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NON-ORIENTED ELECTRICAL STEEL SHEETS

NEORIENTIRANE ELEKTROPLOČEVINE

Darja Steiner Petrovič

Institute of Metals and Technology, Lepi pot 11, Ljubljana, Slovenia
darja.steine@imt.si

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Non-oriented electrical steel sheets are sheets tailored to produce specific properties and are produced from Fe-Si or Fe-Si-Al alloys. Non-oriented electrical steel sheets are incorporated into a wide range of equipment, from the simplest domestic appliances to hybrid and pure electric vehicles. Future efforts will be focused on controlling the residual elements in the steel, optimizing the hot and cold rolling, and optimizing the crystallographic texture development, with the aim to enhance the performance of the finished product.

Key words: Non-oriented electrical steel sheets, silicon steel

Neorientirano elektropločevino izdelujemo iz silicijevega jekla in iz enakega jekla, ki je legirano z aluminijem. Neorientirano elektropločevino uporabljamo predvsem za magnetna jedra električnih motorjev in transformatorjev, v zadnjem času pa tudi za izdelavo hibridnih in elektroavtomobilov. Lastnosti neorientirane elektropločevine lahko v prihodnje še izboljšamo z zmanjšanjem vsebnosti nečistoč v jeklu, z optimizacijo vročega in hladnega valjanja ter z razvojem ugodne kristalografske teksture. Dobre lastnosti elektropločevin povečujejo energijsko učinkovitost električnih naprav, v katere so vgrajene.

Ključne besede: neorientirane elektropločevine, silicijevo jeklo

1 INTRODUCTION

Soft magnetic materials are ubiquitous in the current electronics-based economy. Silicon steel was developed at the beginning of the 20th century and soon became the preferred core material for large transformers, motors, and generators. Silicon-bearing steels are used as soft magnetic materials in electrical appliances and devices and are rated in terms of power loss when magnetized in an alternating electric field. The total amount of these steels is around 1 % of the world production of steel[1]. The Worldsteel Committee on Economic Studies, Brussels, reports that the worldwide production of strip in 2008 was 10,291,000 metric tons, and in the EU it was 1,498,000 metric tons. The production of electrical steel sheet and strip in the last 10 years has almost doubled. The production of non-oriented electrical steel in Slovenia is approximately 100,000 metric tons per year.[2]

Texture is one of the most important parameters determining the magnetic properties of steel sheets. The ideal texture of *non-oriented silicon steel* sheets would be a cubic texture with grains with their (001) or (110) planes parallel to the plane of the sheet and a uniform distribution of the [100] direction, whereas the Goss texture with a (110)[100] crystallographic orientation of the grains is the typical grain structure of *grain-oriented silicon steel*.

Silicon steels are fundamental for the economy of electrical appliances, and offer the best combination for transmitting and distributing electrical energy. The properties required of these steels are a high permeability and induction, low magnetic losses, and low magnetostriction. A high permeability and induction reduce the size and weight of the parts; low magnetic losses diminish the the generation of Joule heat and energy consumption; and a low magnetostriction reduces the noise (which appears as humming) in transformers and high-capacity machines[3].

The basic technology of production for non-oriented, fully processed electrical steels has not changed significantly in recent decades: the basic chemistry is similar in terms of the main alloying elements and the processing steps are basically unchanged. Nevertheless, the losses in a steel with a given Si and Al content are today much lower compared to previous decades. Accordingly, electrical steel producers have made only very small changes to the basic chemistry used for most commercial standard grades. International and national standards only specify the maximum loss (and often also a minimization of polarization/permeability), but have in principle no lower limit to the losses. Consequently, for a given standardized grade the difference between the guaranteed maximum loss and the actual loss of the material produced has increased significantly over time. An electrical steel is a commodity product with a market price very much determined by its grade designation. From the steel user's point of view, this development has brought advantages, but it has also increased the variability in the market and it is uncertain as to what a standardized grade really is.

2 CLASSIFICATION

Non-oriented electrical steel sheets, commercially also called lamination steel, silicon electrical steel, silicon steel or transformer steel, are special steel sheets tailored to produce certain magnetic properties. They are used in the form of lamination stacks, mainly in electric motors, transformers and alternators, depending on their properties.

Non-oriented electrical steel sheets can be divided into two categories:

– fully-processed grades, which are delivered in the finished condition, continuously annealed and sometimes varnished. They have guaranteed magnetic properties, in accordance with standards,[4] e.g., EN 10106:2009.
– semi-processed grades, that are given the final annealing treatment to develop their magnetic properties by the user.

Non-oriented electrical steel sheets are usually manufactured in the form of cold-rolled sheets/strips with thicknesses of (0.35, 0.50, 0.65 and 1.00) mm and are classified according to the value of the maximum specific total loss in W/kg. The non-oriented electrical steel is supplied in stacks in the case of sheets and in coils in the case of strips (**Figure 1**).

