A novel method for synthesizing narrow particle size distribution of holmium-doped strontium hexaferrite by sol-gel auto-combustion

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Abstract
In this study, a new technique put in to the sol-gel auto-combustion method which is the preparation of solutions and treatment of products by using ultrasonic liquid sonicate. Different atomic concentrations of Holmium-doped strontium hexaferrite (SrFe\(_{12-x}\)Ho\(_x\)O\(_{19}\)) been synthesized by the conventional sol-gel auto-combustion method. This new technique estimates as a novel method which escalates the amount of Ho\(^{3+}\) present in strontium hexaferrite of produced powder by 500% compared to the conventional method when Ho\(^{3+}\) substitution was 15% of atomic weight. Characterization of produced powders, porosity, unit cell volume, and lattice parameters were tested and calculated from x-ray diffraction. Morphology, particle size distribution, and shape of nanoparticles were analyzed by field emission scanning electron microscope. Primary particle size and particle size distributions were studied by transmission electron microscope. The purity and elemental composition of products were tested by energy dispersive spectrometer. Bulk density, crystallinity, and purity increased with decreased crystal size and porosity when nanoparticles were treated by ultrasonic method. Morphology, purity, narrow particle size distribution, and nanoparticles with isomorphic geometry can be controlled with Ho\(^{3+}\) substitution by 15% of atomic weight when powder is produced by this novel method. This new technique provides an improved new method for narrowing particle size distribution, increasing density, and substitution limit of rare earth ions to hexaferrites.

1. Introduction

Modern magnets have been used in industry since the 1980s mostly due to their low cost, high corrosion resistance, chemical stability, steadiness at relatively high temperatures, and propriety in a wide variety of applications [1–7]. M-type hexaferrite SrFe\(_{12}\)O\(_{19}\) is usually and essential ferromagnetic structure magnet that has been greatly studied because of its prominent applications in high density magnetic recording, microwave, and electronic devices [8–10]. The main problems in nanoparticle synthesis are wide particle size distribution, large nanoparticles, and low purity. Synthesis of nanoparticles by the sol-gel method is an elaborate chemical reaction involving numerous transitions during chelation, gelation, drying, auto-combustion, and calcination [11]. The sol-gel auto-combustion technique has been widely studied in producing metallic, alloy, and magnetic nanoparticles used in medical, electronics, and telecommunication parts [12, 13]. To prove the properties of nanoparticles made by this method, various studies have focused on the influence of mixing time, controlling temperature, pH value, and concentration of substituted metal nitrates [14–16]. The addition of rare earth ions with a magnetic moment into M-type hexagonal ferrite is advantageous to their magnetic properties [17]. The substitution of heavy rare earths has been found difficult [18]. Hexaferrites with Tb, Eu, Gd, and La substitutions have been studied and the possible degree of substitution found to be limited to <0.3 [19–22]. Studies have employed rare earth–doped ions to constrain grain growth and raise the sintering temperature [23, 24].

To date, no effort has been made in wet chemistry to make use of ultrasonic liquid sonicate with ethanol alcohol, without any detriment to the properties of material rolling as a non-active solvent. This new technique
was used in the present study to attain higher homogenous mixing and better dispersal quality to achieve narrower particle distribution, smaller particle size, less porosity, and higher density. Hard ferrites including SrFe$_{12}$O$_{19}$ present a challenge, and solubility of different rare earth ions into Sr hexa-ferrite has not been systematically studied. In this study, the time of prepared metal nitrate solution was reduced. The temperature of preparation and pH stabilization was increased and controlled at above room temperature, and the stirring method modified by advanced ultrasonic sonication, to obtain a homogenous mixture, narrow particle size distribution, and increased solubility of rare earth ions with ferrites. Holmium rare earth ions substituted Fe ions of SrFe$_{12}$O$_{19}$ in various concentrations. Structure and morphology were characterized by x-ray diffraction (XRD), transmission electron microscope (TEM), field emission scanning electron microscope (FESEM), and energy-dispersive x-ray spectroscopy (EDS).

