Characteristics Comparison and Selection Guide for Selected Magnetic Materials used in Electrical Machines

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Abstract —This article presents an up-to-date magnetic material investigation and overview on magnetic materials used in rotating electrical machines. The focus is on small to medium- sized high-performance and high-efficiency permanent-magnet and induction motors for different application scenarios. The investigated materials include fully processed silicon-iron, nickel-iron, and cobalt-iron lamination steels, as well as soft magnetic composites and amorphous magnetic materials. The technical focus of the article is on the magnetic properties and iron losses as well as the manufacturing influence and required thermal treatments during the manufacturing process. A new loss to flux density factor is introduced to compare the characteristic B H magnetization curve and the iron losses of different materials within the same diagram. The aim of the article is to give the machine designer an efficient material overview and selection guide during the early machine design process.

Index Terms—AC machines, amorphous magnetic materials, cobalt-iron, iron alloys, iron loss measurement, machine design, magnetic materials, nickel-iron, silicon-iron, soft magnetic composites;

1. Introduction

High-efficient electrical machines play a key role in the ongoing concerns to reduce energy consumption and to improve the efficiency of electrical devices. For the electrical machine design process, an accurate understanding of the magnetic material characteristics is a crucial requirement. General magnetic data for magnetic materials is available from the manufacturers data sheets or database collections [1]. This data is usually obtained experimentally with Ep- stein frame samples or toroidal rings, following international material characterization standards [2]. However, stator cores of rotating electrical machine have a round shape and thus a different magnetic field and magnetic flux density distribution, leading to different magnetization schemes and other iron loss hotspots.

In the first part of this article, a broad overview and comparison of possible magnetic materials for high-performance machines is presented. The investigated materials are listed in Table I on the following page. More specialized materials like extra thin high-silicon-iron (SiFe), nickel-iron (NiFe) and cobalt-iron (CoFe) alloys are compared together with soft magnetic composite (SMC), amorphous materials, and a typical non-oriented silicon steel lamination material of grade M400-50A. Furthermore, a new evaluating schematic for an easier magnetic material selection is introduced. In this schematic, both the magnetization curves and iron losses can be studied in the same diagram, which leads to a facilitated material selection process.

In the second part, material deterioration during the machine manufacturing process is discussed together with healing possibilities by heat treatments. The material properties from the data sheet may be significantly different compared to the properties of the final assembled machine [3]. The stacking and welding influence is evaluated experimentally for NiFe and SiFe materials. Experiments also show that the final heat treatment of NiFe and CoFe at specific temperatures and in a special atmosphere is indispensable to achieve advantageous magnetic properties for high flux density demanding applications such as electrical machines.

2. INVESTIGATED MATERIALS

The investigated materials in this paper are shortly introduced in the following subsections and a technical overview is presented in Table I. In the table, the materials are ranked based on their general market price for

fully-finished lamination sheets (most expensive first). Amorphous ribbons and soft magnetic composite are also listed and placed last in the table. Furthermore, general magnetic and electric parameters are given as well.

Cobalt-iron (CoFe)

CoFe is generally the most expensive alloy due to its high cobalt content. If alloyed with iron, cobalt reaches the highest maximum saturation magnetization of all materials at room temperature (2.43T for a 35% Co and 65% Fe alloy [4]). A typical CoFe alloy for electrical machines is presented in Table I with a typical composition of 48-50% cobalt, around 48% iron, and 2% vanadium. However, it should be mentioned that even for this typical composition there are different grades available, which differ in terms of other alloy additions and annealing behavior.

With a larger maximum flux density, it is possible to design electrical machines which are significantly reduced in size and in weight, respectively, which can in turn lead to electrical machines with very high power densities. CoFe materials are mainly used in machine cores for aviation and space applications, where a reduction in weight pays for the higher price. A similar use is observed for electric and hybrid systems in motor sport applications.

The mechanical strength of the material versus lower iron losses and a larger magnetic permeability can be controlled by either varying the ratio between the cobalt and iron content in the material [4], by additional alloying the material with Niobium, or by changing the temperature cycle during the annealing process [5], [6]. This is further discussed in Section IV.

