Review – Micromagnetic Simulation Using OOMMF and Experimental Investigations on Nano Composite Magnets

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Abstract. The main objective of this present study is to perform finite element analysis of nanocomposite magnetic materials using micromagnetic theory. Nowadays modern electric motors, wind turbines, electric generators, hybrid vehicles, electric vehicles and aircraft etc. require high performance magnets. The maximum energy product BHmax in B-H hysteresis loop decides the effectiveness of these magnets. The present rare earth magnets are considered as the best performing magnets and used in many high energy applications. A high throughput research was carried out to increase the BHmax of rare earth permanent magnets and the exchange of coupling between hard and soft phase magnetic materials i.e., materials which combine a high coercivity hard phase material with the high saturation magnetization of soft phase material. In order to understand the effect of soft phase for different particle sizes and volume distributions on behavior of nanocomposites Nd2Fe14B/g15/g81/g72/g76/g70/g89/g68/g74/g81/g72/g87/g76/g70/g3/g41/g40/g48/g3/g76/g86/g3 used. Micromagnetic theory is the studies to understand the microstructure physical properties and to know the performance of magnetic materials at micrometer length scales. To carry out the simulations, the cubic model geometry has to be spatially discretized and need to solve Landau-Lifshitz Gilbert equation and Gibbs energy equation numerically using the finite element method. All these calculations can be carried out by any one of the open source micromagnetic simulation packages (OOMMF, Nmag, Magpar, Mumax and Fidimag). After thorough understanding about the crucial role of microstructures, a new hysteresis model will be developed and it will be compared with experimental data. The various experimental results of difference nano composite magnets is also reviewed. Further, the effect of influence of hybrid materials (hard/soft/hard, hard/soft/soft) on magnetic properties will be analyzed. Being expensive and in high demand, alternates to rare earth magnets (Neodymium) need to be explored.

1. Introduction

Accurate prediction behavior of Electromagnetic systems is a primary concern in developing novel applications. In the modern technology, the micromagnetic is an interesting concept which bridges theoretical and experimental data. In addition to this, it is important to develop modelling techniques used for electromagnetic applications. In order to achieve micromagnetic simulation, the magnetization dynamics are calculated by solving the nonlinear Landau-Lifshitz Gilbert (LLG) equation by linearizing it under small angle approximation [1]. Exchange spring magnets were used to combine the hard phase and soft phase materials to afford high coercivity, saturation and remanence [2]. This material has focused by several researchers in the past two decades [3]. The theoretical maximum energy density product [4] is predicted as 120MGOe. However, it is observed that the value
of experimental remanence is very closer to the expected data but the experimental data for coercivity is different from the theoretical value. By performing micromagnetic simulation using 3D software, OOMMF, some important underlying physics can be revealed. The effect of soft phase on enhancement of coercivity on nanocomposite magnets can also be investigated.

2. Some Related Works

Schrefl and Fidler[1] discussed about finite element modeling of nanocomposite magnets using micromagnetic theory. Gibbs free energy and Gilbert’s equation were used to perform numerical calculations using FEM and the size of soft magnetic materials have to be around two times higher than the domain wall width of the hard magnetic materials (8 nm). They concluded that the exchange of intergrain is used to improve the remanence of nanocomposite materials. By incorporating effect of alloy compositions in hard magnetic materials using micromagnetic calculation, the increase of anisotropy is decrease the saturation polarization and also the increase of Fe3B content in composite materials increases the coercivity and decreases the remanence. The decrease in the magnetic polarization and interchange the constant leads to increase the coercivity.

Saiden et.al [5] reported that the role of size and volume distribution of soft phase grain to determine the magnetic properties. By reducing the grain size, the remanence of micromagnetic materials is increased and the coercivity is getting reduced. The highest remanence of 1.46 T was found for the materials with grain size of 10 nm and volume fraction of 60-40% of Nd2Fe14B/α-Fe. The high coercivity of magnetic material was more than 900 kA/m obtained at 80-20% distribution. The magnetic properties of isotropic nanocomposite with different size distribution of the soft phase materials were studied.

