

Improvement in Magnetic Properties of SR-HEXAFERRITE Nano Powder by Using Modified Co-Precipitation Method

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ABSTRACT

Strontium hexaferrite SrFe₁₂O₁₉ powders have been synthesized using the modified co-precipitation method. Modification was performed via the ultrasonication of the precipitated precursor at room temperature for 2 h and the addition of the 2% KNO₃, surface active agents and oxalic acid. The results revealed that single phase magnetic strontium hexaferrite was formed at a low annealing temperature of 750°C, 900°C, 1150°C for 6 h with Fe³⁺/Sr²⁺ molar ratio 8. The microstructure of the powders appeared as a homogeneous hexagonal structure using 2% KNO₃ as the crystal modifier. A saturation magnetization (47.8 emu/g) was achieved for the SrFe₁₂O₁₉ phase formed at 900°C for 6 h with Fe³⁺/Sr²⁺ molar ratio 8 using 5 M solution of NH₄OH at pH 8 in the presence of 2% KNO₃. Coercivities from 1055 Oe to 4485 Oe were obtained at different substitution of the compounds.

Keywords:- Strontium hexaferrite, Synthesis, Crystal modifier, Microstructure, Magnetic properties.

I. INTRODUCTION

Strontium hexaferrite belongs to a hexagonal M-type magnetoplumbite AFe₁₂O₁₉, where A = Sr, Ba, Ca, Pb and space group P₆/mmc ferromagnetic ceramic material with easy magnetization along c-axis. In addition, Strontium hexaferrite possesses a unique combination of desirable properties such as low production cost, high saturation magnetization ($M_s = 72$ emu/g), high coercive force ($H_c = 6700$ Oe), high Curie temperature (720 K), magnetocrystalline anisotropy along c-axis ($H_a = 1.7$ T), chemically stable and corrosion resistant. Due to these desirable properties, it has a wide range of applications in the high-performance permanent magnetic material, magnetic recording media, ferrofluids, sensors, microwave absorbing materials, ceramic magnets in loud speakers and the rotors in small DC motors [1] - [5].

The Strontium hexaferrite unit cell is a combination of two structural blocks aligned in the direction of hexagonal c-axis. RSR*S* (* indicates 180 rotation of the structural block with respect to the c-axis). It contains ten oxygen layers and is divided into two S-blocks containing two of the oxygen layers and two R-blocks containing three of the oxygen layers. The S-block has a spinel structure with cubic closed-packed oxygen (O²⁻) ions and Fe³⁺ ions on its tetrahedral and octahedral sites. The R-block is formed of hexagonally closed-packed O²⁻ ions and one Sr²⁺ ion. Fe³⁺ ions occupy the interstitial, tetrahedral, octahedral and bipyramidal sites. The magnetic moments of the iron ions are arranged parallel to the hexagonal c-axis, but with opposite spin directions of the sub-lattices (three spin up and two down sub-lattices) [6].

Thus, it is important to obtain Strontium hexaferrite of high purity using an easy preparation method. The preparation technique of SrFe₁₂O₁₉ powder plays an important role in determining the magnetic and the structural properties. The solid state method is used, as conventional synthesis technique involves calcinations of a mixture of blended reactants (oxides or carbonates) in a furnace at temperature up to 1400°C for periods from 2 to 8 h. Moreover, this method requires use of high capital investment, high temperature furnaces and high-energy consumption [7]. Thus preparation of SrFe₁₂O₁₉ powders with high purity, chemical homogeneity, control of structure, fine particle size, narrow particle size distribution and minimum particle agglomeration with high sinter activity has received considerable attention in order to improve the material properties [8]. These are various techniques in order to achieve high quality Strontium hexaferrite powders such as hydrothermal [8, 9], reverse micelle [10], citrate EDTA complexing method [11], glass characterization [12], salt melt technique [13], mechanochemical processing [14]-[15], sonochemical [16], sol-gel method [17]-[18], combustion method [19-21], spray pyrolysis technique [22] and co-precipitation method [23]- [24]. It has been demonstrated that the chemical co-precipitation method is the most suitable technique compared with the other routes due to its low-cost in addition to its suitability for the mass production. Furthermore, the molecular level mixing and the tendency of partially hydrolyzed species to form extended networks facilitate the structure evolution thereby lowering the crystallization temperature of the prepared ferrite. Moreover, the co-precipitation processing offers considerable advantages, such as the better mixing of the starting materials and the excellent

chemical homogeneity of the final product [25]. The main drawback is that the particle size is not relatively small and monodispersed enough for specific applications like recording like recording media applications [26]-[27].