2. Materials and methods

2.1. Materials

Powders used in synthesis of holmium-doped strontium hexaferrite nanoparticles were strontium nitrate Sr(NO$_3$)$_2$, iron nitrate nonahydrate Fe(NO$_3$)$_3$·9H$_2$O, holmium nitrate pentahydrate Ho(NO$_3$)$_3$·5H$_2$O, citric acid monohydrate C$_6$H$_8$O$_7$·H$_2$O, absolute ethanol alcohol (99.5% absolute; EMPARTA® ACS), and ammonia NH$_3$, purchased from Merck (Merck-KGaA, Darmstadt, Germany), with double-distilled water in preparation of solutions.

2.2. Preparation of holmium-doped strontium hexaferrites

Powders of holmium-doped strontium hexaferrite with chemical formula SrFe$_{12-x}$Ho$_x$O$_{19}$ (where $x = 0.1, 0.15, 0.2, 0.25$) were synthesized using the sol-gel auto-combustion method. Stoichiometric amounts of Fe, Sr, Ho, and citric acid with ratios of iron nitrate to strontium nitrate of 12:1 and metal nitrates to citric acid of 1:1 were dissolved in a minimal amount of double-distilled water ($100$ ml for $10$ g of metal nitrates)\[25\]. The mixtures were kept under sonication (Qsonica-700) after stirring for $30$ min at $50 \, ^\circ$C. The pH was adjusted to 7 by adding ammonia to each mixture. The temperature was kept at $100 \, ^\circ$C under constant stirring to obtain a viscous gel, which was heated at $200 \, ^\circ$C in an oven to obtain loose powder, and dried in an oven for $30$ min. The prepared powder was grinded and divided into two groups, conventional and ultrasonic as shown in diagram in figure 1.

**Group 1.** (conventional group): Grinded loose powder annealed using the conventional method [26, 27].

**Group 2.** (ultrasonic group): Each $4$ g of grinded loose powder mixed in $75$ ml of absolute ethanol and sonicated using the novel method. Both groups produced SrFe$_{12-x}$Ho$_x$O$_{19}$ powder (where $x = 0, 0.1, 0.15, 0.2, 0.25$) annealed at $1200 \, ^\circ$C for five hours with a heating rate of $5 \, ^\circ$C min$^{-1}$.

2.3. Characterization

Crystallite phases were identified by XRD (Panalytical Xpert Pro®, ul. Radzikowskiego, Kraków, Poland) monochromatized Cu-K$_\alpha$ radiation, with the 2θ scanning angle in the range $20$ to $85$ degrees with a rate of $0.1$ degrees. Lattice parameter, crystal size, bulk density, crystal density, and porosity were calculated as follows:

Lattice parameters $a$ (Å), $c$ (Å), and $c/a$ were calculated by the analytical method for noncubic crystals (where $a = b$ in hexagonal-shaped nanoparticles) [28].

The volume of the unit cell was calculated by:

$$V = 0.866 \times a^2 \times c$$ \hspace{1cm} (1)

where $a$ and $c$ are lattice parameters of the unit cell.

The crystal size was measured by Scherrer’s formula:

$$D = \frac{k\lambda}{\beta \cos \theta}$$ \hspace{1cm} (2)

where $k$ is the shape factor $0.94$, $\lambda$ is the incident radiation, $\beta$ indicates full width half maximum, and $\theta$ is the angle of the peak.

The crystal density was calculated by:

$$\rho_c = \frac{nM}{N_A V}$$ \hspace{1cm} (3)

where $n$ is the number of atoms per unit cell, $M$ is the molecular weight of the material, $N_A$ is Avogadro’s number, and $V$ is the volume of the unit cell.
Bulk density for nanoparticles tested in the cuboid sample holder was found by:

$$\rho_b = \frac{\text{mass}}{\text{volume}} = \frac{\text{mass}}{\text{length} \times \text{width} \times \text{height}} \quad (4)$$

where mass is the total amount of mass fitted to the sample holder to be tested by XRD.

