Magnesium Non-metallic Inclusions in Non-oriented Electrical Steel Sheets

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During routine metallographic investigations of some fully processed, non-oriented, electrical steel sheets, the typical MnS inclusions were not observed in the microstructures. In the MS-type sulphides, the manganese was substituted by magnesium. A systematic ex-situ characterisation of the non-metallic, magnesium-containing inclusions was carried out and the origin of the inclusions was proposed. The inclusions’ chemistry and morphology were investigated by light microscopy and field-emission scanning electron microscopy. The non-metallic, magnesium-containing inclusions were classified as complex sulphides, oxides and spinels. Magnesium was also detected as being co-precipitated with other non-metallic inclusions, like nitrides. The form of the co-precipitated magnesium inclusions was predetermined by the shape of the thermodynamically most stable inclusions.

KEY WORDS: magnesium; non-metallic inclusions; non-oriented electrical steel.

1. Introduction

The demand for non-oriented electrical steels will continue to grow in the coming years, and to achieve better performance with electrical devices, improved qualities of electrical steel sheets need to be developed. There have been reports about a new generation of high-permeability, low-core-loss, non-oriented, electrical steel sheets based on an improved alloy purity.1,2) In addition, the production of cleaner steels has led to a growing emphasis on the proper control of non-metallic inclusions.3)

Non-oriented, electrical steel sheets are produced from Fe–Si–Al alloys. The production process for these steels and their chemical compositions are left to the discretion of the manufacturer. It is well known, for example, that by adding silicon to iron a ferrite microstructure can be guaranteed, the electrical resistivity can be increased, the eddy-currents are diminished and the core losses are reduced.4) However, a very low carbon content is necessary to ensure the optimum grain size and to prevent magnetic aging.4)

Aluminium additions also lower the core-loss value by increasing the electrical resistivity of the steel.4) Furthermore, aluminium is the most commonly used nitrogen getter in electrical steels.5)

A classical method used by metallurgists to control both the microstructure and the texture of electrical steels is to control the precipitation of second-phase particles that are able to pin the grain boundaries.6)

In silicon steels, for non-oriented, electrical steel sheets, aluminium and manganese form AlN and MnS, respectively. These non-metallic inclusions act as grain-growth inhibitors during the recrystallization. AlN and MnS can precipitate because the solubility of the nitrogen and the sulphur in the steel decreases with decreasing temperature. In addition to Al and Mn, other elements can also form non-metallic inclusions and precipitates.7–10)

The presence of these second-phase particles plays an important role. They can have a negative effect on the primary and secondary recrystallization, the texture formation and the magnetization behaviour of electrical steel sheets.10–14)

Surprisingly, in our metallographic investigation of fully processed, non-oriented, electrical steel sheets made of Fe–Si–Al–Mn alloys, the typical MnS inclusions were not found in the microstructures. Instead, magnesium sulphides were detected.

In recent years, a number of studies focusing on the influence of different chemical elements on the morphology of non-metallic inclusions in grain-oriented and non-oriented electrical steel have been reported,7–10,11,15–17) but none of these studies looked at the influence of magnesium. The aim of the present paper, therefore, is to identify and classify the magnesium-containing inclusions in fully processed, non-oriented, electrical steel sheets by assessing their composition, morphology and origin.

2. Materials and Experimental Procedures

The samples for metallographic analyses were selected from 26 different coils of 0.5-mm-thick, non-oriented, electrical steel sheet with a nominal chemical composition: Fe – 2.1 mass% Si – 1 mass% Al. The chemical composition’s minimum and maximum values for the analysed samples are given in Table 1. The chemical composition of the samples was determined using ICP-AES emission spectrometry, gra-
For the metallographic analyses the samples were ground and polished according to standard metallographic techniques. The metallographic analyses of the non-metallic inclusions were performed using light microscopy and field-emission scanning electron microscopy. The scanning electron microscope was equipped with an energy-dispersive spectrometer.

In this study, the FE-SEM/EDS analyses of the non-metallic inclusions were performed at a 15-kV accelerating voltage. The interaction volume of the EDS at 15 kV was large enough to partially encompass the matrix along with the inclusions; however, within the detection limits of this technique.

