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Analysis of the influence of the parameters of a new low-loss magnetic material of the stator core on the efficiency of a high-speed electric motor

***Abstract**. In the paper a simulational comparison between two low loss amorphous soft magnetic materials is presented. Comparison is based on evaluation of basic properties of a PMBLDC high-speed motor in which the stator core is made of one of them. The reference material is METGLAS which parameters are based on ANSYS Library material Metglas - 2605HB1M. The second one is a NEW MATERIAL (Fe73,8Ni5Nb2,6Cu0,6Si9B9) developed in our laboratory. ANSYS MOTOR-CAD software is employed in the simulation.*

Streszczenie.** W artykule przedstawiono symulacyjne porównanie dwóch niskostratnych amorficznych materiałów magnetycznie miękkich. Porównanie opiera się na ocenie podstawowych właściwości szybkoobrotowego silnika PMBLDC, w którym rdzeń stojana wykonany jest z jednego z nich. Materiałem referencyjnym jest METGLAS, którego parametry bazują na materiale ANSYS Library Metglas - 2605HB1M. Drugi to NOWY MATERIAŁ (Fe73,8Ni5Nb2,6Cu0,6Si9B9) opracowany w naszym laboratorium. Do symulacji wykorzystano oprogramowanie ANSYS MOTOR-CAD.* (Analiza wpływu parametrów nowego materiału magnetycznego o niskiej stratności rdzenia stojana na sprawność silnika elektrycznego szybkoobrotowego***)

Keywords: Brushless DC motor (PM BLDC), amorphous (ASMM) soft magnetic material, Metglas, core manufacturing technology.
Słowa kluczowe: Bezszczotkowy silnik prądu stałego (PM BLDC), amorficzny (ASMM) materiał magnetycznie miękki, Metglas, technologia wytwarzania rdzeni.

Introduction

An electric motor is a device that converts electrical energy into mechanical energy or, in energy recovery, a converter of mechanical energy into electrical energy. One way to improve motor properties (increase efficiency) is to replace commonly used soft magnetic materials such as electrical steel and Fe-Ni permalloy alloys used for cores, with a new generation of amorphous and nanocrystalline materials. These materials are characterised by high saturation induction, narrow hysteresis loop, high resistivity and low loss and can operate at frequencies up to several hundred kHz [1,3,4,5,6].

In the paper a comparison between two low loss materials is presented. The reference one is Metglas - 2605HB1M which parameters are defined in ANSYS Library [14]. The second one is material newly developed in our laboratory (Fe73,8Ni5Nb2,6Cu0,6Si9B9). Both materials are amorphous soft magnetic materials manufactured using quick-cooling, melt-spinning technology [9]. Comparison is based on evaluation of core losses in a high-speed permanent magnet brushless direct current (PMBLDC) motor [7,8,10].

Main aim of the research is to verify if the new material ensures better performance of the machine in terms of efficiency. The choice of this machine for this comparison is that, due to high frequency of the magnetic field in the stator core, they represent another promising area of application of amorphous soft magnetic materials in electrotechnics beside various transducers, sensors etc. used in power electronics [9, 11].

Machine structure

The machine model used in simulation in ANSYS Motor-Cad with its stator parameters is presented in Fig.1 and Table 1. It was designed to produce 3 [kW] of output mechanical power at 30000 [rot/min] with the assumption that the stator core is made of METGLAS. Its supply algorithm uses classical 120 degree conduction mode with DC bus voltage 50 [V] and current chopping restricting the maximum current to 80 [A] [2].

Table 1. The parameters of the motor

Parameter	Value
Internal diameter of the stator	40 [mm].
Outer diameter of the stator	105 [mm].
Width of tooth (pole)	12 [mm].
Number of slots	6
Opening of the slot	3 [mm].
Depth of slot (total)	18 [mm].
Number of wires in the slot	10
DC circuit supply voltage	50 [V]
Max. DC circuit supply current	80 [A]
Wire diameter	AWG 5.5
Stator core length	60 [mm]