The properties of Strontium hexaferrite required for high density recording media depends on the type. For most recording media, high saturation magnetization, high structural with chemical stability and low-cost are important criteria. In case of recording media such as hard disks, floppy disks and video tape, a high coercivity is avoided in order to facilitate re-recording. However, for recording material used in identification cards and credit cards, a high coercivity is required to reduce the risk of data cards; a high coercivity is required to reduce the risk of data getting corrupted when the cards are exposed to stray magnetic fields. High saturation magnetization, sufficient coercivity and structural/chemical stability are also important criteria for the fabrication of permanent magnets [28]. It is previously reported that addition of a surface active agent improves the structural and the magnetic properties of Sr-ferrite particles after annealing at much lower temperature 750°C for period of 6 h. Moreover, the saturation magnetizations increase considerably by 20-40% in magnitude by addition of surface active agents [24].

In this study, the magnetic properties of barium hexaferrite nanopowders were improved using modified co-precipitation method. The formed powders were precipitated using 5 M NH₄OH solution as an alkali at pH value 8. The modified co-precipitation method was performed by the ultrasonication of the precipitated precursors for 2 h at room temperature with the frequency of 60 KHz and addition of crystal modifiers, namely 2% KNO₃, surface active agents 500 ppm of either cetyltrimethyl ammonium bromide (CTAB) as a cationic surfactant or sodium dodecyl sulfate (SDS) as an anionic surfactant in comparison to the previous one published in which they used 1000 ppm of each surfactant [23]-[24]. Moreover, the addition of oxalic acid as a crystal modifier before the precipitation of the precursor and annealed at 750°C to 1150°C temperature for 6 h and its impacts on the crystal structure and microstructure were studied. The change in magnetic properties of the produced hexaferrite powders at different synthesis conditions was also investigated using a vibrating sample magnetometer in a maximum applied field of 15kOe at room temperature.

II. EXPERIMENTAL TECHNIC

The co-precipitation method was applied for the preparation of Sr-hexaferrite SrFe₁₂O₁₉. The analytically pure materials: Fe(NO₃)₃·9H₂O, Sr(NO₃)₂ were weighed in the desired proportions and dissolved with small amounts of deionized water. Surface active agents, namely cetyltrimethyl ammonium

bromide (CTAB) as an anionic surfactant, potassium nitrate KNO₃ and oxalic acid H₂C₂O₄ were used as starting materials. A series of ferric nitrate and strontium nitrate solutions with various Fe³⁺/Sr²⁺ molar ratios 8 was prepared. The ferrite precursors were precipitated from these mixtures by gradually adding 5 M ammonium hydroxide solution at room temperature at pH value 8. The aqueous suspensions were stirred gently for 15 min to achieve a good homogeneity and a stable pH condition. The brownish co-precipitate were filtered off, washed with deionized water and then dried at 100 °C overnight. For the formation of SrFe₁₂O₁₉ phase, the dry precursors were annealed at a rate 10 °C/min in static air atmosphere up to different temperatures 750°C, 900°C and 1150°C and then maintained at these temperature for annealed time 6 h. The crystalline phases present in the different annealed samples were identified by X-ray diffraction (XRD) on a Bruker axis D8 diffractometer with crystallographic data software Topas 2 using Cu-Kα (λ = 1.5406) radiation operating at 40 kV and 30 mA at a rate of 2/min. The diffraction data were recorded for 2θ values between 20 to 80. The ferrite particles morphology was observed using the scanning electron microscope (JEOL, SEM, JSM-5400).

The magnetic properties of the ferrites were measured at room temperature using a vibrating sample magnetometer (VSM: 9600-1, LDJ, USA) in a maximum applied field 1500 kOe. From the obtained hysteresis loops, the saturation magnetization (M_s), remanance magnetization (M_r) and the coercive field (H_c) were determined.

III. RESULTS AND DISCUSSIONS

The XRD patterns of the SrFe₁₂O₁₉ powders obtained from the Sr-Fe nitrate precursors with a Fe³⁺/Sr²⁺ molar ratio 8 ultrasonicated for 2 h at room temperature with the frequency 60 KHz and thermally treated at different temperatures 750°C, 900°C and 1150°C for 6 h are illustrated in Fig. 1. The results revealed that, on the start of the annealing process at temperatures 750°C, 900°C and 1150°C, mixture of Sr-Fe oxide SrFe₁₂O₁₉ (JCPDS# 84-757) and the hematite Fe₂O₃ (JCPDS# 73-2234) phases appeared. The peaks related to the SrFe_{12-2x-y}(CoZr)_xO₁₉ phase at 2θ of 30.35, 32.40, 34.25, 38.15, 40.40, 55.24, 56.82 and 64.62 were present. These peaks were ascribed to (1 1 1), (1 0 6), (0 0 8), (1 1 3), (1 0 8), (1 0 4), (2 0 11) and (2 2 0) diffraction planes of hexagonal Sr-Fe oxide SrFe₁₂O₁₉ phase. The crystalline sizes of the produced strontium hexaferrite Sr-Fe oxide SrFe₁₂O₁₉ powders for the most intense peak (0 0 8) plane is estimated from the X-ray diffraction data using the Debye-Scherrer equation. The crystallite size of the produced nanopowders was increased with the increase in the annealing temperature. It is seen that the minimum crystalline size appeared at 750°C (14-29 nm), which most likely is

