Magnetic Powder and Nano-powder Composites for Electrical Converters

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Abstract On the base of experience in development of Magnetic Powder Composites, and particularly Soft Magnetic Composites, authors are trying to systematize classification and indicate possible development prospective of Magnetic Nanocomposites (MN) technology and their applications in electrical converters. Clear classification and systematization, at an early stage of any materials and technology development, are essential and lead for better understanding and communication between researchers and industry involved. This concern MN as well and it seems to be the right time to make it at present stage of their development. Presented proposal of classification distinguishes various types of MN by their magnetic properties and area of possible applications. It is not a close set of types, and can be extended due to increase of knowledge concern these nanocomposites.

Generally, Magnetic Nanocomposites (MN) are materials in which the basic component is a magnetic nano-powder, or powder mixture, typically formed to net shape by application of powder metallurgy techniques, with the fabrication process playing a significant role in determining the final properties of the resultant composite. Such composites could be used, among others, for the magnetic cores of various electrical converters, including electrical micro and nano machines.

Possible MN technologies routs are presented in form of morphological analyze, based on technology transfer of Magnetic Powder Composites (MPC). It can be useful for planning research and technology development of MN, because it reveals variety of ways and possible solutions to reach final composite with defined properties. The morphological analyze should be supplemented, as in case of proposed classification, due to development of MN and their technologies.

Observed world progress in development of electrical converters miniaturization creates interesting challenges for MN. These require essential changes in philosophy of magnetic cores design. It should be based not on traditional replacement of one material by another, but on active redesigning, taking into account favorable properties of magnetic powder composites, such as possibilities of spatial magnetic flux distribution, and hybrid magnetic cores creating, for instance. Examples of such solutions, made of MPC up till now, are presented in the paper.

Additionally, high pressure liquid jet technology, presented by authors at this Conference, creates new possibilities to manufacture nano-size powders, with unprecedented rheology, which can influence MN development as well. Furthermore, prospective of reaching significant production rate of nano-powders, achieving hundred kilograms per hour, open possibilities of promising industrial applications for magnetic nanocomposites.

1. Introduction

MPC, being natural predecessors of MN, can be defined as materials in which the basic component is a magnetic powder or powder mixture, which are

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*Corresponding Author : [Tel : +82-42-868-8551; E-mail : ckrhee@kaeri.re.kr] both formed to net shape, and with the resultant properties greatly determined by, the application of powder processing techniques.

They can be divided into two basic groups:

- Soft Magnetic Composites (**SMC**) [1],
- Hard Magnetic Composites (**HMC**).

They are manufactured from soft or hard magnetic powders which size is within microns range.

Soft magnetic composites (SMC) are particularly suitable for application as materials for magnetic cores of various electrical converters, in particular for contemporary small electrical machines. Their development was initiated with work carried out at Wroclaw University of Technology (Poland) in 1972, with the term Dielectromagnetics [2] being adopted for such materials with low proportions of dielectric phase.

The application potential for SMC materials was recognized and described from the early stages of their development [3, 4, 5]. It has become apparent that: "Changes and new design solutions for converters are necessary to widen the usability of powder composites resulting from new materials and new technologies used" [1].

- The principal features, which should be exploited for the effective applications of SMC's in magnetic cores, are:
- The ability to engineer alternative spatial distribution of magnetic flux in a magnetic core as a result of the isotropy of their structures [3, 6],
- The ability to create shapes of magnetic cores which are difficult or even impossible to manufacture of conventional electrical sheets [6],
- The technological potential to introduce new functionality, through novel structures such as hybrid magnetic cores [3, 6, 7],

The manufacturing simplicity inherent in this technology, allowing net shape components to be obtained without additional machining.

All the above findings are still applicable today, and are confirmed and followed by present-day researchers involved in applications of SMC for magnetic cores.

The above described principles are also valid for magnetic nanocomposites (**MN**), which are manufactured from magnetic crystallites (commonly called – nanopowders), which size is within nano range (below 100 nm at least in one direction). This has essential influence on their technology, magnetic properties, features and range of applications. Nanocrystallite materials can possess bulk properties quite different from those commonly associated with conventional large-grained MPC. New magnetic phenomena and unusual property combinations are responsible for these observed differences. It has been found, that cobalt or iron based nanocomposites can possess permeability much higher than that which can be obtained from the bulk metal. It is worth to mention about so called giant magnetoresistive effect (GMR), which may have influence on high frequency applications of MN.