Shulihe et al.[6] investigated the behavior and magnetic properties of nanocomposite Pr2Fe14B/α-Fe with solid materials by micromagnetic FEM. The constant decrease of Jc is observed during the standard deviation σ is increased with particle size to 10-30 nm and α-Fe content to 10-30%. It was noted that magnets with 30% α-Fe and d=10nm show highest energy BHmax and the low BHmax energy was observed at 10% α-Fe. The enhancement of hard magnetic material alignment increases the coercivity and the remanence of nanocomposite.

Li et al. [7] reported that the effect soft phase on the magnetic behavior and properties of MnBi/α-Fe by Micromagnetic FEM. They have developed cubic model with 64 irregular grains and the average particle size was considered as 20nm. The increase in the volume fraction of soft magnetic phase decreases the coercivity of the nano composite. Similarly, the remanence is raised to peak value at initially and falls down. The maximum energy products of isotropic and anisotropic magnets were 84 and 200 kJ/m³ respectively.

Sergey Erokhin et al. [8] reported that the polyhedron based micromagnetic nanocomposite was used for simulations of magnetic microstructure of nano crystalline Nd-Fe-B. It provided the highly accessible mesh based magneto dipolar field with FFT speed. The grain size of the hard and soft magnets is highly depends on the interchange interactions on magnetic properties of nanocomposite magnetic materials. Hence, the fine grain size is used to achieve high magnetic energy product for the nanocomposite magnet.

Sang et al. [9] studied the effect of interface exchange coupling using various soft layer thickness of hysteresis loops and spin distributions for Sm-Co/α-Fe bilayers via three dimensional and one dimensional micromagnetic calculations. The results showed that the increase of soft layer thickness leads to decrease of the nucleation field and exchange coupling.

Wenjing Si, et al [10] demonstrated the weakening of the coercivity owing to the interface atomic diffusion based on three dimensional (3D) micromagnetic software. They reported that the resultant method for the pinning field in a hard and soft multilayer can be enforced to both permanent magnets and exchange-coupled-composite (ECC) media. Further, they concluded that an enrichment of the magnetic properties in multilayers can be accomplished by providing anon-magnetic layer in between the hard and soft phases magnetic materials.
3. Micromagnetic Theory

The Micromagnetic theory involves Landau-Lifshitz-Gilbert equation and brown’s equation. LLG describes the magnetization motion \( M \) by applying an effective field \( H_{\text{eff}} \) (Landau-Lifshitz 1935). This equation (1) was developed by Landau-Lifshitz-Gilbert equation and the phenomenological Gilbert-damping was included to express the experimentally noticeable damping in ferromagnetic structures.

The equation of Landau-Lifshitz-Gilbert is given by

\[
\frac{dM}{dt} = -\gamma_0 M \times H_{\text{eff}} + \frac{\alpha}{M_s} M \times \frac{dM}{dt} \tag{1}
\]

Where, \( M \) = instantaneous magnetization ; \( M_s \) = Saturation magnetization ; \( H_{\text{eff}} \) = effective magnetic field; \( \alpha \) = Phenomenological damping parameter ; \( \gamma_0 \) = gyromagnetic ratio

3.1 Brown’s Equations

By writing down the magnetic Gibbs free energy, as given in equation (2), Brown derived a set of equations under the assumption of micromagnetic theory (Brown 1963).

\[
E = \int \varepsilon_\text{ex} + \varepsilon_\text{a} + \varepsilon_\text{z} + \varepsilon_\text{d} \ dv \tag{2}
\]

The integral runs over the volume of the ferromagnetic body. The details of constituent energies are as follows

- Exchange energy \( \varepsilon_\text{ex} \) indicates the interaction of spins with next neighbors
- Volume anisotropy energy \( \varepsilon_\text{a} \) indicates the crystal structure with easy and hard axes. It depends on the crystal type of specimen material i.e. uniaxial or cubic symmetry.
- Zeeman energy \( \varepsilon_\text{z} \) indicates an applied external field \( H_{\text{app}} \)
- Stray field energy or demagnetizing energy \( \varepsilon_\text{d} \) indicates the dipolar nature of the individual magnetic particles that produce the stray field.

