

Predicting Effective Permeability of Nanodielectric Composites Bonded by Soft Magnetic Nanoparticles

A. Thabet, M. Repetto

Abstract—Dielectric materials play an important role in broad applications, such as electrical and electromagnetic applications. This research studied the prediction of effective permeability of composite and nanocomposite dielectric materials based on theoretical analysis to specify the effects of embedded magnetic inclusions in enhancing magnetic properties of dielectrics. Effective permeability of Plastics and Glass nanodielectrics have been predicted with adding various types and percentages of magnetic nano-particles (Fe, Ni-Cu, Ni-Fe, MgZn_Ferrite, NiZn_Ferrite) for formulating new nanodielectric magnetic industrial materials. Soft nanoparticles powders that have been used in new nanodielectrics often possess the structure of a particle size in the range of micrometer- to nano-sized grains and magnetic isotropy, e.g., a random distribution of magnetic easy axes of the nanograins. It has been succeeded for enhancing characteristics of new nanodielectric magnetic industrial materials. The results have shown a significant effect of inclusions distribution on the effective permeability of nanodielectric magnetic composites, and so, explained the effect of magnetic inclusions types and their concentration on the effective permeability of nanodielectric magnetic materials.

Keywords—Nanoparticles, Nanodielectrics, Nanocomposites, Effective Permeability, Magnetic Properties.

I. INTRODUCTION

NANO-DIELECTRIC industrial materials challenge traditional materials such as porcelain, plastics and glass in electric and magnetic applications. New developments in dielectric materials and new production techniques make nano-dielectric material interesting for application in electromagnetic applications. Nowadays, many researchers have tried to improve the magnetic properties performance of dielectrics, by selecting suitable magnetic materials and applying a suitable mixing method or preparing composites based on the amorphous or nanocrystalline powders. On the other wise, the developments in magnetic materials and new production techniques make SMC material interesting for application in electrical machines [1]-[4] or preparing composites based on the amorphous or nanocrystalline powders [5]-[8]. With respect to the main goal of material science is developing new materials at the nanometric scale. This class of materials becomes particularly important

because its physical properties change dramatically with the size and with the local structure of the grains.

Modeling that describes the magnetic behavior of nanocrystalline properties and characteristics of soft magnetic materials are useful for simulations of electronic circuits that contain inductors or transformers using these cores. Thus, predicting the effective magnetic properties of composite and nanocomposite materials are the utmost importance in both academic and industrial research. Maxwell-Garnett's formula, Bruggeman's formula are well established techniques for the evaluation of effective permeability of disordered hetero-structures. But, there is no exact solution for the magneto-static problem in the heterogeneous geometry, and none of the existing mixing formulas can be applied to composite or nanocomposite materials of all types. In recent years, it has been modified Maxwell-Garnett and many mixing rules to predict effective parameter calculation for studying the macroscopic magnetic properties of composite and nanocomposite industrial materials in the simulation techniques [9]-[13]. Also, it can be proposed permeability effects of nano-size magnetic particles on polymers [14].

The applications of soft magnetic materials in AC electrical and electronic devices require soft magnetic core materials that possess high saturation magnetization, high Curie temperature, high initial permeability, low eddy current loss, low hysteresis loss, and low dielectric loss. Nanocomposite processing offers a new approach for fabricating materials with novel magnetic and electric properties. In a magnetic/ceramic nanocomposite, the resistivity can be dramatically increased; the exchange coupling between neighboring magnetic nanoparticles can overcome the anisotropy and demagnetizing effect of the individual particles, resulting in much better soft magnetic properties than with conventional (large grain-size) materials. Nowadays, there is a tremendous effort being undertaken by designing and manufacturing soft magnets with excellent physical properties and high corrosion resistance for industrial applications. To be considered for engineering applications, these materials should be of low cost and should be easy to prepare, allowing them to be highly competitive with the already-existing ones used in such applications. It can be modeled and manufacture a linear and nonlinear artificial material in which the effective permeability is negative in the low and very low frequency range. At such frequencies, a diffusion equation drives the field into the medium and this leads to exploring unusual effective – constitutive laws [15]-[21].

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In this paper, it has been suggested new nanodielectric composites magnetic industrial materials that have been enhanced their magnetic characterization response with respect to types and concentrations of selected nano-particles.