The main types of non-oriented electrical steels produced in Slovenia, by Acroni d.o.o., Jesenice, are:

– Cold-rolled, fully-processed electrical steels – DINAMO,
– Cold-rolled, semi-processed electrical steels – ELMAG,
– Cold-rolled, fully-processed, high-permeability electrical steels – PERMAG FP
– Semi-processed, high-permeability, electrical steels – PERMAG SP.[5]

The precise technologies and metallurgical processes, combined with technical development and investments in new equipment and plants, place Acroni, d. o. o., Jesenice at the same world quality level as other leading manufacturers of non-oriented electrical steels.

The losses of many grades with a low or medium content of alloying elements have been reduced and in some cases the permeability has been increased[6]. Lean grades of non-oriented steel sheets have been developed. A lower slab-re-heating temperature, the better defined process of hot rolling and the higher final annealing temperature are processing parameters that have been used to improve the properties[6].

Figure 1: Coils of cold-rolled, non-oriented electrical steel[5] (Acroni, d. o. o., Jesenice)

Slika 1: Kolobarji hladno valjane neorientirane elektropločevine[5] (Acroni, d. o. o., Jesenice)

3 CHARACTERISTICS AND MAGNETIC PROPERTIES

The majority of reputable manufactures of electrical machines will use fully or semi-processed silicon steel with high quality. The principal quantity of interest for soft magnetic materials is the power loss under alternating current excitation (core loss) at a particular operating frequency and at a particular maximum flux density.

The electrical steel must satisfy several requirements, with priorities that depend on the specific application, such as high magnetic permeability, low hysteresis losses, the anisotropy of the losses as well the ease of cutting the laminations to shape. Various cutting processes are applied, such as mechanical and laser cutting. Mechanical cutting has been widely used in industry due to its low cost. The magnetic properties of the region at the edge are degraded after cutting. During laser cutting, rapid heating and cooling cause thermal stresses, which are also considered harmful for the magnetic properties. On the other hand, by laser cutting, the high temperatures may cause a grain growth near the cut edge, which is beneficial for the magnetic properties[7].

Steel cuts-laminations are then built into the cores. The laminations within the cores are physically rotated relative to one another in order to equalize both the reluctance of the flux paths within the material and the variations in the thickness across its width. The designs are usually optimized to utilize to the fullest the magnetic and electric loading of the active materials, copper and steel. This generally means that the steel is pushed close to magnetic saturation and the copper/ insulation system is working close to its thermal limit[8]. Electrical steel sheets are usually coated to increase the electrical resistance between the laminations, to provide resistance to corrosion or rust, and to act as a lubricant during the cutting. There are various coatings, organic and inorganic, and the coating used depends on the application of the steel.

The magnetizing properties required for an NO electrical steel sheet are achieved through measures such as the purification of steel and the control of alloying elements, the grain orientation and the grain size. When the content of an alloying element such as Si is increased, the electric resistance increases, the eddy-current intensity in the steel sheet is decreased and as result, the iron loss is reduced. However, the saturation magnetic flux density is also reduced at the same time. Thus, it is necessary to control the iron loss and the saturation magnetic flux density in a well-balanced manner.

Another factor to be considered is the influence of magnetic domains. During an *in-situ* observation of the magnetic domain structures a discontinuous movement of irregularly distributed domain walls was observed, as was the pinning of these domain walls by small oxide precipitates and their strain fields. It was considered that one of the causes of the domain-wall pinning is a reduction in the magnetostatic energy inside the precipitates. The domain walls were observed to move in curved lines around the precipitates in non-oriented steel sheet.[9,10]

The domain width increases with the increase of the grain size, resulting in an increase of the eddy-current loss. As a result, a critical grain size exists to decrease the iron loss. The relationship between the grain size and the domain-wall width is given as follows:[11]

$$d^{3/4} = \lg (\gamma/K_1)^{(\delta/1.32)}$$

d … the grain size
γ … the domain-wall energy in a unit domain area
K_1 … the magnetocrystalline anisotropy constant
d … the domain width.

If any strain or stress remains in the steel sheet, its magnetic domain structure becomes complicated, the magnetizing properties are deteriorated and the iron saturation loss is increased. Thickness also significantly influences the iron loss. The thinner a steel sheet is, the more the eddy-current intensity is decreased.[12] The eddy-current losses are proportional to the square of the frequency and the thickness of the sheet (the current loops appear in the sheet section perpendicular to the magnetic flux, and create a counter-field which opposes the induction of the induction field). But when the steel sheet is too thin, the iron loss increases rather than decreases.[12]

Magnetic polarization and specific total loss are measured by applying the Epstein method (EURONORM 118, IEC 404-2). Sometimes a single-sheet tester (IEC 404-3) may be used as an alternative[4].

4 APPLICATIONS

The laminations form the laminated cores of transformers or the stator and rotor parts of electric motors. There is a wide range of equipment in which non-oriented electrical steel sheets are incorporated, from the simplest domestic appliances to hybrid electric vehicles.