In FE-SEM/EDS analyses the teardrop-shaped interaction volume extends from less than 100 nm to around 5 μm into the surface, depending on the element and the accelerating voltage. The factors that determine the detection limits of the EDS are the counting time, the accelerating voltage, the beam current, the line used to measure the element and the compositions of both the sample and the standards. The theoretical detection limits in SEM–EDS measurements are about 0.08 mass%, depending on the element and the sample matrix.18)

3. Results

3.1. Microstructural Analysis

Since the aim of this study was to determine the effect of magnesium on the chemistry and the morphology of non-metallic inclusions in Fe–Si–Al alloys for non-oriented, electrical steel sheets, the identification and characterization of the magnesium inclusions were performed on selected samples of fully processed steel sheets with a nominal chemical composition of Fe – 2.1 mass% Si – 1 mass%Al. The representative, non-metallic inclusions containing magnesium were analysed.

Figure 1 shows a typical microstructure of non-oriented, electrical steel sheet, composed of recrystallized ferrite crystal grains with many non-metallic inclusions. The chemical compositions of the non-metallic inclusions that were found in the microstructures were determined.

### Table 1. Chemical composition of the steel samples (mass%).

<table>
<thead>
<tr>
<th></th>
<th>%C</th>
<th>%Si</th>
<th>%Al</th>
<th>%Mn</th>
<th>%P</th>
<th>%S</th>
<th>%N</th>
<th>%Cr</th>
<th>%Ni</th>
<th>%Cu</th>
<th>%Ti</th>
<th>%Zr</th>
<th>%Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>0.003 ±</td>
<td>1.85 ±</td>
<td>0.78 ±</td>
<td>0.23 ±</td>
<td>0.010 ±</td>
<td>0.0005 ±</td>
<td>0.010 ±</td>
<td>0.11 ±</td>
<td>0.13 ±</td>
<td>0.26 ±</td>
<td>0.005 ±</td>
<td>0.003 ±</td>
<td>0.002 ±</td>
</tr>
<tr>
<td>max</td>
<td>0.005 ±</td>
<td>2.13 ±</td>
<td>1.01 ±</td>
<td>0.27 ±</td>
<td>0.020 ±</td>
<td>0.0015 ±</td>
<td>0.004 ±</td>
<td>0.44 ±</td>
<td>0.21 ±</td>
<td>0.40 ±</td>
<td>0.008 ±</td>
<td>0.003 ±</td>
<td>0.004 ±</td>
</tr>
</tbody>
</table>

N = 26 coils.
using FE-SEM/EDS. The inclusions were classified into sulphides and oxysulphides, oxides, and nitrides.

3.2. Non-metallic Inclusions

3.2.1. Sulphides and Oxysulphides

Fe–Si–Al alloys for the production of non-oriented, electrical steel sheets can contain from 0.1 to 0.3 mass% Mn, which ensures the formation of MnS. Our FE-SEM/EDS analyses of selected inclusions revealed that in typical sulphide inclusions of the MS-type there was no manganese present.

**Figure 2** shows a representative MS-type inclusion embedded in a ferrite matrix. Using X-ray elemental mapping the distribution of the elements shows the predominant presence of magnesium and sulphur in the selected elongated inclusion.

Moreover, magnesium was also detected in complex sulphide and oxysulphide inclusions. **Figure 3** presents a SE image of a typical sub-micron spherical inclusion. Its chemical composition is given in **Table 2**.

From the results of FE-SEM/EDS analysis given in **Table 2** a type of complex inclusion can be characterized. From the EDS analysis it could be determined as a complex sulphide of the (Mg, Cu),S type. Both Mg and Cu possess a limited solubility in ferrite, which decreases with decreasing temperature. Due to the high contents of magnesium and copper in these non-oriented, steel sheets the magnesium and copper can precipitate, thus forming a sulphide.

Groups of spherical inclusions were also observed in the microstructures. A small group of spherical inclusions can be seen in **Fig. 4**. Besides magnesium, sulphur and oxygen the EDS revealed the presence of calcium. The results of the EDS analysis of the inclusion from Fig. 4 are listed in **Table 3**.

**3.2.2. Oxides**

Oxide inclusions identified in the examined microstructures were predominantly spinels of the MgO·Al2O3 and MgO·Al2O3–CaO types, of irregular shapes and lengths of several micrometers. A typical spinel of the MgO·Al2O3–CaO type can be seen in **Fig. 5**. This evidently non-deformable spinel inclusion is irregular in its morphology. **Table 4** gives its complex chemical composition. Spectra 2 and 3 denote the chemical composition at two different points.