The porosity was calculated from equations (3) and (4):

$$P = 1 - \frac{\rho_b}{\rho_r} \quad (5)$$

The particle shape and size with particle size distributions were calculated by FESEM obtained on SIGMA VP from ZEISS Company. Morphology, crystal size, and crystal size distribution were studied using TEM model EM10C with an accelerating voltage of 100 Kv. Element concentrations were obtained using EDS model AZtec (Oxford Instruments plc., UK).

3. Results and discussion

3.1. X-ray diffractometer

The XRD of prepared ferrites by two routes with different concentrations is shown in figure 2. The peak intensity of ultrasonically treated powders was higher than that of conventionally synthesized powder. The existence of two peaks in the $2\theta$ range (32.34, 34.2) in the conventionally synthesized method is shown in figure 2(a). The intensity of the peak with a $2\theta$ range 34.2 was higher than 32.34 for $x = 0$ and $x = 0.15$ substitutions, with this proportionality reversed when holmium was substituted by 0.15, 0.2, and 0.25. The intensity of peak with $2\theta$ (32.34) was higher than 34.2. The second part of the XRD images shown in figure 2(b) shows the continuous proportionality of higher intensity and crystallinity of peak $2\theta$ with 34.2 compared to the peak of 32.34 $2\theta$ range for all substitutions when powders were synthesized by the ultrasonic method. To indicate the appropriate substitution of Ho$^{3+}$ and to prove the rare earth–doped hard ferrite for two routes, eight parameters were found, as shown in table 1. No change was observed in lattice parameter a(A), while there was a slight decrease in lattice parameter c(A) as well as c/a. In some cases, the lattice parameter c increased when iron in hexaferrites substituted with large radius rare earth ions [29, 30]. Lattice parameter c decreased for all cases that described the
existence of strain within lattice inhibiting nucleation rate \[31\]. From figure 3 which is the magnified part of x-ray diffraction patterns of synthesized powders for peaks (200) and (006) by which these peaks responsible in determining lattice parameter a and lattice parameter c. In order to observe the change in lattice parameters there must be shift in peaks from x-ray diffraction patterns. But as noted from figure 1 by increasing of Ho doping concentration, the lattice parameter value was found to remain unchanged no shifting observed remains the same as that of undoped Strontium hexaferrite. And most researches indicate that Holmium crystallizes in hexagonal closed packed form which may cause the holmium-doped strontium hexaferrite powders synthesized by our sol-gel auto-combustion method act as virtually stress-free and highly c-axis oriented. By which lattice parameter a remain unchanged with slight change of lattice parameter c when first holmium introduced to

Table 1. Result of XRD data for calculating \(a(\text{Å})\): lattice parameter a; \(c(\text{Å})\): lattice parameter c; \(V(\text{nm}^3)\times10^{-3}\): unit cell volume calculated in nm\(^3\); \(D(\text{nm})_{av}\): average crystal size in nm; \(\rho_b\): bulk density; \(\rho_x\): for crystal density; P: porosity for conventional and ultrasonic methods.

| Substitutions | \(a(\text{Å})\) | \(c(\text{Å})\) | \(c/a\) | \(V(\text{nm}^3)\times10^{-3}\) | \(D(\text{nm})_{av}\) | \(\rho_b(\text{g/cm}^3)\) | \(\rho_x(\text{g/cm}^3)\) | P     |
|--------------|----------------|----------------|--------|-----------------|----------------|----------------|----------------|------|
| \(x = 0\)   | 5.8648         | 23.0826        | 3.935  | 687.562         | 41.5435        | 0.4220         | 5.12           | 0.9175 |
| \(x = 0.1\) | 5.8648         | 23.0334        | 3.927  | 686.097         | 44.9618        | 0.6145         | 5.13           | 0.8801 |
| \(x = 0.15\)| 5.8648         | 23.0334        | 3.927  | 686.097         | 38.1435        | 0.4268         | 5.13           | 0.9167 |
| \(x = 0.2\) | 5.8648         | 23.0334        | 3.927  | 686.097         | 33.3438        | 0.8512         | 5.13           | 0.8340 |
| \(x = 0.25\)| 5.8648         | 23.0334        | 3.927  | 686.097         | 41.5390        | 0.9245         | 5.13           | 0.8197 |