Modern technologies were developed for the hybrid electric vehicle, which is driven by an internal combustion engine and an electric motor to lower the fuel consumption and decrease the emission of exhaust gases. Electrical steel sheets used for the core of the traction motors of hybrid electric vehicles (HEV) and electric vehicles (EV) affect the performance of HEV/EV. The demand for smaller, lighter, more powerful and more efficient motors is the driving force for the development of electrical steel sheets.

5 METALLURGY

Iron-silicon alloys used for magnetic applications are known as silicon steels. The production process of these steel for NO electrical steel sheets and its chemical composition are left to the discretion of the manufacturer. The iron–silicon binary phase diagram is shown in **Figure 2**.

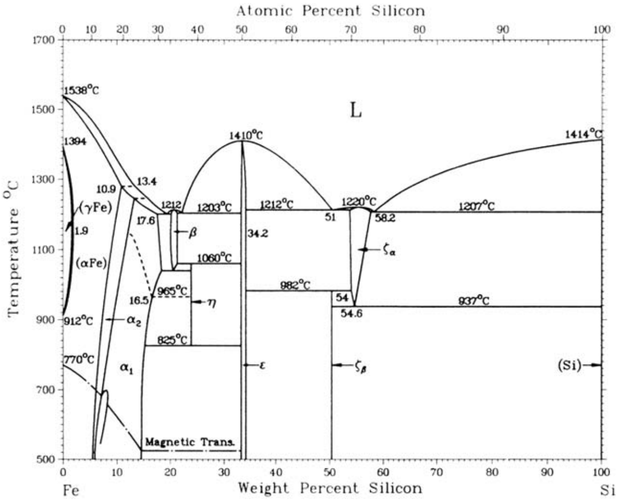

Figure 2: Binary phase diagram of Fe-Si[13]
Slika 2: Binarni fazni diagram Fe-Si[13]

The a $\alpha \rightarrow \gamma$ transformation temperature is increased and that of the $\gamma \rightarrow \delta$ transformation is lowered until the two meet at about 2.5 % Si, forming a closed "gamma loop". As a result, an alloy containing more than about 2.5 % Si is body-centered cubic at all temperatures up to the melting point. The a solid solution of the silicon in iron is often called silicon iron. The presence of carbon widens the ($\alpha + \gamma$) region, and only 0.07 % C shifts the nose of the gamma loop to about 6 % Si[14]. In practice, the carbon content in electrical steels is much lower, less than 0.01 % C. A typical microstructure of a fully processed, non-oriented, electrical steel sheet is shown in **Figure 3**.

The addition of silicon to iron has the following effects on its (magnetic) properties:[14]

1. The electrical resistivity is increased, the eddy-currents are diminished and the losses are lowered.
2. The magnetocrystalline anisotropy decreases, causing an increase in the permeability.

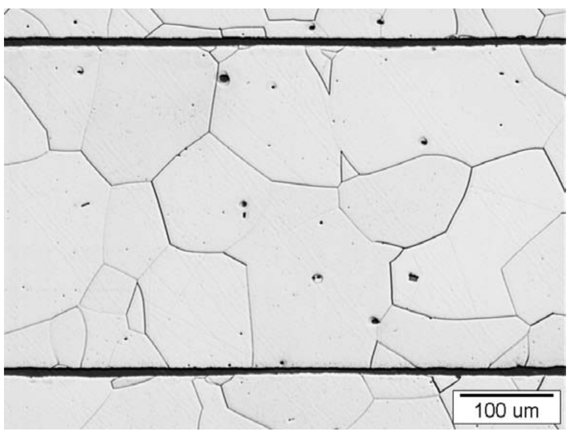

Figure 3: Polygonal grains of ferrite in the microstructure of the fully processed, non-oriented, electrical steel sheet (LM, mag. 100-times; etchant: Nital)[15]
Slika 3: Poligonalna feritna zrna v mikrostrukturi izdelane neorientirane elektropločevine (SM, 100-kratna povečava; jedkalo: Nital)[15]

3. The magnetostriction decreases, leading to smaller dimensional changes with magnetization and demagnetization, and to a lower stress-sensitivity of the magnetic properties.
4. The saturation induction decreases.
5. When the Si content is higher than 3%, the brittleness of the steel is increased and the cold deformability is significantly impaired.

Nowadays, other alloying elements instead of, or in addition to, silicon are widely used. Among them the most important is aluminium, which affects the magnetic properties of iron similarly as silicon does. For non-oriented electrical steels with aluminium addition the sum of contents of both base elements (Si + 2Al) is up to 4 % [1].

Al and Mn form the non-metallic inclusions AlN and MnS in the steel; however, impurity elements like Cu, Ti, Se, Cr, Zr etc. can also form inclusions and thus influence both the texture development and the magnetic properties.