II. ANALYTICAL MODEL

In our research, it will be focus on calculation techniques for the frequency dependent permeability (complex intrinsic permeability μ_{int} and effective permeability μ_{eff}) of magnetic industrial materials composite consisting of micron/submicron-sized nanocrystalline particles embedded in different matrix, considering the nanocrystalline structure of magnetic particles and skin effect. So that, based on the following analytical models [11], [13] that has been used to formulated an theoretical theories for predicting an effective permeability of composite and nanocomposite materials, So, it can be calculate the true intrinsic permeability ($\mu_{i,true}$) for a magnetic spherical particle considering the skin effect. Generally, the particle size should not exceed the skin depth δ significantly in radar absorbing applications [11].

$$\delta = \sqrt{\frac{\rho}{\pi\mu_{int}f}} \quad (1)$$

where, ρ is the resistivity, μ_{int} is the intrinsic magnetic permeability, and f is the frequency.

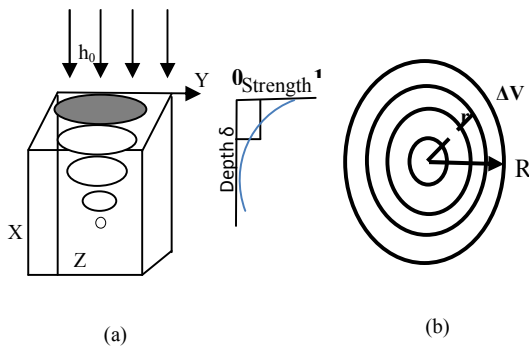


Fig. 1 Schematic for calculating true intrinsic permeability of a magnetic spherical particle

Also, considering a spherical metallic particle subject to a dynamic field, the penetrated dynamic magnetic field h decreases with increasing penetration into the spherical particle size with d as shown in Fig. 1, so that, the dynamic magnetic field can be obtained as follows:

$$|h| = h_0 e^{-(R-r)/\delta} \quad (2)$$

Whatever, R is the radius of the spherical particle, the true intrinsic permeability of the spherical particle considering skin effect will be as follows:

$$\mu_i = 1 + \frac{\iiint h_i(\mu_{int}-1)dv/V}{h_0} \quad (3)$$

With respect to classical mixing rules of particles with main matrix for determining the effective permeability by

Maxwell-Garnett's law, the effective permeability of composites if the inclusion phase is dispersed in the matrix phase random distribution [13], it will be as follows:

$$\mu_{eff} = \mu_m + f\mu_m \frac{\mu_i - \mu_m}{\mu_m + (1-f)(N_v \cos^2 \theta + N_w \sin^2 \theta)(\mu_i - \mu_m)} \quad (4)$$

where θ stands for an acute angle between the direction of three main axes of flake like inclusion and the external magnetic field H . And so, the inclusions are modeled as equivalent oblate spheroids to evaluate the demagnetizing factors N_v , and N_w . Adding the effect of nonrandom distribution of inclusions on the effective permeability of the composite for the same model, there are two fitting parameters α and β as spatial position distribution factors to be as follows:

$$\mu_{eff} = \mu_m + f\mu_m \frac{\mu_i - \mu_m}{\mu_m + (1-f)(\alpha N_v \cos^2 \theta + \beta N_w \sin^2 \theta)(\mu_i - \mu_m)} \quad (5)$$

Also, it can be calculate the effective permeability of nanodielectric magnetic materials that has been characterized by adding various percentages of magnetic nano-fillers random distributions in polymer matrix material as [14]. The effective permeability μ_{eff} of micro and nano iron particles/nonmagnetic matrix composite can then be calculated using the above theories based on true intrinsic permeability of magnetic materials. However, influences of types, concentration of micro-/nano-sized iron particle, and frequency will be shown on the performance of effective permeability in this paper.

III. SUGGESTED DIELECTRICS AND MAGNETIC NANOPARTICLES

Nanodielectrics are used in electromagnetic applications, and can be described as ferromagnetic powder particles embedded in electrical insulating materials. The choice of nanodielectrics is complex and depends on many factors – the primary ones being frequency, the size of the component, and the physical strength and the magnetic properties.

