Calculations of magnetic field in dynamo sheets taking into account their texture

Abstract: Magnetic measurements have shown that the most dynamo steel sheets have certain anisotropic properties, which are due to the presence of textures in these sheets. These anisotropic properties have been taken into account usually in a simplified way assuming that iron particles of the dynamo sheets have only one axis of the easy magnetization. In the proposed approach, these particles are treated as grains which have three axes of the easy magnetization, and therefore the magnetization processes can be considered along each of these axes. These processes depend on the actual value and on the direction of the field strength and also on textures occurring in the given dynamo sheet. A method which allows calculations of the field distribution as a function of the assumed changes of external currents is described in this paper.

Keywords: anisotropy, dynamo sheet, magnetic field, texture

PACS: 75.30.Gw, 75.40.Mg, 75.50.Bb

1 Introduction

Dynamo steel sheets should have the same magnetic properties in each direction on the sheet plane. However, magnetic measurements have shown that very often these sheets have certain anisotropic features [1]. Special crystallographic research, performed with the use of the X-ray diffractometer, allows obtaining the so-called pole figures [2], and on the basis of these figures it has been confirmed that different amounts of the sheet grains create certain textures, i.e. these grains have certain privilege crystallographic orientations with respect to the rolling direction, that is the characteristic direction on the dynamo sheet plane. The occurrence of textures in the dynamo sheets is the main reason of their anisotropic properties. It has significant meaning during different magnetization processes, especially during the rotational magnetization in cores of electrical machines. Influence of these properties on the magnetization processes is visible especially in the comparison of the hysteresis loops measured for selected directions on the dynamo sheet plane [3]. Differences between characteristic magnetic values (coercive force, remanence flux density) measured for the rolling direction and the transverse direction can be up to 30 percent. Due to the anisotropic properties, changes of the flux density in dynamo sheets depend not only on the field strength value, but they also depend on the texture types occurring in the given dynamo sheets. The anisotropy of the dynamo sheets causes a certain increase of the hysteresis losses during magnetization processes along other directions than the rolling direction [4, 5].

2 Textures of dynamo sheets

The given texture is described unambiguously by means of the indicators \( \{hkl\} \langle uvw \rangle \) where \( h, k, l \) denote the co-ordinates of the normal vector of the crystallographic planes parallel to the sheet plane, and \( u, v, w \) are the indicators of the specific direction parallel to the rolling direction of the given dynamo sheet; the above mentioned indicators are associated with the co-ordinate system of the considered iron grains. On the basis it is possible to determine the angle between the rolling direction and one of three easy magnetization axes of the iron crystals creating the given texture. The dynamo sheets can have an infinite number of texture types; however, it is practically impossible to take into account all textures. Therefore, it is assumed that all textures can be reduced (with some approximation) to one of three basic textures: cube-on-face tex-
tecture \{100\}, cube-on-edge texture \{110\}, and the so-called cube-on-vertex texture \{111\} (Figure 1). It is necessary to stress that the anisotropic properties of the dynamo sheet depend not only on the texture types but the percentage share of the given texture with respect to the volume of the sheet sample has significant influence on the anisotropic properties.

Research of the texture types was performed for four dynamo sheets from different manufacturers: M400-50A (Russia), M530-50A (Czech Republic), M530-50A (South Korea), and M800-50A (Sweden) (Table 1). The percentage share of some textures can be up to over thirty four percent with respect to the whole volume of the given dynamo sheet sample. All three basic textures occur in the tested dynamo sheets, but their percentage share is different. For example, the cube-on-face texture \{100\} of the sheet M400-50A takes about 43 percent of the sheet sample volume; in turn, the cube-on-edge texture \{110\} in the sheet M800-50A has the lowest share (about 16 %). In the sheet type M530-50A (Czech Republic) the cube-on-vertex texture \{111\} is almost half of the whole volume of this sheet sample. It is worth mentioning that in some dynamo sheets two textures of the same type may occur, but these textures have different angles between the rolling direction and one of three easy magnetization axes of grains of the considered texture.