The fabrication route for non-oriented electrical steels includes:

– for fully processed, non-grain-oriented electrical steels the process route is: steel making, casting, hot rolling, pickling with or without annealing, cold rolling in one or two steps with an intermediate annealing, final annealing and coating.
– for semi-processed material grades, a temper rolling follows the annealing. The final annealing of the stamped parts takes place at the customer's site.

With the final annealing of the semi-processed materials decarburization, surface oxidation and/or grain growth are achieved and the required magnetic properties are obtained[1].

Depending on the alloy type (e.g., silicon content) and the fabrication process, the hot rolling is carried out as austenitic, two-phase, mixed or ferritic rolling. Typically, a hot band with a thickness in the range 2.0–3.0 mm is used for the production of NO-material grades. With respect to the steel's final thickness of 0.35 mm, the total cold-rolling deformation is fixed to values smaller than 85 % [1].The hot and cold rolling in combination with the thermal treatment (annealings) and the variation of the composition of the alloy are the processing variables for achieving the required magnetic and other physical properties of the silicon steel sheets.

The decarburization of the cold-rolled steel sheets is a very important processing step because the texture development and the magnetic properties are strongly dependent on the carbon content. Iron carbides can precipitate and degrade the magnetic properties by interfering with the magnetic domain-wall motion. The slow precipitation of the carbides during service is called "magnetic aging" and can cause a substantial increase in the core losses[14]. This magnetic aging anisotropy can be associated with the crystallographic and morphological characteristics of cementite (Fe_3C) and ε-carbide ($Fe_{2.4}C$) precipitates formed during the aging treatment, taking into account the texture developed in the steel.

The decarburization is performed by annealing in a gas mixture of hydrogen and water vapor H_2-H_2O with a controlled partial pressure ratio of water vapor and hydrogen $p(H_2O)/p(H_2)$ in the temperature range from 700 °C to 900 °C. The decarburization process of steel consists of:[16]

1. Diffusion of carbon to the steel surface
2. Transport of water vapor to the steel surface and equilibration at the phase boundary steel-gas mixture
3. Dissociation of water vapor molecules into hydrogen and oxygen and adsorption on the steel surface
4. Oxidation of carbon
5. Oxidation of iron and alloying elements

The decarburization proceeds predominantly according to the reaction:

$$[C]_{Fe} + H_2O(g) = CO(g) + H_2(g).$$

The reaction:

$$[C]_{Fe} + 2\ H_2(g) = CH_4(g)$$

can be neglected at a $p(H_2O)/p(H_2)$ greater than 0.01 [17]. The thermodynamical calculations of equilibrium of complex reactions for various furnace temperatures and gas compositions have shown the conditions (gas-composition, temperature) for the formation of an oxide-scale on the surface of non-oriented electrical sheet steel during the decarburisation and thermal processing in industrial continuous furnaces[18].

While carbon is oxidized to the gases CO and CO_2, the steel surface is continually oxidized to a scale layer, which is influenced by alloying elements, affecting the oxidation process of iron. A typical oxide layer on the steel surface of an Fe-Si-Al alloy is designated by the arrow in **Figure 4**[19].

The decarburization annealing of electrical steels has a significant effect on the final magnetic properties. The process coarsens the grain size, removes the harmful

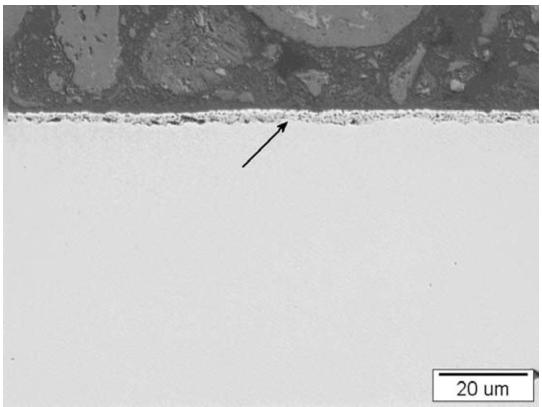

Figure 4: Oxide layer on the steel surface of an Fe-Si-Al alloy for non-oriented electrical steel after decarburization annealing (LM, non-etched)[15]

Slika 4: Oksidna plast na površini zlitine Fe-Si-Al za neorientirano elektropločevino po žarjenju za razogljičenje (SM, nejedkano)[15] effect of carbon, but it can produce a strong texture in the sheet. Namely, during the decarburization annealing of cold-rolled sheets also the recrystallization processes take place that may lead to the generation of texture components unfavorable to the magnetization and thereby adversely affect the magnetic properties of the material. The temperature profile during the decarburization process due to differences in the heating rate can lead to significant changes in the mechanism of grain-boundary motion. Some elements, e.g., antimony, decrease the solubility of the carbon in ferrite, promote the precipitation of carbides and decrease the decarburization kinetics[20,21]. For these reasons the decarburization process requires a judicious optimization, with the aim to achieve a favorable recrystallization and grain-growth process.

6 TEXTURE

Non-oriented electrical steels have been among the steel products that benefit most from texture optimization for the improvement of magnetic properties; however, the focus of processing technology has largely been on the control of grain size. Grain-size optimization has been achieved by controlling the chemical compositions and optimizing the processing variables during each processing step.