For over 20 years, it has been necessary to actively focus the attention of, often sceptical, designers and manufacturers of electrical machines on SMC, which in many applications can replace traditional electrical sheets. This is a strong indication that finally, the psychological barrier of designers to the use of these novel materials has been, at least partially overcome, opening up a huge range of potential future applications of these composites. The authors hope that such critical situation will not be repeated in the case of MN.

Observed world progress in automation, robotics, and power electronic equipment, generates development trends for electrical converters, which largest group are electrical machines. These trends can be described as:

- Increasing trend for size reduction/miniaturization
- Increase of working frequency of magnetic flux in magnetic cores
- Growing need for custom designed electrical machines – for specific applications.

In 1988, Professor Muller and colleagues (in Berkeley) made the first operating micromotor, which was 100 microns diameter, what is about the thickness of a human hair. In 2003, Zettl's group created the first nanoscale motor in which a gold rotor turned on a carbon nanotube shaft. Among others, nanomotors could be used in optical circuits to redirect light, a process called optical switching. Futurists envision a day when nanomachines, powered by electrical nanomotors, roam inside human body to find disease and repair damaged cells [Internet].

The above are extreme examples. Anyway, there is grooving need for micro converters which require various magnetic elements, exhibiting unusual magnetic properties which could force miniaturization and which could be manufactured in long series and even in mass production – this is a real challenge for MN. This requires development of more effective methods of magnetic nanopowders production. One of them could be, the high pressure liquid jet technology, presented by authors at this Conference [8]. It creates new possibilities to manufacture nano-size powders, with unprecedented rheology, which can influence MN development as well. Furthermore, prospective of reaching significant production rate of nanopowders, achieving hundreds kilograms per hour, open possibilities of promising industrial applications for magnetic nanocomposites.

It is also worth to mention a further feature and significant potential benefit of MN. That is the technological potential to offer new or improved functionality by exploiting the possibilities offered by the powder processing routes. A particular example is the possibility of hybrid magnetic cores creation.

The history of magnetic powder composites applications for manufacturing of magnetic cores is as old as the use of electrical sheets for the cores. Both ideas appeared almost simultaneously in 1880s. Edison's proposal was to apply iron sheets of thickness 0.4 to 0.8 mm for magnetic cores working in alternating magnetic fields, while Fritts's idea was to build magnetic cores of a material composed of iron particles bound with wax (presently named as dielectromagnetic, or SMC). Better magnetic parameters and mechanical strength of sheeted structures, together with development of medium power electrical machines at that time, limited practical application of powder structures for electrical machines. Renaissance and even booming of SMC applications is observed for last 15 years.

The history of nanocomposites dates back to about 1970s, when original suggestions concern crystalline. materials were born. It was noticed, that the nanocrystallite state is fundamentally different from the large grain state, and it is also different from the amorphous state. Nevertheless, systematic research on nanocrystallite materials has begun around 1990s. A journal entitled "Nano Structured Materials" was started in 1992. New conferences and sessions at general conferences confirmed the boom of the nanocomposite materials.

Taking into account possible applications of MN in electrical converters, interest of authors is mostly focused on soft magnetic nanocomposites.

2. Classification of Magnetic Nanocomposites

Clear classification and systematization of MN, at an early stage of their development, is essential, because it leads for better understanding and communication between researchers and industry involved in their applications. It seems to be the right time to make a proposal of such classification. Presented in Table 1 proposal distinguishes various types of MN, by their magnetic features and area of potential applications.

The above classification is not a closed set of MN types, and can be extended due to increase of knowledge concern these nanocomposites.

