Recent Advances in Nanocomposite Soft Magnetic Materials: a Review

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Recent Advances in Nanocomposite Soft Magnetic Materials: A Review

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Abstract: Conventional micro-sized magnetic materials have same magnetic and electrical properties irrespective of size. The control and tunability of the magnetic properties would be a difficult task. With the development of nano magnetic fillers, the magnetic and electrical properties can be varied by controlling the size, shape and weight percentage of the nanoparticles. In the recent years many with the addition of nano sized fillers, excellent nanocomposite with unique magnetic properties like high permeability and low coercivity have been developed. The magnetic nanocomposites have shown remarkable improvements in the magnetic properties as compared to the conventional counterparts. Henceforth, research investigations in this area is increased. The use of new generation magnetic nanoparticles is demonstrated to be suitable for many power electronics devices such as DC-DC converters, microwave devices, sensors. These magnetic nanoparticles are characterised by moderate magnetic saturation, low coercivity, improved electrical resistivity and low eddy current loss which are also desirable for all the devices.

The proposed research presents a comprehensive review of different fillers capable of imparting magnetic properties to the polymer composites. In the proposed research, the advantages of using zinc-cobalt ferrites for the development of magnetic material has been reviewed along with other magnetic fillers such as zirconium, nickel and their combination. The advantages of polymer nanocomposite are improved physio-chemical properties, ease of processing, thermo-mechanical stability, high electric breakdown strength and low cost.

The electromagnetic properties can be tailored by incorporating appropriate fillers and weight percentage. Review on assessment of different synthesis and fabrication techniques and the resulting improvement in magnetic properties has been undertaken.

Index Terms – Soft magnetic material, Nanocomposite, Permeability, coercivity, nanocrystalline.

I. INTRODUCTION

The soft magnetic material (SMM) is used as core material for inductors, motors, generators and transformers. The frequency of operation of magnetic cores varies from 50-60 Hz to several of MHz region. The transformers, generator and motors operates at power frequency of 50-60 Hz whereas the power electronic circuits operate from few KHz to several hundred MHz. The various magnetic materials have been used as core material for specific requirements of various applications. The core used in different devices can be broadly classified into five main categories

i. Steel/iron-based cores
ii. Ferrite cores
iii. powder-based cores
iv. Non-crystalline amorphous alloy based cores
v. Nanocrystalline/nanocomposite cores.

Nanocomposite cores show an attractive range of magnetic properties which cannot be achievable by conventional micro-scale magnetic material.

The present research is mainly focussed on review of inductor cores used in power electronic circuits for Energy Storage and in Electro Magnetic Interference filters. The compact, lightweight and enhancement of energy efficiency of power electronics devices are the key factors for the growth of power electronics industry. Even though the active components of power electronics converter have gone through substantial improvement, the research on passive elements, like inductor, have been very minimal and this has become a limiting factor for high switching frequency and high power application. The development of magnetic nanocomposite core capable of operating efficiently at high flux densities with low core losses has improved the performance of passive elements at high frequency of above 1 MHz in power electronic circuits.

The inductor core requires properties such as high permeability, low coercivity for wide range of required operating frequencies. Conventional magnetic material for power applications has several limitations for these requirements. Even though ferromagnetic materials like cobalt, iron and nickel have high permeability, not suitable due to high eddy current losses at high-frequencies. Ferrites are suitable for power inductor applications in the frequency range of 100 kHz -1 MHz, because of their higher resistivity. However, for frequency above 1 MHz, the ferrites have limitations such as lower saturation magnetization and poor frequency response.

Magnetic nanocomposites of polymer-metal having high saturation magnetization with high resistivity can be used for frequencies from 1 MHz - 10 MHz region. These magnetic nanocomposites are metallic nanoparticles which are coated by an insulating polymer.

Magnetic nanocomposites are comprised of magnetic particles in nanoscale dimension in an amorphous matrix, can be used for the power inductor application above 10 MHz range. The Co-or Fe-based nanocomposites have high permeability and frequency stability at frequencies above 10 MHz than their micro-scale counterparts.