In contrast, the control of texture has received little attention; hence, there is an unexplored possibility of improving the magnetic properties of non-oriented steels through texture control. A combination of metallographic and texture analyses with the measurement of magnetic properties on annealed specimens allows the most important microstructure and texture evolution stages to be distinguished.[22]

The texture is a population of crystallographic orientations whose individual components are linked to their location within the microstructure[23].

The ideal texture for a non-oriented silicon steel is a random cube texture (001)[uv0], where each grain has the <100> plane in the sheet plane, and the properties are nearly isotropic. However, no industrial process has so far been developed to produce this ideal texture commercially. Texture improvement has been achieved mainly by reducing the volume fraction of the [111]||ND fiber, which is the main recrystallization texture component of a-iron, and increasing the volume fraction of texture components belonging to [001]||RD and [001]||ND fibers[24].

The experimental technique used nowadays to determine crystallographic information in non-oriented electrical steel sheets and other materials as well is EBSD (Electron Backscatter Diffraction) in a scanning electron microscope (SEM).

The forerunner of EBSD was first reported in the 1930s as observations of high-angle Kikuchi patterns. The biggest step forward, which was to result in the emergence of EBSD as a sophisticated experimental tool, occurred when diffraction patterns could be viewed live by video detection and indexed on-line. Nowadays, patterns from any crystal system can, in principle, be indexed automatically. A very exciting EBSD output is an "orientation map", which is a quantitative depiction of the microstructure in terms of its orientation constituents[23].

In EBSD a stationary electron beam strikes a tilted crystalline sample and the diffracted electrons form a pattern on a fluorescent screen. This pattern is characteristic of the crystal structure and the orientation of the sample region from which it was generated. The diffraction pattern can be used to measure the crystal orientation, measure grain-boundary misorientations, etc. When the beam is scanned in a grid across a polycrystalline sample and the crystal orientation is measured at each point, the resulting map will reveal the constituent grain morphology, orientations, and boundaries[25]. In **Figure 5** an EBSD orientation map of the microstructure of a non-oriented electrical steel sheet is shown.

The recrystallization texture is determined by both the orientation of nuclei in the deformed matrices and the growth rate of these nuclei into the deformed matrix. Two main theories of recrystallization texture have been currently accepted after a controversy lasting for over 50 years. The first one, oriented nucleation theory, assumes that nuclei of specific orientations are faster in forming than those of other orientations, and consequently determine the recrystallization texture. The second one, oriented growth theory, claims that there exist specific rotation relationships with rapid grain-boundary migration.

It was shown[26] for a steel with 2 % Si that the formation of recrystallization texture is explained by

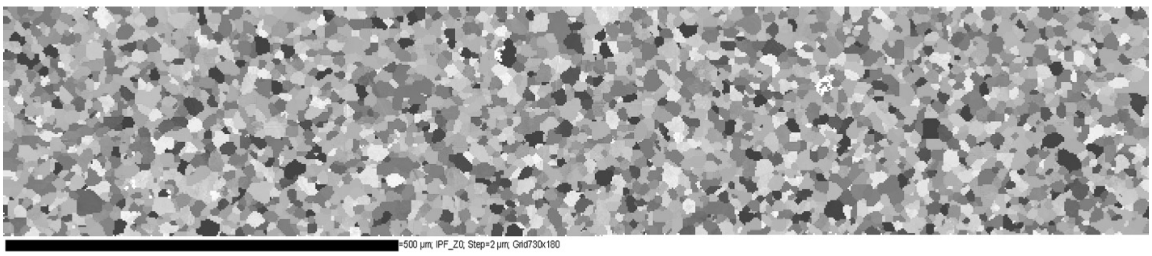

Figure 5: EBSD Orientation map of the microstructure of non-oriented electrical steel sheet (using coloring)[15]
Slika 5: EBSD-prikaz orientacije feritnih zrn mikrostrukture neorientirane elektropločevine (z uporabo barvne lestvice)[15]

oriented nucleation. Most nuclei have a high misorientation angle of 25–55° with the surrounding deformed matrices. New Goss grains are mainly nucleated within shear bands in the deformed {111}p, {111}n and {112}n grains, and the number of shear bands decreases in the same order. The nucleation of new cube grains also takes place within the shear bands. New {111}p grains are nucleated within the deformed {111}n grains and new {111}n grains originated in the deformed {111}p grains. The influence of the applied thermo-mechanical treatments on microstructure progress in the non-oriented steels was also studied. A columnar microstructure can be obtained after combining the temper rolling and appropriate annealing conditions. It was confirmed that the obtained columnar microstructure possesses pronounced cube-texture components.[27]

The evolution of the texture during the processing of silicon steels for non-oriented electrical steel sheets and the influence of small additions of the surface-active element antimony on the recrystallization and texture formation of silicon steels have been studied[28-31]. The positive effect of antimony addition to the silicon steel was reflected in a greater remanent induction and a lower coercive force, which should lead to a smaller area of the demagnetization loop and to smaller inductive-energy losses for the NO electrical steel sheet[31].

