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Influence of production technology on magnetic properties of nanocrystalline stacked and block magnetic cores

***Abstract**. Nanocrystalline soft magnetic materials are more and more commonly used in power electronic industry. New production techniques and different treatment methods are still developed and as a result new solutions are available. Two types of large nanocrystalline magnetic cores are proposed in the paper. First, nanocrystalline magnetic stacked core (NMSC) with distributed air gap. Second, nanocrystalline magnetic block core (NMBC) with a specific number of air gaps. Differences in cores construction and magnetic properties are presented.*

***Streszczenie.** M*ateriały nanokrystaliczne są coraz bardziej powszechne w przemyśle energoelektronicznym. Opracowywane są co raz to nowsze technologie produkcji, czego rezultatem są nowe rozwiązania. W artykule przedstawiono dwa typy nanokrystalicznych rdzeni magnetycznych o dużych masach. Nanokrystaliczne rdzenie pakietowane (NMSC) z rozproszoną szczeliną powietrzną oraz nanokrystaliczne rdzenie blokowe (NMBC). (**Wpływ technologii produkcji na własności magnetyczne nanokrystalicznych rdzeni pakietowanych oraz blokowych**).

Keywords: magnetic cores, nano structured materials, power engineering.
Słowa kluczowe: rdzenie magnetyczne, materiały nanokrystaliczne, energetyka

Introduction

Constant and fast development of power electronic and related industrial sectors force the magnetic cores manufactures to improve their products and technologies and to develop new inductive solutions. The research in many areas like e.g. material engineering, thermodynamics, magnetics and electrotechnics must be conduct in order to make it possible. Construction of magnetic cores have been changing over the years being dependent on application requirements [1 – 3]. The most widely used cores types now are toroidal cores, toroidal cut cores, oval cores, oval cut cores and nowadays stacked and block cores with various configurations.

Such a magnetic cores are made of different soft magnetic materials: conventional electrotechnical SiFe steels, ferrites, metallic powders, amorphous and most promising nanocrystalline materials. From all above materials the nanocrystalline materials invented in 1980's are characterized by very high applicability level [4]. It is also well known that nanocrystalline materials has a wide range of magnetic properties possible to get after annealing what expands their usage [5]. Validation of final product – magnetic core are magnetic properties measurements [6]. Most important and useful for engineer informations are flux density Bm, magnetic relative permeability μr, power loss P and inductance Ls. The lack of commercially available large (around 15 kilos and more) magnetic nanocrystalline cores force the designers and engineers to assemble large magnetic cores from several or tens of smaller nanocrystalline cores [7, 8, 9]. Existing solutions of large nanocrystalline and amorphous magnetic cores are offered as unconsolidated products made on special demands to specific applications and this fact has a negative influence on productions costs. The next disadvantage is having no feedback information about repeatability of achieved magnetic properties. The demand for large nanocrystalline magnetic cores is determined by rapid development of power electronics and associated with that process increase of magnetizing current frequency of power electronic devices [10].

The following paper describes the production technology of nanocrystalline magnetic stacked cores (NMSC) and nanocrystalline magnetic block cores (NMBC). In this study the magnetic properties of both core types are shown and discussed. The production process is arranged and divided into five stages (Fig 1). Nanocrystalline cores under consideration are characterized by very good magnetic properties what enables their high efficiency operation, especially in high frequencies. Low power losses level of nano-structured soft magnetic materials allows to very effective energy conversion, specially at higher frequencies i.e. 1 kHz – 30 kHz and even up to several of MHz when it comes to chokes [4].

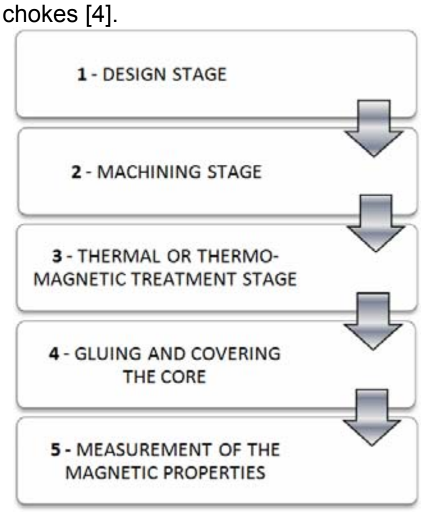

Fig. 1. Stages in the production of nanocrystalline cores.