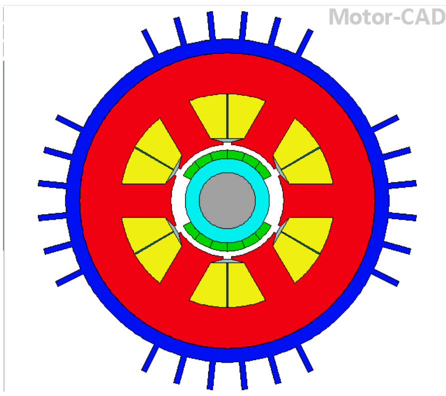


Fig.1. BLDC motor simulation model in ANSYS Motor-Cad environment

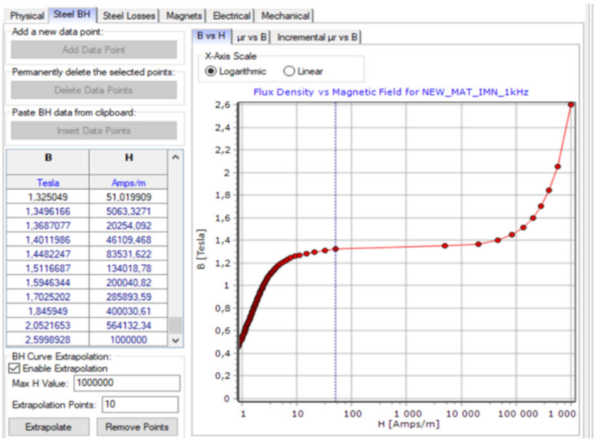
Material data

Data of both stator materials (averaged B(H) curves and coefficients of the Bertotti formula (1) [12]) used in simulation models are shown in Fig.3 and Table 2. The chemical composition of the NEW MATERIAL is Fe73,8Ni5Nb2,6Cu0,6Si9B9. The technology of its production is the same like in case of METGLAS [9]. The properties of the material were evaluated using Magnet-Physik Remacomp C-1200 computer-controlled measurement instrument [8]. The measurement procedure was performed using a toroidal sample under sinusoidal supply (Fig.2). The data of the sample are : mass 58,31 [g], cross-section area 0,726 [cm^2] and average length of the path 10,8 [cm].

Fig.2. Measurement stand

The averaged B(H) curve is presented in Fig.3a along with the characteristic for METGLAS (Fig.3b). It is shown in ANSYS Motor-Cad environment.

a)



b)

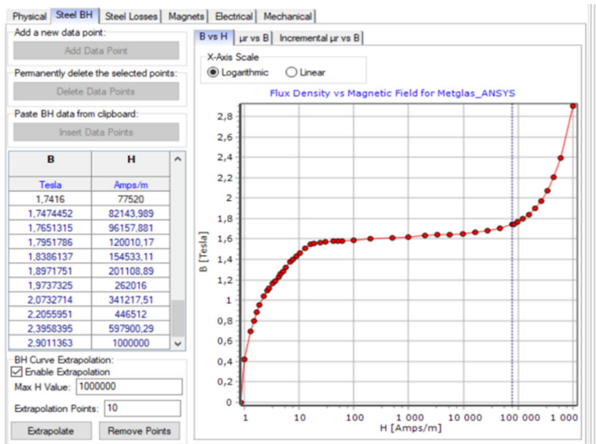


Fig.3. Averaged B(H) curves of both materials (extrapolated to 1 [MA/m] in logarithmic scale) a) NEW MATERIAL, b) METGLAS

It can be easily noticed that saturation level is case of the NEW MATERIAL (approx. 1.3 [T]) is much lower than in case of METGLAS (approx. 1.6 [T]).

The characteristics for evaluation of loss densities for NEW MATERIAL were obtained for:

- the range of frequencies: f = 50 [Hz] … 8 [kHz],
- the range of magnetic flux density amplitude B_{max} = 0.1 [T] … 1.3 [T].

Its results are shown in Fig.4.

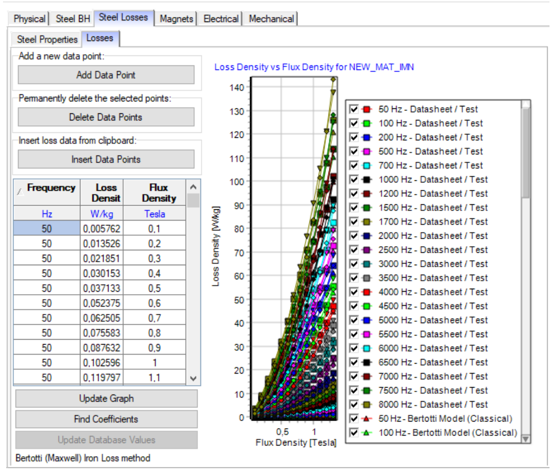
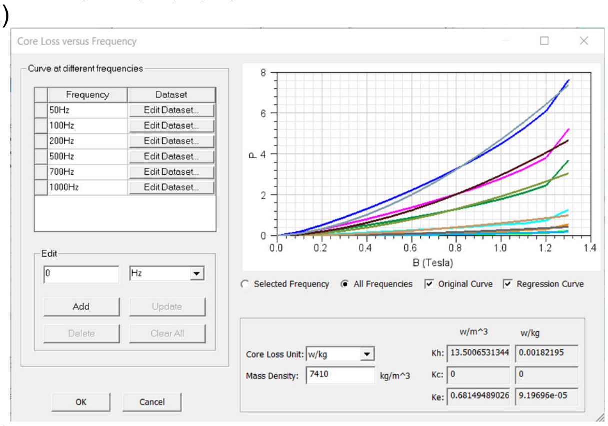