Later, the kinetics of the surface segregation of antimony in silicon steel was investigated[32] and the segregation of antimony at the grain boundaries of a-iron was also quantitatively determined[33]. It was confirmed that the positive effect of antimony on the recrystallization behavior and on the texture of the silicon steel is related to the surface segregation of antimony[34]. A similar segregation propensity was observed for tin. During the recrystallization annealing tin segregated to the surface and decreased the surface energy selectively and also selectively increased the mobility of some of the grain boundaries. By alloying the silicon steel with 0.05 % Sn, a positive effect on the texture development was achieved[35,36].

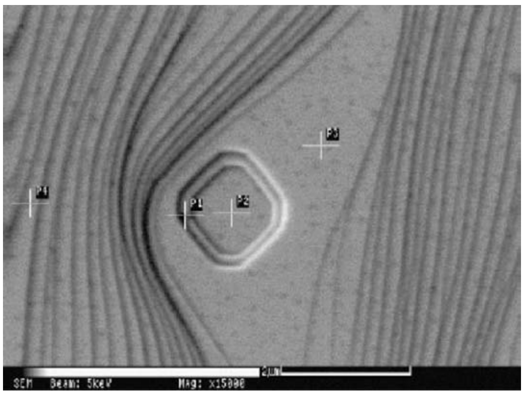

Figure 6: SE image of the surface reconstruction during the heating of a selenium-doped FeSi alloy[37]

Slika 6: SE-posnetek rekonstruirane površine med žarjenjem zlitine FeSi, legirane s selenom[37]

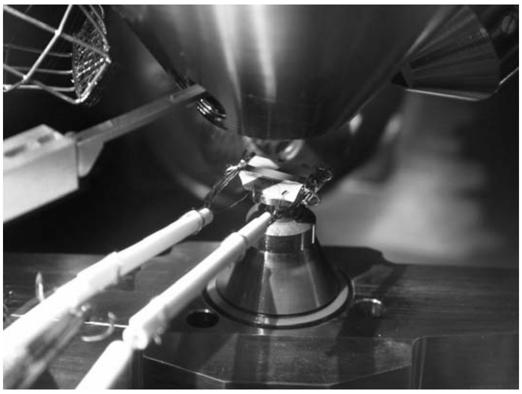

Figure 7: Resistive heating of a steel sample in the ultra-high vacuum of an Auger spectrometer for *in-situ* studies of surface-segregation phenomena; Institute of Metals and Technology, Ljubljana.[38]

Slika 7: Elektrouporovno gretje vzorca v ultravisokem vakuumu Augerjevega spektrometra, kar omogoča *in-situ* analizo procesov segregacije; Inštitut za kovinske materiale in tehnologije, Ljubljana.[38]

The surface segregation of selenium was also studied. It was found that this segregation critically affected the reconstruction of the (110) surface of the grains in the FeSi alloy, resulting in the formation of (100) planes at 850 °C (**Figure 6**).[37]

Since scrap steel is used in the industrial production of non-oriented electrical steel the content of an impurity, copper, is constantly increasing in steel. The surface segregation of copper in silicon steels was measured *in-situ* (**Figure 7**) in the analysis chamber of an Auger spectrometer[38,39]. It was found that the intensity of the surface segregation of copper increased with increasing annealing temperature (**Figure 8**) and the process of the surface segregation of copper during the annealing of Fe-Si-Al alloys was described by the dynamic equilibrium: [38,39]

Cu(dissolved) = Cu(segregated) → Cu(desorbed)

Using EBSD it was possible to determine that the mictrotextures of silicon steel sheets containing copper

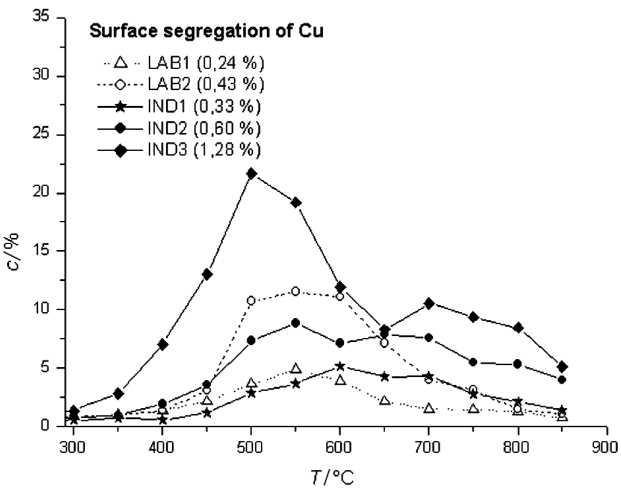

Figure 8: The surface segregation of Cu in Fe-Si-Al alloys[38,39]

