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Performance Factor Comparison of nanocrystalline, amorphous and crystalline soft-magnetic Materials for medium-frequency Applications

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The efficiency of electromagnetic devices is influenced by the losses of the applied soft-magnetic material. Different structured materials are available. Choosing the most appropriate material for a medium frequency application is not intuitive. Electromagnetic circuits of power transformers or electric motors are usually made of conventional silicon-iron sheets. Higher power densities can be achieved by an increased operational frequency, but the loss density increases with higher frequencies as well. Amorphous and nanocrystalline materials benefit from reduced eddy current losses at higher frequencies. In this paper, a performance factor is evaluated to determine the suitability of each material in a frequency range up to 10 kHz. The geometric parameters of electromagnetic designs depend on the applied material. A performance factor may help to identify the most appropriate material at a specific frequency. The final application is a medium frequency transformer. The losses of the magnetic materials are measured by using standardized measurement equipment such as single sheet tester or Epstein frame. A semi-physical iron loss model is used to describe the measured losses. These results are used to determine the performance factor.

***Index Terms*—Magnetic materials, material modelling, medium frequency application, performance factor**

I. Introduction

The iron losses of soft-magnetic materials depend on many factors such as the material parameters, the applied frequency, and the peak flux density. Conventional materials such as silicon-steels are established in applications with frequencies below 1 kHz. Non-oriented silicon-steel is used in case of electrical machines, where the direction of magnetic flux is varying. The magnetic cores of common grid transformers, which operate at 50 Hz or 60 Hz, are usually constructed of grain-oriented silicon-steel due the reduced iron losses along the rolling direction. The introduction of amorphous and nanocrystalline materials enabled new possibilities to design electromagnetic circuits for devices such as power transformers. To reduce the no-load losses of grid transformers, one approach is to apply amorphous core material [1]. According to [1], the core price was up to 40% more expensive than its silicon-steel counterpart in 2010. With increasing electricity prices, grid devices with higher material cost but lower losses will make good economic sense.

At higher frequencies, amorphous and nanocrystalline materials can be more beneficial. When compared to standard silicon iron, these materials benefit from reduced eddy current losses due to thin layer widths [2]. Eddy current losses are proportional to the square of the frequency and they can increase to the major part of the overall losses at high frequencies. In addition, loss components such as hysteresis losses and excess losses [3] with their individual dependency on frequency and flux density also influence the total losses. Different alloys, process of machining, and annealing processes all result in different grain sizes [4], which influences the quantity of these loss components. An iron-loss prediction [5] is used to describe the individual loss components for all studied materials. The IEM-5-Parameter iron-loss formula, which is based on semi-physical parameters, allows a comparison of hysteresis, eddy current, excess and non-linear loss terms independently which is not possible by using the Steinmetz equation [6].

The design processes of magnetic devices such as transformers are described in [7]. The required area product A_p is calculated and a predesigned magnetic core is chosen from a manufacture. Design concepts for medium frequency applications are not well represented and a material choice for a medium frequency application is therefore not intuitive. In addition, higher operational frequencies result in compact designs, but high specific losses make the designer to choose a lower operational flux density, which increased the required volume. Amorphous and nanocrystalline materials do have low saturation flux densities, which can be disadvantageous at low frequencies, but the operational flux density at higher frequencies can be increased due to the reduced iron losses when compared to silicon-iron. The material choice for a medium frequency application is also difficult due to the different material costs.

The performance factor $\mathcal{F}$ [8] is the combination of flux density and frequency and describes the utilization of a material under the boundary of a limited iron-loss dissipation. This paper evaluates the performance factor also in a third dimension, which describes different loss limits. The IEM-5-Parameter model is used to extract the required information. The material parameters are extracted from a mathematical fitting process. The material measurements are performed with standardized Epstein frames or a standardized ring coil testing module for frequencies up to 10 kHz.