4. Different Types of the Micromagnetic Software

Micro magnetic theory is to understand the microstructure physical properties and to discern the performance of magnetic materials in micrometer length. To carry out the micromagnetic simulations, LLG equations have to be solved repeatedly. In order to carry out the solution, the cubic model geometry can be developed and discretized using finite element method (FEM) or finite difference method (FDM). Using the FDM, the numerical method of solving Landau-Lifshitz Gilbert equation and Gibbs energy equation is primary [11-12]. All these calculations can be carried out by the micromagnetic packages as given in table 1. It is listed according to types of method and cost to utilize them.

Using FDM, a discrete set of lattice points were used to replace the continuous solution domain. The boundary conditions and finite difference operators have to be assigned. The space is being discretized using regular (rectangular) grid. As a result of complicated geometry like curved boundary or irregular microstructures FDM creates some artificial edge roughness unless used with care. The disadvantage of a regular grid is a pure approximation for the curved boundaries which cannot represent the accurate interphase boundaries for a proper system.

FEM employs to discretize the model into finite elements. The shape of the element determines the problem and it can be triangle, square or rectangle for two dimensions and tetrahedrons or hexahedra or cubes for three-dimensional problems and used to construct complex geometries effortlessly. However, FEM is much slower as compared to the FDM and for larger problems it is easier and reasonable to use FDM as opposed to FEM.
Table 1. Various Types of the Micromagnetic Software

| Name of the software Developer | Open source | Method | Source website                      |
|--------------------------------|-------------|--------|-------------------------------------|
| OOMMF-Object OrientedMicromagnetic Frameworks | Free        | FDM    | www.math.nist.gov/oommf/            |
| NMAG                          | Free        | FEM    | http://nmag.soton.ac.uk             |
| MAGPAR                        | Free        | FEM    | http://magnetoatp.tuwin.ac.at/sc/holz/magpar |
| Mumax                         | Free        | FEM    | http://mumax.github.io/             |
| Fidimag                       | Free        | FDM    | http://computationalmodelling.github.io/fidimag/ |
| LLG Simulator                | Paid        | FDM    | http://llgmicro.home.mindspring.com/|
| MicroMagus                    | Paid        | FDM    | http://www.micromagus.de/           |

5. OOMMF

OOMMF (Object Oriented Micromagnetic Framework) was first introduced in the year 1998. OOMMF was developed by M. Donahue and D. Porter [13] in the Information Technology Laboratory (ITL) at the National Institute of Standards and Technology. TCL/TK and C++ are used to write this toolkit. C++ is used to make Oxs tool. The simulation is performed in Oxs tool. It offers to control and visualize the tools via TCP/IP. C++ based OOMMF core interfaces using TCL/TK to write a configuration for performing the simulation.

OOMMF deals with three different levels to change the code:

- In the first level, programs interact individually through known protocols across network sockets.
- In the second level, TCL/TK scripts can be introduced and executed at run time. The first level scripts are easier than this level to change the scripts.
- In the last level, the modification of the C++ source can be done by third party modules such as VODE91 and VTK. 155, 156.