Slika 8: Površinska segregacija Cu v zlitini Fe-Si-Al[38,39]

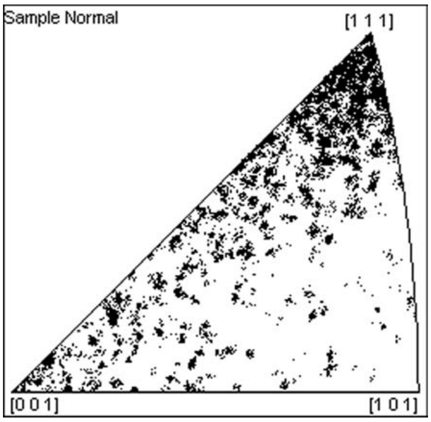

Figure 9: Inverse pole figure of an industrial, non-oriented, electrical steel containing 0.60 % Cu[38]
Slika 9: Inverzna polova figura industrijske neorientirane elektropločevine z 0,60 % Cu[38]

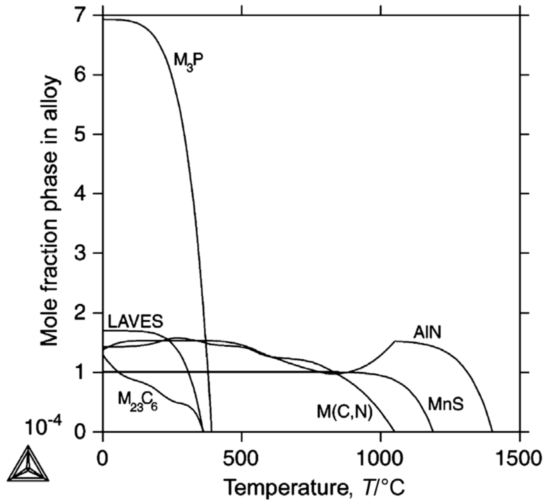

Figure 10: Precipitates in silicon steel[57]
Slika 10: Precipitati v silicijevem jeklu[57]

had fewer crystal grains oriented with the easy axis of magnetization and that grains with hard orientations were more numerous (**Figure 9**)[40].

The required texture of non-oriented electrical steel sheets can only be obtained by controlling the content of alloying and the trace elements[40–44], and the dispersion of precipitates and inclusions[45,46], which all influence the the recrystallization and grain growth processes.

7 NON-METALLIC INCLUSIONS AND PRECIPITATES

The non-metallic inclusions in steels can be classified as primary inclusions, formed during the refining stage, and secondary inclusions, precipitated during the solidification and afterwards. Depending on the generation source, non-metallic inclusions can be endogenous and exogenous. Numerous studies focusing on the correlation between the chemical composition and the morphology of the inclusions and precipitates in electrical steels have been performed over the past 15 years.[44,47–59]

The size of the non-metallic inclusions is normally around 1 µm or more. The inter-inclusion distance is much larger (micrometer scale). On the other hand, the size of the precipitates is within the nanometer range. The inter-particle distance can also be very small. These small precipitates precipitating in the solid phase deteriorate the magnetic properties of electrical steels by pinning the motion of the domain walls.[9,10]

The precipitation reactions in alloys are thermally activated atomic movements and are induced by the change of the temperature of an alloy that has a fixed bulk composition. 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.

Oxygen, sulfur, and nitrogen are chemical elements that have a decreasing solubility in iron with a decreasing temperature. To prevent any deleterious precipitation in electrical steels their content should be rigorously controlled.[44] One very harmful feature is the effect of the sulfides, carbides or nitrides in the size range 10–400 nm, which is stronger with a greater density of particles per unit volume[57].

The stability of precipitates in silicon steels depends on the temperature (**Figure 10**) and it is the greatest for AlN.[57]

The precipitation of AlN and MnS is used to control the texture development in electrical steel sheets. The presence of these particles plays an important role in the formation of the Goss texture. A classical method used by metallurgists is to add to the alloy a solute element with a low solubility, which precipitates as second-phase particles that are able to pin the grain boundaries at low temperature and allow grain growth at high temperature.

A typical AlN inclusion formed during the solidification of steel is shown in **Figure 11**.

A prerequisite for the formation of a high density of grains with the Goss texture in NO electrical steels sheets is the inhibition of recrystallized grain growth up