II. LITERATURE REVIEW

Passive components mainly affect the efficiency and miniaturization of power electronic circuits. Among the passive components, inductors are the main setback in power electronic circuits due to conventional magnetic micro-scale materials operating inefficiently at higher frequency above 1 MHz. Using the magnetic material structure at nano-scale, eliminates the limitations for magnetic material caused at high frequencies. These magnetic nanocrystalline materials can reduce the size and weight of conventional microscale material [1]. The polymer bonded SMM can be an alternative for the magnetic material used in inductors operating at high frequencies above 1 MHz in power electronic circuits. The NiZn-ferrite is used as filler material and was produced by sintering at high temperature. Ultramid B27 and epoxy were used as polymer material. The filler and polymer material were dry mixed with different weights of filler material upto 80% [2]. Polymer Bonded Soft Magnetic Materials (PBSMM) were studied for electromagnetic shielding application and inductor core in EMI filter. The $FeSi_{6.8}$ is used as filler powder and Ultramid B27 is used as polymer material. The filler and polymer material were mixed with different weights of filler material upto 65%. The permeability has remained constant of value 30 upto 1 MHz [3]. NiFeZn based ferrite powder was used and the epoxieAW4510 + HW4804 is used as binder for fabrication. The result shows that the increase in ferrite powder percentage increases the relative permeability of the core [4]. Thick ferrite - epoxy nanocomposite paste and Co-silica- BCB nanocomposite pastes were prepared and characterized for permeability from few MHz to 3 GHz frequency range. Both nanocomposite paste shows high permeability [5]. Nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ powder was synthesized by ball milling method in the range from 25 to 1200 μm. Organo-silicon polymer Dublisil 20 is used as binder for fabrication. The magnetic properties and core permeability were studied by vibration sample magnetometer (VSM)and Ferrometr and Remacomp C-100 device respectively [6]. The magnetic properties of organo-silicon polymer bonded nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ powder particles were investigated. The permeability of polymer bonded nanocrystalline powder particles is nearly constant in a frequency range between 50 Hz and 10 kHz [7]. The $Ni_{0.48}Cu_{0.12}Zn_{0.4}Fe_2O_4$ nanoparticles were synthesized using microwave hydrothermal synthesis. The synthesised nanoparticles were mixed with paraformaldehyde for various weightage percentages. The result shows that the permeability of all samples under remains constant for a frequency range between 1 MHz-110 MHz [8]. The $Ni_{0.2}Zn_{0.8}Fe_2O_4$ nanoparticles were synthesised using electro-spinning technology. The synthesised ferromagnetic powder was coated with boron-modified phenolic resin (PFRB). The result showed that the Complex permeability had stable value of 52 up to high frequencies of about 1 MHz.

III. PROPERTIES OF SOFT MAGNETIC MATERIAL

The soft magnetic material (SMM) which is suitable for power inductor application must have following basic properties.

i. Low coercivity(Hc)
ii. High relative permeability
iii. High resistivity(ρ)
iv. High saturation magnetization(Ms)

i. Low coercivity: The hysteresis loss can be reduced by reducing the coercivity. If the coercivity reduces then the hysteresis loop width reduces and this in turn reduces the hysteresis losses. Coercivity mainly depends on the grain size. By limiting crystalline growth below the ferromagnetic exchange length, coercivity can be reduced.

ii. High relative permeability: The permeability represents the responding time of the material for the applied magnetic field. If the value of permeability is high, then it shows that the material responds very fast to the magnetic field. Hence the permeability of SMM should be as high as possible.

iii. High resistivity: High resistivity reduces the eddy current losses. The high resistivity increases materials skin depth. Skin depth should be high to keep the magnetic field intensity constant.

iv. High saturation magnetization: High value of saturation magnetization results in higher value of permeability.

IV. MAGNETIC MATERIALS

The conventional alloys of Silicon-steel and Fe-Co have large value of magnetization but have lower value of permeability. The alloys of Cobalt based amorphous have high value of permeability but lower magnetization. The nano crystalline soft magnetic alloys possess the higher values of both permeability and magnetization. The Fig.1 below shows the magnetic permeability vs, saturation induction at 1 kHz for various SMM.

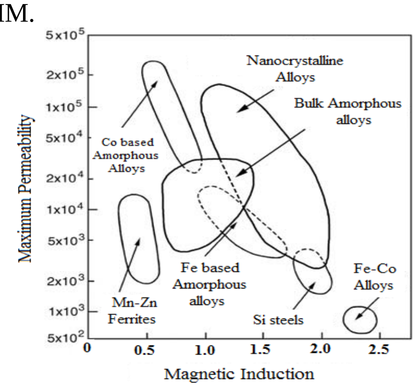

Fig. 1: Magnetic permeability vs saturation induction at 1 kHz for various SMM.