![Fig. 3. A complex (Mg, Cu),S inclusion embedded in a ferrite matrix. SEI.](image)

**Table 2.** EDS analysis of the inclusion from Fig. 3.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>Cu</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mas%</td>
<td>2.90</td>
<td>0.52</td>
<td>1.45</td>
<td>2.06</td>
<td>1.60</td>
<td>91.48</td>
<td>100.00</td>
</tr>
<tr>
<td>at.%</td>
<td>6.22</td>
<td>1.00</td>
<td>2.70</td>
<td>3.34</td>
<td>1.31</td>
<td>85.43</td>
<td>100.00</td>
</tr>
</tbody>
</table>

**Fig. 4.** (Mg, Ca)-oxysulphide inclusions embedded in a ferrite matrix. SEI.

**Table 3.** EDS analysis of the inclusion from Fig. 4.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>O</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Ca</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mas%</td>
<td>7.26</td>
<td>8.09</td>
<td>0.44</td>
<td>0.85</td>
<td>0.35</td>
<td>6.56</td>
<td>1.94</td>
<td>74.51</td>
<td>100.00</td>
</tr>
<tr>
<td>at.%</td>
<td>18.67</td>
<td>13.68</td>
<td>0.68</td>
<td>1.25</td>
<td>0.46</td>
<td>8.41</td>
<td>1.99</td>
<td>54.86</td>
<td>100.00</td>
</tr>
<tr>
<td>2 mas%</td>
<td>16.87</td>
<td>9.11</td>
<td>0.28</td>
<td>0.89</td>
<td>–</td>
<td>10.18</td>
<td>3.92</td>
<td>58.75</td>
<td>100.00</td>
</tr>
<tr>
<td>at.%</td>
<td>35.88</td>
<td>12.75</td>
<td>0.36</td>
<td>1.08</td>
<td>–</td>
<td>10.81</td>
<td>3.32</td>
<td>35.80</td>
<td>100.00</td>
</tr>
<tr>
<td>3 mas%</td>
<td>8.24</td>
<td>6.56</td>
<td>0.38</td>
<td>1.04</td>
<td>–</td>
<td>9.04</td>
<td>3.27</td>
<td>71.47</td>
<td>100.00</td>
</tr>
<tr>
<td>at.%</td>
<td>20.77</td>
<td>10.88</td>
<td>0.57</td>
<td>1.49</td>
<td>–</td>
<td>11.38</td>
<td>3.29</td>
<td>51.62</td>
<td>100.00</td>
</tr>
</tbody>
</table>
whereas spectrum 1 represents the chemical composition of the steel matrix.

3.2.3. Nitrides

In addition, the magnesium was found to be co-precipitated with nitride inclusions. In Fig. 6 an AlN inclusion is presented with the X-ray elemental mappings for Al, Fe, N, Mg, and S. Based on these results, it could be assumed that the magnesium co-precipitated with the AlN. This co-precipitation could take place at the free surfaces, e.g., at

Table 4. EDS analysis of the inclusion from Fig. 5.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>O mass%</th>
<th>Mg</th>
<th>Al mass%</th>
<th>Si</th>
<th>S mass%</th>
<th>Ca</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–</td>
<td>–</td>
<td>1.07</td>
<td>2.34</td>
<td>–</td>
<td>–</td>
<td>96.58</td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>at.%</td>
<td>–</td>
<td>2.14</td>
<td>4.51</td>
<td>–</td>
<td>–</td>
<td>93.35</td>
<td>100.00</td>
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<tr>
<td>2</td>
<td>42.41</td>
<td>3.03</td>
<td>14.40</td>
<td>–</td>
<td>0.55</td>
<td>32.11</td>
<td>7.50</td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>at.%</td>
<td>62.20</td>
<td>2.93</td>
<td>12.52</td>
<td>–</td>
<td>18.80</td>
<td>3.15</td>
<td>100.00</td>
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<tr>
<td>3</td>
<td>42.19</td>
<td>19.17</td>
<td>6.67</td>
<td>–</td>
<td>0.45</td>
<td>16.89</td>
<td>14.62</td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>at.%</td>
<td>60.35</td>
<td>18.04</td>
<td>5.66</td>
<td>–</td>
<td>9.64</td>
<td>5.99</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Table 5. EDS analysis of the inclusion from Fig. 6.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>N mass%</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35.94</td>
<td>1.58</td>
<td>57.32</td>
<td>1.31</td>
<td>3.85</td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>at.%</td>
<td>52.67</td>
<td>1.33</td>
<td>43.62</td>
<td>0.96</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Fig. 7. Polygonal inclusions in the sample of non-oriented, electrical steel sheet exhibiting a very complex chemical composition. SEI.
inclusions where a heterogeneous nucleation is favoured.