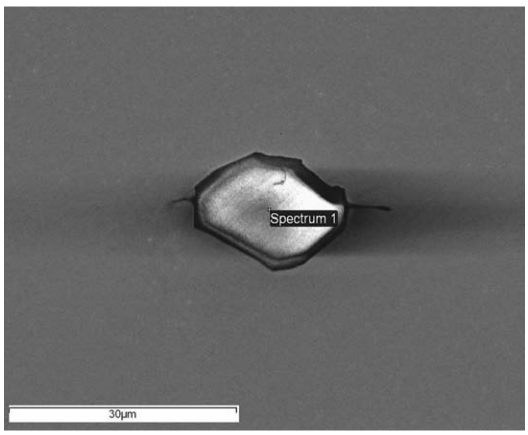

Figure 11: SE image of AlN in a non-oriented electrical steel sheet[15]
Slika 11: SE-posnetek AlN v neorientirani elektropločevini[15]

to a temperature above 1050 °C, when the conditions for the texture formation are achieved by annealing in dry hydrogen. AlN and MnS inclusions inhibit the grain growth. The solubility products are therefore very important for the texture formation. The solubility of the complex sulfide $(Mn_xFe_{1-x})S$ in a 3 % Si steel in the temperature range from 1100 °C to 1300 °C was calculated[53]. This solubility was in good agreement with the analyzed microstructures and precipitates. Some results show[50] that the particles of AlN and MnS in non-oriented electrical steel grades have grown, to some extent, in the soaking stage. The temperature range from 1000 °C to 1200 °C is appropriate for reheating before hot rolling for the majority of steels.[60] It is reported that the effect of particles AlN and MnS precipitated during and after the hot rolling is much stronger. In non-metallic inclusions in the selenium-containing, non-oriented, electrical steel sheet, both copper-selenides and complex copper-selenide inclusions were found. The complex selenides were found to grow on the nitride, oxide or oxysulfide particles in the steel[51].

Using a statistical multivariate analysis on a data set of 409 coils of non-oriented electrical steel sheet it was found that the titanium content has a strong and negative effect on the core losses, much greater than other elements. The trend of its influence is similar to that of copper[61] (**Figure 12**).

Titanium is a non-magnetic element and as such diminishes the saturation magnetization. For this reason the negative effect of titanium shown in **Figure 12** could be explained by the presence of titanium precipitates of the nitride, carbide, and carbonitride type. This is similar to the effect of copper, which has a much stronger negative effect on the magnetic properties in the form of precipitates than as present in the solid solution.

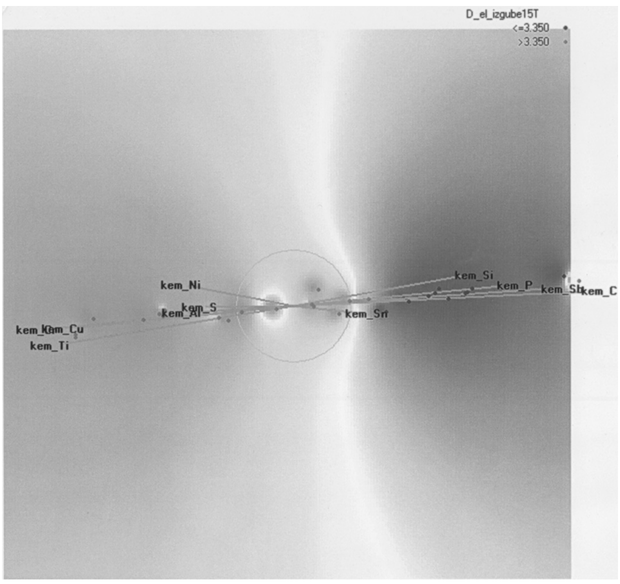

Figure 12: Influence of some chemical elements on the core losses of non-oriented electrical steel sheets[61]

Slika 12: Vpliv kemijskih elementov na močnostne izgube neorientirane elektropločevine[61]

To ensure the improved magnetic properties of NO electrical steel sheets the content of the impurity elements should be minimized[44]. Namely, the process of grain growth in the primary recrystallized matrix mainly depends on the number and the dispersion of second-phase particles[46]. Particles that are precipitated from a supersaturated solid solution can have a negative effect on the secondary recrystallization and also on the texture formation[58,59]. Nanoscale precipitates play an important role since they can hinder the process of magnetization by pinning the wall movements of the magnetic domains[62].

Generally, for good soft-magnetic properties, i.e., low losses and a good permeability, electrical steels should have as few precipitates as practically and economically possible.

Recently, a new generation of high-permeability, non-oriented grades was developed, based on an improved crystallographic texture and purity. Due to the beneficial effects of texture and purity on the core losses, the new grades could be produced with a lower alloy content (Si+Al), with positive effects on the mechanical properties, the thermal conductivity, the saturation polarization and the magnetic permeability[24].

8 CONCLUSIONS

The metallurgy of silicon steels for non-oriented electricals steel sheets is very complex. Numerous precautions must be taken during the manufacturing process. Nevertheless, the processes are now well controlled and little further improvement can be expected from simple compositional modifications. Future efforts must be focused on controlling the residual elements in the steel melts, optimizing the hot and cold rolling and optimizing the crystallographic texture development in order to enhance the performance of the finished product, since being environmentally friendly is one of the essential requirements for the future.

The market for electrical steels is large, since there is a wide range of equipment, from the simplest domestic appliances to heavy electrical engineering applications. The introduction of high-permeability products and particularly the development of hybrid electric vehicles will be a major source of the expansion of non-oriented electrical steel sheets in the future.

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