The main class of magnetic materials used for various applications are

i. Iron-Silicon Alloys
ii. Amorphous Nano-Crystalline Alloys
iii. Soft Ferrites
iv. Nickel-iron alloys

i. Iron-Silicon Alloys: Fe-Si alloys are mainly used in transformer cores which operates at 50Hz to 60Hz.Mixing 3 weight percentage of Si with Fe has a positive effect on material's resistivity, which in turn reduces the eddy current losses. Addition of Silicon helps in reducing the magneto-striction and magneto-crystalline anisotropy. The adding more than 4% weight of silicon results the brittleness of material.

ii. Amorphous nanocrystalline Alloys: The nanocrystalline alloys can be synthesized by various chemical synthesis and mechanical milling methods. These alloys are made from the combination of nickel, iron, zinc, cobalt, silicon etc. The nickel, iron, zinc, cobalt are ferromagnetic materials with high permeability value. The Fe-Si based nanocomposites have low hysteresis losses but lower magnetisation and hence not used for higher current applications. The NiFe, NiZnFe and CoFe based nanocomposite has large value of permeability and hence can be used for the high frequency power applications.

iii. Soft Ferrites: Metallic SMM cannot be used at high frequencies due to the eddy current loss. The Ferromagnetic soft ferrites are attractive materials for these applications. The metals are generally composed of$MnFe_2O_3$, $NiFe_2O_3$, $ZnFe_2O_3$composites.These materials can operate effectively upto 1 MHz for power applications and can operate efficiently up to few hundreds of GHz for small signal applications.

iv. Nickel-iron alloys: These alloys are also called permalloy, are exceptionally flexible and are used for various applications with nickel varying from 30% to 80% of weight. Higher the Nickel content in the alloy, higher will be the permeability. For equal propositions of Nickel and iron, saturation magnetisation will be higher. For low Nickel content, the electrical resistance will be higher.

V. HISTORY OF SOFT MAGNETIC MATERIALS

SMM plays a key role in energy conversion process. This is mainly used in inductors, Motors and generators. Starting from the initial years of 19^{th} century, the only soft magnetic material known for mankind was iron. Iron was very extensively used in those days for all the applications. As the technology progressed, a better material was needed than iron for better performance. Then the silicon steel was first developed in the year 1912. The performance of silicon steel was superior to that of iron and it replaced the iron in most of the applications during that time. Even today silicon steel is more widely used in transformers and motors. But as the frequency of operation is increased, the performance of the silicon steel decreases. In 1914 Permalloy was invented, which a nickel iron SMM is made up of 80% nickel and 20% iron. A major advantage of permalloy is its high permeability, but it has high eddy current losses, so not used in power electronics applications. By 1940's ferrites were invented, these have better properties than any other previous magnetic materials. One of the major advantages of Ferrites is that its production cost is very less. Presently soft ferrites are the most commonly used material for inductor in high frequency applications. Molybdenum Permalloy Powder (MPP) was developed in the year 1940.MPP was developed using 2% Molybdenum 82% Nickel and 16% Iron. The MPP cores have made greatest impact in high frequency switching applications in power supplies. Table 1 below shows the properties of various conventional magnetic materials.

Table 1: Properties of conventional magnetic materials

Name of material	Composition	Initial Permeability (μ_r)	Flux Density (Bs)	Coercive Force (He)
Iron				
Silicon steel	3% Si, 97% Fe	1.5K	1.5-1.8	0.4-0.6
Permalloy	79% Ni, 17%Fe 4% Mo			
Supermalloy	78% Ni, 17%Fe 5% Mo	10K-50K	0.65-0.82	0.003-0.008
Manganese Zinc Ferrites		750-15K	0.3-0.5	0.04-0.25
Nickel ZincFerrites		15-1500	0.3-0.5	0.3-0.5
Molybdenum Permalloy Powder	2% MO, 82% Ni 16% Fe	14-550	0.7	0.3
CO based Amorphous alloys	$Co_{67}Fe_4B_{14.5}Si_{14.5}$	5×10^5		0.5-1

VI. ADVANCEMENT IN SOFT MAGNETIC MATERIALS FIELD

By 1960s, use of power electronics circuits have increased and this increased the operating frequency of the circuits. Then a material with better performance was needed to operate at higher frequency. Then in the early part of 1960's, amorphous alloys were developed, whose performance was better at higher frequencies.