In OOMMF, finite difference method is used to find the solution of LLG equation. The input parameters and the initial conditions of any problem are specified in OOMMF micromagnetic input format (MIF). Most of the free software available for micromagnetic simulations are considered as temperature $T = 0^\circ C$ for simulation. Some commercial software may consider an option with the finite value of the temperature. The solution domain is divided into rectangular prism-like cells having the same dimensions. The rectangular cell size should be less or equal to the exchange length that is given by $(A/2\pi M)^{1/2}$. Here, A is taken as the exchange constant whereas M is taken as the magnetization. It calculates the total energy within individual cells by considering exchange energy, self-magneto static energy, magneto crystalline anisotropy energy and Zeeman energy. The magnetization in each cell can be updated by two types of evolvers. First one is a time evolver which tracks the LLG dynamics and another one is an energy minimization evolver which calculates the local minima in energy by using energy minimization techniques. A 4th order Runge-Kutta evolver is used as a time evolver to solve LLG equation as on ODE in time. There are two drivers, namely time driver and minimization driver, which control the time and minimization evolver, respectively. Depending upon the stopping criteria described in the MIF the driver will determine whether the simulation stage will be stopped or
continued. In the MIF, users provide either the stopping time or the stopping value of \( \frac{dm}{dt} \). The stopping value in the MIF is set in such a way that the value of maximum torque \( (m \times H) \) should be less than \( 10^{-6} \) A/m. When the stopping criteria will match, the simulation will terminate. The advantage of OOMMF software is that it is a collection of programs and each program can be modified or redesigned without changing the entire system. It has a good magnetization file display program (mmDisp) which can display the initial magnetization profile, demag field profile, etc. It can easily calculate the magnetization dynamics for any arbitrarily shaped elements consisting of one or more than one of the different magnetic materials.

5.1 OOMMF Procedure

5.1.1 STEP 1: Open the mmLaunch window.

Open Command Prompt and link to OOMMF root directory, then type

tclshoommf.tcl

or double click oommf.tcl to open oommf launch window. It will open a small window labeled mmLaunch in background mode. Then another prompt in original window will appear earlier to open mmLaunch window.

5.1.2 STEP 2: Open Solver window

In the mmLaunch window, the following are available in the menu options

- mmArchive is used to save field data of scalar and vector form automatically
- mmDataTable is used to show the present values of scalar outputs
- mmDisp is used to record the vector fields
- mmGraph is used to create x-y plots
- mmProbEd is used to change a problem parameters for mmSolve2D or Oxsii
- mmSolve2D is used to change solver of 2D problems
- Oxssi is used to change solver of 3D problems

Open mmDisp, mmGraph, and mmDataTable which depends on type of output form we want. Materials types and geometry details can be modified as per our requirements as shown in figure 1. In order to carry out the 3D simulation by OOMMF, Oxssi (OOMMF extensible solver interactive interface) should be used. The simulations of double layers using OOMMF are carried out. In this work, the length and width of soft and hard materials are taken as 300nm. The intrinsic magnetic properties of Nd\(_2\)Fe\(_{14}\)B/\(\alpha\)-Fe are given in table 2. In this simulation, Driver “Oxs_MinDriver” and solver “Oxs_CGsolve are preferred. The mesh size is considered as 5nm which is approximately equal to the bloch wall width of hard magnetic materials. As shown in figure 1 to 4, the graph between \( B_x(mT) \) and \( m_x \) is displayed in mmgraph window of OOMMF.

| Properties                        | Nd\(_2\)Fe\(_{14}\)B | \(\alpha\)-Fe |
|-----------------------------------|---------------------|---------------|
| Saturated Magnetization \( J_s \) | 1.61 T              | 2.15 T        |
| Anisotropic Constant \( K_I \)    | 4.331 MJ/m\(^3\)   | 0.046 MJ/m\(^3\) |
| Integral Exchange Constant \( A \)| \(0.77 \times 10^{-11}\) J/m | \(2.5 \times 10^{-11}\) J/m |
Figure 1. Snapshot of simulation and magnetization in 2D graph
By using 2D OOMMF, total energy (BH$_{\text{max}}$) developed in two phase magnets is analyzed for various thicknesses of soft phase magnets as shown in figure 3. The energy product of Nd$_2$Fe$_{14}$B/α-Fe increases slowly and decreases quickly when size increased. The maximum value obtained at size of soft phase magnets is 8nm. With the increase of size of α-Fe, magnetization ratio (M/M$_s$) decreases. The high magnetization ratio shows the important remanence enhancement effect due to proper coupling interaction between two magnets. According to block wall theory, size of the soft phase magnets must not be greater than two times the domain wall width of hard phase magnets. To keep in mind, effective size of soft phase is 8.4 nm for two phase Nd$_2$Fe$_{14}$B/α-Fe magnets.
6. Experimental Investigations

Development of new materials and their understanding on a smaller length scale is important concern to introduce for a variety of electromagnetic applications. This study intends to review the various nanocomposite materials with their magnetic properties and synthesis method used.