| Substitutions | \(a(\text{Å})\) | \(c(\text{Å})\) | \(c/a\) | \(V(\text{nm}^3)\times10^{-3}\) | \(D(\text{nm})_{av}\) | \(\rho_b(\text{g/cm}^3)\) | \(\rho_x(\text{g/cm}^3)\) | P       |
|--------------|----------------|----------------|--------|-----------------|----------------|----------------|----------------|-------|
| \(x = 0\)   | 5.8648         | 23.0826        | 3.935  | 687.562         | 41.5435        | 0.4220         | 5.12           | 0.9175 |
| \(x = 0.1\) | 5.8648         | 23.0334        | 3.927  | 686.097         | 44.9618        | 0.6145         | 5.13           | 0.8801 |
| \(x = 0.15\)| 5.8648         | 23.0334        | 3.927  | 686.097         | 38.1435        | 0.4268         | 5.13           | 0.9167 |
| \(x = 0.2\) | 5.8648         | 23.0334        | 3.927  | 686.097         | 33.3438        | 0.8512         | 5.13           | 0.8340 |
| \(x = 0.25\)| 5.8648         | 23.0334        | 3.927  | 686.097         | 38.3580        | 2.2666         | 5.13           | 0.5581 |

Figure 2. XRD pattern of SrFe\(_{12-x}\)Ho\(_x\)O\(_{19}\) (holmium-doped strontium hexaferrite) at different concentrations of Ho\(^{3+}\) (where \(x = 0, 0.1, 0.15, 0.2, \) and \(0.25\)) annealed at 1200 \(^\circ\)C. Group (a) refers to powders produced by the conventional method, and group (b) to powders produced by the ultrasonic method.
strontium hexaferrite \cite{32, 33}. The ratio of $c/a$ may indicate the structure type, as ratio $<3.98$ confirms M-type structure with magneto plumbite \cite{34}. The volume of the unit cell decreased for some contractions in the system due to lattice parameter $c$ changing \cite{35}. The average crystal size calculated from equation (2) for powders is shown in table 1. The crystal size of SrFe$_{12-x}$Ho$_x$O$_{19}$ (where $x = 0.15$) synthesized by the ultrasonic method, and SrFe$_{12-x}$Ho$_x$O$_{19}$ (where $x = 0.2$) synthesized by the conventional method, decreased to 35.6792 nm and 33.3438 nm respectively. This can be interpreted on the basis that Ho$^{3+}$ restrains grain growth, resulting in reduced crystal size and $c/a$ ratio by that increasing strain \cite{36}. The bulk density, calculated from equation (4) as shown in table 1, increased when Ho$^{3+}$ substituted in the conventional method. Bulk density doubled when Ho$^{3+}$ and ultrasonic sonication was used, leading to increased mass and density of powder measured in the XRD sample holder, as shown in table 2. These bulk density increases are due to grain growth inhibition with Ho$^{3+}$ doping. The larger atomic weight of Ho$^{3+}$ (164.93 amu) substituted smaller atomic weight of iron (55.845 amu) in the hexagonal structure. Ultrasonic sonication avoids aggregation, hence narrow particle size distribution. Porosity significantly decreased when nanoparticles were synthesized using the ultrasonic method with holmium substituted as shown in table 1, compared to the conventional method, which had a higher porosity.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Substitutions & Mass (g) \\
\hline
$x = 0$ & 0.1013 \\
x = 0.1 & 0.1475 \\
x = 0.15 & 0.1127 \\
x = 0.2 & 0.2043 \\
x = 0.25 & 0.2219 \\
\hline
\end{tabular}
\caption{Required mass to fill XRD standard holder for bulk density measurements in both conventional and ultrasonic methods.}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Substitutions & Mass (g) \\
\hline
$x = 0$ & 0.3090 \\
x = 0.1 & 0.2774 \\
x = 0.15 & 0.4004 \\
x = 0.2 & 0.5440 \\
x = 0.25 & 0.5626 \\
\hline
\end{tabular}
\caption{SrFe$_{12-x}$Ho$_x$O$_{19}$ powders synthesized by conventional method}
\end{table}