TABLE I
 ELECTRIC AND MAGNETIC PROPERTIES OF SELECTED MAGNETIC PARTICLES AND DIELECTRIC MATERIALS

Materials	Electric and Magnetic Properties	
	μ (H/m)	ρ ($\Omega \cdot m$)
Plastics	1.25×10^{-6}	$10^{16} - 10^{22}$
Metglas	125×10^{-2}	142×10^{-8}
Fe "High Purity"	1500×10^{-3}	10×10^{-8}
Ni-Fe	400×10^{-3}	55×10^{-8}
Co-Fe	70×10^{-3}	40×10^{-8}
Ni	1.25×10^{-4}	69.9×10^{-9}
Isoperm Ni-Cu	0.65×10^{-4}	10^{-9}
Ferrite MgZn	8×10^{-4}	0.5
Ferrite NiZn	$2 \times 10^{-5} - 8 \times 10^{-4}$	300

Nowadays, nano-technology science can be made huge enhancement in the magnetic properties of the composite materials which will be affected on performance of the

electromagnetic industrial applications. Thus, this research illustrates the effects of nanoparticle size (50nm_diameter), Iron high purity particles (single crystals in preferred directions), Ni-Cu, Ni-Fe, MgZn, and NiZn. Table I depicts the main electrical description properties of usage of magnetic nano-particles which have been used for enhancing magnetic properties of dielectric materials.

IV. RESULTS AND DISCUSSIONS

Particularly, nanodielectrics strategy is an effective in yielding high performance composites; whenever it has a good dispersion of the fillers that achieved and had properties of the nanoscale filler are substantially different or better than those of the matrix. Thus, this theoretical study of polymeric nanocomposites is recommended to be fabricated using various nanoparticles to formulate nanostructures. The following suggested new nanodielectric composites magnetic industrial materials have been enhanced their magnetic characterization response with respect to types and concentrations of selected nano-particles.

A. Characterization of Plastics Magnetic Nanodielectrics

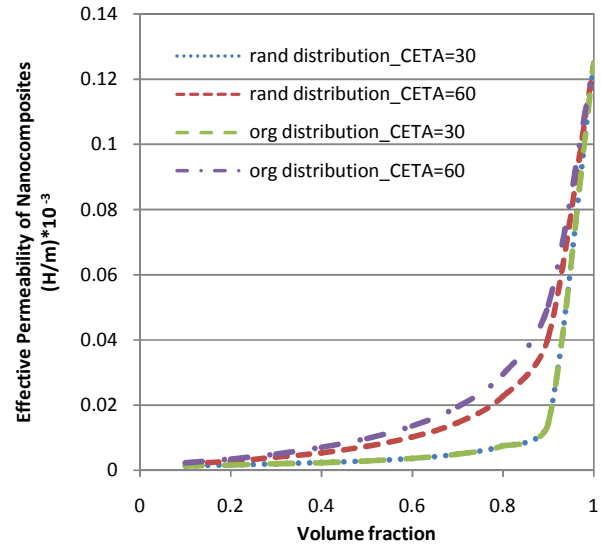
Table II depicts the effective permeability of Plastics/Fe nanocomposite that has been increased by adding various percentages of iron nano-fillers random and organized distributions in plastics matrix material. The effective permeability of Plastics/Fe nanocomposite increases with increasing volume fraction of iron nanofillers, especially through volumetric fractions (90%wt: 100%wt) in the nanocomposite. Whatever, increasing acute angle (0:90) doesn't have an effectiveness factor on the effective permeability of nanocomposites.

TABLE II
 EFFECTIVE PERMEABILITY OF PLASTICS/FE NANOCOMPOSITE WITH VARIOUS VOLUME FRACTIONS

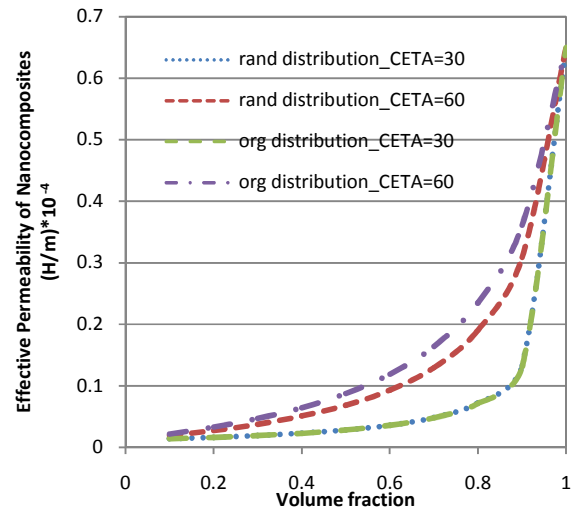
Volume Fraction	μ_{eff} (Plastics/Fe nanocomposite)			
	Random Distribution		Organized Distribution	
	CETA=30	CETA=60	CETA=30	CETA=60
0.1	1E-6	1.5E-6	1E-6	2.3E-6
0.3	1E-5	2E-5	1E-5	3.2E-5
0.5	1E-3	2.8E-3	1E-3	3.8E-3
0.7	1E-2	4E-2	1E-2	4.5E-2
0.9	0.5	0.6	0.5	0.7
1	1.5	1.5	1.5	1.5