In last 3 decades, lot of research has been carried out to study the effect of material composition on the nanocrystalline material's soft magnetic properties. A first breakthrough in the field was in the year 1988 when Yoshizawa, Oguma and Yamaguchi discovered FINEMET alloy [24][25].This material is synthesised using iron, Silicon and Boron, with small amounts of Copper and Niobium. The typical composition of FINEMET is $Fe_{73.5}Si_{13.5}B_9Cu_1Nb_3$. The frequency dependency of permeability and core loss of FINEMET compared to that of other core material is shown in figure 2(a) and 2(b) [23].

In addition to the FINEMET, the other relevant families of nanocrystalline alloys are NANOPERM, HITPERM, and NANOMET.

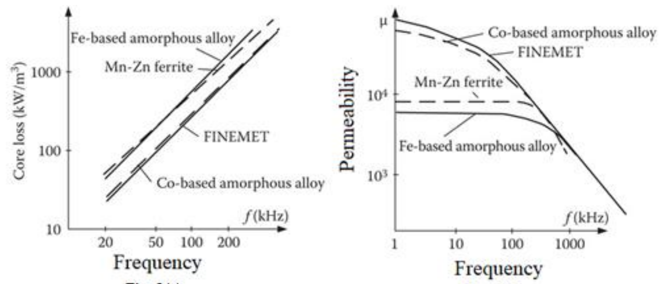

Fig. 2(a) Fig. 2(b)

Fig. 2(a): Core losses vs Frequency Curve Comparison of FINEMET with Various magnetic materials
Fig. 2(b): Permeability vs Frequency Curve Comparison of FINEMET with various magnetic materials

NANOPERM alloys have a typical composition of $Fe_{86}Zr_7B_6Cu_1$. This has higher saturation magnetization than FINEMET [27]. Due to its excellent saturation magnetization, its core is the main choice for common mode choke coil, pulse- transformer and flux gate magnetic detector [28]. The frequency dependency of permeability and core loss of NANOPERM compared to that of Amorphous FeBSi alloy core material is shown in figure 3(a) and 3(b) [23].

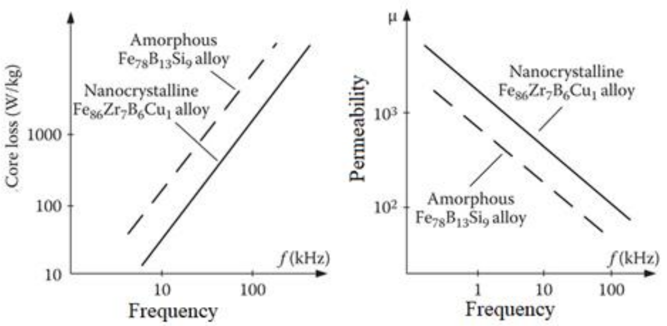

Fig. 3 (a) Fig. 3 (b)

Fig. 3(a): Core losses vs Frequency Curve Comparison of NANOPERM with Various magnetic materials
Fig. 3(b): Permeability vs Frequency Curve Comparison of NANOPERM with various magnetic materials.

HITPERM are high-temperature SMM and their initial composition is $Fe_{44}Co_{44}Zr_7B_4Cu$.The Co maximizes magnetic and Curie temperature of the alloy [22]. This family of alloys exhibits high magnetic inductions and better soft magnetic properties than other family of materials at high temperatures. Škorvánek and co-authors [30] showed in his experiment that copper free HITPERM exhibits the same microstructure that of HITPERM. That means copper element is not needed to form an ultrafine structure HITPERM [30].

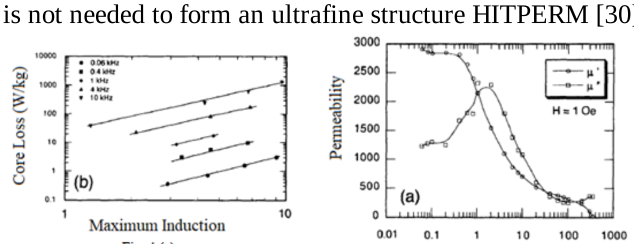

Fig. 4 (a) Fig. 4 (b)

Fig. 4(a): Core losses vs Maximum Induction Curve of HITPERM
Fig. 4(b): Permeability vs Frequency Curve of HITPERM

The NANOMET alloy is the recent development in the family of soft magnetic nanocrystalline alloys. It has a typical composition of $Fe_{83.3–84.3}Si_4B_8P_{3–4}Cu_{0.7}$. NANOMET has higher saturation magnetization and its cost is less compared to other two families [20].