Figure 3. Magnified region for (200) and (006) peaks for doped and undoped holmium to strontium hexaferrite which have been synthesized conventional sol-gel auto-combustion denoted by a and for those synthesized by ultrasonic by b.
range due to higher amorphousness, defects, and wide particle size distribution leading to crack and fracture [32]. The peak positions of SrFe$_{12}$O$_{19}$ synthesized by conventional and ultrasonic methods without holmium doping showed no shift, indicating that the ultrasonic method did not change any properties of the produced powder. The peak position of the substituted samples shifted to a larger 2θ compared to pure hexagonal ferrite, as shown in figure 4. This is attributed to lattice strain and decrease in the lattice constant, as well as unit cell volume due to Ho$^{3+}$ substitution. The grain size clearly decreased after substitution. Indexing for undoped strontium hexaferrite and holmium-doped strontium hexaferrite can be shown at figure 5 [28]. Which the indexing remain same for samples otherwise plane orientation may altered by doping.

3.2. Field emission - scanning electron microscopy

Particle size, particle size distribution, and morphology of conventional and ultrasonic method samples were studied by FESEM imaging, as shown in figure 6 for SrFe$_{12-x}$Ho$_x$O$_{19}$ powder (where x = 0, 0.15, and 0.25). Generally, all samples consisted of agglomerated platelet-like grains with a hexagonal shape that did not noticeably change when holmium substituted, until substitution reached 25% of atomic weight. The mean diameter of crystalline nano-sized strontium hexaferrite particles produced by the conventional method was 500.29 nm for x = 0, 780.20 nm for x = 0.15, and 1452 nm for x = 0.25. Powders produced by the ultrasonic method had mean diameters of 410.92 nm for x = 0, 721.88 nm for x = 0.15, and 1327.53 nm for x = 0.25, as shown in table 3.
It can be concluded from figures 6, 7, and the calculations shown in table 3 that the ultrasonic method lowers agglomeration of particles, and hence holmium substitution leads to increased agglomeration. Porosity decreased continuously when holmium substituted for powders synthesized using ultrasonic method compared to those powders produced by the conventional method, leading to smooth surface and denser material. The conventional method obtained a wide particle size distribution with a different shape and size, leading to loosen material and increased porosity. The ultrasonic method plays a great role in narrowing particle size distribution, with the same particle size and shape increasing density and lowering porosity. At 25% of Ho$^{3+}$ atomic weight substitution, the particles have no hexagonal shape and are more likely to be an oval shape. powders synthesized