Furthermore, magnesium was also found being co-precipitated with other non-metallic inclusions containing nitrogen and oxygen. From Fig. 7 and the corresponding Table 6 the complexity of the precipitates can be seen. It is clear from the results of the EDS analysis given in Table 6 that the precipitates have a very complex chemical composition with one common aspect: all of them contain large amounts of zirconium, and smaller amounts of magnesium. The analyzed particles also contained titanium and, in certain parts, calcium was detected, as is evident from the results given in Table 6. Spectrum 5 in Table 6 represents the chemical composition of the steel matrix, which is also given in Table 1.

The results show very good agreement between the classical quantitative techniques of analytical chemistry and the FE-SEM/EDS analysis. The high concentrations of silicon in the inclusions were apparent due to the large interaction volume of the EDS technique, described in Section 2.

4. Discussion

It is well known that the non-metallic inclusions in steels can be classified as primary inclusions, formed during the refining stage, and secondary inclusions, precipitated during solidification and afterwards. Depending on the generation source, non-metallic inclusions can be endogenous and exogenous. Endogenous inclusions in steels are mainly formed in a deoxidation process, while exogenous are caused by the reoxidation of molten steel, slag entrapment and the breakdown of refractory materials.

In a systematic, ex-situ characterisation of the non-metallic inclusions of fully-processed, non-oriented, electrical steel sheets, magnesium was detected in the sulphides, oxysulphides, spinels, nitrides and other complex inclusions. The variable size of the non-metallic magnesium inclusions ranged from submicron to several micrometers in length. Most of the small, submicron inclusions were of spherical or polygonal shape. The bigger magnesium inclusions were predominantly elongated in the rolling direction. The non-metallic magnesium inclusions indentified in this case study were classified as primary and secondary formed inclusions. The examined non-metallic inclusions were of endogenous as well as exogenous origin.

Magnesium is an element with a high affinity for oxygen and sulphur. Magnesium also has a very low solubility in iron, which decreases with decreasing temperature. This low solubility of Mg in Fe is due to the very large size mismatch between the two alloy components. In addition, this magnesium has a very high vapour pressure at steelmaking temperatures.

During vacuum refining, the magnesium solubility at the steel-bath surface is only about 5 ppm, while at a depth of 1 m the apparent solubility of the magnesium is about 300 ppm. This shows that even at a very low external pressure there are thermodynamic conditions under which the reaction of magnesium with molten steel occurs.

Magnesium, which was found in the non-metallic inclusions of representative samples of non-oriented, electrical steel sheet, could originate from two sources. Firstly, from non-metallic additions to the molten steel during the processing, e.g., MgO-containing dolomite, which is used before the oxidation of C, P, Al, and Si. MgO-containing dolomite is important for the chemistry of the slag and its foaming; it leads to the formation of a slag saturated with MgO, which can minimize lining wear. Secondly, from refractories that contain magnesium oxide. These refractories are ubiquitous in secondary steelmaking and they easily interact with highly deoxidized steels.

Various reductants could act as the reducing agent for MgO, e.g., Al, C, Si. Comparing the reactions of the reduction of MgO in molten slag and in refractory material, the reaction in molten slag is more dominant.

The molten steel is deoxidized by aluminium; therefore, an aluminothermic reduction of the magnesium oxide is possible. In modern electrical steels, the aluminium content is also higher than the stoichiometric value required for the precipitation of AlN, which is necessary for the prevention of magnetic aging.

Assuming the aluminothermic reduction of magnesium oxide, the dissolved aluminium is able to reduce magnesia at temperatures higher than 1 823 K, but only when the amount of dissolved aluminium is high and when the chemical potential of the oxygen in the melt is very low.