Nickel-iron (NiFe)

From the cost point of view, NiFe alloys lie generally in between CoFe and SiFe lamination sheets. NiFe laminations are a good choice if iron losses are a key factor, e.g. for small high-speed machines. The strongest advantage is their very low magnetic coercivity, which leads to a superior relative permeability μ_r compared to CoFe and SiFe materials. However, a drawback is the low saturation and small maximum flux density, as shown in Table I. Typical NiFe laminations for electrical machines have a nickel content of 40-50%, where a higher nickel content typically leads to a larger permeability. However, the electric conductivity and thus eddy current losses are also increasing with nickel content [11]. The investigated NiFe lamination in this article is NiFe with 40% nickel and 60% iron, which is also further investigated in Section IV. Among the presented materials in this paper, this NiFe has the lowest Curie temperature (360◦ C) [4].

Silicon-iron (SiFe)

The most widely used material in electrical machines is iron alloyed with some amount of silicon. It is available in a grain-oriented state (i.e. the material is anisotropic and has a different permeability in different directions) or a non-oriented state (i.e. almost isotropic magnetic properties in all directions [12]).

Electrical transformers usually use grain-oriented magnetic materials due to their unidirectional flux change in the core legs and yoke. In contrast, rotational electrical machines mainly use non-oriented materials since the flux direction is generally not unidirectional but changes direction (it rotates in the stator yoke). In large electrical machines, where the stator is constructed of several yoke parts, or in research projects dedicated to smaller electrical machine topologies, such as axial-flux machines, grain-oriented SiFe material might be used as well [13]–[15]. However, the vast majority of electrical machines are manufactured from non-oriented grades. Therefore, this article concentrates in the following only on non-oriented SiFe materials.

The non-oriented SiFe material can be ordered from the steel mills as semi-processed or fully processed material. The first mentioned one usually does not go through a final annealing process and is delivered without any coating. These two production steps are done at the machine manufacturers' side after the cutting/stamping of the lamination. On the other hand, fully processed non-oriented SiFe is sold fully annealed and with the desired

coating. Since the focus of the study is on comparing typical material characteristics for electrical machines, only the fully processed material is regarded in the following analysis.

For non-oriented SiFe lamination sheets, the iron content varies between 93% for highly alloyed SiFe, and up to 99% for low SiFe steels. The remaining content of SiFe is then amongst others silicon (Si) with weight % contents up to 6.5%, aluminum (Al) up to 1%, and manganese (Mn) up to 0.5%. The silicon makes the iron mechanically harder and increases the electrical resistivity. The downside is a slight decrease in the saturation magnetization and smaller permeability [16]. Aluminum has a similar increasing effect on the electrical resistivity but also lowers the permeability of the material. A higher manganese content leads to larger grains and thus a higher permeability, but increases the losses as well [17].

Non-oriented SiFe with a (relatively) high silicon-content (up to 6.5%) are mostly used for high-speed machines due to their large electrical resistivity and thus low eddy current losses. However, the silicon content not only reduces the maximum flux density and permeability, it also makes the alloy more brittle, leading to more complicated and expensive manufacturing processes. The investigated material for 6.5% SiFe has a uniform distribution of the silicon content. Other materials with a non-uniform material distribution are not regarded in this study.

Less expensive and capable of higher flux densities are so called thin SiFe alloys (0.1mm to 0.27mm thickness). They have around 3% silicon content and thus a lower electrical resistivity. However, the small lamination thickness still keeps the eddy current losses low at the cost of larger core assembly efforts and thus production costs, compared to thicker non-oriented SiFe laminations. The vast majority of industrial machines are manufactured with standard non-oriented SiFe laminations, having silicon contents of 0.5% to 3%. Sheet thicknesses of 0.5mm or thicker keep the manufacturing costs low and give, in most cases, a good compromise between efficiency and costs for general industrial machines. Non-oriented SiFe is usually not annealed for industrial electrical machines due to the low performance increase with regard to the annealing costs and increased manufacturing time [18].