SMN - SOFT MAGNETIC NANOCOMPOSITES are considered as materials exhibiting significant application potential for the development of contemporary and future electrical micro and nano-

Table 1. Classification of basic magnetic nanocomposites

DENO-TATION	NANOCOMPOSITE TYPE	COMPONENTS	APPLICATIONS
		SMN - SOFT MAGNETIC NANOCOMPOSITES	
SNS	SOFT MAGNETIC NANOSINTER	Soft magnetic nanopowders – able to be sintered.	Basic magnetic cores penetrated by main magnetic fluxes. Range of applications is limited to dc and low frequencies, unless insulated nanopowders are sintered.
SND	NANODIELECTRO-MAGNETIC	Soft magnetic nanopowders plus a second phase – organic or inorganic dielectric.	Any magnetic cores penetrated by ac magnetic fluxes, including high frequencies. SND are of the greatest application potential in electrical converters
SNF	NANOFERRITE	Various ferrites nanopowders.	High frequency magnetic cores and impedance matching circuits. Applications include signal processing, power conversion and EMI suppression.
		HMN - HARD MAGNETIC NANOCOMPOSITES	
HNS	HARD MAGNETIC NANOSINTER	Hard magnetic nanopowders – able to be sintered.	Serves as permanent magnet when high magnetic energy is required. Its applications are well established and welcome in electrical converters.
HND	NANODIELECTRO–MAGNET	Hard magnetic nanopowders plus a second phase – organic or inorganic dielectric.	Serves as a permanent magnet when middle and low magnetic energy is acceptable. SHD are of great application potential in electrical converters.
		SMN - SENSITIVE MAGNETIC NANOCOMPOSITES	
TMN	THEROMO-SENSITIVE MAGNETIC NANOCOMPOSITE	Thermomagnetic nanopowders, and eventually a dielectric as a second phase.	Its function is correction and thermal control of generated magnetic fields due to changes of a magnetic core temperature.
MMN	MAGNETO-SENSITIVE NANOCOMPOSITE	Magnetic nanopowders–sensitive for changes of magnetic field.	Serves as magnetic sensitive regulation or control elements of operation a magnetic converter due to changes of magnetic field, as well as for measurements of magnetic fields.
XMN	OTHERS SENSITIVE MAGNETIC NANOCOMPOSITE	Magnetic nanopowders–sensitive for changes of various factors.	Can serve as detectors for measurement of various factors, as well as for control of operation of an electrical converter by particular factor, like radiation, pressure, electrical field, etc.

converters, mostly Fe, Co, Ni

SNS - Soft Magnetic Nanosinter can be described as a material in which consolidation of nanoparticles is achieved through a sintering. Sintering, in classical form, is executed as high temperature heat treatment and in effect sintered composite should exhibit higher saturation magnetization and permeability in comparison with unsintered one. However, applied high temperature can destroy structure and the same favourable properties of magnetic nanocrystallites. A reasonable solution seems to be minimizing of sintering temperature or high temperature acting time. This requires development of new sintering methods. One of them could be application of low temperature sintering. Another more sophisticated, but more effective might be application of spark discharge for instance. SND consolidated by sintering of their dielectric phase can be also counted to this group. It should be mentioned, that sintered dielectromagnetics were first identified as interesting potential magnetic materials in the late 1980's [5].

SND - Nanodielectromagnetic can be described as a composite consisting of a soft magnetic nanopowders (mostly Fe, Co, Ni), and a dielectric being second phase, which insulates and binds the magnetic particles.

The term "dielectromagnetic", primary used for one type of soft MPC, defined as above. As a matter of fact, many different names are commonly applied to dielectromagnetic. One can find such their names as: SMC - soft magnetic composite, insulated iron powders, iron-resin composite, bonded magnetic, etc. The theory and practical principles of dielectromagnetic, initially developed in the 1970's, have been widely presented [2, 3, 4, 7]. Many of these principles, as well as dielectromagnetics theory and technology are also applicable for SND. At present development of SMN, nanodielectromagnetics exhibit the most significant development and application potential. They are practically in focus of researchers involved in magnetic nanocomposites for last 15 years. SND can be successfully exploited in many applications but it remains essential - to optimise the design to accommodate their particular features.

HMN - HARD MAGNETIC NANOCOMPOSITES are at the most advanced development among MN. It concerns particularly HDM, which properties and technology are widely presented in literature [9], supplementing the family of permanent magnets.

SMN - SENSITIVE MAGNETIC NANOCOMPOSITES are promising, from application point of view, group of magnetic nanocomposites. The high sensitivity and small size make them to have an enormous potential in sensor and control technology. In effect increase of their research activity can be expected.

3. Technology of Magnetic Nanocomposites

Set of technological procedures for the production of MN's can be developed by use of technology transfer of procedures applied for MPC.