Observables

A magnetic core is a final product that has to be examined for proper realization. Physical parameters (e.g. geometrical dimensions, shape and dimensions tolerances) and magnetic properties are taken into account. Magnetic flux density B_m, magnetic relative permeability μ_r, power loss P and inductance L_s are measured. When it comes to magnetic cores NMSC and NMBC made of nanocrystalline tapes it is very important to control the quality (linearity and uniformity) of nanocrystalline mechanical cuts [8]. Proper shapes of every one nanocrystalline rectangular cut shape determines correct arrangement of magnetic circuit what results in smaller air gaps between single shapes and made the whole magnetic core better. It should be noted that thickness of nanocrystalline tape has also significant influence on magnetic properties of the core. With increase of nominal frequency of magnetizing current the thinner tapes should be used. Nowadays available thickness of nanocrystalline tapes are in the range 18 μm – 35 μm [1, 2]. Depending on the application requirements the specific way of core construction is selected and as a result there can be stacked NMSC or NMBC core type (Fig. 2).

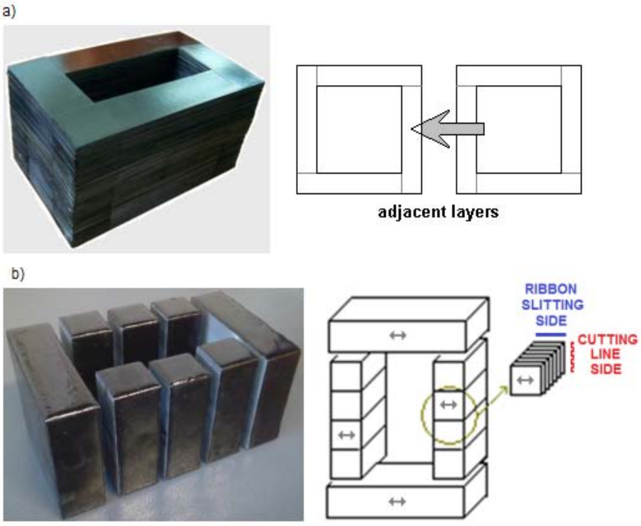

Fig. 2. Cores made of nanocrystalline tapes: a) NMSC cores, b) NMBC cores.

Proposed technology of stacking NMSC cores and assembling NMBC cores allows us to arrange the nanocrystalline rectangular cuts in line or in opposite to the ribbon casting direction (Fig. 3). Another method of improving the uniformity of magnetic field distribution in the core is thermomagnetic T+H treatment based on own technology with recuperation system. Proper applying of magnetic field on the core being annealed induces in it easy magnetisation directions (directional anisotropy) and improves magnetic properties of the core [7]. Based on own results the following improvements have been observed: decrease the power los level of 3% – 5% and increase the magnetic permeability of 5% – 10%.

As a fast and industrial validation method of constructed core it is often used the measurement of the noise generated during the operation of the core and examination by thermal imaging camera. The following paper presents results of the measurements realised by the use of measurement system operating in accordance with normalization standards [6].

Experimental setup

Production process (Fig. 1) of NMSC and NMBC cores starts from calculations and design stage realized in one of common available software, e.g. RALE. The mass, shape and cross section of the core is determined based on magnetics properties (Bs, μr, P, Ls) of the material. Second stage is the preparation of nanocrystalline rectangular shapes by the use of the unique cutting line for nanocrystalline and amorphous ribbons (Fig. 3a). The cutting line was designed and constructed based on proprietary solutions [7]. Productivity of constructed cutting line depends on the length of cut shapes and can reach up to 15 kg/hour.

Cutting the nanocrystalline tapes which are the type of metallic glass is difficult and technologically complicated process. The cutting head of the device from Fig. 3a has to be adjust in very precise way to achieve high quality rectangular shape cuts [8]. Most important parameters are [9]: cutting heads arrangement, velocity and force of cutting, temperature and tension of nanocrystalline tape. Above parameters are different for each type of nanocrystalline tape and have to be evaluated and matched by the successive approximation method. Different types of nanocrystalline ribbons vary from each other in thickness and chemical composition. Example photographs of nanocrystalline rectangular cut edges are presented in Fig. 4.