On the other side, Fig. 2 shows the effective permeability of Plastics/Ni and Plastics/Ni-Cu Alloys nanocomposite that has been increased by adding various percentages of Nickel and Ni-Cu Alloys nano-fillers random and organized distributions in silicon matrix material. Fig. 2 (a) shows the effective permeability of Plastics/Ni nanocomposite that increases by increasing volume fraction of Nickel nanofillers in the nanocomposite. Whatever, increasing acute angle (0:90) increases the effective permeability of nanocomposites, nevertheless; the effective permeability of Plastics/Ni nanocomposite of random and organized distributions have identical characterization performance at lower acute angle

(0:30).The organization distribution of nickel nanoparticles inside plastics matrix has been aided to increase the effective permeability by increasing acute angle (60:90) with respect to random distribution.



(a) Effects of Nickelnano-particles on Plastics



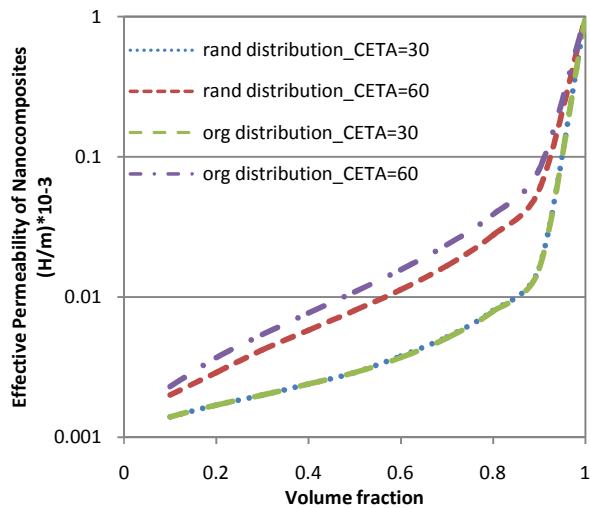
(b) Effects of Ni-Cu Alloys nanoparticles Plastics

Fig. 2 Effective permeability of Plastics nanocomposite with various nanoparticles volume fractions

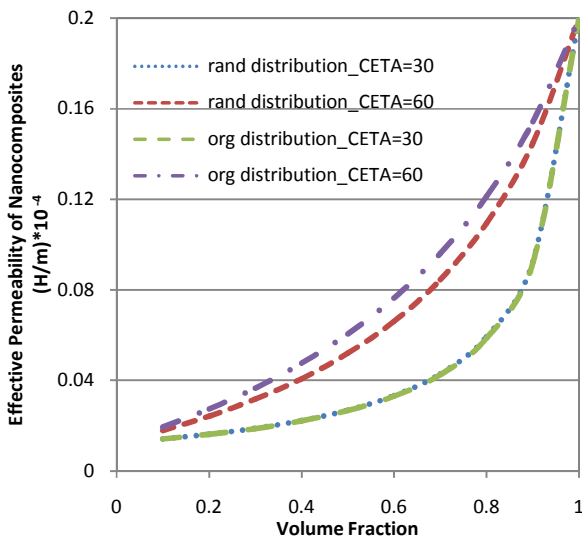
Fig. 2 (b) shows that increasing Ni-Cu Alloys nanoparticles increases the effective permeability of Plastics but Ni-Cu Alloys nanoparticles have lower magnetic effects than Nickel nanoparticles on Plastics, then; acute angle has an importance factor for increasing the effective permeability performance by using Ni-Cu Alloys nanoparticles in organization distribution inside plastics matrix.

B. Characterization of Ferrite Magnetic Nanodielectrics

On the other wise, Fig. 3 illustrates the effective permeability of Plastics/Ferrite MgZn and Plastics/Ferrite NiZn nanocomposites that have been increased by adding various percentages of Ferrite nano-fillers random and organized distributions in plastics matrix materials. Fig. 3 (a) shows that increasing acute angle (0:90) increases the effective permeability of nanocomposites.