II. Performance Factor

Choosing for the most appropriate material grade is difficult and needs to be examined for each design and application. One way to compare different materials as a function of the frequency is to evaluate their performance factor. Examples for the comparison of ferromagnetic materials are given in [8] and [9], and ferrites are compared in [10]:

$$\mathcal{F} = Bf. \tag{1}$$

The multiplication of the maximum allowed peak flux density B and the sinusoidal frequency f describes the performance factor $\mathcal{F}$. The evaluation of an allowed flux density requires detailed information about the occurring losses in a material and the information about a loss dissipation boundary value is mandatory. Equation (1) is also present in Faraday's law and describes the compactness of a magnetic circuit. The cross sectional area A is calculated in (2) by the root mean square voltage V_{rms} and the number of turns N.

$$A = V_{\mathrm{rms}} \Big/ \left(\frac{2\pi}{\sqrt{2}} \cdot B \cdot f \cdot N \right) = V_{\mathrm{rms}} \Big/ \left(\frac{2\pi}{\sqrt{2}} \cdot \mathcal{F} \cdot N \right) \tag{2}$$

III. Measurements and Materials

The measurements are performed with standardized Epstein frames or a ring coil testing module according to DIN EN 60404-2 [11] and DIN EN 60404-6 [12]. All measurement instruments are limited to a maximum flux density of 2.0 T and a maximum frequency of 10 kHz. The studied specimens are one nanocrystalline, one amorphous and two crystalline alloys. We performed quasistatic measurements and sinusoidal measurements with frequencies up to 10 kHz to identify the required loss parameters for the IEM-5-Parameter model.

TABLE I
Overview of the Studied Specimens

Name	Material grade	Type of specimen
Vitroperm 500F	nanocrystalline	Core, l_m = 178 mm
2605SA1	amorphous	Core, l_m = 100 mm
H80-23L	GO, silicon steel	Epstein
10JNEX900	NO, silicon steel	Epstein

NO = non-oriented. GO = grain-oriented. l_m = Magnetic path length.

Table I lists the studied specimens. Due to the low saturation, flux density of nanocrystalline materials and the abrupt transition from linear to saturated material behavior, the non-linear loss term (a_3 and a_4) is neglected in this case. Apart from that, the parameters $a_1 - a_5$ and α are identified by a mathematical fitting process done on measured data sets of iron losses. The resulting parameters and the calculated parameter a_2 are summarized in Table II.

TABLE II
Identified Materialparameters for IEM-5-Parameter Model

	a_1 $\cdot 10^{-3}$	a_2 $\cdot 10^{-6}$	a_3	a_4	a_5 $\cdot 10^{-3}$	α
Vitroperm 500F	0.58	0.07	-	-	0.01	2.09
2605SA1	1.9	0.09	4.97	2.82	0.14	1.89
H80-23L	1.40	5.56	1.28	1.70	0.70	1.51
10JNEX900	10.47	2.68	0.41	2.63	0.13	1.88

IV. Iron-Loss Estimation

The IEM-5-Parameter [13] formula separates between three loss components such as hysteresis (a_1), eddy current (a_2), and excess losses (a_5). By least-square fitting all parameters towards measured losses, we gained all needed information. The exception is parameter a_2, which is calculated and represents the classical eddy current losses with the sheet thickness d (m), the specific electrical resistivity ρ_e (Ωm), and the material specific density ρ (kg/m^3) of the soft-magnetic material. The iron losses $P_{IEM,5}$ are calculated by the peak flux density $\hat{B}$ and the unit of (3) is W/kg.

$$P_{\mathrm{IEM,5}} = a_1 \hat{B}^{\alpha} f + a_2 \hat{B}^2 f^2 (1 + a_3 \hat{B}^{a_4}) + a_5 \hat{B}^{1.5} f^{1.5} \tag{3}$$

$$a_2 = \frac{\pi^2 d^2}{6 \rho_e \rho} \tag{4}$$

The IEM-5-Parameter formula introduced a non-linear term (a_3 and a_4) and by a rule of thumb it can be said it is required for flux densities above 1.2 T [5]. Nanocrystalline materials have low saturation flux densities, common values are approximately below 1 T. The non-linear loss component part is therefore be neglected in case of these materials.

V. 2D Performance Factor

A high performance factor implies that a high flux density can be applied at a specific frequency. The value for the flux density is chosen based on the occurring losses at that frequency.

Fig. 1 shows the classical, two-dimensional comparison between all three different material alloys [14]. All flux density and frequency combinations in the figure, which define the performance factor, result in a loss dissipation, which is below, or right at the allowed loss dissipation.

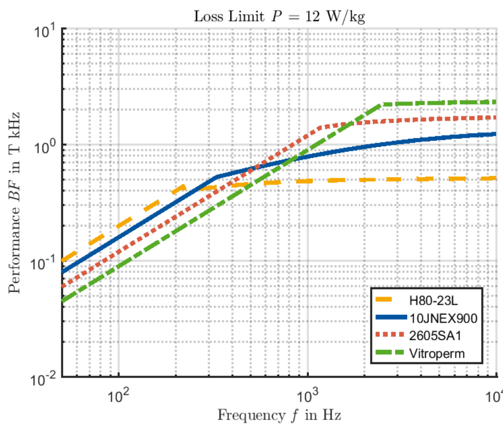

Fig. 1 Performance factor evaluated for one fixed loss limit P = 12 W/kg.