Table 3. Magnetic properties of various Nanocomposite magnetic materials

| S. No. | Nanocomposite magnets / Size | Methods used for synthesis | Magnetic Properties | Remarks | Ref. |
|--------|-----------------------------|----------------------------|---------------------|---------|------|
| 1      | CuFe₂O₄/ MnO₂ 40–118 nm     | Two-step wet chemical method without any impurities, 10 – 50 % of MnO₂ | If concentration of MnO₂ increases, then coercivity, saturation of MnO₂-CuFe₂O₄ nano composite decreases. | If volume increases, then coercivity of the nano particles increases. | [14] |
| 2      | Sr₀.₅Co₀.₅Nd₀.₅Fe₁₀.₅O₁₉ / NiFe₂O₄ | Prepared by Two-step method by self-combustion. Temperature value is very low 50 -50 % | Ms = 42.7 emu/g Mr = 26 emu/g Hc = 4.52 kOe | | [15] |
| 3      | Soft Phase = spinel ferrite (Ni₀.₈Zn₀.₂Fe₂O₄) Hard Phase : (BaFe₁₂O₁₉) 1:1, 35-100 nm | Sol–gel process | At 400°C, Hc=2750 G Ms = 63 emu/g Mr = 36 emu/g | The different size of soft phase micromagnetic nanocomposites in high temperature are gradually decrease the interchange coupling that leads to reduction in the magnetic properties | [16] |
| 4      | SrFe₁₂O₁₉ / γ-Fe₂O₃ 80 to 100 nm | Sol-gel process | At 800°C Flake sample, Hc = 6015 Oe Ms= 75.6 emu/g BHmax = 1.87 MGOe As powder, Hc = 6400 Oe, Ms= 75.9 emu/g BHmax = 1.52 MGOe | The powder and flake samples of nanocomposites are achieved the maximum of saturation and coercivity during high temperature. | [17] |
| 5      | Ba- hexaferrite (hard magnet) /NiZn ferrite | Self-propagating combustion | For 30 vol% NiZn ferrite Ms=49.5 emu/g. | When vol% of NiZn increases, Ms and Mr | [18] |
| No. | Alloy Composition | Method/Process | Magnetization Parameters | Remarks |
|-----|-------------------|----------------|--------------------------|---------|
| 6   | SrFe_{10}Al_{12}O_{19}/NiZnFe_{2}O_{4} | Auto combustion method | Mr = 22.8 emu/g, Hc = 1234 Oe | Increases and Hc reduces, 40% increase in Ms value was observed for nanocomposite with 30% weight of the soft phase. Mr/Ms is linearly increased with soft-phase content. 0.68 was highest Mr/Ms ratio that obtained for nanocomposite containing 30% weight of the soft-phase. |
| 7   | BaFe_{3}O_{10}/Ni_{0.8}Zn_{0.2}Fe_{2}O_{4} | Sol-gel process | At 30% of soft phase, Ms = 43.7 emu/g, Mr = 29.7 emu/g, Mr/Ms = 0.67, Hc = 3510 Oe | The temperature increases above 800°C creates the ferrite nano composite that modulates the magnetic property. The magnetic property of the nanocomposites is highly affected by the presintering treatment and temperature. |
| 8   | Effects of adding Dy, Nb, and Ga on Nd_{2}Fe_{14}B/Fe nanocomposite | Substitution of Dy for Nd is an effective method to increase the coercivity in nanocomposite alloys by rising the anisotropy field of the hard magnetic Nd_{2}Fe_{14}B phase | The theoretical experiments revealed that the mixing of nanocomposite magnets with 5%-of soft phase materials increases the high-energy product and decreases the coercivity. |
| 9   | Sm_{2}Co_{17}/Nd_{2}Fe_{14}B Hybrid nanocomposite magnets (Two hard phases) | Ball milling and warm compaction | Increasing amount of Nd_{2}Fe_{14}B, the Ms value significantly increases while Hc | Sm-Co-based permanent magnets can have the properties of very high value of |
10nm decreases. BH\textsubscript{max} increases with increase of Nd\textsubscript{2}Fe\textsubscript{14}B up to weight ratio 1:0.15 then reduces.