Morphological method seems to be good to illustrate various possibilities, problems and features associated with technology of magnetic nanocomposites. This method provides the possibly full analysis of the problems associated with these materials design. Ability of designing a material with assumed properties is essential with a view to future applications of these composites. The aim of the morphological analysis is to widen the scope of possible solutions of the analyzed problems. The essence of the method is to determine all potential snags, functions or relations that are important for the considered problems and, on the other hand, to determine a wide range of features and possible solutions of these problems. As a rule, these problems should be logically independent from each other. It is a real challenge for an open mind fantasy to create problems and solutions - even unrealistic, at first glance. For simplifying the analysis, the problems and their solutions may be set in form of a table (Table 2).

4. Applications of Soft Magnetic Nanocomposites

It seems to be obvious that MN can find application anywhere where magnetic cores/elements of micro and nano sizes are present. This includes electrical converters (electrical machines, actuators, transformers, chokes, etc.), elements of power electronics, various magnetic relays and switches, etc. It is worth to indicate, that today fully equipped car has hundreds of sensors, actuators and electronic elements, what shows a market power for MN.

Constructional structure of the magnetic core has

Table 2. Morphological analysis of magnetic nanocomposites technologies

No.	CONSTITUENS OF PROBLEM	FEATURES OR POSSIBLE SOLUTIONS			
		A	B	C	D
1	2	3	4	5	6
1	NANOCOMPOSITE	SMN	HMN	SNM	-
2	FERROMAGNETIC MATERIAL	Element	Alloy	Mixture	Other
2.1	Shape of particles	Globular	Needle	Flakes	Irregular or other
2.2	Particle size fraction	Fines < 10 nm	Average ($10 \div 100$ nm)	Oversize (>100 nm)	-
2.3	Impurities content	Very low	Low	Average	Not essential
2.4	Compressibility	Very good	Good	Average	Not essential
3	DIELECTRIC	Organic	Inorganic	-	-
3.1	Added in form	Solid	Liquid	Gas	-
3.2	Distribution to ferromagnetic	Superficial (layers)	Volumetric	In clusters form	Other
3.3	Number and kind of layers	One layer	Few layers of one kind	Few layers of different kind	Other
3.4	Ways of dielectric layers forming	Chemically	Mechanically	By diffusion	Other
3.5	*Connection with ferromagnetic*	*Compound*	*Suspension*	*Other*	-
3.6	Distribution in volume of composite	Homogeneous	Heterogeneous	-	-
3.7	Magnetic properties	Nonmagnetic	Slightly magnetic ($\mu \leq 10$)	Semi–magnetic (μ = 10-100)	Magnetic ($\mu > 100$)
4	ADMIXTURES AND FILLERS	Magnetic	Electrical	Mechanical	Other or none
4.1	*Kind*	*Metallic*	*Non–metallic*	-	-
4.2	Shape	Grains	Flakes, foil, sheet	Needles, fibers, wires, rods	Other
4.3	Form	Elemental	Alloy	Mixture	Other
4.4	Type of its connection with ferromagnetic	Compound	Mixture	Suspension	Other
4.5	Way of introduction	Elemental	Chemical compound with ferromagnetic	By diffusion	Alloys, mixtures and other
4.6	Form of connection with ferromagnetic nanoparticles	Compound	Mixture	Suspension	Other
4.7	Distribution in nanocomposite	Volumetrically homogeneous	Vol. heterogeneous	Superficial or laminar	Separate clusters

essential influence on design of the electrical converter [10]. The cores made of electrical sheets impose, due to their specificity, certain rules on the converter design. The main their feature is anisotropy of the core resulted from concordance of sheet passes. It creates privileged directions of the core properties that are along sheet surfaces. MPC and MN cores are, as a rule isotropic, what means that their properties are the some in any direction of vectors of magnetic induction. This difference, putting aside other less essential differences, create a general rule for design of the composite's cores - shaping of such cores should not be done by coping, in mechanical manner, shapes of sheeted cores. The soft magnetic composites are not substitutes of the electrical sheets. They are quite different materials, which require individual methods of shaping the magnetic cores. These methods should be each time