(a) Effects of MgZn Ferrite nano-particles



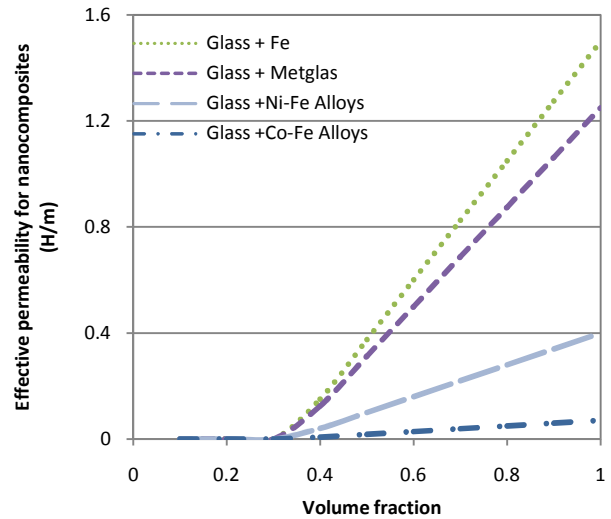
(b) Effects of NiZn Ferrite nano-particles

Fig. 3 Effective permeability of Plastics nanocomposite with various Ferrite volume fractions

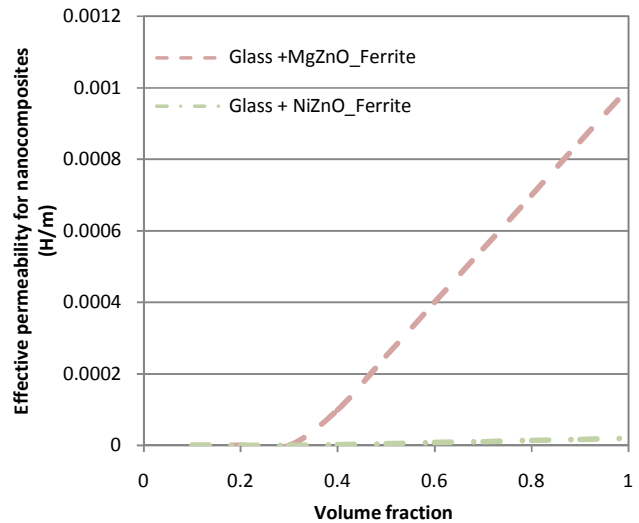
Fig. 3 (b) shows that NiZn Ferrite nano-particles have lower magnetic effects than MgZn Ferrite nanoparticles on Plastics, then; acute angle has an importance factor for increasing the effective permeability performance by using Ni-Cu Alloys nanoparticles in organization distribution inside plastics matrix.

C. Characterization of Glass Magnetic Nanodielectrics

Glass that has not contains any magnetic charges; it can be magnetized by various volume fractions of magnetic nanoparticles to be used in many electrical industrial applications. Thus, Fig. 4 (a) shows the effective permeability of glass nanocomposite that has been increased by adding various percentages of magnetic nano-fillers random distributions in glass matrix material.



(a) Effects of various magnetic nano-particles on Glass



(b) Effects of various Ferrite magnetic nanoparticles

Fig. 4 Effective permeability of Glass nanocomposite with various nano-particles volume fractions

Iron is the highest effective nanofillers in the studied nanoparticles for increasing the effective permeability of glass nanocomposite, whatever; Ni-Fe Alloys is the lowest effective nanofillers for increasing the effective permeability of glass nanocomposite.

On the other hand, Fig. 4 (b) shows the effective permeability of glass nanocomposite that has been increased

by adding various percentages of ferrite magnetic nano-fillers random distributions in glass matrix material. Mg-ZnO Ferrite is higher effective nanofillers than Mg-ZnO Ferrite nanoparticles in the studied glass nanocomposites for increasing the effective permeability of Glass nanodielectric composites.

D. Characterization of Dielectric Composites

Soft magnetic nanoparticles gives an enhancement of magnetic properties of the composites [1], [3], [5], [9], [11], [13] but comparing results of nanodielectric composites, it has been cleared that nanoparticles gives a great enhancement in magnetic properties of the composites. But, dielectric composites can be reach to the same results of nanodielectric composites at specified special position distribution factors (α , and β) and at specified identical flake-like scatters of the composite.

V. CONCLUSION

- Plastic organized nanodielectric composites distribution can be done by fabricating devices that aids increasing Effective permeability of nanocomposites more than Plastic random distribution nanodielectrics at acute angle (30:90) in dielectric matrix.
- Characterization of the effective permeability of Glass nanodielectric composite has been enhanced by adding various percentages of magnetic nano-fillers random distributions according to types and volume fraction of nanoparticles inside the dielectric matrix.
- Dielectric Composites can be reach to the same results of nanodielectric composites at specified special position distribution factors (α , and β) and at specified identical flake-like scatters of the composite.

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