Erratum to: Microstructure and Magnetic Properties of $\text{SrFe}_{12}\text{O}_{19}$ Nano-sized Powders Prepared by Sol-Gel Auto-combustion Method with CTAB Surfactant

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Abstract In this research, nano-sized powders of strontium hexaferrite were synthesized by sol-gel auto-combustion route using stoichiometric ratio of Fe/Sr. The effect cetyltrimethylammonium bromide (CTAB) addition on microstructure and magnetic properties of hexaferrite have been studied. The samples were characterized using X-ray diffraction (XRD), dynamic light scattering (DLS), vibration sample magnetometer (VSM), field emission scanning electron microscope (FESEM), and transmission electron microscope (TEM) techniques. The results revealed that CTAB addition causes a noticeable reduction in the amount of residual $\alpha\text{-Fe}_2\text{O}_3$ phase, since presence of CTAB in the sol facilitates the entrance of Sr^{2+} ions into the reactions of hexaferrite formation. Also, the morphology of the particles was affected by CTAB addition. Irregular-shaped nanoparticles were synthesized without CTAB additions, while platelet-shaped nanoparticles were obtained by CTAB addition. The mechanism of strontium hexaferrite nanopowder formation has been explained. Magnetic measurements in the sample calcined at 800°C for 1 h represented that CTAB addition increased the coercivity force (H_c) from 4.9 to 5.2 kOe and maximum magnetization (M_{max}) from 48.4 to 60.4 emu/g, respectively.

Keywords Strontium hexaferrite · Sol-gel auto-combustion · Surfactant · Magnetic properties

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The original version of this article unfortunately contained mistakes. References were incorrectly cited in the text. The correct version of the article is shown below.

1 Introduction

M-type strontium hexaferrite ($\text{SrFe}_{12}\text{O}_{19}$) has wide applications due to its appropriate magnetic properties, corrosion resistance, chemical stability, and high performance-to-cost ratio. It has been recognized that they can be used as permanent magnets and high-density magnetic reordering media; they can also be used in telecommunication and as components in microwaves, higher frequencies, and magneto-optical devices [1–4]. The purity, size, and morphology of the powders affect its magnetic properties [5]. Therefore, various synthesis methods such as chemical coprecipitation [6, 7], hydrothermal [8, 9], self-propagating high temperature route [10], mechanical alloying [11, 12], sol-gel [13–15], and sol-gel auto-combustion [16] have been developed to synthesize M-type hexaferrite nano-sized powders.

It was observed that some additional Sr was needed to synthesize strontium hexaferrite without residual $\alpha\text{-Fe}_2\text{O}_3$ phase in the sol-gel auto-combustion process [16], and the same result was also reported for some other wet chemistry routes, since the solubility of $\text{Sr}(\text{OH})_2$ is low in an aqueous solution. This low solubility poses problems in maintaining the stoichiometry of the strontium ferrite; therefore, some

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excess strontium is needed to be introduced into the starting composition [17].

There are some investigations on the effect of different surfactant additions on synthesis of strontium hexaferrite by sol-gel auto-combustion method using Fe/Sr ratio of 10, which represented that the mean crystallite size and calcination temperature of synthesized single-phase strontium hexaferrite had been reduced by surfactant addition [18, 19].

Up to authors' knowledge, the effect of CTAB addition on microstructure and magnetic properties of strontium hexaferrite synthesized with Fe/Sr ratio of 12 (stoichiometric Fe/Sr ratio) with sol-gel auto-combustion route was not studied yet. Therefore, in this research, strontium hexaferrite nano-sized powders have been synthesized with the stoichiometric ratio of Fe/Sr by a sol-gel auto-combustion route and the effect of CTAB addition and calcination temperature on phase formation, microstructure, and magnetic properties of strontium hexaferrite nanopowders have been studied.

2 Materials and Methods

In order to synthesize strontium hexaferrite nano sized powders, proper amounts of metal nitrates: 19.16 g $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (99 % Merck) and 0.82 g $\text{Sr}(\text{NO}_3)_2$ (99 % Merck) were dissolved into 50 ml of distilled water to make an aqueous solution. Then, citric acid ($\text{C}_6\text{H}_8\text{O}_7$ 99 % Merck) was added to the above mixture as a chelating agent. The molar ratio of Fe/Sr was fixed to 12 in different samples and the nitrate to citrate ratio was fixed to 1:1. The pH of the solution was increased to 7 by addition of ammonia solution. Then cetyltrimethylammonium bromide (CTAB) $\text{C}_{19}\text{H}_{42}\text{BrN}$ (99 % Merck) was added to the solution as surfactant. The resulting sol had been heated at constant temperature of 80 °C on magnetic stirrer to complete the reaction for forming the gel precursor. Then the dried precursor undergoes a self-ignition reaction to form a very fine brown foamy powder. Finally, the samples were calcined at 800 and 900 °C for 1 h.