explained by the increase in crystallinity of the pure single phase of strontium hexaferrite with the increase in concentration.

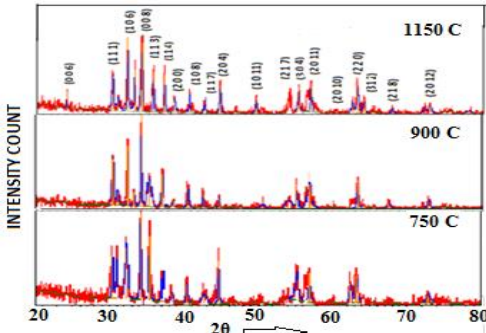


Fig.1: XRD patterns of produced strontium ferrite M-type powder precipitated using NH₄OH as alkali ultrasonicated for 2h at Fe³⁺/Sr²⁺ molar ratio 8 annealed at different temperatures 750°C, 900°C and 1150°C for 6 h.

Fig. 2 shows the SEM morphologies of the co-precipitated specimens with Fe³⁺/Sr²⁺ molar ratio 8 annealed at different temperatures 750°C, 900°C and 1150°C for 6 h and ultrasonicated for 2 h. At this temperature the powders possessed an irregular hexagonal shape with a small particle size. As the annealing temperature increased to 1150°C, the particles appeared in the elongated hexagonal shape with the high particle size distribution.

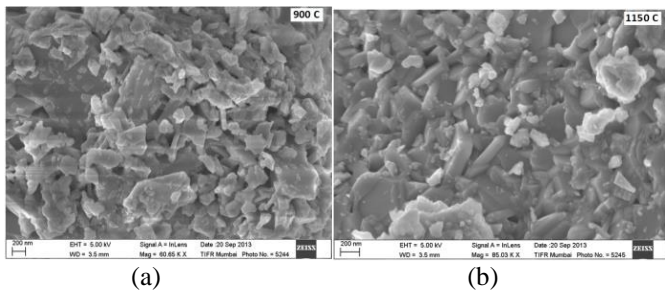


Fig.2: SEM micrographs of the strontium hexaferrite powders annealed at 900°C and 1150°C for 6 h using NH₄OH as alkali at pH 8 ultrasonicated for 2 h at Fe³⁺/Sr²⁺ molar ratio 8.

Table-1

Magnetic properties of the produced strontium hexaferrite precipitated using 5 M NH₄OH solution at pH 8 ultrasonicated at room temperature for 2 h at different annealing temperature for 6 h.

Sr. No.	Temperature (°C)	M _s (emu/g)	M _r (emu/g)	H _c (Oe)	M _r /M _s
1.	750	25.61	13.38	4500	0.52
2.	900	48.75	28.04	2835	0.57

3.	1150	65.70	33.12	1500	0.5
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The magnetic properties of the resulting powders were measure using a vibrating sample magnetometer with a maximum applied field of 15 kOe at room temperature and the magnetic parameters are summarized in Table-1. The results indicated that the saturation magnetization was increased with increasing the annealing temperature. It increased from M_s = 25.61 emu/g at 750°C to M_s = 48.75 emu/g at 900°C. High saturation magnetization M_s = 65.7 emu/g was achieved at annealing temperature 1150°C, which was related to the increase in the crystallite size and the formation of pure single phase of strontium hexaferrite with a good morphology. The obtained saturation magnetization value was lower than the theoretical saturation magnetization for the single crystals of strontium hexaferrite (M_s = 72 emu/g) as reported by shirk and Buessem [23]. However, this value is higher than that published by Shepherd et al. [29](M_s = 60.2 emu/g) using co-precipitation annealed at 800 C for 3 h and then sintered at 1300 C for 1 h [28]. Furthermore, the M_s values were higher than the previous one published [23]-[24] using direct co-precipitation for the powder with Fe³⁺/Sr²⁺ molar ratio 8 annealed at 900 and 1150 C for 6 h in which the saturation magnetizations M_s were 28.8 and 44.12 emu/g, respectively. Considerably, the obtained saturation magnetization values showed increments by ~ 31% to 53% in magnitude compared to the corresponding values of the direct co-precipitation. The values of intrinsic coercivity H_c obtained for our samples were lower than the theoretical calculations (H_c = 6700 Oe) using the Stoner and Wohlfarth model of single domain particles. Various theories including surface area, spin-canting and the sample inhomogeneity have been proposed to account for the relatively low magnetization in the fine particles. The ratio of remanance magnetization and saturation magnetization M_r/M_s was approximately 0.5, indicating the SrFe₁₂O₁₉ powder of randomly oriented single domain particles [29].