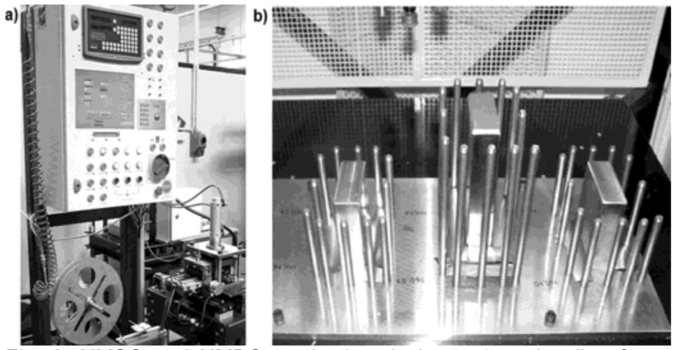

Fig. 3. NMSC and NMBC production devices: a) cutting line for nanocrystalline tapes, b) stacking robot system.

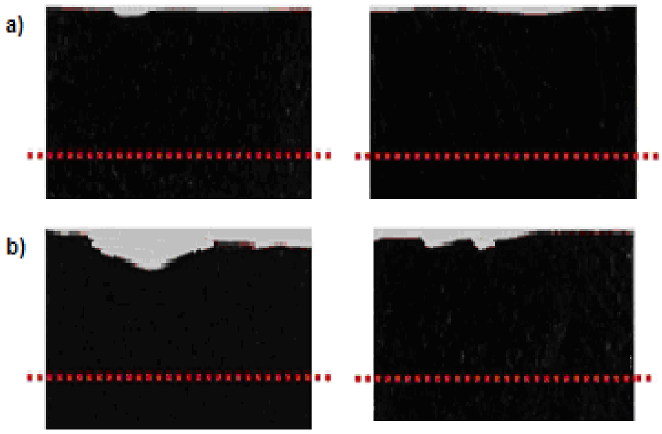

Fig. 4. Asperities of cut edges of nanocrystalline 30 mm width tapes: a) tape after proper cut, b) tape after inappropriate cut with mismatched adjust of cutting head parameters.

After cutting the nanocrystalline tape into rectangular shapes, forming of desired magnetic core (NMSC or NMBC) can be started. In order to do that the 3-axis stacking robot system is used (Fig. 3b). It operates from outer sides with four (or more) nozzles, stacking the ready core layer by layer in the robot centre. Subsequent layers are taken from two side storage boxes. Each storage box has different lamination configuration in the case of NMSC cores and identical in the case of NMBC cores. Operation sequence of robot arm is programmed by the operator. Robot arm allows to grab nanocrystalline layers of the core from storage boxes on demanded way. Also in the second stage of the production process (Fig. 1) the interlaminar insulation between every nanocrystalline layer is placed by special system. Placing interlaminar insulation decrease the power loss level of the magnetic core and it is necessary when the magnetic core will work under higher frequencies, i.e. f > 8 kHz. Interlaminar insulation reduces the negative phenomenon of eddy currents which is more noticeable with the increase of magnetizing current frequency [10, 11].

Next, the third stage of production process is thermal T or thermomagnetic T+H treatment. Strong DC magnetic field is generated around the rod with current up to I=1000 A. The strength of generated magnetic field can be stepless changed in whole range. Generated magnetic field present during the thermal treatment induces anisotropic properties in the core being annealed. Direction of the magnetic field is determined by the shape and arrangement of the rod to the magnetic core being annealed. Different shapes of rods can be used – depending on the magnetic core type and construction. Thermal treatment is crucial point to achieve nanocrystalline structure in the material and this is achieved avoiding hydrogen. Appropriate controlling of temperature levels during treatment time allows us to achieve optimal magnetic properties of the annealed core. Changing the temperature levels during the treatment has a great impact on magnetic permeability and power loss level of annealed core. Optimal thermal treatment with protection atmosphere is the way to control the annealing process completely, including the exothermal peak occurring during nanocrystalline material annealing [12].