Table 2. Continued

No.	CONSTITUENS OF PROBLEM	FEATURES OR POSSIBLE SOLUTIONS			
		A	B	C	D
1	2	3	4	5	6
5	MIXING OF COMPONENTS	In solid phase	In liquid phase	In gas	In vacuum
5.1	Type of mixer	Rotating - classical	Ball mill	Generating jet stream	Other
5.2	Applied method of mixing	Classical - few components	Creating insulating layers	Mechanical alloying	Other
5.3	Temperature	Ambient	Elevated	Cryogenic	-
5.4	Medium	Air	Liquid	Protective atmosphere	Other
5.5	Pressure	Atmospheric	Elevated	Vacuum	Other
6	FORMING/CONSOLIDATION	Compacting/ pressing	Casting	Spraying	Explosion or other
6.1	Type of press	Mechanical	Isostatic	Injection	Other
6.2	Applied method	Traditional compacting	Isostatic compacting	Metal injection molding	Plasma spraying
6.3	Action of pressing	Uniaxial	2-dimensional	Spatial	-
6.4	Type of die	Rigid	Flexible	Complex	Other or without any die
6.5	Kind of exerted pressure	Punch pressure	Pressure of pressing medium	Pressure of plasma flux	Gravitation pressure or other
6.6	Way of exerted pressure	Continuous static force	Oscillation force vibrations	Dynamic forces: by explosion, magnetic impulse, etc.	Other
6.7	Way of pressing	Single pressing	Double pressing	Multipressing	-
6.8	Temperature of forming	Ambient	Middle 500 K	High > 500 K	Other
6.9	Additional operations	Sizing	Forging or redensification	Forming in magnetic field	Other or none
6.10	Orientation of ferromagnetic	By magnetic field	Mechanically or intrinsically	By setting	Other
7	HEAT TREATMENT AFTER FORMING	Sintering	Curing	Spark sintering	Other or none
7.1	Temperature	Ambient temperature	Low, <830 K	Average, 830^{3}1300 K	High, >1300 K
7.2	Atmosphere	Reducing (H_2)	Neutral	Air	Steam or other
7.3	Cooling	At controlled rate of cooling	At presence of magnetic field	Rapid	Other
8	ADDITIONAL TREATMENT	Thermal recrystallizing	Stabilizing	Mechanical working	Low temperature annealing or other

based on strict correlation among type of the core, its function and required features of design structure of the core. A complex consideration of the above relationships may only guarantee to reach an optimal magnetic core made of the magnetic composite.

Considering an application of any magnetic mate-

Table 3. Classification of magnetic elements due to their magnetic function

TYPE	DESCRIPTION	APPLICATIONS
BASIC	Magnetic cores penetrated by the magnetic fluxes, necessary for generation of electromotive force (*emf*) in armature windings. Such cores require the best possible magnetic parameters.	• Armatures. • Yokes and teeth of stators • Main poles • Field magnet cores • Commutating poles • Transformers, chokes, ralays cores
AUXILIARY	Magnetic cores penetrated by various magnetic fluxes, such as: total or partial main flux, shifted, dissipated or leakage flux. Such, auxiliary cores can perform various magnetic functions, such as complementary and supplementary. Auxiliary cores require materials of wide spectrum of magnetic parameters.	• Auxiliary poles and yokes. • Shunts of poles. • Pole shoes – to protect a pole from demagne tisation • Induction concentrators or deco ncentrators of permanent magnet poles. • Induction concentrators of arm atures. • Slot wedges or semi-magnetic partitions for groove closures. • Porous or finned magnetic frames of stator or rotor hubs – used as cooling radiators. • Various magnetic screens.
CONTROL	Magnetic elements sensitive for various factors, such as: magnetic field, temperature, pressure, radiation, etc.	• Elements controlling, or measuring performance of an electrical converter. • Various sensors technology. • Thermocompensators for induction of poles made of permanent magnets.

rial for a magnetic core or element, its magnetic function should be analyzed. Three essential types of functions can be distinguished: basic, auxiliary and control. Range of potential applications of MN is presented in Table 3.

Effective applications of both SMC as well as SMN require to follow a few basic design principles, presented below, that should be considered by designers of electrical converters (including first of all electrical machines as the most sophisticated converters):

- Avoid simple, direct replacement of electrical sheet by a magnetic composite.
- Change the 2D flow of magnetic flux within a core into the 3D – if possible.
- Change the cross-sections of the core elements containing windings into round sections where possible – to decrease copper loss,
- Be imaginative in considering unusual shapes of a magnetic core of an electrical converter that were constrained, or even impossible, for application of electrical sheet.
- Ensure that the composite used is optimal for the core function(s), making use of suitable composite combinations where appropriate/practicable.