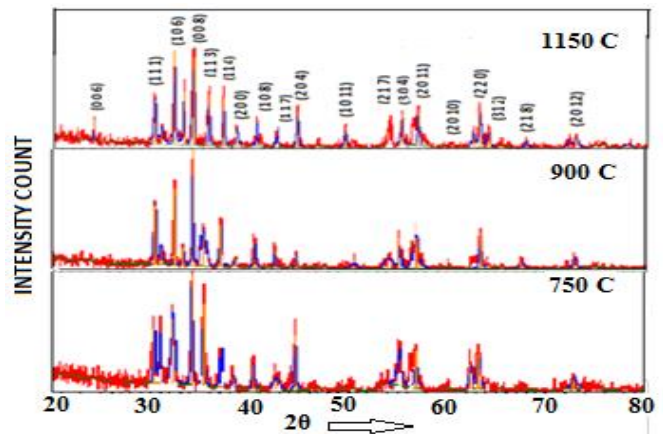


Fig.3: XRD patterns of produced strontium ferrite M-type powder precipitated using NH_4OH as alkali with 2% KNO_3 at $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 annealed at different temperatures 750°C , 900°C and 1150°C for 6 h.

Fig.3 shows the XRD patterns of the produced strontium-M-type ferrite in the presence of 2% KNO_3 precipitated using 5 M NH_4OH solution at pH 8 with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 and annealing at different temperature from KNO_3 . The powder pattern of $\text{SrFe}_{12}\text{O}_{19}$ phase taken from JCPDS 84-757 indicated the presence of single phase of strontium-M-type ferrite at different temperatures from 750°C to 1150°C . A small amount of KNO_3 used to peptize the hydrolyzed nitrate solution and form a clear solution. Furthermore, addition of potassium nitrate was used to prevent the formation of impure $\alpha\text{-Fe}_2\text{O}_3$ phase [5]. The crystallite size for the most intense peak (0 0 8) of the strontium hexaferrite was increased with increase in the annealing temperature. It increased from 14.5 nm at 750°C to 27.3 nm at 900°C , then to 56.4 nm at 1150°C .

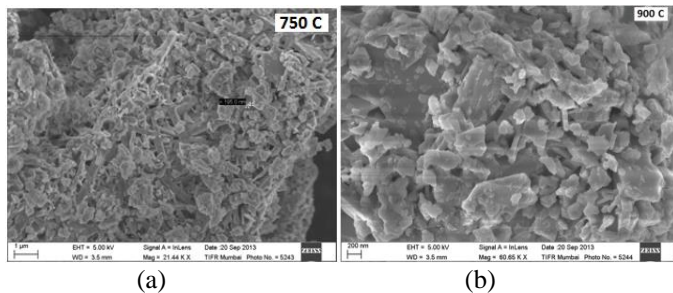


Fig.4: SEM micrographs of the strontium hexaferrite powders annealed at 750°C and 900°C for 6 h using NH_4OH as alkali in the presence of 2% KNO_3 at pH 8 for 2 h at $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8.

Further investigation was carried out by SEM micrographs to show the change in the morphology of the strontium ferrite particles produced from the precipitated precursors in the presence of 2% KNO_3 annealed at 750°C to 1150°C for 6 h as well as the development of the grain structure. Fig. 4 (a) reveals very fine particles of ferrite powder that started to agglomerate at 750°C . No clear crystalline microstructure can be seen in this stage, which provides evident that the annealing at 750°C is insufficient for completely well crystalline M-type structure. However, this stage most likely was the nucleation of particles followed by the growth of the larger particles. With an increase in annealing temperature up to 1150°C , grains have coalesced to form larger grains with the uniform hexagonal platelet-like crystals as shown in Fig. 4 (b).

