material density, $d$ is the strip thickness and $f$ is the test frequency [17–19]:

$$W_{cl} = \frac{\sigma^2 \pi^2 f^2}{6 \rho} J_p.$$

The excess energy losses were determined as the difference between the total, hysteresis and classical energy losses:

$$W_{exc} = W_{tot} - W_{cl} - W_h.$$

The samples were cut through mechanical punching and laser cut technology.

The mechanical punching was made by means of a TRUMPF TRUMATIC 500 Machine, which makes all the cutting steps in an automatic way. This machine offers a fast production time, with short set-up times and high component quality. Its wide range of applications makes it the ideal tool for cutting the electrical steel. It provides the integration of work piece positioning and tool changing within a coordinate system of low mass and high rigidity yields considerable service benefits. AC servomotors and a rack and pinion drive system produce the highest component accuracy, combined with the lowest maintenance requirements. Through programmable control of both punching speed and stroke length, the electro-hydraulic ram within the punching head has been developed by TRUMPF into a virtual 3rd axis [20].

The laser cutting machine is a TRUMPF TRUFLOW CO2 LASER 3030 Classic with a maximum power of 3200 W. The wavelength of this laser is equal to 10.6 μm, beam quality K 0.6 and it has beam stability, in correlation with laser power, of ± 2 %. The square-folded construction of this laser device and consistent temperature stabilization of all resonator components, in contact with heat, give it unique thermal and mechanical stability. The practical advantage of this laser technology is the reproducibility of optimal quality processing results. Wear-free gas circulation by magnetically suspended turbo blowers together with the radio-frequency excitation of the laser gas provides optimal effectiveness of the laser and minimal maintenance and operating costs, while permitting highest availability. With the TruFlow high-power lasers with better optimized energy efficiency, the power consumption has been further reduced through an optimized cooling concept and modern transistor-based excitation. The open interface architecture of the laser control simplifies integration of the laser into super-ordinate control concepts. When the laser is operated manually, operating functions are easily found with the interactive menu of the laser operating software [21].

The hysteresis cycles provided by the single strip tester are interpolated through a Matlab program, in order to have the right representation at exactly the same values of the magnetic polarization. The SST reaches the given value within an error of ± 2 %, so the applied correction was necessary, especially in the case of the polar diagrams $H(\theta)$ at constant peak magnetic polarizations.

3. RESULTS AND DISCUSSIONS

In Fig. 2 are presented the polar diagrams of the dependencies $H(J)$ at peak magnetic polarizations $J_p = \{250, 500, 1000\}$ mT and at industrial frequency $f = 50$ Hz.
It can be noticed, that in the case of both cutting technologies, in the low and medium magnetic polarization range \((J_p = 250 \, \text{mT} \text{ and } J_p = 500 \, \text{mT})\), the easy magnetization axis is placed at 0º (parallel to the rolling direction of the strips) and the hard magnetization axis is at 90º (perpendicular to the RD). In the high magnetic polarization region \((J_p = 1000 \, \text{mT})\), the easy axis is at 0º, but the hard magnetization axis makes a switch from 90º to about 60º, fact that is in a good accordance with the literature [22 –24].

By comparing both technologies it can be seen that the magnetic field strength \(H\) has almost the same values (493 A/m for \(J_p = 500 \, \text{mT}\) and 450 A/m for \(J_p = 1000 \, \text{mT}\)) for the 90º direction in the case of laser cut samples. For \(J_p = 1000 \, \text{mT}\) the value of \(H\) (550 A/m) at 60º cut sample is bigger than that, measured for 90º cut one. It can be concluded that the mechanical punching, although induces mechanical stresses in the process of cutting the material, does not affect in an important way the crystalline structure of the material. The thermal stresses, noticed in the case of laser technology, affect strongly the crystalline lattice. In the case of punching the values of the magnetic field strength, determined for the 90º cut sample are very different (137 A/m for \(J_p = 250 \, \text{mT}\), 176 A/m for \(J_p = 500 \, \text{mT}\) and 286 A/m for \(J_p = 1000 \, \text{mT}\)).

In Fig. 3 are presented comparisons between the polar diagrams, obtained in the case of the two cutting technology for three values of the peak magnetic polarization at 50 Hz. In all the cases and for all the cutting angles, the laser technology leads to bigger values of magnetic field strength \(H\). This underlines the fact that the induced thermal stresses affect the magnetization process of the material. The con-ventional GO strips are characterized by a regular pattern of 180º domain walls, directed along the RD and subjected to back-and-forth motion under alternating magnetic fields. The magnetic domains evolve in a complex way when the magnetic field is applied along the 90º axis [25]. When the applied field is increased, a transition takes place, where the basic 180º domains transform, through 90º domain wall processes, into a pattern made of large domains, having the saturation polarization symmetrically directed along [100] and [010], and of surface flux closing domains [22].