Amorphous iron

Amorphous magnetic materials (often also called metallic glass) have the advantage of very low iron losses due to their very thin foil structure (typically 0.025mm thickness) and low manufacturing process costs [19]. Instead of the typical hot and cold rolling procedures for forming the steel sheets, the amorphous material is usually produced by melt spinning. In this single step process the molten alloy composition is dripped on a fast spinning internally cooled wheel having a controlled temperature. The amorphous state of the material is achieved by the rapid cooling process (up to $10 \times 106 °C/ s$) when the molten alloy touches the cold wheel surface. This quenching process fixes the iron molecules in their current position, leading to the amorphous structure without any crystalline order in the material. The non-crystalline structure gives also a higher resistivity, about 3 times compared to typical SiFe lamination sheets. The thickness and width of the amorphous materials are limited by the equally distributed dripping and cooling properties during the manufacturing process [4]. The typical application areas of amorphous materials are in electronics and sensors [20]. However, iron based amorphous material is nowadays also used in premium distribution transformers and tested in small high-speed machine applications [21], [22]. Publications about electrical machines with stator cores made of amorphous material are typical in the range of 10W to 5kW. The machine cores build from amorphous materials are typically not stacked in the same way as general steel sheet lamination due to their very small sheet thickness, even if prototypes were built in this way [23], [24]. More research is focusing on new core geometries, incorporating the amorphous material as pre-manufactured stacks and rings [25], [26], as it is similarly done for transformer cores [27]. For cutting, water- jet technology or shearing is often recommended in order to avoid a local recrystallization of the material due to induced heat. The same yields for the core assembly, where epoxy resins are the preferred method for creating solid cores [24], [25]. An annealing inside a magnetic field is not mandatory for amorphous materials but advised in order to achieve best possible

magnetic properties and a desired anisotropy direction [28]. However, an annealing process makes the sheets mechanically more brittle and thus more difficult to handle during the rest of the manufacturing process.

Soft magnetic composites (SMC)

Special attention has to be paid to soft magnetic composites, which consist of a powder of very small isolated iron particles. Machine parts made of this material are not produced as stacked lamination sheets but directly pressed together to single-part or multi-part machine cores. The advantage of the powder is the possibility for special machine geometries with three-dimensional flux paths [29]. However, the arbitrary geometries are limited by the compacting process ability to achieve a uniform pressure and thus density in the manufactured part. Furthermore, the mechanical strength of SMC materials is in general lower compared to laminated magnetic materials [30]. From the electromagnetic point of view, SMC materials have a very high resistivity. This leads to low eddy current losses, which is a significant advantage in high frequency applications. The downside is its relatively low permeability and flat BH magnetization curve, leading to relatively small maximum flux density values at typical magnetic field strengths in electrical machines [31] [32]. SMC material is preferable used for electrical machines where a three-dimensional flux distribution has advantages, e.g. in transverse flux and in axial flux machine designs. Further information about the compositions of SMC materials and possible future developments are described in [29], [33].

3. MATERIAL COMPARISON AND DETERIORATION INFLUENCES

Due to the saturation effect in ferromagnetic materials, electrical machines are generally designed to work just below the saturation knee point of the BH magnetization curve, as it is shown in Fig. 1. However, since the BH magnetization curve is different for each magnetic material, the machine geometry has to be adapted to have an efficient material utilization in terms of ohmic winding losses (efficient current use) and the volume and weight of the core (efficient core material use).

Material manufacturers provide in general typical magnetic and physical data of their lamination steels. Electrical machine designers can use this data in the early stages to compare different materials in terms of BH magnetization curves and iron loss densities. However, it is difficult to evaluate both parameters at the same time.
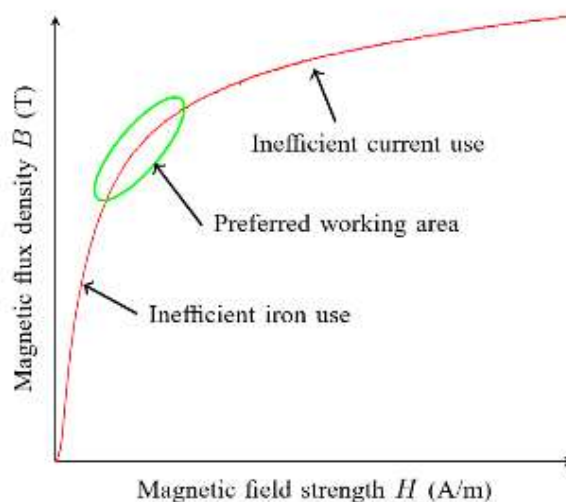

Fig. 1. Machine operating points on the initial hysteresis magnetization curve.