At room temperature, the $M-H$ magnetic hysteresis loops of the produced strontium ferrite powders in the presence

of 2% KNO_3 at different temperature are shown in Fig. 5. (a, b & c). A good saturation magnetization ($M_s = 41.336\text{emu/g}$) was achieved at annealing temperature 900°C , which attributed to the formation of clear and regular hexagonal platelet-like structure. Moreover, the shape of the hysteresis loop curves confirmed that the strontium ferrite was a hard magnet. In contrast, the low saturation magnetization M_s at low annealing temperature of 750°C was attributed to the surface spin-canting phenomenon, purity and particle size effects. The remanance magnetization and the coercive force were low at the annealing temperature of 750°C due to the insufficient grain growth [31]. When the grain size exceeds a critical value, which is reported to be 460 nm, the grains exhibit a multidomain behaviour. As a consequence of the domain walls in multi-domain grains, H_c gets lower values. On the other hand, the M_r/M_s ratio was almost constant (between 0.58 and 0.6) for all the powders. These values were very close to 0.5, the theoretical value for randomly oriented single domain particles having the shape anisotropy [32].

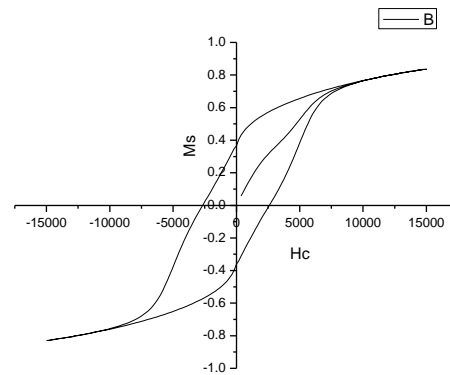


Fig.5 (a): $M-H$ hysteresis loops of the produced strontium hexaferrite from the precursor precipitated in the presence of 2% KNO_3 using 5 M NH_4OH at pH 8 with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio annealed at temperature 750°C for 6 h.

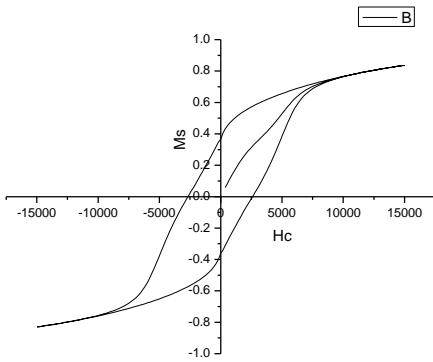


Fig.5 (b): M-H hysteresis loops of the produced strontium hexaferrite from the precursor precipitated in the presence of 2% KNO_3 using 5 M NH_4OH at pH 8 with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio annealed at temperature 900°C for 6 h.

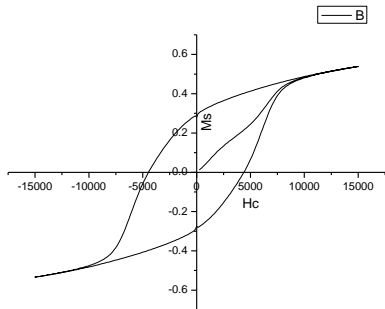


Fig.5 (c): M-H hysteresis loops of the produced strontium hexaferrite from the precursor precipitated in the presence of 2% KNO_3 using 5 M NH_4OH at pH 8 with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio annealed at temperature 1150°C for 6 h.

Rashad et al. [23]-[24] studied the effect of surface active agents, namely cetyltrimethyl ammonium bromide (CTAB) as cationic surfactant and sodium dodecyl sulfate (SDS) as anionic surfactant and the concentration of 1000 ppm on the structural and magnetic properties of strontium hexaferrite via the co-precipitation route. The results confirmed that a strontium surplus is important to synthesize single phase $\text{SrFe}_{12}\text{O}_{19}$ powder by chemical co-precipitation method. Pure ultrafine strontium hexaferrite powders (100-150 nm) were obtained from precursor with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 after annealing temperatures $\geq 900^\circ\text{C}$ for 6 h in static air atmosphere.

Furthermore, addition of surface active agents formed a single phase at low temperature 750°C with the increase in the magnetic properties and improvement of the morphology. In this work, 500 ppm of both surfactants was added with the similar mentioned conditions. The dry precursors were then annealed at 750 , 900 and 1150°C for 6 h. XRD analysis of various annealed samples revealed the formation of only single phase strontium hexaferrite powders as shown in Fig. 6 and 7. The patterns showed the well-defined Bragg peaks, which were significant of a good crystalline state of the sample.