A good example of possibilities, which give magnetic powder composites, is a non-conventional design solution of an asynchronous motor stator shown in Fig. 1 [11]. The core is made of a dielectromagnetic in form of two identical halves. They lock-up, separately made, wave form, winding after assembling in finally ready stator. Recycling of copper in such solution is very simple.

Another example can be the armature of an asynchronous linear-tube motor presented in Fig. 2 [12]. In this case, the core is assembled of sectors compacted of Fe-Si soft magnetic sinter. Execution of such core of electrical sheet would be very difficult and costly, whereas conversely, its manufacture from composite materials does not create any particular problem.

5. Hybrid Magnetic Cores

A novel and challenging feature of MPC and MN

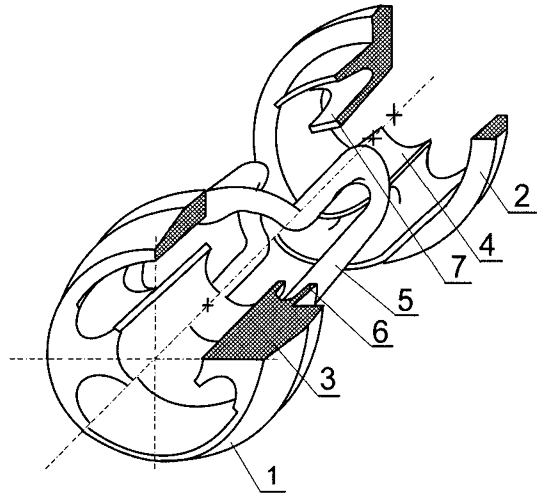

Fig. 1. Stator of salient pole asynchronous motor; 1, 2-halves of core made of SMC, 3, 4-poles, 5-winding, 6, 7-recesses for winding.

is their ability to create hybrid magnetic cores. Such an approach offers the possibility to engineer new functionality and enhanced performance offering the prospects of new applications for this family of materials.

A hybrid magnetic core can be defined as a core that is composed of various materials distributed in a specified arrangement in the core volume. Its essential feature is that the resultant core integrates different functions in one component, and is able to replace two or more single elements of a magnetic circuit.

Hybrid magnetic cores may integrate:

- Single uniform and non-uniform elements
- Various desired physical phenomena
- Both, elements and phenomena.

Hybrid cores can be in the form of single elements, subassemblies or assemblies, which can simultaneously provide different functions including soft magnetic, hard magnetic, thermo-magnetic, electrically conducting, insulating, mechanically strengthening, etc. Various technologies can be applied to manufacture such cores, but the simplest way is their creation through die filling with multiple, segregated components prior to conventional compaction.

The first experiments on the development of hybrid magnetic cores were carried out at Wroclaw University in Poland in the1970's. In these experiments, a soft magnetic sinter was joined with copper in form of powder, wires and rods. Copper elements were inserted during filling of a die, and after sintering, a hybrid core, integrated magnetic and electric circuits, was obtained [6]. Recent works have extended this to demonstrate the feasibility of producing a wide range of hybrid cores of the various types [13, 14].

The development of suitable process technology is the most essential factor in creating hybrid cores. The typical process steps are shown in Table 4.

An example of a hybrid rotor core, with spatially distributed dielectromagnetic, dielectromagnet and copper, is presented in Fig. 3.