TABLE I
TYPICAL MAGNETIC MATERIALS USED IN ELECTRICAL MACHINE CORES [1], [7], [8], [9], [10].

Sample	Material Type	Material Composition	Sheet thickness [mm]	Flux density @ 0.8 kA/m [T]	Flux density @ 2.5 kA/m [T]	Resistivity [μΩcm]	Material density [g/cm³]
A	Cobalt-iron (CoFe)	49% Co, 49% Fe, 2% V	0.2-0.5	2.1	2.23	40	8.12
B	Nickel-iron (NiFe)	40% Ni, 60% Fe	0.1-0.5	1.44	1.48	60	8.2
C	High Si content SiFe	6.5% Si, Fe bal	0.1-0.2	1.29	1.4	82	7.49
D	Thin non-oriented SiFe	3% Si, 0.4% Al, Fe bal	0.1-0.3	1.15	1.63	52	7.65
E	Non-oriented SiFe	1-3% Si, Fe bal	0.35-1		1.64	20-60	7.6-7.8
F	Amorphous iron	20% (Si + B), 80% Fe	0.025	1.55		130	7.18
G	Soft magnetic composite (SMC)	< 1% lubrication, Fe bal	solid material	0.71	1.22	20000	7.57

In order to help choosing the best material for a certain machine design, a loss-to-squared-flux- density (PB2) factor is introduced. This factor is defined as the specific iron loss density (W/kg) over the square of the flux density (T^2), yielding (W/kg/T^2). Fig. 2 gives a comparison of the BH magnetization curves for the materials listed in Table I, together with the PB2 factor at 50Hz and 400Hz.The data is collected from several material manufacturers. The idea flux density, which allows a visual representation of its value in the BH magnetization curve by filled circles of different sizes. This means the area of the filled circles is proportional to the PB2 factor and the trend of the iron losses in the material is represented by the PB2 factor which is almost independent of the flux density B. For a given material and frequency, a variation of the circle size means that the specific iron losses are not proportional to the square of the flux density B

Furthermore, the size of the circles reflects the iron loss dependency of different materials with the frequency as it can be seen by comparing Fig. 2a and Fig. 2b. Finally, to get a rough estimation about the absolute value of the specific iron losses, the circles are mapped to a color bar below the x-axis. This also helps to identify the specific loss range of the different diagrams for different frequencies. A visual comparison between materials is possible and gives an objective material grading to select the most suitable material for a certain machine application in terms of magnetic saturation, material utilization, and iron losses. The size of the circles is scaled with a constant factor to fit the comparison between the different materials in a linear way.

From Fig. 2 it can be seen that the non-crystalline amorphous material has by far the lowest iron losses (darkest and smallest circles). For the crystalline materials, the two most expensive materials NiFe and CoFe, are at 50Hz also the best in terms of iron losses and saturation magnetization (largest magnetic flux density), respectively. For larger frequencies (400Hz), very thin and high alloyed SiFe (6.5% Si) can reach the same level of iron losses as the investigated NiFe sheets. However, NiFe sheets with a nickel content of 48% and higher reach typically even lower iron loss values.