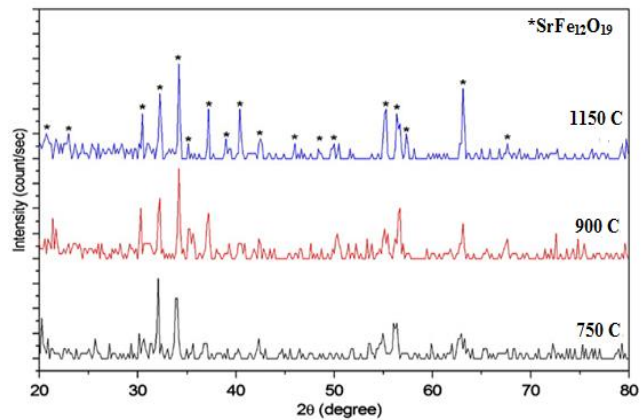


Fig. 6: XRD patterns of produced strontium ferrite M-type powder precipitated using NH_4OH as alkali for $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 at $\text{pH} = 8$ in the presence of 500 ppm CTAB at different annealing temperatures 750°C , 900°C and 1150°C for 6 h.

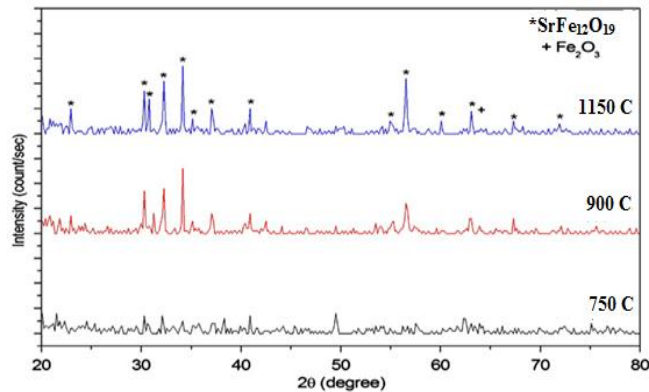


Fig. 7: XRD patterns of produced strontium ferrite M-type powder precipitated using NH_4OH as alkali for $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 at $\text{pH} = 8$ in the presence of 500 ppm SDS at different annealing temperatures 750°C , 900°C and 1150°C for 6 h.

Fig. 8 indicated the effect of the surfactants before the co-precipitation step could prevent the agglomeration of

particles and the grain growth during annealing course, which led to the decrease in grain size and the formation of nanocrystalline single phase strontium hexaferrite powder. Then, the crystalline size was increased from 14.5 nm and 24.6 nm at 750°C to 27.3 nm and 48.7 nm at 900°C, then to 56.4 nm and 74.2 nm at 1150°C using 500 ppm of CTAB and SDS surfactant respectively.

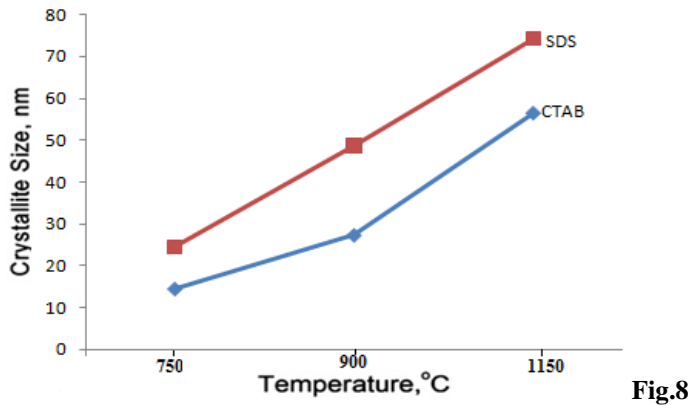


Fig.8 : Effect of annealing temperature on the crystallite size of the produced strontium hexaferrite in the presence of 500 ppm CTAB and SDS respectively, using NH₄OH as alkali for Fe³⁺/Sr²⁺ molar ratio 8 at pH = 8.

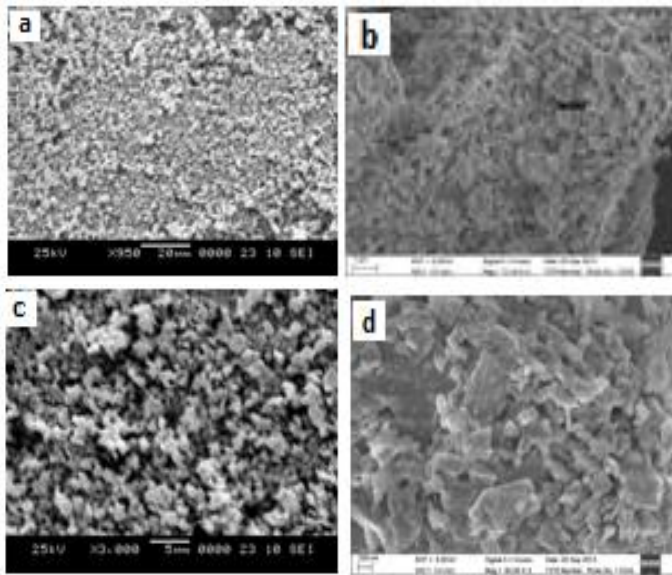


Fig.9: SEM micrographs of the product Sr-M-type ferrite annealed at 750°C and 900°C respectively in the presence of 500 ppm of (a, b) SDS and (c, d) CTAB.