It was reported that the aluminothermic reduction of magnesium oxide can be roughly classified into two stages. During the first stage, spinel is formed, as evident from Eq. (1).
4MgO (s) + 2Al (l) = MgO-Al2O3 (s) + 3Mg (l)........................ (1)

\[ \Delta G^{o}_1 = -423.01 + 0.275T \text{ (kJ/mol)} \] ............................. (2)

The free energy change of equilibrium reaction, \( \Delta G^{o} \), can be related to its equilibrium constant, \( K \):

\[ \Delta G^{o} = \Delta H - T \cdot \Delta S = -RT \cdot \log K \] ............................. (3)

The equilibrium constant of reaction (1) is expressed by:

\[
K_1 = \frac{a_{MgO} \cdot a_{AlO}_3 \cdot f^3_{Mg}}{a_{MgO} \cdot a_{AlO}_3 \cdot f^3_{Al}} \left[ \frac{\text{mass}\% \text{Mg}}{\text{mass}\% \text{Al}} \right]^3
\] .................................................. (4)

where \( K_1 \) is the equilibrium constant of reaction, \( a_i \) is the activity, and \( f_i \) is the activity coefficient of the component. During the second stage, the spinel can further be reduced by aluminium.25

3(MgO-Al2O3)(s) + 2Al (l) = 4MgO-Al2O3 (s) + 3Mg (l).... (5)

\[ \Delta G^{o}_5 = -390.34 + 0.285T \text{ (kJ/mol)} \] ............................. (6)

Accordingly, the equilibrium constant of reaction (5) is:

\[
K_5 = \frac{a^4_{MgO} \cdot a^3_{AlO}_3 \cdot f^3_{Mg}}{a^4_{MgO} \cdot a^3_{AlO}_3 \cdot f^3_{Al}} \left[ \frac{\text{mass}\% \text{Mg}}{\text{mass}\% \text{Al}} \right]^3
\] .................................................. (7)

The standard states of the oxides are taken as pure solids in Eqs. (1) and (5).

The strong deoxidation of molten steel by aluminium generates Al2O3 particles, which tend to form clusters and remain in the molten steel as inclusions. These are harmful, not only for the mechanical properties of steel products, but also for the manufacturing process, because they cause the nozzle-blockage problems that are encountered in continuous casting.25,30,31

If the dissolved magnesium in the melt reacts with the dissolved oxygen, it can be written as:25,27

\[ \text{Mg} (l) + O (l) = \text{MgO} (s) \] ........................... (8)

Alumina can react with magnesium oxide, thus forming spinel MgO-Al2O3. The reaction of Al2O3 with magnesium oxide is given by equation (10):27

\[ \text{Al}_2\text{O}_3 (s) + \text{MgO} (s) = \text{MgO-Al}_2\text{O}_3 (s) \] ........................... (10)

\[ \Delta G^{o}_{10} = -20.790 - 0.0157T \text{ (kJ/mol)} \] .......................... (11)

The spinel formation is also possible according to Eq. (12):27

\[ \text{4Al}_2\text{O}_3 (s) + 3\text{Mg} (g) = 3(\text{MgO-Al}_2\text{O}_3) (s) + 2\text{Al} (l) \] .......................... (12)

\[ \Delta G^{o}_{12} = -571.11 + 0.2438T \text{ (kJ/mol)} \] .......................... (13)

Spinel (MgO-Al2O3) is known as one of the most harmful non-metallic inclusions in steel. Such inclusions have a high melting point and are hard, very harmful to the quality of the final products, especially the mechanical properties and the surface quality of steels.25,26,33–35 Therefore, it is very important to avoid the formation of spinel in the deoxidation process of steel.35 It was reported that the magnesia content in ladle slag increases during the operation due to the dissolution from the refractory material.36,37

Oxide magnesium inclusions found in the examined samples of non-oriented electrical steel sheets were predominantly complex spinels of the MgO-Al2O3 and MgO-Al2O3–CaO type. Calcium is generally used for the modification of alumina inclusions.25,31 A typical MgO-Al2O3–CaO spinel is represented in Fig. 5. Its chemical composition is given in Table 4. Spinels could be classified as primary inclusions formed during the steel-refining process.