In this case (Fig. 3) the rotor comprises the form (DM-DH-C) with DM as soft magnetic, DH as hard magnetic, plus copper and tin powders as conducting components (C). The specified configuration of components in these hybrid cores was engineered

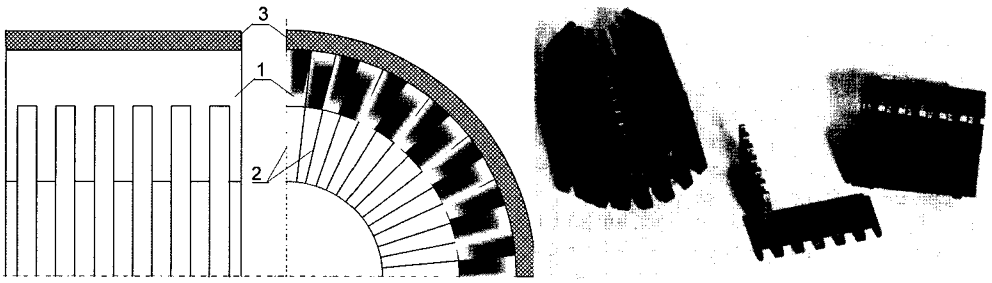

Fig. 2. Armature core of asynchronous linear motor and its practical execution; 1-sector (Fe-Si sinter), 2-sector insulation, 3-frame.

Table 4. Typical processes employed for production of hybrid cores

PROCESS STAGE	INTEGRATION METHOD
MIXING	Various soft or hard magnetic nanopowders. Magnetic nanopowders and conductive additions together. Magnetic nanopowders with strengthening elements. Magnetic powders with other materials.
FILLING OF DIE	Non uniform filling, to get differentiated densities/properties in particular parts of a magnetic core. By use of filling aids to introduce different powders in various spatial configuration in the die, allowing clear distribution of components. Introduction of various inserts in the form of wires, rods or elements. With various preliminary compacted elements.
COMPACTING	Multi-step pre-compaction between following filling steps. Full or semi isostatic - temporary inserts can be removed.
SINTERING OR CURING	Respective elements are compacted separately, and after assembling are sintered or cured altogether to achieve the final bond. Porous compact is infiltrated by conductive (copper, bronze, brass), or insulating materials (possible prior to, during or post sintering) Various layers of different materials can be deposited.
OTHER FORMING OPERATIONS	Plasma/thermal spraying of various layers: conductive, magnetic, insulating, etc. Other methods, including fluidisation, transfer moulding technology, PVD coating, vacuum deposition, etc.

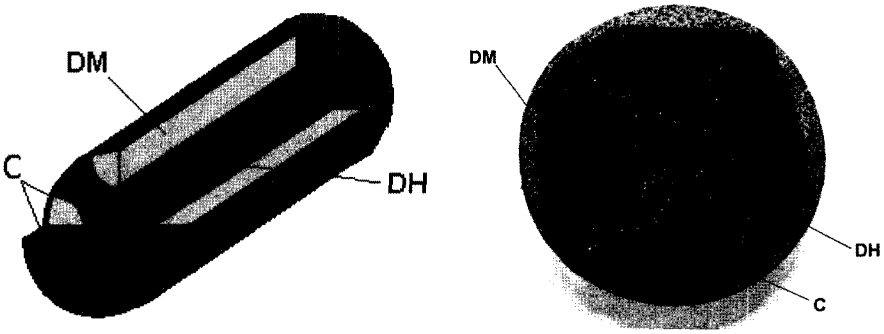

Fig. 3. Theoretical spatial configuration of a hybrid magnetic core and its practical execution; DM-dielectromagnetic, DH-dielectromagnet, C-copper[14].

initially through discrete stages of die filling, followed by compaction and thermal treatment to achieve permanent consolidation in the required configuration.

One may say that the hybrid magnetic cores create challenge for electrical converters of the future.

6. Summary

- At present, research on magnetic nanocomposites is focused practically on soft and hard nanodielectromagnetics (SND, HND). Nevertheless, received up till now achievements imply excellent prospective of these composites.
- The goal of this paper is to present proposal of magnetic nanocomposites taxonomy, and point out problems associated with their technology and applications as magnetic cores and elements. It is hoped that proposed taxonomy might

encourage the adoption of a standard terminology within this field, as well as provide a useful insight to those, currently considering the application of such composite materials in electrical design.

- Successful applications of MN, and especially SMN, have to be based on appropriate design, exploiting the 3D distribution of magnetic flux in a magnetic core, and enabling creation of more compact electrical converters whilst maintaining satisfactory performance, with additional benefits of low cost and ease recycling.
- The technological potential to create hybrid magnetic cores, outlined here, opens new opportunities for MN applications.
- Features of magnetic nanocomposites, which fulfill the current trends towards miniaturization, make them well-placed to meet to the challenges of 21st century electrical micro and nano converters.

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