The total energy losses \(W_{tot}\) increase less than linearly with the frequency [23, 24].

In Fig. 4 is represented the total energy variation \textit{versus} frequency. For the exemplification of the anisotropy influence on energy losses there were chosen for the graphical representations only the dependencies for 0º, 30º, 60º and 90º in the case of \(J_p = 250 \, \text{mT}\) and \(J_p = 1000 \, \text{mT}\).

At lower magnetic polarization \((J_p = 250 \, \text{mT})\) the easy axis is placed at 0º and the hard axis is at 90º in the case of both cutting technologies and for high magnetic polarization range the hard axis is placed at 60º. The total energy losses, measured in the case of laser cut technology are bigger than those, obtained for mechanical punching.

The hysteresis \(W_h\) and the excess \(W_{exc}\) energy losses are determined in the terms of relative proportions of 180º and 90º domain wall (DW) processes, the last one becoming increasingly important with the increase of \(\theta\), under alternating fields.

In Fig. 5 are presented the hysteresis energy losses \textit{versus} \(\theta\) for the two cutting technologies at two peak magnetic polarizations. In the case of low \(J_p\) the hysteresis losses for
the laser technologies have quite a constant value, since those, determined for punching increase with the cutting angle. In the case of high polarization range both dependencies have a maximum for 60° cut sample.

The excess loss component follows an approximation law of the type $W_{ex} \approx f^{1/2}$ [24]. This kind of dependence could be done by the magnetization process that becomes increasingly homogenous with the frequency, in a good accordance to a well defined balance equation involving the applied magnetic field and the eddy current counter fields [25]. The hysteresis and the excess losses are associated with the localized eddy current phenomena, which is connected with the specific displacement mechanisms of the domain walls. At saturation point in grain oriented materials it appears coherent rotations of the magnetization vector [11, 12]. The DW processes, involved in the magnetization of the material are the displacements of the 180° DWs, oriented along the crystal axis [001] and the 90° DWs transitions from [001] to the directions [100] and [010]. The 180° DW displacements provide a reversal in the rolling direction, which is a suitable wide distribution for the pinning fields, which leads to an approximate law $W_{h} \approx f_{p}^{n}$ [24, 25].
In Fig. 6 are presented the excess energy losses versus frequency. The observations, noticed in the case of the total energy losses are valid also in the case of the excess energy losses.

The coercive field $H_c$ is a main characteristic of the magnetic hysteresis cycle and it does not depend on the geometry of the sample. It could be considered as the effect of the magnetocrystalline anisotropy and internal elastic stresses [26]. The anisotropy of the energy losses and magnetization processes is different from the anisotropy of the coercive field and they depend not only on the crystalline structure or texture of the material, but also on the magnitude of the external field, frequency, size of the crystals, domain structure and DW movements [27, 28, 29].

In Fig. 7 is presented the variation of the coercive field versus frequency for two peak magnetic polarization. One can notice that in the case of both cutting technologies the minimum value of the $H_c$ is in the [100] direction, which is located parallel to the RD at $\theta = 0^\circ$. The maximum of the coercive field is placed in [110] at $\theta = 90^\circ$ and not in the [111] axis, which is located at $\theta = 60^\circ$. This phenomenon could be explained in terms of DW dynamics. The 180° DW are oriented parallel to the rolling direction and when the magnetic field is applied perpendicular to the RD the motion of these domain walls become impossible. In this case an irreversible 90° rotation should occur before the DW movement, which indicates that the material has a low initial magnetic permeability for the 90° cut samples (Table 1) [30].

### Table 1

<table>
<thead>
<tr>
<th>Cutting process</th>
<th>$\theta$ [deg]</th>
<th>250 mT</th>
<th>1000 mT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punching</td>
<td>0°</td>
<td>23551</td>
<td>29755</td>
</tr>
<tr>
<td>Laser</td>
<td>90°</td>
<td>1561</td>
<td>2792</td>
</tr>
<tr>
<td></td>
<td>0°</td>
<td>1672</td>
<td>4380</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>457</td>
<td>1502</td>
</tr>
</tbody>
</table>

9. CONCLUSIONS

Anisotropy in grain oriented silicon iron strips is a very interesting research subject, because it is of great importance to design in a proper manner the magnetic cores of the electrical transformers.

In this paper it was analyzed the magnetocrystalline anisotropy in FeSi GO and its influence on the total, hysteresis and excess energy losses. It was underlined also, that the anisotropy of the coercive field is different from the anisotropy of losses and magnetization processes. It was found, that in the low and medium magnetic polarization range the easy magnetization axis is placed at 0° and the hard magnetization axis at 90° and in the high polarization range the hard axis is located at 60°. The anisotropy effects were interrelated with the DW dynamics and rotation of the magnetic moments, and this complex phenomenon was explained in physical terms. Two cutting technologies of the electrical steel were tested; one of them, used at the industrial level and one in prototyping manufacture of the electrical transformers.

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