![Figure 6. FE-SEM images of SrFe$_{12-x}$Ho$_x$O$_{19}$ (where $x = 0$, 0.15, and 0.25) for group (a) conventional method and group (b) ultrasonic method.](image)

| Table 3. Number of particle size produced by both conventional and ultrasonic methods (mean and standard deviation [SD]) |
|---------------------------------------------------------------|
| SrFe$_{12-x}$Ho$_x$O$_{19}$ powders synthesized by conventional method | SrFe$_{12-x}$Ho$_x$O$_{19}$ powders synthesized by ultrasonic method |
| Substitutions | Mean | SD | Substitutions | Mean | SD |
|----------------|------|----|----------------|------|----|
| $x = 0$ | 500.29 | 263.88 | $x = 0$ | 410.92 | 212.37 |
| $x = 0.15$ | 780.20 | 435.96 | $x = 0.15$ | 721.88 | 368.05 |
| $x = 0.25$ | 1452 | 976.18 | $x = 0.25$ | 1327.53 | 813.68 |
using the ultrasonic method compared to those powders produced by the conventional method, leading to a smooth surface and denser material. The conventional method obtained a wide particle size distribution with a different shape and size, leading to loosen material and increased porosity. The ultrasonic method plays a great role in narrowing particle size distribution, with the same particle size and shape increasing density and lowering porosity. At 25% of Ho\(^{3+}\) atomic weight substitution, the particles have no hexagonal shape and are more likely to be an oval shape.

3.3. Transmission electron microscope

TEM analysis was used to assess SrFe\(_{12}\)-Ho\(_{x}\)O\(_{19}\) nanoparticles to determine particle size and size distribution, and to judge whether agglomeration was present in the system. TEM images for SrFe\(_{12}\)O\(_{19}\) as burnt at 200 °C and when 15% of Ho\(^{3+}\) atomic weight substituted and annealed at 1200 °C for both conventional and ultrasonic methods are shown in figure 8. For which agglomeration of nanoparticles exist at each TEM image. Nanoparticle agglomerations from a few major particles were termed minor particles [37]. Agglomerations occur either when major particles are kept together by weak surface forces (soft agglomerations) or by strong chemical bonds (hard agglomerations) [37]. Mean grain size was calculated and found to be 27.63 nm for \(x = 0\) and 8.41 nm for

![Figure 7. Particle size distributions of SrFe\(_{12-x}\)Ho\(_{x}\)O\(_{19}\) (where \(x = 0, 0.15,\) and 0.25) for group (a) conventional method and group (b) ultrasonic method from FE-SEM images.](image)
x = 0.15 for particles produced by the conventional method, and 31.33 nm for x = 0 and 14.22 nm for x = 0.15 for those produced by the ultrasonic method as shown in figure 9 and table 4. The mean grain size for the ultrasonic method was greater than the conventional method, with a narrow size distribution, compared to the conventional method, which had a wide distribution with different sizes. When holmium-doped strontium hexaferrite annealed at 1200 °C for five hours, the grain size decreased compared to burnt strontium hexaferrite, due to rare earth impeding the growth of grain size at high temperatures. This decreased grain size is of an interest in super-paramagnetic nanoparticles which requires nanoparticles below 50 nm as a single domain [38].

3.4. Energy dispersive spectroscopy analysis
The chemical composition and purity of the produced strontium hexaferrite with different holmium substitutions was determined from EDS analysis. Figure 10 shows the EDS patterns of conventional and ultrasonic method produced powders at different concentrations of Ho $^{3+}$. The elements in the products were strontium (Sr), iron (Fe), oxygen (O), and holmium (Ho) in the doped samples, with an excess amount of 5.5 carbon (C) when SrFe$_{12-x}$Ho$_x$O$_{19}$ (where x = 0) was synthesized by the conventional method, as shown in table 5. The probability of rare earth (Ho $^{3+}$) substitution was limited for powders produced by the conventional method: 0.9 where x = 0.15 and 0.7 where x = 0.25. The amount of rare earth (Ho $^{3+}$) present in solution increased when powders were synthesized by the ultrasonic method, by 5.3 for x = 0.15 and 7.4 when x = 0.25. In preparation of SrFe$_{12-x}$Ho$_x$O$_{19}$ (where x = 0.15) 1.411gr of Sr(NO$_3$)$_2$, 31.916 of Fe(NO$_3$)$_3$9H$_2$O, and 0.441 of Ho(NO$_3$)$_3$5H$_2$O were mixed. With 1.411gr of Sr(NO$_3$)$_2$, 31.647 of Fe(NO$_3$)$_3$9H$_2$O, and 0.735 gr of Ho(NO$_3$)$_3$5H$_2$O were mixed in preparation of SrFe$_{12-x}$Ho$_x$O$_{19}$ (where x = 0.25) Since the doped concentrations were too low (0.1, 0.15, 0.2 and 0.25) the corresponding peaks would be low as compared to the major element concentrations [39]. When powders synthesized conventionally and ultrasonically modified sol-gel auto-combustion method with same stoichiometric amount of starting materials leads to big difference in the atomic % of Ho from EDS results. That have a good agreement in above found calculated mass and bulk density from tables 1 and 2. It has been found that results almost tripled when synthesized by ultrasonic method compared to conventionally synthesized method. Which might be due to the fact that ultrasonic increases
nucleation at lowest level of supersaturation with increased nucleation rate followed by narrowed particle size distribution as in TEM and FE-SEM results [40].