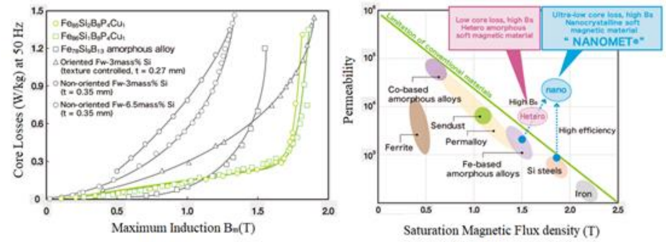

Fig. 5 (a) Fig. 5 (b)

Fig. 5(a): Core losses vs Maximum induction curve of NANOMET.
Fig. 5(b): Permeability vs Saturation Magnetic Flux density curve Comparison of NANOMET with various magnetic materials.

Polymer Bonded SMM: Polymer bonded nanocrystalline powder was developed to study the effect of magnetic properties due to addition of polymer [6]. The powder used for the investigation is $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ and the polymer used is organo-silicon polymer. The dynamic magnetic properties at the frequency range from 50 Hz up to100 kHz were studied in this paper. The particle size used varied from a size of 25μm to 750μm.Two characteristics describing magnetic properties are shown below.

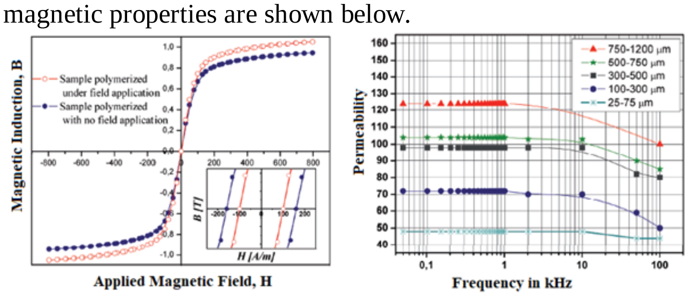

Fig. 6 (a) Fig. 6 (b)

Fig. 6 (a): Magnetic Induction Vs Applied
Fig. 6 (b): Permeability vs. Frequency Magnetic field

From the above permeability vs frequency curve, we can observe that this material can be operated upto 100 kHz.

New Amorphous Core Material by Bourns in collaboration with Tyndall Research Institute

The Bourns in collaboration with Tyndall Research Institute developed an amorphous material composed of Cobalt and Iron together with mixtures of Silicon and other elements such as Niobium. Core losses at 1 MHz were lesser than other ferrite materials [21]. The core loss comparison with Ni ferrites is shown in Fig.7 below.

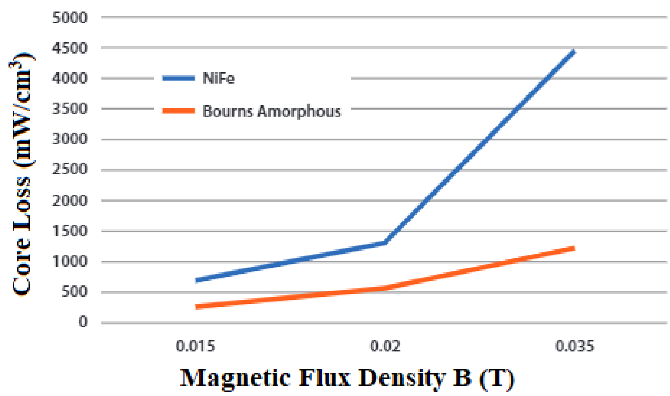

Fig. 7: Core losses Vs Magnetic Flux density for Bourns Amorphous and Ni Ferrites

VII. CONCLUSION

Based on the literature review, the following conclusions can be drawn:

- The different properties required for the efficient operation of the magnetic materials for various applications.
- The conventional soft magnetic material exhibits very good properties at lower frequencies but at higher frequencies, performance deteriorates.
- The need of advanced SMM based on nanocrystalline families like FINEMET, NANOPERM, HITPERM, and NANOMET, which can overcome the drawbacks of the conventional SMM.

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