10.1. Introduction

All magnetic materials show magnetic response after applying magnetic field, but effects are usually small. Magnetism originates from the movement of electric charges in materials. The electron in an atom governs the magnetic properties of materials in two different ways [1]. The first one is the electron behaves like spinning charged sphere, where the spin resembles magnetic field of tiny bar magnet. Spin is a quantum mechanical property and oriented in one of two directions. Second one is the effect of electrons circulating around the nucleus of an atom which resembles a current loop [2]. The flow of charge in circular current loop produces magnetic lines of force known as magnetic dipoles [3]. The magnetic moment is the measure of strength of the dipoles. Electrons in an atom have magnetic moment due to their spin and orbital motion.

Magnetic property is too much sensitive to their chemical composition, crystalline nature, microstructure of the materials. Dependence of magnetic properties in a preferred direction known as magnetic anisotropy and the amount of energy required to turn the magnetization from preferred direction to the desired direction is called as anisotropic energy. The magnetic anisotropy mainly affects the shape of hysteresis loop and controls the coercivity, remanance; also it affects the magnetic susceptibility and initial permeability of materials [4]. ME composites have high frequency applications in various fields of electronic technology. The magnetic parameters of ME composites such as saturation magnetization, magnetic moment, remnant magnetization and
coercivity were strongly depends on chemical composition, grain size, crystalline nature and porosity of the materials [5].

10.2. Experimental Details

Magnetic hysteresis loop of ME composites at room temperature were carried out by using vibrating sample magnetometer (VSM Model: 735, Lakeshore) at National Physical Laboratories, New Delhi. The measurement of magnetic parameters such as saturation magnetization, magnetic moment, remnant magnetization and coercivity were carried out by using vibrating sample magnetometer at high magnetic field. Saturation magnetization per gram of the samples ($\sigma_s'$) for a given porosity was estimated by using the relation:

$$M_s = (1 - p)d_x \sigma_s'$$

(10.1)

where $p = \text{Porosity} = \frac{(d_x - d_a)}{d_x} \times 100$

$d_x = \text{X-ray density}, d_a = \text{Actual density}.$

Magnetic moment in Bohr magneton was estimated by using the relation:

$$\sigma_s' = \frac{\mu_B N_A}{M} \times \mu = \frac{5585}{M} \times \mu_B$$

$$\mu_B = \frac{M \sigma_s'}{5585}$$

(10.2)

Where $M = \text{Molecular weight}, N_A = \text{Avogadro’s number} \ (6.023 \times 10^{23} \text{ molecules/mole}), \mu = 9.273 \times 10^{-21} \text{ Bohr magneton}.$
10.3. Results and Discussion

Magnetic properties of ME composites was studied by using M-H hysteresis loop measurement at room temperature with applied magnetic field of $-6\ \text{kOe} \leq H \leq 6\ \text{kOe}$ as it helps to understand the magnetic behavior of materials under the influence of external magnetic field. ME composite shows hysteresis loop type of magnetic behaviour which indicates the presence of ordered magnetic structure in mixed system of cubic spinel-tetragonal perovskite structure in composites [6]. The magnetic properties of ME composites with different mole% of ferrites at room temperature was studied by M-H hysteresis loop shown in figure and 10.1 to 10.3. The variation in magnetic parameters with increase in mole% of ferrite is listed in table 10.1. Magnetic parameter of ME composites like saturation magnetization, magnetic moment and remnant magnetization was found to increase with increase in mole% of ferrite in composites, whereas the coercivity is found to decrease (Table 10.1.) [7]. The increase of retentivity with increase in mole% of ferrites in composites suggests that most of the magnetization vectors are turned out of the magnetically preferred direction by making a small angle with the direction of applied field and suffer stresses which results in getting high magnetization of ME composites [8]. The large value of remnant magnetization at room temperature is helpful for the achievement of high ME voltage coefficient [9]. Maximum saturation magnetization of about 10.5563 emu/gm was observed for (30%) Ni$_{0.9}$Mg$_{0.1}$Fe$_2$O$_4$ + (70%) BaZr$_{0.2}$Ti$_{0.8}$O$_3$, whereas the minimum saturation magnetization of about 1.7876 emu/gm was observed for (10%) NiFe$_2$O$_4$ + (90%) BaZr$_{0.2}$Ti$_{0.8}$O$_3$ composites [10]. It is observed that the hysteresis loop shifts towards the field axis with decrease in Mg content in nickel ferrites.