4. Conclusion

Using this novel ultrasonic method, different from the conventional method with sol-gel auto-combustion, increased crystallinity with bulk density, and porosity with crystal size decreased because of contraction within unit cell volume and Ho$^{3+}$ substitutions that impede grain growth. Nanoparticles obtained by the ultrasonic method presented homogeneity, higher purity, decreased particle size, and narrow particle size distribution with isomorphic nanoparticles. The appearance of some agglomerations from primary nanoparticles leading to larger nanoparticles decreased when the novel method was used. The amount of Ho$^{3+}$ present in the produced powder increased by 500% when Ho$^{3+}$ was doped by 15% atomic weight. This amount increased to 957% when Ho$^{3+}$ was doped by 25% of the atomic weight for powders prepared by ultrasonic method, compared to conventionally produced powders with the same substitution.

![Figure 9. Particle size distributions of SrFe$_{12-x}$Ho$_x$O$_{19}$ as burnt at 200 °C for $x = 0$ and $x = 0.15$ annealed at 1200 °C for group (a) conventional method and group (b) ultrasonic method from TEM images.](image)

![Table 4. Number of crystal size produced by both conventional and ultrasonic methods (mean and standard deviation [SD]).](table)

| SrFe$_{12-x}$Ho$_x$O$_{19}$ powders synthesized by conventional method | SrFe$_{12-x}$Ho$_x$O$_{19}$ powders synthesized by ultrasonic method |
|---|---|---|---|
| Substitutions | Mean | SD | Substitutions | Mean | SD |
| $x = 0$ | 27.63 | 10.40 | $x = 0$ | 31.33 | 14.29 |
| $x = 0.15$ | 8.41 | 5.17 | $x = 0.15$ | 14.22 | 9.81 |

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Figure 10. EDS spectrum of SrFe_{12-x}Ho_xO_{19} (where x = 0, 0.15, and 0.25) for group (a) conventional method and group (b) ultrasonic method.

Table 5. Elemental concentrations from EDS analysis of produced SrFe_{12-x}Ho_xO_{19} powders (where x = 0, 0.15, and 0.25) for conventional and ultrasonic methods.

| Substitutions | Sr | Fe | Ho | O | C |
|---------------|----|----|----|---|---|
| x = 0         | 12.2 | 58.3 | 0   | 24.0 | 5.5 |
| x = 0.15      | 12.8 | 60.9 | 0.9 | 24.4 | 0   |
| x = 0.25      | 14.2 | 61.1 | 0.7 | 24   | 0   |

| Substitutions | Sr | Fe | Ho | O | C |
|---------------|----|----|----|---|---|
| x = 0         | 15.5 | 59.7 | 0   | 24.8 | 0   |
| x = 0.15      | 11.3 | 59.5 | 5.3 | 24   | 0   |
| x = 0.25      | 13.5 | 56.5 | 7.4 | 22.5 | 0   |
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