Fig.4. Loss densities for the NEW MATERIAL

However, to obtain reliable comparison with METGLAS, the frequency range for evaluation of coefficients of the Bertotti formula was reduced to 1 [kHz] as the data for METGLAS in ANSYS library are available only for that frequency range (Fig.5).

a)



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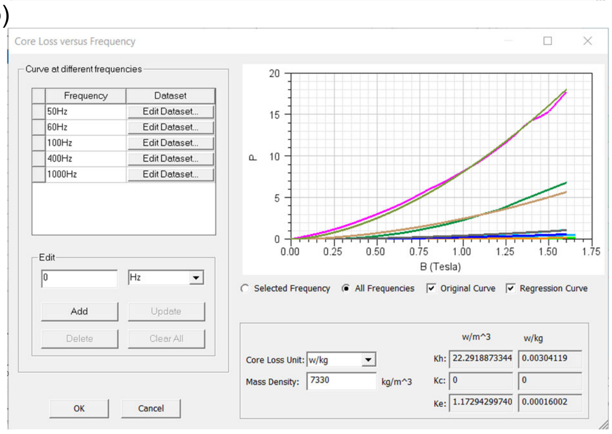


Fig.5. Loss densities for both materials (f ≤ 1 [kHz], ANSYS Maxwell environment) a) NEW MATERIAL, b) METGLAS

Based on approximation for that range of f and B (Fig.5) the coefficients of the Bertotti formula are evaluated:

(1) $$P_c = K_h f B^2 + K_c f^2 B^2 + K_e f^{1.5} B^{1.5}$$

where: K_h – is a hysteresis loss coefficient, K_c is a classical eddy currents coefficient, K_e is excess losses coefficient.

Table 2. The coefficients of the Bertotti formula for both materials

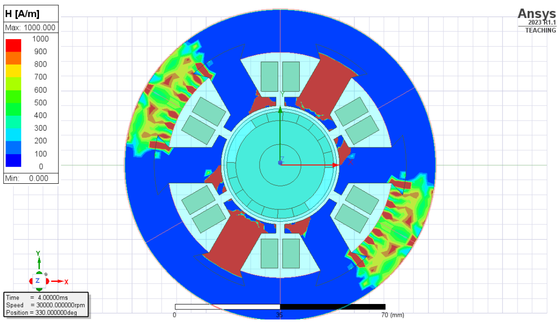
Coefficients	METGLAS	NEW MATERIAL
K_h	22.29	13.5
K_c	0	0
K_e	1.17	0.68

Their values for both materials are shown for in Table 2. It can be noticed that NEW MATERIAL has much lower values of both hysteresis K_h and excess K_e loss coefficients than METGLAS. Numerical values of coefficient are defined for core losses P_c evaluated in [W/m^3].

Simulation for cold conditions (20°C)

The machine models with stator cores made of both materials were initially simulated for temperature of 20°C. The reason for such artificial condition was to verify the influence of core saturation on losses just after starting the machine, when the temperature is equal to the ambient temperature. Obtained results are shown in Fig.6, presenting the distribution of magnetic field intensity *H* (at the same time instant 4 [ms] and angular position 330 [deg]). Much higher saturation of the core in case of the NEW MATERIAL is evident.

a)



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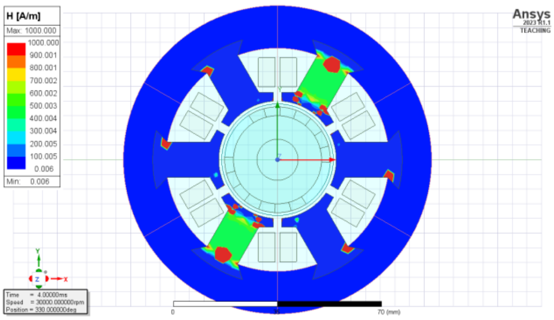