Magnetic properties have been taken out at room temperature at the maximum applied field of 14 kOe by vibrating sample magnetometer (VSM) model MDK. The phase identification of the combustion products and calcined nanopowders has been performed by Philips X'pert Pro X-ray diffractometer (XRD) using Cu $\text{K}\alpha$ radiation ($\lambda = 0.1541 \text{ nm}$).

The XRD patterns were submitted to a quantitative analysis by the Rietveld method using Material Analysis Using Diffraction (MAUD) software [20]. The size of calcined nanoparticles were determined using dynamic light scattering technique (DLS) model Nano ZS90. The morphology and microstructure of the nanoparticles were studied by a

field emission gun scanning electron microscope (FESEM) model (TESCAN) and transmission electron microscope (TEM) at 200 kV (Philips CM200). Selected area electron diffraction (SAED) patterns were also taken on TEM.

3 Results and Discussions

X-ray diffraction patterns of the samples synthesized without CTAB addition and with CTAB addition calcined at 800 and 900 °C for 1 h in air are shown in Fig. 1. The observed phases are $\text{SrFe}_{12}\text{O}_{19}$ as the main phase and some amount of residual $\alpha\text{-Fe}_2\text{O}_3$. The amount of residual $\alpha\text{-Fe}_2\text{O}_3$ varied in different samples. Quantitative analysis of the results for the sample synthesized without CTAB addition calcined at 800 °C (Fig. 1a), by MAUD software, represent that the amount of residual $\alpha\text{-Fe}_2\text{O}_3$ is about 20 wt% in this sample. By increasing the calcination temperature to 900 °C, the intensity of $\alpha\text{-Fe}_2\text{O}_3$ peaks are diminished which represents that the amount of residual $\alpha\text{-Fe}_2\text{O}_3$ in the sample is reduced remarkably.

Fig. 1 XRD patterns of the samples synthesized **a** without and **b** with CTAB addition, calcined at 800 and 900 °C for 1 h

Fig. 2 Schematic representation for the exchange of the hydroxide ion by the positive CTAB micelle [22]

XRD patterns of the sample prepared with CTAB addition under calcination temperatures of 800 (Fig. 1b) revealed that addition of the CTAB decreases the amount of residual α -Fe₂O₃ phase considerably at 800 °C.

Studies on the synthesis of strontium hexaferrite by sol-gel auto-combustion process have been shown the need of additional Sr [16]. The ability of Fe³⁺ ions to form complex with citric acid ($pK_a = 11.5$) is higher than that of the Sr²⁺ ions ($pK_a = 3.05$) [21]. Also, a fraction of Sr(OH)₂, which is formed by dissolution of Sr nitrate, reduces the solubility of the Sr²⁺ ions in the sol as a result of low solubility of Sr(OH)₂ in an aqueous solution. It was reported that addition of KOH allowed a small fraction of the CTAB molecules to become hydroxylated to form cetyltrimethylammonium hydroxide (CTAH). The mechanism can be explained on the basis of an exchange of hydroxide ion by the positive CTAB micelle as shown in Fig. 2 [22]. Sr(OH)₂ may also hydroxylate the CTAB molecules with the same mechanism and form SrBr₂ which has much higher solubility (100 g/100 ml) in water compared with Sr(OH)₂ (0.8 g/100 ml) [23]. So it could be concluded that the CTAB addition may facilitate the dissolution of Sr(OH)₂ in the aqueous solution that may facilitate the formation of more complexes between citric acid and Sr²⁺ ions in the sol, resulting in the formation of less amount of residual α -Fe₂O₃ after calcination of the combustion product at the same temperature.

Fig. 3 FESEM micrographs of the combustion products in samples synthesized **a** without and **b** with CTAB addition

Figure 3 represents the FESEM micrographs of the combustion products in the samples synthesized with and without CTAB addition. According to the XRD results of the previous work of the author, the combustion product consists of γ -Fe₂O₃, α -Fe₂O₃, and SrCO₃ phases, and the combustion product of the sample with CTAB addition consists of the same phases [24]. The FESEM images represent that although the phase constituents of the samples are the same, the morphology of the combustion product is affected by CTAB addition and the morphology changes from a nearly spherical shape to a nearly platelet-like morphology with highly aggregated plates using CTAB addition.

FESEM images of the samples synthesized with and without CTAB addition calcined at 800 °C for 1 h have been shown in Fig. 4. It could be observed that the morphologies of the samples are completely different. When the sample was synthesized without CTAB addition, the particles have irregular shapes with wide size distribution, while CTAB addition causes the formation of coarse hexagonal platelet-like morphology. However, it could be observed that the particle size in the sample without CTAB addition is totally smaller. The smooth reaction interfaces in the combustion product of the sample with CTAB addition leads to the formation of hexagonal platelet-like particles after calcination, as it was observed in the samples synthesized with coprecipitation method with and without CTAB which were led to the formation of platelet-like and rod-like morphologies, respectively, after calcination at 900 °C [25]. Chen et al. had proposed that platelet-shaped hexaferrite crystals prefer to grow on the smooth Fe₂O₃ surfaces, whereas precursors of isometric shape (spherical, cubical) with rough interface are difficult to form the hexagonal platelet-like morphology. So the precursor morphology impresses the morphology of the final product [25]. Their suggested formation mechanism for hexaferrite particles from the obtained precursors by coprecipitation method is shown in Fig. 5.