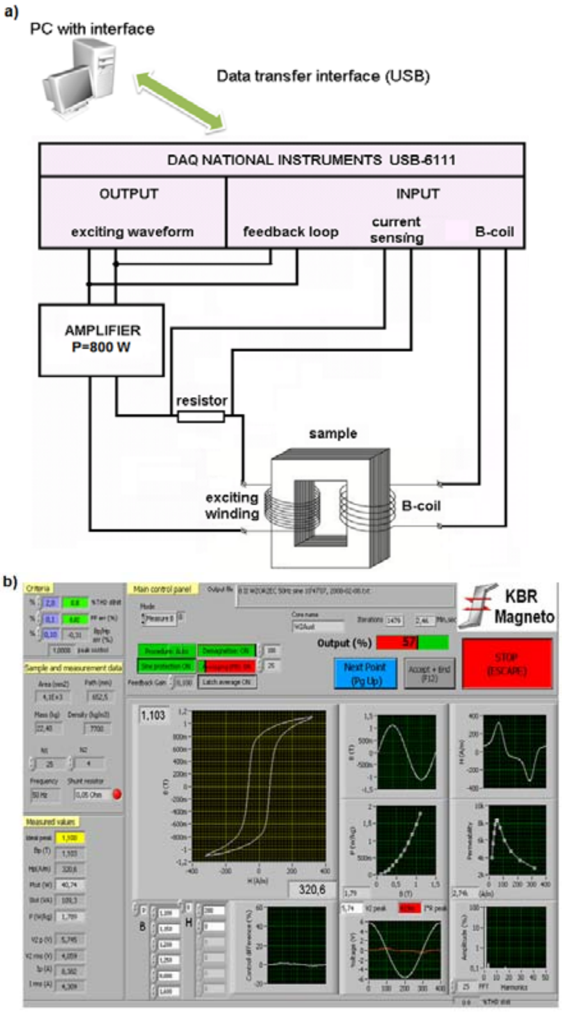

Fig. 5. Measurement system: a) schematic diagram, b) control panel of LabVIEW program.

Annealed and cooled down nanocrystalline core has to be protected against the mechanical damage – that is fourth stage of the production process (Fig. 1). When it comes to stacked NMSC cores the outside protection layer is used. As an outside layer a polyurethane or epoxy resin may be used. It should be noted that the resins with minimal shrink level are recommended to prevent from good magnetic properties loss [13]. With regard to application requirements the specific resin with optimal temperature class and hardness is selected. Low pressure technique and dedicated moulds are used to get the core cover. Depending on the core size and mass the thickness of the covers may vary from 2 – 5 mm. In NMBC cores an additional protection method is interlaminar gluing of blocks. It is realized by the use of very low viscosity and shrink glue in the low pressure chamber [14]. NMBC cores are used most often in magnetic chokes with several air gaps with thickness greater than 0 mm. Due to this fact grinding the surfaces of adjacent blocks is not required. Advantage of proposed assembling technology of NMBC cores (Fig. 2b) is that the surfaces of adjacent blocks are composed of the ribbons slighting sides of the nanocrystalline tape. Therefore, the adjacent layer has a very low grittiness. When there is a need to use the NMBC core to be a part of a transformer it is necessary to grind and polish the adjacent block layers to reduce the size of the air gaps.

In the production process it is very hard to make reliable and fast evaluation of the magnetic properties of the core being created. Thus, it is very important to strict control of all stages in every detail. The magnetic properties of created core are examined in last fifth stage (Fig. 1) by the use of measurement system. Schematic diagram and operator interface are presented in Fig. 5.