On the other hand, the presence of sulphur in the steel melt results in the formation of sulphide inclusions. The maximum volume fraction of the sulphides (and oxy sulphides) is determined by the contents of S (and O) in the melt. The typical MnS inclusions were not observed in the examined microstructures of fully processed, non-oriented, electrical steel sheets, which is evident from Figs. 2–7 and Tables 2–6. The reaction equilibrium for the formation of MnS inclusions can be written as:

\[ \text{Mn} (l) + S (l) = \text{MnS} (s) \] ........................... (14)

\[ \Delta G^{o}_{14} = -168.822 + 0.09887T \text{ (kJ/mol)} \] .......................... (15)

Due to the fact that because of the reduction of magnesium oxide the magnesium was present in the steelmaking process, and that the magnesium sulphidization energy is greater than that of manganese, MgS inclusions instead of MnS were formed.

The formation of MgS, e.g. desulphurization with magnesium, can be written as:24

\[ \text{Mg} (g) + S (l) = \text{MgS} (s) \] ........................... (16)

\[ \Delta G^{o}_{16} = -404.070 + 0.16921T \text{ (kJ/mol)} \] .......................... (17)

\[ \text{Mg} (g) = \text{Mg} (l) \] ........................... (18)

\[ \Delta G^{o}_{18} = -331.459 + 0.17209T \text{ (kJ/mol)} \] .......................... (19)

The image of a MgS inclusion embedded in a ferrite matrix is shown in Fig. 2.

Furthermore, complex sulphides of the (Mg, Cu)S type were also detected. A typical representative is shown in Fig. 3. Due to the high contents of magnesium and copper in these non-oriented, steel sheets the magnesium and copper can precipitate, thus forming a sulphide of the (Mg, Cu)S type. Both Mg and Cu possess a limited solubility in ferrite, which decreases with decreasing temperature.19 Precipitation reactions are thermally activated atomic movements induced by the change of temperature, and from a metastable supersaturated solid solution stable or metastable precipitates are formed, resulting in a more stable solid solution with a composition closer to the equilibrium.39

Complex spherical inclusions containing magnesium, calcium, sulphur and oxygen were also observed in the microstructures. They can be seen in Fig. 4. The investigated magnesium-containing sulphides and oxy sulphides are most probably the secondary inclusions, which were formed during solidification.

During the production route of the non-oriented, electrical steel sheets the magnesium also co-precipitated on other inclusions formed in the steel, e.g., the AlN and complex nitrides presented in Figs. 6 and 7.

The reaction equilibrium for the formation of AlN inclusions can be written as:
As the temperature drops during the solidification and since the solubility of Mg in ferrite decreases with decreasing temperature, magnesium could co-precipitate with AlN since the solubility of Mg in ferrite decreases with decreasing temperature, magnesium could co-precipitate with AlN

$$\Delta G^{\circ}_{298} = 319.096 - 0.1417 \cdot T \text{ (kJ/mol)}$$

$$\text{(20)}$$

$$\text{(21)}$$

5. Conclusions

In the microstructures of non-oriented, electrical steel sheets magnesium sulphides and other non-metallic magnesium inclusions were detected. However, in representative samples of fully processed alloys with the nominal chemical composition Fe – 2.1 mass% Si – 1 mass%Al, and 0.23 – 0.27 mass% Mn, the typical MnS inclusions were not observed. Complex Mg-sulphide inclusions with various contents of magnesium completely replaced the MnS inclusions.

Moreover, magnesium was present in the primary and secondary formed inclusions, which were of endogeneous and exogeneous origin. The detected magnesium can originate from two sources: non-metallic additions to the molten steel during the processing and from refractories that contain magnesium oxide.

The primary inclusions were formed during the steel-refining process and were predominantly complex spinels of the MgO·Al₂O₃ and MgO·Al₂O₃–CaO type. The secondary inclusions, formed during the solidification, were complex sulphides and oxysulphides. Moreover, during the production route of the non-oriented, electrical steel sheets, the magnesium also co-precipitated on other inclusions formed in the steel, e.g., AlN. The form of the co-precipitated magnesium inclusions was predetermined by the shape of the thermodynamically most stable inclusions.

The variable size of the non-metallic magnesium inclusions ranged from submicron to several micrometers in length. Most of the small, submicron inclusions were of spherical or polygonal shape. The bigger Mg inclusions were predominantly elongated in the rolling direction.

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REFERENCES

8) D. Steiner Petrović and M. Jenko: Vacuum, 71 (2003), 33.
19) Binary Phase Diagrams: Thermo-Calc TCFE5, database TCFE5.