Fig.6. Magnetic field intensity at nominal conditions (30000 [rot/min], 50 [V]) at 20°C a) NEW MATERIAL, b) METGLAS

a)

b)

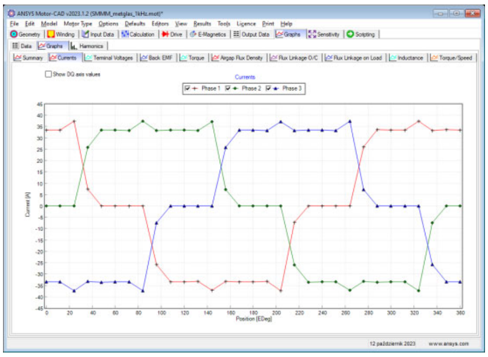


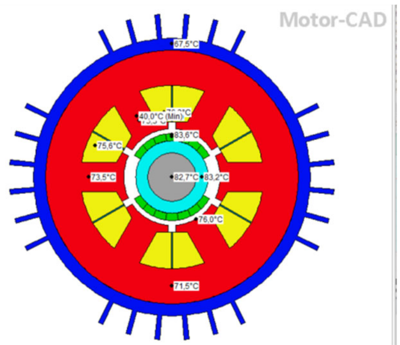
Fig.7. Steady-state current profiles at nominal conditions (30000 [rot/min], 50 [V]) at 20°C a) NEW MATERIAL, b) METGLAS

Much higher values of magnetic field intensity *H* both in the pole and back iron regions for NEW MATERIAL are observed. The result of this saturation difference is much higher current supplied to the machine (Fig.7) for NEW MATERIAL (I_{rms} = 75 [A]) than in case of METGLAS (I_{rms} = 37.5 [A]). It results in much higher copper losses in case of the NEW MATERIAL at these conditions.

Simulation for steady-state thermal conditions

To verify the influence of material parameter differences on steady-state behaviour of the machine, the coupled electromagnetic - thermal simulation in ANSYS Motor-CAD was performed at nominal conditions (30000 [rot/min], 50 [V]) [14]. Obtained results are shown in Fig.8.

a)



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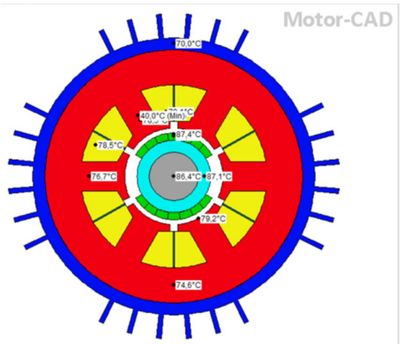


Fig. 8. Temperature distribution in the machines for steady-state thermal conditions a) NEW MATERIAL, b) METGLAS

Maximum temperatures in the cross section of the machines are respectively:

a) T_{max} = 83,6 °C for NEW MATERIAL,
b) T_{max} = 87,4 °C for METGLAS.

The most important result of the temperature change in case of analyzed machines is a substantial change of operating point of PM made of N38SH, which is shown in

Fig. 9 for the case of the NEW MATERIAL (83.5 °C is an average temperature of the PM).