| 10 | Nd\textsubscript{2}Fe\textsubscript{14}B/a-Fe 5:1 | Reduction-diffusion process, mechanical ball mill technique | Ms =186.5 emu/g Mr = 45 emu/g Hc = 12000Gs |

7. Conclusion

From this study, it is concluded that the microstructure behavior of nano composite magnets is very significant to find actual magnetic properties in addition to high spontaneous magnetization and high energy anisotropy. Hence, the effect of microstructure on coercivity, remanence, and energy density product can be understood by using micromagnetic simulations. This theoretical idea can be extended to choose the proper size of soft phase to prepare bulk nanocomposite magnets experimentally. The BH loop of this magnet can be easily computed by using suitable numerical methods and computer software. The performance of rare-earth reduced and rare-earth free permanent magnets can be investigated using micromagnetic simulations.

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9. References

[1] Schrefl T, Fidler T, Modelling of exchange-spring permanent magnets, J. Magn. Mater. 177–181, 970–975, 1998.
[2] Kneller W and Hawwig R, The Exchange-Spring Magnet: A New Material Principle for Permanent Magnets, IEEE Trans. Magn. 27, 3588–3600, 1991
[3] Komski, R. and Coey, J. M. D. Giant energy product in nanostructured two-phase magnets. Phys. Rev. B 48, (1993).
[4] Parhofer, S. M., Wecker, J., Kuhrt, C., Gieres. G. & Schultz, L. Remanence enhancement due to exchange coupling in multilayers of hard and soft magnetic phases, IEEE Trans. Magn. 32, 4437–39 (1996).
[5] Saiden NM, Schrefl, Davies, Hrkae, Micromagnetic finite element simulation of nanocrystalline α-Fe/Nd\textsubscript{2}Fe\textsubscript{14}B/Fe\textsubscript{B} magnets, Journal of Magnetism and Magnetic Materials, 365, 45-50, 2014
[6] Shulihe, Hong Wei Zhang, Chuan Bing Rong, “Investigation on magnetic properties of orientated nanocomposite Pr\textsubscript{3}Fe\textsubscript{12}B/α-Fe permanent magnets by micromagnetic finite-element method”, Journal of Magnetism and Magnetic Materials, 324, 2012.
[7] Y.Q.Li, M.YueJ.H.Zuo, D.T.Zhang, W.Q.Liu, J.X.Zhang, Z.H.Guo and W.Li, Effect of α-Fe content on the magnetic properties of MnBi/α-Fe Nano composite permanent magnets by Micromagnetic calculations, Journal of Magnetics, 18, 2013.
[8] Sergey Erokhin, Dmitry Berkov, Masaaki Ito, Akira Kato and Andreas Michels, Towards understanding of magnetization reversal in NdFeB nano composites analysis by high throughput micromagnetic simulations, *Journal of Physics, condensed matter*, 7, 2018.

[9] C.X.Sang, G.P.Zhao, W.X.Xia and P.Liu, Effect of exchange coupling on magnetic property in Sm-Co/α-Fe layered system, *Chin.Phys.B*, 25, No.3, 2016.

[10] Wenjing Si, G.P.Zhao, N.Ran, Y.Peng, F.J.Morvan and X.L.Wan, Deterioration of the Coercivity due to the diffusion induced interface layer in hard-soft multilayers” *Nature Scientific reports*, 5:16212, 2015.