All calculations are based on the IEM-5-Parameter formula and the parameters listed in Table II. A knee point divides each plot into two sections. At low frequencies the saturation flux density is chosen, the combination of low frequencies and

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highest possible flux density value results in losses below the loss limit. As a result, silicon iron material, such as H80-23L or 10JNEX900, has the highest performance factor at low frequencies. At the knee point, the combination of saturation flux density and frequency value reaches the loss limit and for higher frequencies, the flux density is decreased accordingly. Amorphous material has the highest performance factor between 500 Hz and 1.5 kHz. At higher frequencies, the nanocrystalline material benefits from reduced eddy current iron losses and a higher flux density value can therefore be chosen.

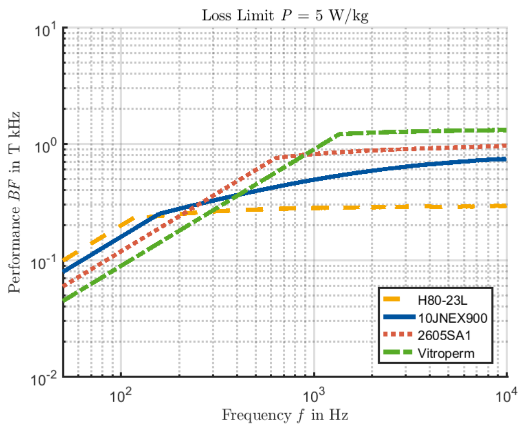


Fig. 2 Performance factor evaluated for one fixed loss limit $P = 5$ W/kg.

Fig. 2 shows the performance factor for a loss limit of 5 W/kg. The knee points have shifted and the material 10JNEX900 can be recommended only at 200 Hz. Above that frequency and below 1 kHz, the amorphous material has the highest performance factor. In contrast to Fig. 1, the nanocrystalline material is already beneficial above 900 Hz.

VI. 3D Performance Factor

The boundary of one fixed maximum loss dissipation per plot (Fig. 1 and Fig. 2) is discarded by the introduction of a third dimension respectively axis, which describes different loss limits (Fig. 3). The IEM-5-Parameter model is used to extract the required information. A top view of the overlapping 3D surfaces is used. The surface with the highest performance factor is in the foreground. The actual value of the performance factor is a minor importance and only the material with the best performance is relevant. All listed materials are represented in the plot. None of the studied materials is redundant and each material has its own range of application. Fig. 1 and Fig. 2 are cross-sectional areas of Fig. 3 at 10 W/kg, respectively 5 W/kg.

VII. Material Cost

The material cost in Euro/kg can be included into the comparison for an economic based solution regarding the inset of volume, because of the direct link between performance factor and required material weight (2) is given. Due to the relationship between performance factor and cross-sectional area, a direct relation to the needed amount of mass is present. Fig. 4 (b) shows a cost distribution taken from [10]. The average cost of each material type is calculated and taken into account for Fig. 4 (a).

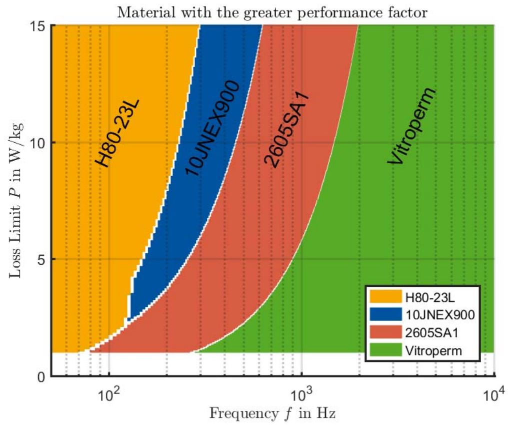
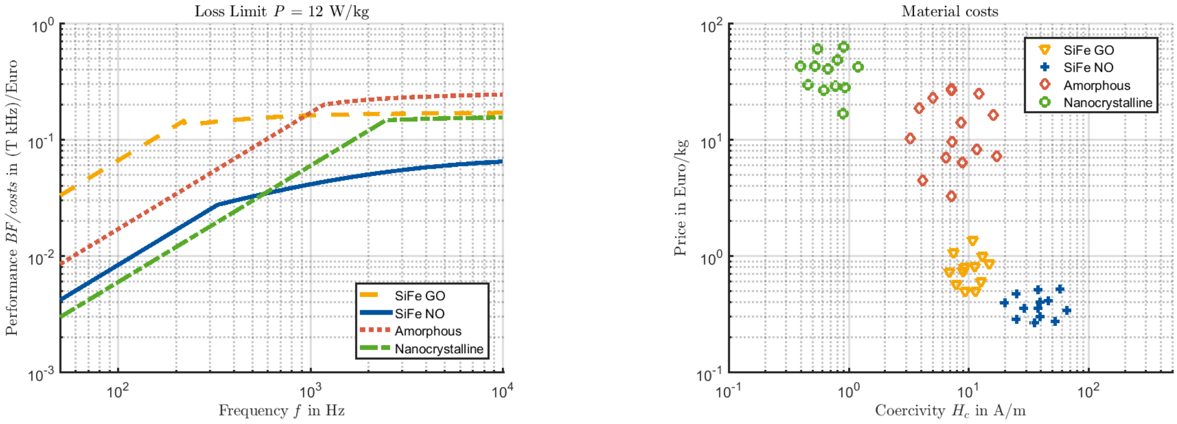