(a) Iron losses at 50 Hz
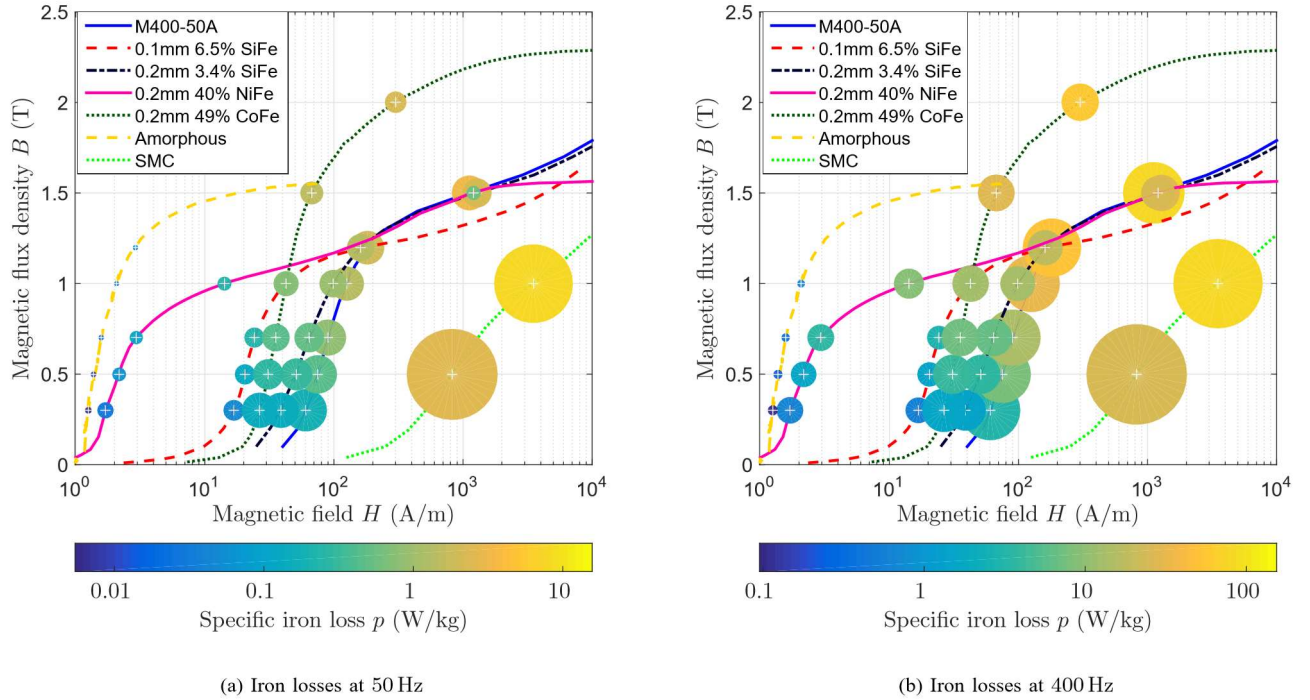
(b) Iron losses at 400 Hz

Fig. 2. Loss-to-squared flux density factor PB2 for typical electrical machine materials with the specific iron losses at 50 Hz and 400 Hz.

However, machine designers should be aware that the magnetic materials in the manufactured motor may show quite different properties than expected due to the deterioration during the manufacturing process. This is due to the fact that the manufacturer data does not take into account the stresses from cutting and welding or other manufacturing steps [34], [35]. It should be added as well that different materials react differently to each manufacturing step and other influences due to a different sensitivity to mechanical and thermal stress. Laser cutting, typically used in prototyping and small production series, introduces a thermal stress on the cut edge of the lamination sheet. On the other hand, punching, usually used in larger scale production, introduces a mechanical stress on the cut edge [36]. Regarding the change in iron losses due to the welding process, e.g. NiFe alloys are more sensitive to mechanical stress and have a larger percentage loss increase than SiFe alloys [37].

Factors influencing the iron losses and magnetic properties for typical SiFe lamination sheets are given in Table II. In this table, P_{hyst} denotes the hysteresis losses, P_{ec} the classical eddy current losses and P_{exc} the excess losses, according to the loss separation approach from [38]. J_s and H_c are the saturation magnetization and the coercive field strength, respectively. It can be seen that the hysteresis losses are mainly influenced by the manufacturing process and resulting internal stresses. Larger magnetic grains result in better magnetic properties and a decrease in hysteresis losses. This decrease is usually more pronounced than the loss increase of the excess losses due to larger grains.

Still looking at Table II, it is interesting to observe that the sheet thickness has an impact on the hysteresis losses, even if an explicit dependence to the thickness is not present in the hysteresis loss formulations. A detailed explanation of the relationship between material thickness, material impurities and hysteresis losses can be found in [43].

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TABLE II
INFLUENCE OF DIFFERENT PHYSICAL AND MANUFACTURING FACTORS ON
TYPICAL SIFE LAMINATION SHEET PROPERTIES [3], [4], [17], [39]–[42].