Fig. 9 shows the effect of surfactants on the morphology of the co-precipitated specimens for the Fe³⁺/Sr²⁺ molar ratio 8 annealed at 750°C and 900°C for 6 h. It is clear that agglomeration of very fine particles with irregular structure appeared at low annealing temperature of 750°C using both the surfactants. As the annealing temperature increased at 900°C, the hexagonal platelet-like crystals of strontium hexaferrite were formed. Moreover the grain size increased in the presence of 500 ppm of SDS compared to CTAB.

Table-2

Magnetic properties of the produced strontium hexaferrite precipitated using 5 M NH₄OH solution at pH 8 in the presence of 500 ppm of SDS and CTAB at different annealing

Temperature (°C)	Ms (emu/g)		Mr (emu/g)		Hc (Oe)		Mr/Ms	
	A	B	A	B	A	B	A	B
750	41.3	45.1	22.5	26.3	4163	4322	0.54	0.58
900	54.5	57.2	28.4	29.8	4352	4485	0.52	0.51
1150	56.8	59.7	20.7	23.2	1055	1234	0.36	0.38

temperatures for 6 h (A = SDS and B = CTAB).

The magnetic properties of the produced powder in the presence of CTAB and SDS surfactants are given in Table-2. The formed SrFe₁₂O₁₉ powders have good magnetic saturations (41.3-59.7emu/g) and wide intrinsic coercivities (1055-4485Oe). Higher saturation magnetization (59.7emu/g) was obtained using 500 ppm CTAB as the cationic surfactant at annealing temperature of 1150°C for 6 h, which implied the increasing of saturation magnetization with the increase in the particles size. High coercivity (Hc = 4485 Oe) was confirmed for the sample annealed at 900°C for 6 h using 500 ppm CTAB due to the change in microstructure and the increase in the crystallite size of the obtained powders. The ferrite powder exhibited the particle coarsening (plate-like hexagonal structure) with the grain growth at such a high annealing temperature. The reduction in coercivity by increasing the temperature to 1150°C was attributed to the fall in the magnetic anisotropy and the multi-domain behaviour where the squariness ratio (Mr/Ms) for annealed samples at 1150°C in the presence of surfactants was~0.36-0.38 whereas for the other samples, the squariness ratio was around 0.5 [24].

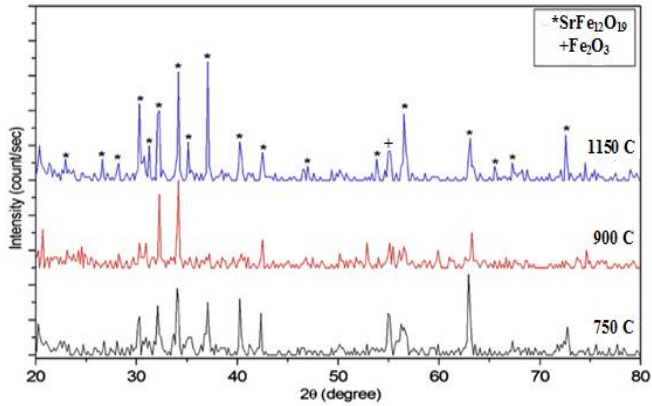


Fig. 10:

XRD pattern of the produced strontium hexaferrite powders using NH_4OH as alkali at $\text{pH} = 8$ with stoichiometric ratio of oxalic acid for $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 at different annealing temperatures 750°C , 900°C and 1150°C for 6 h.

Fig. 10 shows the XRD patterns of strontium hexaferrite produced from the precipitation precursors in the presence of oxalic acid molar ratio precipitated using 5 M NH_4OH solution at $\text{pH} = 8$ for $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 annealed at 750°C to 1150°C for 6 h. The peaks patterns are assigned to hexagonal Sr-M-type ferrite at all studied annealing temperatures. The crystalline size estimated from the most intense peak was increased by increasing the annealing temperatures. It increased from 26.4 nm at 750°C to 52.6 nm at 900°C , then to 81.7 nm at 1150°C .

More aspects of the particles are revealed using SEM micrographs for the strontium-iron precursor samples annealed at 750°C and 900°C for 6 h as shown in Fig. 11. It is clear that the formed $\text{SrFe}_{12}\text{O}_{19}$ nanopowders at 750°C exhibited a regular morphology consisting of fine nanocrystalline hexagonal platelet-like crystal structures as shown in Fig. 11(a). The grain size of hexagonal platelet-like crystal increased with the increase in the annealing temperature up to 900°C as shown in Fig. 11(b).