### Table 1: Type of textures in dynamo sheets

<table>
<thead>
<tr>
<th>Dynamo sheet</th>
<th>Texture</th>
<th>Percentage share</th>
<th>Direction angle*</th>
</tr>
</thead>
<tbody>
<tr>
<td>M400-50A (Russia)</td>
<td>{100}/{027}</td>
<td>33</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>{100}/{057}</td>
<td>10</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>{111}/{332}</td>
<td>29</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>{111}/{123}</td>
<td>14</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>{111}/{145}</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>M530-50A (Czech Republic)</td>
<td>{100}/{049}</td>
<td>19</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>{100}/{011}</td>
<td>6</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>{110}/{111}</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>{111}/{123}</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>{111}/{112}</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>M530-50A (South Korea)</td>
<td>{100}/{049}</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>{100}/{011}</td>
<td>9</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>{110}/{233}</td>
<td>34</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>{111}/{112}</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>M800-50A (Sweden)</td>
<td>{100}/{049}</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>{100}/{011}</td>
<td>8</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>{110}/{111}</td>
<td>16</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>{111}/{347}</td>
<td>41</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>{111}/{011}</td>
<td>11</td>
<td>0</td>
</tr>
</tbody>
</table>

*The direction angle is the angle between one of the easy magnetization axes and the rolling direction.*


3 Equations of magnetic field distribution

In order to calculate the magnetic field distribution, the sheet sample should be divided into elementary segments, because the field strengths and the flux densities in individual parts of the dynamo sheet proceed differently. Appropriate components of the field strengths and appropriate components of the flux densities are assigned to individual parts of the dynamo sheet. The direction angle \* of one of the easy magnetization axes of grains of the considered texture.

\[
A_m H_m + A_p H_p = S_i J_{ex}
\]

(1)

\[
C_{bx} B_{bx} + C_{by} B_{by} + C_{tx} B_{tx} + C_{ty} B_{ty} = 0
\]

(2)

where \(H_m, H_p\) are column vectors of the field strength components \(H_m, H_p\), \(A_m, A_p\) denote matrices of distances between vertexes, \(S_i\) is the matrix of surfaces of the meshes related to division of the sheet sample into elementary seg-
ments, $\mathbf{J}_{ex}$ denotes column vector of the density values of the external currents, $\mathbf{B}_{bx}$, $\mathbf{B}_{by}$, $\mathbf{B}_{tx}$, $\mathbf{B}_{ty}$ are column vectors of flux density components $B_{bx}$, $B_{by}$, $B_{tx}$, $B_{ty}$, and $\mathbf{C}_{bx}$, $\mathbf{C}_{by}$, $\mathbf{C}_{tx}$, $\mathbf{C}_{ty}$ are matrices of segment face areas which are penetrated by magnetic fluxes with the corresponding components.

The components $B_{bx}$, $B_{by}$, $B_{tx}$, $B_{ty}$ have to be saved as nonlinear functions of the field strength components $H_m$, $H_p$. Equation (2) should be transformed to the form which contains only the column vector $\mathbf{H}_p$ because the magnetization processes are caused by changes of the field strength vector inside each subsegments of the sheet sample [7]. However, it is important to note that saving these components as functions of the field strength components have to take into account the textures, which occur in the considered dynamo sheet.

4 Calculation algorithm with taking into account sheet textures

Calculations of the magnetic field distribution in the given sheet sample is possible by means of an appropriate model of the magnetization process, which can allow us to take into account anisotropic properties of the dynamo sheets. These properties can be considered in a simplified way assuming that the sheet grains have only one easy magnetization axis. However, the iron crystals have three axes of the easy magnetization, so changes of the flux density depend also on the field strength direction [8, 9].

Different approaches which allow us to take into account the anisotropic properties of the dynamo sheets are presented in scientific papers, e.g. the so-called elliptical model of the magnetic anisotropy [10] and the model based on the co-energy density are described in [11], however, these proposals refer to non-hysteresis materials. The magnetic anisotropy of the dynamo sheets can also be considered using the reluctivity or permeability tensor [12]. It is necessary to stress that these methods do not take into account the texture types of the dynamo sheets. It should be emphasized, as it is pointed in [13], that the anisotropic properties of the dynamo sheets should be considered taking into account a real crystallographic structure of the tested dynamo sheet.

The magnetization processes in electrical steel sheets are usually considered as two-dimensional processes. However, the magnetization in the iron crystals (iron grains) should be treated as three-dimensional processes because these processes in iron crystals occur along all three easy magnetization axes (edges of the cubic shape). The exception here is the magnetization in grains creating the cube-on-face texture (100); in this case two easy magnetization axes are parallel to the sheet plane. When the direction of the field strength in an elementary segment of the tested sheet sample is not parallel to any easy magnetization axis, then during increase of the field strength value the flux density value increases along the easy magnetization axis which is the closest to the field strength direction. This problem is qualitatively described in [14], where physical mechanism of this magnetization process is explained; similar comments of this process are contained in [15]. Due to changes of the magnetic field strength in the given sheet sample, reconstructions of the domain structures occur; it means that apart displacements of the 180° walls there occur also changes of the 90° walls.