Influencing Factor	P_{hyst}	P_{ec}	P_{exc}	J_{s}	H_{c}
Grain size (d_{grain} ↗)	↘		↗		↘
Sheet thickness (d ↗)	↘	↗			↘
Internal stress (↗)	↗				↗
Cutting/punching process	↗				
Impurities (↗)	↗			↘	↗
Alloy content (%Si ↗)		↘		↘	↗

TABLE III
ANNEALING PARAMETERS OF COFE AND NIFE STATOR CORES.

| Sample	Annealing Temperature	Annealing Atmosphere
A1 (CoFe)	no annealing	H_2
A2 (CoFe)	2 h at 760 °C	H_2
A3 (CoFe)	3 h at 850 °C	H_2
B1 (NiFe)	no annealing	H_2
B2 (NiFe)	5h at 1150 °C	H_2

4. TREATMENT OF LAMINATED MATERIAL

During the manufacturing process, the cutting effect deteriorates the material to a certain degree. A thermal treatment process (annealing) can, to a great extent, restore this deterioration of the magnetic properties. Therefore, it is mainly a question of the cost if annealing should be applied [44]. In many instances, fully processed SiFe, amorphous materials, and soft magnetic composite materials may be used without a post-manufacturing annealing process, in order to keep the manufacturing costs low. However, for materials such as CoFe and NiFe, the annealing process is indispensable in order to obtain the desired magnetic properties at all.

For these materials, a trade-off has to be made between the magnetic and mechanical properties of the material. Higher annealing temperatures support the grain size growth, leading to better magnetic properties and higher saturation magnetization. But, on the other hand, larger grain sizes reduce the mechanical strength of the material and its hardness. Thus, the annealing process should be adapted to the needs of the machine design requirements [45]. Microscopic investigations (optical and electron backscatter diffraction measurements) are applied to show the change in the magnetic properties due to the heat treatment. Samples A and B are annealed according to the data in Table III.

The grain structure of the materials is studied in a microscopic analysis before and after the described annealing process. The magnetization of ferromagnetic materials are heavily depending on the magnetic domains, which are related to the grain structure of the ferromagnetic material. Larger grains are in general an indication for better magnetic properties in terms of saturation magnetization and magnetic coercivity. It should be mentioned that with the method of laser scribing, the large grains can be split, leading to a decrease in iron losses of typical SiFe lamination sheets. However, for NiFe and CoFe lamination sheets, the laser scribing does not show a significant improvement, as compared to SiFe [46].