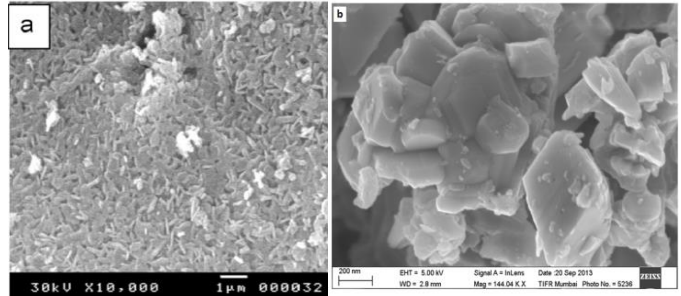


Fig.11: SEM micrographs of the produced strontium hexaferrite powder using NH_4OH as alkali at $\text{pH} = 8$ with stoichiometric ratio of oxalic acid for $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 at annealing temperature (a) 900°C and (b) 1150°C for 6 h.

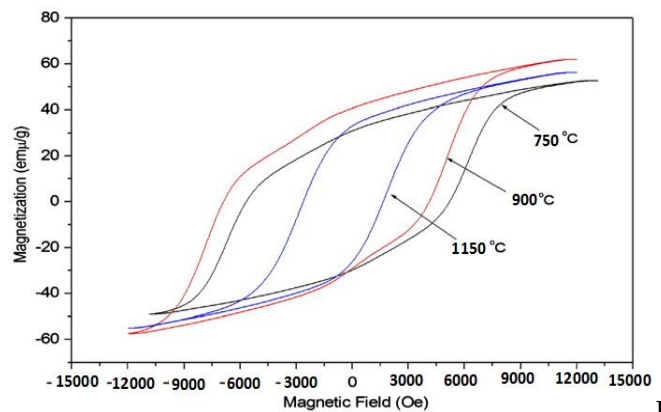


Fig. 12:

$M-H$ hysteresis loops of the produced strontium hexaferrite from the precursors precipitated using NH_4OH as alkali at $\text{pH} = 8$ with stoichiometric ratio of oxalic acid for $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 at different annealing temperatures 750°C , 900°C and 1150°C for 6 h.

Plots of magnetization (M) as a function of applied field (H) for the produced strontium hexaferrite precipitated as $\text{pH} = 8$ with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 in the presence of oxalic acid annealed at 750°C to 1150°C for 6 h are shown in Fig. 12. It is worth noting that the saturation magnetization was grain size dependent. The saturation magnetization value ($M_s = 60.9$ emu/g) for the sample annealed at temperature 900°C for 6 h, which was attributed to high grain growth with well hexagonal platelet microstructure of the produced powders compared with the sample annealed at 750°C . The reduction in coercivity by increasing the temperature to 1150°C was due to the increase in

the grain size with high pores, the fall in the magnetic anisotropy and the multi-domain behaviour [24], [30]-[33].

IV. CONCLUSIONS

The conclusions from XRD, SEM and VSM studies are summarized as follows:

1. Single nanocrystalline strontium hexaferrite $\text{SrFe}_{12}\text{O}_{19}$ powders have been synthesized by the modified co-precipitation method.
2. A pure hexagonal strontium ferrite phase was obtained from the precursors precipitated using 5 MNH_4OH solution at pH 8 with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8 ultrasonicated at room temperature for 2 h and then annealed at temperatures 900°C and 1150°C for 6 h. The similar trend was performed for the precipitated powders in the presence of 2% KNO_3 annealed at temperatures from 750°C to 1150°C for 6 h.
3. Addition of 500 ppm of cetyltrimethyl ammonium bromide (CTAB) as a cationic surfactant or sodium dodecyl sulfate (SDS) as an anionic surfactant to the formation of a single phase strontium-M-type ferrite at low annealing temperature of 750°C with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8. Furthermore, the presence of oxalic acid and during the precipitation improved the formation of a single phase of strontium hexaferrite at low temperature of 750°C with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio 8.
4. Saturation magnetization ($M_s= 47.8$ emu/g) was achieved for the formed $\text{SrFe}_{12}\text{O}_{19}$ phase with $\text{Fe}^{3+}/\text{Sr}^{2+}$ molar ratio using NH_4OH solution at pH 8 in the presence of 2% KNO_3 annealed at 900°C for 6 h. The highest saturation magnetization ($M_s= 65.7$ emu/g) was obtained from the precipitated precursor using 5 MNH_4OH solution at pH 8 ultrasonicated for 2 h and annealed at temperature 1150°C for 6 h.

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