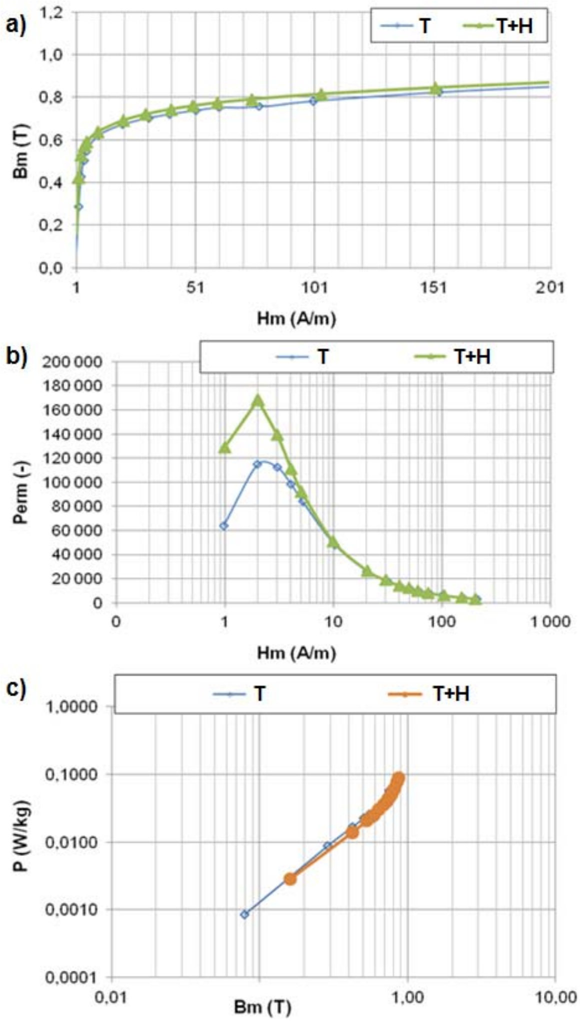

Fig. 6. Magnetic properties at f = 50 Hz of NMSC core stacked layer by layer, after thermal T and thermomagnetic T+H treatment: a) flux density B_m = f(H), b) magnetic relative permeability μ_r = f(H), c) power loss P = f(B).

All presented in the paper measurement results of magnetic properties were made in the system developed based on National Instruments LabVIEW software (Fig. 5). In the system the high speed NI PCI-6110 DAQ card was used, with 5MS/s/ch., simultaneous sampling, extended input voltage ranges to ±42V and additional over-voltage protection what is very important for industrial use.

Results

Specific applications and devices determine the use of proper magnetic core construction. For voltage transformers, the most often are used the cores with close magnetic circuit (like NMSC). But when the magnetic chokes are concerned and the calibration of inductance Ls is required, then the block cores (like NMBC) are applied. The operating point of the magnetic core is evaluated based on magnetic properties of the core (Bs, μr, P, Ls). Ambient conditions like: temperature, presence of acids, oils and dust, vibrations, EMC compatibility are also taken into account. Magnetic properties of example stacked NMSC core are presented in Fig. 6. The tested sample was 6 kg NMSC core stacked 20 by 20 nanocrystalline layers.