The NiFe alloys were investigated by the Electron Back Scattered Diffraction (EBSD) method. Fig. 3 shows the grain structure. The colors are related to the pole figure shown in the lower right corner of the figure. No detailed grain structure is noticeable before the annealing process. However, after the annealing process with a temperature of 1150◦ C, the grains reach sizes of up to 200μm in diameter.
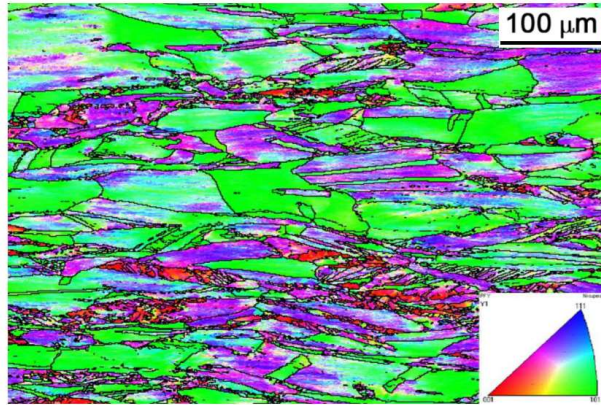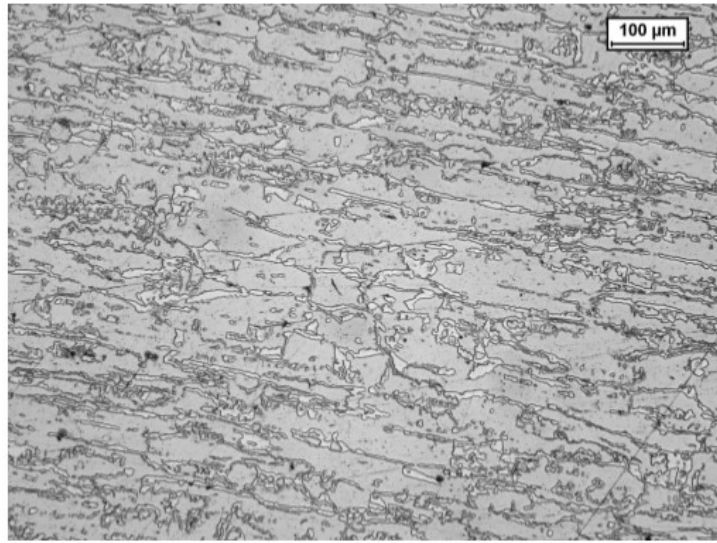
(a) NiFe Sample B1 - no annealing
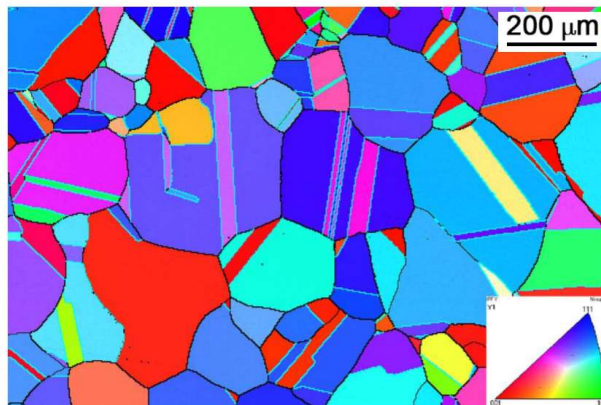
(b) NiFe Sample B2 - 5h at 1150 °C

Fig. 3. Grain structure of NiFe sheets before and after the annealing process.

For CoFe laminations, the micrographic structure also changes with different annealing processes. An optical mi- croscopic study of the three investigated CoFe samples from Table III is shown in Fig. 4. A grain structure is not recognizable for sample A1 (not annealed), while for sample A2 (annealing for 2 h at 760◦ C) and sample A3 (3 h annealing at 850◦ C) the structure is well defined. Grain sizes of up to 20µm and 100µm, respectively, are reached for the annealed samples.

(a) CoFe Sample A1 - no annealing
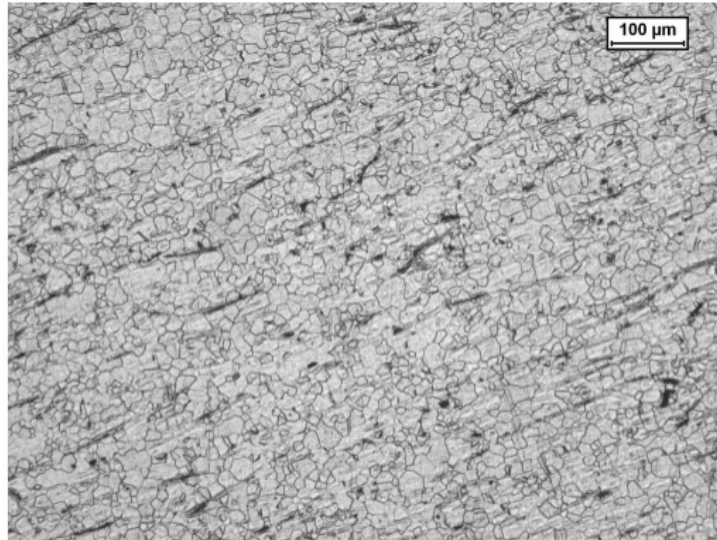
(b) CoFe Sample A2 - 2 h at $760\,°C$
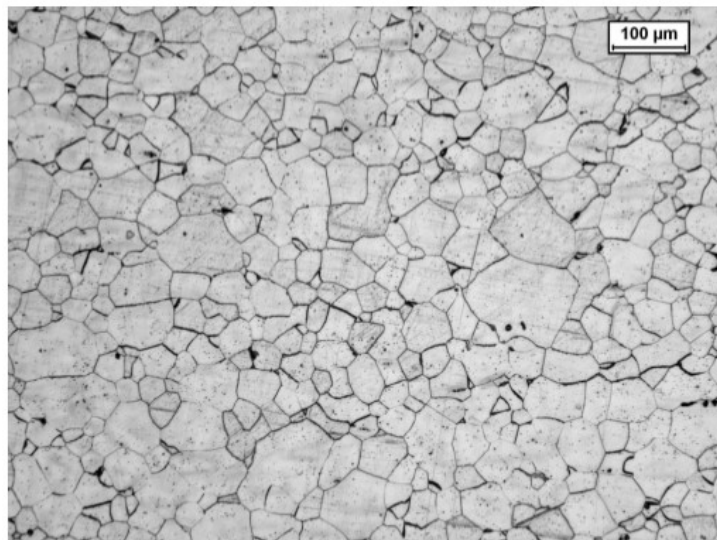
(c) CoFe Sample A3 - 3 h at $850\,°C$