The saturation magnetization of ME composites increases with increase in mole% of ferrites was due to individual ferrite grains acts as centre of magnetization and non-magnetic ferroelectric grains incorporate into the ferrite phase and break the magnetic circuit in samples, and also it was due to the
interaction between magnetic dipoles [11]. As the magnetic contact increases with mole% of ferrite, the net magnetization increases. The increase of average grain diameter and decrease of porosity with increase in mole% of ferrite in composites affect magnetic parameters. The ferroelectric materials acts as pore in presence of magnetic field that breaks the magnetic circuit and it shows the magnetic parameters increases as the ferroelectric materials decreases in composites [12]. After saturation of materials in strong magnetic field, the magnetization vector rotates towards the nearest preferred field direction and results in the high anisotropy when the field is reduced to zero in composites.

However, stress and shape anisotropy are the most important parameters for getting high ME voltage coefficient in ME composites. The decrease of porosity with increase in mole% of ferrite results in the increase of saturation magnetization that affect the resistance of magnetization and increase the average grain diameter of ME composites.

However, the parameters which affect the saturation magnetization are average grain diameter, porosity and microstructure of composites [13]. Each grain has its own resultant magnetic moment in the composites. The increase of pore concentration leads to the increase in grain surface area that opposes the domain wall motion results the high resistance to domain wall motion in composites [14]. The net grain surface area of ME composites decreases by increasing sintering temperature. Thus, the increase of sintering temperature leads to the densification of ME composites resulting in low porosity and smaller net grain surface area [17]. Thus, the domain wall motion becomes more mobile that results in the increase of saturation magnetization [15, 16].
Fig. 10.1. M-H hysteresis loop of (x) NiFe$_2$O$_4$ + (1-x) BaZr$_{0.2}$Ti$_{0.8}$O$_3$ (x = 0.1, 0.2 and 0.3) composites

Fig. 10.2. M-H hysteresis loop of (x) Ni$_{0.9}$Mg$_{0.1}$Fe$_2$O$_4$ + (1-x) BaZr$_{0.2}$Ti$_{0.8}$O$_3$ (x = 0.1, 0.2 and 0.3) composites
Fig. 10.3. M-H hysteresis loop of (x) Ni$_{0.8}$Mg$_{0.2}$Fe$_2$O$_4$ + (1-x) BaZr$_{0.2}$Ti$_{0.8}$O$_3$ (x = 0.1, 0.2 and 0.3) composites
Table 10.1. The magnetic parameters of ferrites and their composites

<table>
<thead>
<tr>
<th>x Content</th>
<th>Saturation magnetization (M_s) (emu/gm)</th>
<th>Magnetic Moment (μ_B)</th>
<th>Coercivity (M_r)</th>
<th>Retentivity (M_r/M_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiFe_2O_4 + (1-x) BaZr_0.2Ti_0.8O_3</td>
<td>0.1 1.7876 0.0898 0.0046 0.4945 0.2598</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2 5.1964 0.2564 0.0058 1.2813 0.2465</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3 8.6839 0.4205 0.0074 1.8983 0.2186</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni_0.9Mg_0.1Fe_2O_4 + (1-x) BaZr_0.2Ti_0.8O_3</td>
<td>0.1 2.4384 0.1224 0.0072 0.6110 0.2505</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2 5.7096 0.2810 0.0081 1.2600 0.2207</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3 10.5563 0.5092 0.0087 2.1761 0.2061</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni_0.8Mg_0.2Fe_2O_4 + (1-x) BaZr_0.2Ti_0.8O_3</td>
<td>0.1 2.1552 0.1081 0.0041 0.5389 0.2500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2 5.4828 0.2692 0.0045 1.2353 0.2253</td>
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<tr>
<td></td>
<td>0.3 8.8303 0.4243 0.0046 1.7446 0.1975</td>
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<td></td>
<td></td>
</tr>
</tbody>
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10.4. References