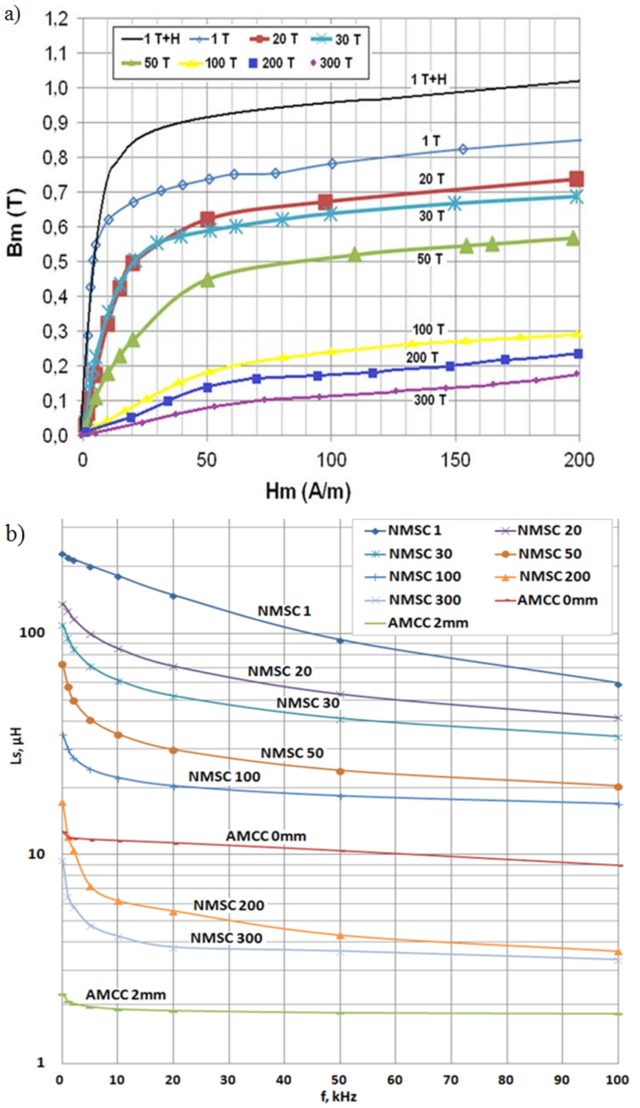

Fig. 7. Properties of NMSC cores with different numbers of layers: 1, 20, 30, 50, 100, 200 and 300 [14]: a) B-H curves at 50 Hz, b) inductance per one turn L_s = f(f) in comparison to amorphous wound cut core AMCC1000 with air gap 0 mm and 2 mm [15]; where T – thermal treatment and T+H – thermomagnetic treatment.

As can be seen in Fig. 6, applying longitudinal magnetic field during annealing T+H of NMSC core improves its magnetic properties. Core from Fig. 6 was stacked layer by layer (NMSC 1) in the way as presented in Fig. 2a. When there is a need to use the magnetic core with more linear magnetization curve it is possible to change the number of nanocrystalline layers in identical configuration. Thus, stacking the NMSC core can be realized by 2 … 300 and more layers. Magnetic properties of NMSC stacked with different numbers of layers are presented in Fig. 7.

By increasing the number of laminations per one layer (like 20, 30, 100, 200, 300 and more) it is possible to change the inductance as can be seen in Fig. 7b. The measurement results of NMSC were also compared to amorphous wound cut core with 0 mm and 2 mm air gap.

Calibrating the NMBC core (Fig. 2b), i.e. changing its inductance L_s level is realized in different ways. One of possible way is thermomagnetic T+H treatment and apply the magnetic field under different directions. Another way is design the core based on possessed magnetic characteristics. The specific number of air gaps (number of inner blocks) with defined thickness are placed into magnetic circuit. Next step is changing the size of the air gaps and adjust the desired inductance L_s level (Fig. 8).

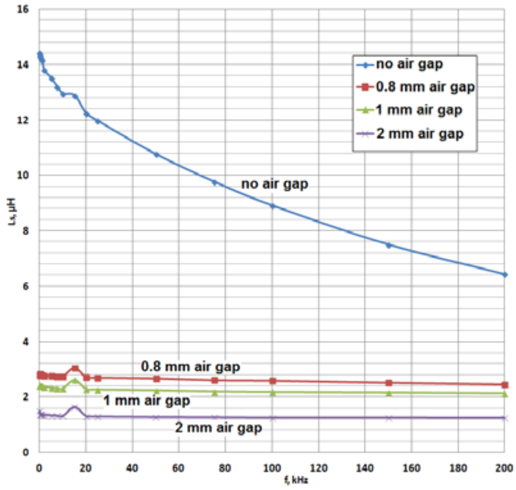

Fig. 8. Inductance L_s per one turn of 5 kg NMBC core with 6 inner blocks (Fig. 2b), in the range of 50 Hz – 200 kHz (the aggregate air gap in whole magnetic circuit in mm).