Fig. 4. Grain structure of CoFe sheets without annealing and with different annealing time and temperatures, respectively.

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Fig. 5 shows the influence of the annealing on the magnetization curve of the studied 0.2mm thick CoFe and NiFe laminations. It is clearly shown that the annealing process is indispensable for obtaining the full magnetic performance of the lamination sheets. For crystalline materials, the results of the two topologies of materials confirm the link between larger grain material structure and improved magnetic properties, such as an increased permeability and saturation magnetization. Furthermore, even if not shown here, the iron losses of the studied lamination sheets were also significantly improved after the annealing process. This is in line with the publications about the annealing effect on SiFe lamination sheets, where the hysteresis losses are significantly reduced after the annealing process [47], [48]. The annealing process relieves mainly the imposed stress from cutting and punching the material, but the magnetic grains are also growing during this process [49]. Both mentioned factors influence basically only the hysteresis losses, as it is also shown in Table II. For the electrical machine performance, the annealing process usually leads to a reduction of iron losses as it is shown in [50].
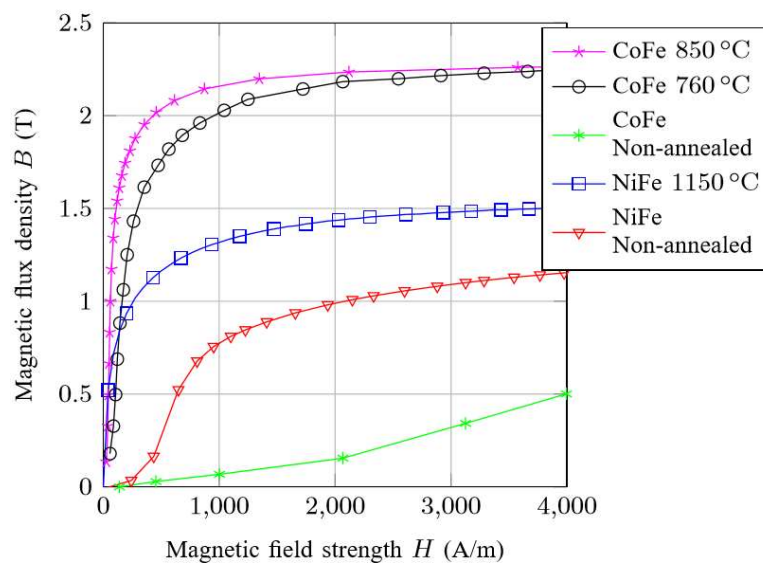

Fig. 5. Annealing influence on CoFe and NiFe initial BH magnetization curves.

5. CONCLUSIONS

Different soft magnetic materials such as CoFe, NiFe, SiFe, as well as amorphous magnetic materials and soft magnetic composites (SMC), were compared. A new evaluation scheme, the loss-to-squared-flux-density (PB2) factor, was introduced for fast and simple soft magnetic material comparisons. Furthermore, the indispensable annealing process and its influence were studied for CoFe and NiFe laminations by magnetic and microscopic measurements. Finally, articles investigating the influencing factors of the electrical machine manufacturing process such as cutting, punching and welding were collected and their main conclusions discussed.

6. ACKNOWLEDGMENT

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