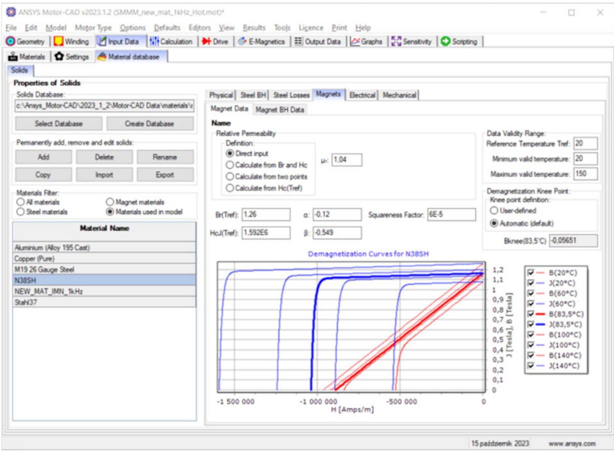


Fig.9. Temperature change of B(H) curves for PM

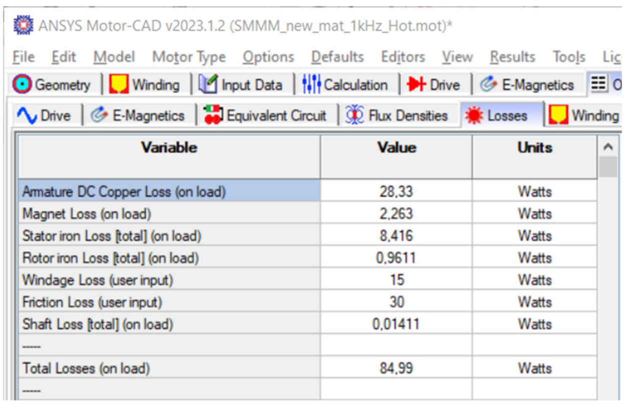
Change of operating point of PM compared to 20°C case resulted in decrease of magnetic flux density in the core of the stator. The result of this was decreased influence of different saturation levels and very close values of current supplied to the machine for NEW MATERIAL (I_{rms} = 78 [A]) and METGLAS (I_{rms} = 74.2 [A]).

Comparison of losses for steady-state thermal conditions

Comparison of losses in both machines for steady-state thermal conditions are shown in Table 3. Respective values of the following loss components are provided:

- copper losses P_{Cu} ,
- iron losses in the stator $P_{Fe,s}$,
- total losses in the machine P_{total}, including windage and friction losses.

In case of total losses, a requirement for their maximum value is defined (P_{total} < 100 [W]), which is a result of assumed natural convection cooling of the machine housing. Values of windage and friction losses are assumed to be equal to 15 [W] and 30 [W] respectively [10]. Output power on the shaft P_{output} is evaluated using ANSYS MOTOR-CAD. Data for the case of the NEW MATERIAL are shown in Fig.10.



Variable	Value	Units
Armature DC Copper Loss (on load)	28,33	Watts
Magnet Loss (on load)	2,263	Watts
Stator iron Loss [total] (on load)	8,416	Watts
Rotor iron Loss [total] (on load)	0,9611	Watts
Windage Loss (user input)	15	Watts
Friction Loss (user input)	30	Watts
Shaft Loss [total] (on load)	0,01411	Watts

Total Losses (on load)	84,99	Watts

Fig. 10. Components of losses for the NEW MATERIAL machine

Based on these data and obtained output power P_{out} values of efficiency η are evaluated for both machines (Table 3).

Table 3. Components of losses in both machines at nominal conditions (30000 [rot/min], 50 [V]) for steady-state thermal conditions

Parameter value	METGLAS	NEW MATERIAL
P_{Cu}	25,9 [W]	28,3 [W]
$P_{Fe,s}$	17,45 [W]	8,4 [W]
P_{total}	93.04 [W]	84.99 [W]
P_{output}	2700 [W]	2670 [W]
η	96,6 [%]	96,9 [%]

Conclusions

Based on obtained results it can be concluded that the NEW MATERIAL has both advantages (lower losses than METGLAS) and disadvantages (lower saturation level than METGLAS). The result is that in a motor designed to employ METGLAS in the stator core the flux level in the yoke is too high for the NEW MATERIAL resulting in high saturation level. It results in very small improvement of efficiency η of the machine (approx. 0.3 [%]) compared to the reference one using METGLAS (Table 2). Implementation of NEW MATERIAL seems to be dependent on economic considerations as overall losses meet maximum loss requirements (P_{total} < 100 [W]) for both materials.

It can be concluded that the more promising application of the NEW MATERIAL can be achieved in case of devices where magnetic flux densities are lower than in typical machines (e.g. PMBLDC), which includes:

- very high speed slotless machines [10],
- power electronic devices (eg. chokes, transformers) [9, 11].

It must be underlined that the material parameters used in simulation are "perfect" as they do not consider degradation due to mechanical and thermal treatment performed during stator core assembly [13].

Artykuł jest wynikiem prac w ramach projektu badawczego NCBiR pt.: „Nowoczesne technologie wytwarzania funkcjonalnych materiałów magnetycznych dla zastosowań elektro-mobilnych i medycznych" o numerze: TECHMATSTRATEG2/410941/4/NCBR/2019 oraz projektu Doktorat Wdrożeniowy pt.: „Badanie wpływu wybranych warunków wytwarzania wielobiegunowych amorficznych i nanokrystalicznych rdzeni magnetycznie miękkich w aspekcie zastosowania ich w stojanach silników elektrycznych".

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