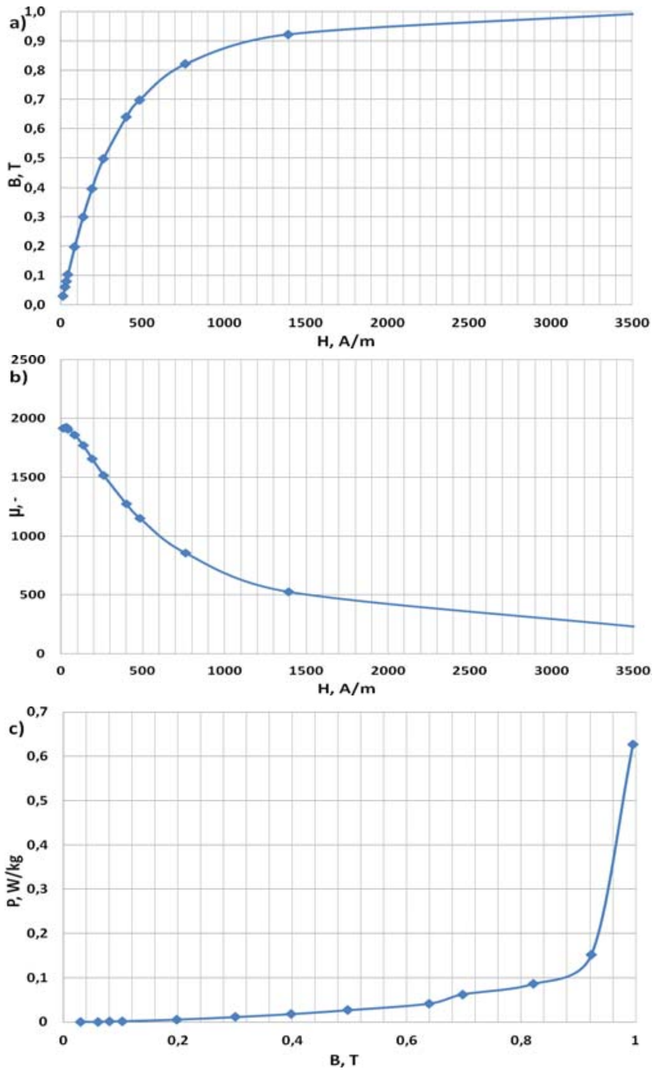

Fig. 9. Magnetic properties of 5 kg NMBC core after thermal T treatment: a) flux density Bm=f(H), b) magnetic permeability μr=f(H), c) power loss P=f(B).

Grinding and polishing the inner blocks layers of NMBC core decrease the air gap size and leads to inductance L_s increase. Only adjacent active layers of inner blocks need to be grinded and polished (as they are of ribbons slighting sides). However, such processes are long-term processes and are required only in reasonable instances. In the Fig. 9 further magnetic properties of 5 kg NMBC core with 6 inner blocks are presented. Measurements were taken at frequency f = 50 Hz.

Presented in the paper measurement results of NMSC and NMBC concern the cores without the interlaminar insulation. Carried out so far laboratory tests with applying interlaminar insulation have to be repeated and confirmed on larger number of samples. Reliability of the results has to be evaluated as well. Obtained results confirm decrease of the power loss level in higher frequencies of magnetizing current after interlaminar insulation [15, 16]. Table 1 shows comparison of the magnetic properties for three types of magnetic cores made of nanocrystalline ribbons.

Table 1. NMBC, NMSC and toroidal cores magnetic properties at f = 50 Hz of magnetizing current [7]

	NMBC	NMSC	TOTOIDAL
Induction B_s, T	up to 1.15	up to 1.15	up to 1.23
Relative permeability μ_r, –	up to 15 000	up to 200 000	up to 500 000
Power Loss P at 0.5 T, W/kg	≤ 0.05	≤ 0.01	≤ 0.01
Inductance Ls, μH	up to 50	up to 300	up to 500

Presented in Table 1 measurement results were obtained from own tests made on different samples of different core types. Shown wide magnetic properties ranges results from different core sizes, masses and constructions. Being dependent on the core geometrical dimensions and type of treatment (thermal T or thermomagnetic T+H) different magnetic properties can be obtained. Magnetic properties ranges are showing possible values to achieve by applying different construction and treatment types. All results presented in this study were measured in accordance with normalization standards [6].

Conclusions

Proposed production process of NMSC and NMBC cores is a complex process and real validation of obtained results is possible on final product. Therefore, the very strict control of every realized stage in every detail is required. Despite that complexity the technology has a great advantage. It is the ability to produce different types of cores with very wide range of magnetic properties possible to achieve. That fact makes the NMSC and NMBC very high applicable for different devices. The technology is constantly developed and improved. At the moment on the semi industrial scale but there are no obstacles to expand it to large scale. The NMSC and NMBC cores will fill the lack of the large nanocrystalline cores with pre-programmed magnetic properties to be able to operate under higher frequencies.

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