Considerations were carried out with the assumption that rotations of the flux density vectors towards the direction of the field strength vectors in elementary subsegments can be neglected. So, the flux densities can change only along the easy magnetization axes of the individual iron crystals. In order to determine the flux densities in each easy magnetization axis, the values of the field strength in these axes have to be calculated with respect to the field strength occurring in the two-dimensional space of each elementary segment of the tested dynamo sheet. In this purpose we have to save the field strengths in these axes as functions of the field strength components, which are associated with the branches of the elementary segments (Figure 2). Considering e.g. the cube-on-edge texture (110) we can write the following relationships for all elementary segments (Figure 3)

$$H_{g1} = f_{hlg1}M_{hm}H_m + f_{hlg1}M_{hp}H_p \quad (3a)$$
third easy magnetization axis of the considered texture, respectively, \( f_n \) denotes nonlinear relationship between the field strength and the flux density in the form \( B = B_{sat} f_n(H) \), where \( B_{sat} \) denotes the saturation flux density of the given axis of the easy magnetization, \( f_n(H) \) is a nonlinear function of the field strength.

It is necessary to stress that the value of the saturation flux density which refers to each easy magnetization axis, does not have a constant value in contrary to proposals which have treated iron crystals as particles with only one easy magnetization axis. The saturation flux density depends on, among other, the value and direction of the field strength vector in particular elementary segments.

In order to save vectors \( B_{bx}, B_{by}, B_{bx}, B_{by} \) in (2) as dependences on the column vectors \( H_m, H_p \), the flux densities occurring in particular easy magnetization axes of all textures have to be projected on the sheet plane. Considering the chosen cube-on-edge texture we can write the following relationships

\[
B_{bx} = f_{bxg1} M_{bxg1} B_{g1} + f_{bxg2} M_{bxg2} B_{g2} + f_{bxg3} M_{bxg3} B_{g3}
\]  
\( (5a) \)

\[
B_{by} = f_{byg1} M_{byg1} B_{g1} + f_{byg2} M_{byg2} B_{g2} + f_{byg3} M_{byg3} B_{g3}
\]  
\( (5b) \)

\[
B_{tx} = f_{txg1} M_{txg1} B_{g1} + f_{txg2} M_{txg2} B_{g2} + f_{txg3} M_{txg3} B_{g3}
\]  
\( (5c) \)

\[
B_{ty} = f_{tyg1} M_{tyg1} B_{g1} + f_{tyg2} M_{tyg2} B_{g2} + f_{tyg3} M_{tyg3} B_{g3}
\]  
\( (5d) \)

where \( M \) are matrices that assign components \( B_{bx}, B_{by}, B_{tx}, B_{ty} \) to the appropriate components \( B_{g1}, B_{g2}, B_{g3} \), \( f \) are appropriate trigonometric functions.

This described algorithm allows us to transform (2) to the form that contains the functions of the column vectors \( H_m, H_p \). Using (1) we can eliminate the vector \( H_m \) and finally we obtain one nonlinear, matrix equation, where only the column vector \( H_p \) is unknown. In order to solve this equation the Newton-Raphson method is used for assumed values of the external currents as sources of the magnetic field.

The experimental system for validation of the correctness of the formulated equation, which takes into account the textures occurring in the dynamo sheets, is shown in Figure 5. The magnetic field was induced in the pack of electrically insulated dynamo sheets by two mutually perpendicular coils. For assumed value of the sinusoidal current, the voltages of the measurement coils were stored. Tests were carried out for two cases; in the first one the
Figure 5: Measurement system for indirect validation of the correctness of the equation describing the magnetic field distribution taking into account the textures, RD, TD – the rolling and transverse direction, respectively.

Figure 6: Voltages of the measurement coils in the rolling direction of the dynamo sheet M400-50A (Russia): a) both coils were supplied, b) only coil parallel to the transverse coil was supplied; continuous lines – measured waveforms, dashed lines – calculated waveforms.

Both coils were supplied but the currents were shifted in phase by 90 degree, in the second case the sinusoidal current was flowing only through the coil which is parallel to the transverse direction. These voltages were compared with the corresponding voltages calculated numerically for the same conditions, as in the experiment; this comparison is presented in Figure 6.

5 Conclusions

The occurrence of certain textures in the dynamo steel sheets is the main reason of their anisotropic properties. In order to take these properties into considerations, changes of the flux density along each easy magnetization axis of all textures should be included in the equations describing the magnetic field distribution.

It is necessary to stress that due to the variable magnetic field, the calculations of the magnetic field distribution should be performed with taking into account eddy currents. This is possible using a separate network and additional equations for these currents; however, both networks have to be coupled.

Acknowledgement: The research presented in this paper was funded by subsidies granted by Polish Ministry of Science and Higher Education under the theme No. E-2/619/2016/DS “Modeling of magnetization processes in magnetic circuits of electrical machines and devices for diagnostics and loss estimation”.

References