[11] C X Sang, G P Zhao, W X Xia, X L Wan, F J Morvan, Effect of exchange coupling on magnetic property in Sm-Co/α-Fe layered system, *Chin.Phys.B*, Vol. 25, No. 3, 2016.

[12] Wei Zhang, G P Zhao, X H Yuan and L N Ye, 3D and 1D micromagnetic calculation for hard/soft bilayers with in-plane easy axes, *Journal of Magnetism and Magnetic Materials*, Volume 324, issue 24, pp 4231-4236, 2012.

[13] M. J. Donahue and D. G. Porter, OOMMF User's Guide, Version 1.0, Tech. Rep. NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD (1999).

[14] Kashif Ali, Ali Bahadur, Abdul Jabbar, Shahidilqbal, Ijaz Ahmad, Muhammad Imran Bashir, Synthesis, structural, dielectric and magnetic properties of CuFe$_2$O$_4$/Mn$_2$O$_3$ nanocomposite, *Journal of Magnetism and Magnetic Materials*, 434, 30-36, 2017.

[15] Silvia E.Jacobo, Paula G. Bercoff, Carlos A. Herme and Leandro A. Vives, Srhexaferrite/Ni ferrite Nanocomposites: Magnetic behavior and microwave absorbing properties in the X-band, *Journal of Magnetism and Magnetic Materials*, 157, 2017.

[16] Qing Li, Christina W. Kartikowati, Shinji Horie, Toru Iwaki and Kikuo Okuyama, Correlation between particle size / domain structure and magnetic properties of highly crystalline Fe$_3$O$_4$ nan particles, Scientific Reports, 7, 2017.

[17] Xiansong Liu, Wei Zhong, Benxi Gu and Youwei Du ,Exchange Coupling interaction in nanocomposite SrFe$_2$O$_9$ / γ-Fe$_2$O$_3$ permanent ferrites, *Journal of Applied Physics*, Vol. 92 No.2 2002.

[18] K.W.Moon, S.G.Cho, Y.H.Choa, K.H.Kim and J.Kim, Synthesis and magnetic properties of nano Ba-Hexaferrite/NiZn ferrite composites, *phys. Stat. sol.* 204, No. 12 pp 4141 – 44, 2007.

[19] B.K.Rai, Lijia Wang, Sanjay R. Mishra and Vuong Van Nguyen, Synthesis and magnetic properties of Hard-Soft SrFe$_{10}$Al$_2$O$_{19}$/NiZnFe$_2$O$_4$ Ferrite Nanocomposites, *Journal of Nanoscience and Nanotechnology*, Vo. 14, 5272-77, 2014.

[20] Yan Wang, Ying Huang and Qifeng Wang, Preparation and magnetic properties of BaFe$_{12}$O$_{19}$/Ni$_{10}$Zn$_{12}$Fe$_2$O$_4$ nano composite ferrite, *Journal of Magnetism and Magnetic Materials*, 324, 3024-28, 2012.

[21] Kezhi Ren, Xiaohua Tan, Heyun Li, Hui Xu and Ke Han, The effects of the addition of Dy, Nb and Ga on microstructure and magnetic properties of Nd$_2$Fe$_{14}$B/α-Fe nano composite permanent magnetic alloys, *Microsc. Microanal*, 1 – 6, 2017.

[22] Narayan Poudyal, Jeotikanta Mohapatra, Meiyi Xing, Choong Un Kim and J. Ping Liu, High Temperature Magnetic Properties of Exchange Coupled Sm-Co/Nd-Fe-B Hybrid Nanocomposite Magnets, *IEEE Magnetic Letters*, Vol. 9, 2018.

[23] Hyun Gil Cha, Young Hwan Kim, Chang Woo Kim, Young Soo Kang and Hae Woong Kwon, Preparation and Characterization of Nd$_2$Fe$_{14}$B/α-Fe nanocomposite magnetic material by reduction diffusion process, *Mol. Cryst. Liq. Cryst.*, Vol. 464, pp 127-135, 2007.