Fig. 3 Top view of a three-dimensional evaluation. The material with the highest performance factor is plotted.

VIII. Results

At loss limits from 5 W/kg up to 15 W/kg the materials are distributed almost in a constant way (Fig. 3). The recommended frequency for each material moves towards lower frequencies for lower allowed losses. Silicon iron materials benefit from a high saturation polarization at low frequencies. Due to a high saturation flux density, the H80-23L has a high performance factor at low frequencies and up to 300 Hz. Due to thinner material sheets, the 10JNEX900 is advantageous in the frequencies above approximately 125 Hz – 300 Hz, which depends on the allowed losses. The amorphous material 2605SA1 is applicable in even much lower frequency ranges as shown in Fig. 1 and Fig. 2. If low losses are in the focus, 2605SA1 can even applied at frequencies above approximately 60 Hz. This material is applicable in a wide range up to 2 kHz, if high losses are allowed. The boundary line between the amorphous material and the nanocrystalline material is the most important for medium frequency applications. The Vitroperm material is the best material for frequencies above 2 kHz. As the allowed loss limit decreases, the nanocrystalline material becomes favorable even at frequencies above 300 Hz.

The cost weighted performance factor (Fig. 4) shows that standard grain-oriented silicon iron is a solid choice due to the high saturation polarization and the low material cost. At frequencies above 1 kHz, the amorphous material benefits from the combination of the lower material cost and reduced eddy current losses at higher frequencies. The nanocrystalline material shows the best performance, but the material cost is in the range of 15 – 50 Euro/kg and therefore relatively high. The studied non-grain oriented material is more expensive as indicated in Fig. 4 (b) and a more expensive price as listed is chosen. This is due to a high silicon content of 6.5%wt and a low material thickness, which increases the production cost.



(a) (b)

Fig. 4 Cost weighted 2D performance factor (a), and (b) material cost in Euro/kg [10].

IX. Conclusions

In this paper, different soft-magnetic alloys are evaluated objective to magnetic properties e.g. the losses in their application and the grades are regarded to the cost. The different materials are introduced and discussed based on their material properties and the IEM-5-Parameter model. A performance factor is evaluated for the materials. It can be stated, that in high frequency applications above 1 kHz, the amorphous and nanocrystalline material perform better in this comparison. The critical frequency is loss-dependent (Fig. 3). In case of lower loss limitations, the cutoff frequency decreases and the application of the modern materials becomes worthwhile for lower frequencies as well. It is shown, that in case of low frequencies (60 Hz – 200 Hz), the amorphous materials can perform better than SiFe materials depending on the allowed losses. In addition, an economic based solution regarding the inset of volume is discussed. A cost weighted performance factor is introduced and the material costs are in a direct relation to the performance factor. Due to the high initial cost of the studied nanocrystalline and non-grain oriented material, these materials perform in a cost-weighted comparison poorly. The higher initial cost of modern materials can be amortized over the period of application due to the lower iron losses and the increased efficiency. Amorphous and nanocrystalline materials will be the recommended choice for medium frequency applications. They can be applicable in case of lower frequencies. It is verified that 60 Hz amorphous grid-transformers can be built up from amorphous core material. By regarding the low coercivity field strengths, the efficiency of modern material devices is also increased due to the reduced magnetizing currents and reduced winding losses.

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