Fig. 4 FESEM micrographs of the samples synthesized **a** without and **b** with CTAB addition calcined at 800 °C for 1h

It was shown that CTAB addition in the sol-gel auto-combustion process increases the exothermicity of the reaction strongly [26]. So the different morphologies in the combustion product may be as a result of higher combustion exothermicity obtained in the presence of CTAB since it plays the role of fuel in the combustion process. The higher combustion temperature and its higher exothermicity may lead to the formation of more crystallized and aggregated precursors. Also, presence of surfactant in the sol may affect the morphology of the precursors and facilitates the growth of precursors in some preferred directions leading to the formation of platelet-like morphologies, since there are some reports that represent that the presence of CTAB and its concentration in the aqueous wet chemistry methods affect the

Fig. 5 The proposed formation mechanism of $\text{SrFe}_{12}\text{O}_{19}$ particles from precursors obtained by co precipitation method synthesized **a** without and **b** with CTAB addition [25]

morphology of the synthesized nanoparticles of different materials (e.g., $\alpha\text{-Fe}_2\text{O}_3$, Cu_2O and Au) [27–29].

Figure 6 represents the TEM images of the strontium hexaferrite nano-sized powders with and without CTAB

Fig. 6 TEM images of the strontium hexaferrite nano particles **a** without and **b** with CTAB additions, calcined at 800 °C for 1 h

Fig. 7 The size of particles synthesized **a** without and **b** with CTAB additions, calcined at 800 °C for 1 h characterized with DLS

additions, calcined at 800 °C for 1 h. TEM images represent the high aggregation of the particles which is the result of the combustion process. The small hexagonal-shaped particles with nanometric sizes could be observed in these images. The selected area diffraction pattern of both samples represents ring patterns which is the characteristic of the nanopowders [30]. The SAED rings in the sample without CTAB addition represent more uniformity, and fewer

dots are observable in them which is a proof for smaller particle size in the sample without CTAB addition.

The particle size of the samples synthesized with and without CTAB additions, calcined at 800 °C were characterized using DLS. Figure 7 represents that the mean particle size is 131 nm in sample synthesized without CTAB and 191 nm in sample synthesized with CTAB additions. It should be mentioned that DLS represents the hydrodynamic size or diameter of a particle including the fluid molecules around the electrostatic double layer which is bigger than the real particle size and also the obtained mean particle sizes are the size of aggregated particles as it was observed in the TEM images.

The magnetic properties of the different samples were measured using a VSM. The intrinsic coercivity force (iH_c) and maximum magnetization (M_{max}) of samples are shown in Fig. 8 and Table 1. As shown in the graphs, the intrinsic coercivity force (iH_c) and maximum magnetization (M_{max}) of the sample without surfactant addition calcined at 800 °C was 4.95 kOe and 48.41 emu/g, respectively. The obtained amounts of M_{max} for other samples are in the range of 60.4 to 61.3 emu/g. As mentioned before, according to the XRD results, the amount of residual α -Fe₂O₃ was diminished with surfactant addition or increasing the calcination temperature. It was reported that presence of considerable amount of antiferromagnetic α -Fe₂O₃ can reduce the value of M_{max} [31].

Another point which could be observed in the hysteresis loops of these two samples is the existence of a step in the demagnetization curves of the second and fourth quadrants. These steps may represent two-phase magnetic behavior [32], since α -Fe₂O₃ is a weak anti-ferromagnet at room temperature [33, 34], or represent the presence of a large distribution in the particle size of the synthesized powders as could be observed in the FESEM image of the sample without surfactant addition

Fig. 8 VSM results of the samples synthesized **a** without and **b** with CTAB additions calcined at 800 and 900 °C for 1 h

Table 1 Magnetic properties of the samples synthesized without and with CTAB addition with Fe/Sr ratio of 12 calcined at 800 and 900 °C for 1 h

Calcination Temperature (°C)	CTAB addition (Yes/No)	$M_{\max}$ (emu/g)	iH_c (Oe)
800	No	48.41	4950.89
900	No	61.35	5521.31
800	Yes	60.40	5221.47
900	Yes	61.35	4994.77

(Fig. 4a), since differently sized and shaped particles will reverse at different field strengths. The relationship between intrinsic coercivity force and the particle size in hexagonal ferrites is schematically shown in Fig. 9 [35]. As the size of the sample is reduced from the bulk, the coercivity initially increases as single-domain particles are formed. Below some critical radius, however, the coercivity decreases and eventually drops to zero since the particles are starting to approach the super paramagnetic behavior [36]. It was reported that the critical particle size for strontium hexaferrite below which the particles have starting to approach the super paramagnetic behavior is about 40–60 nm [31, 37], and the maximum critical particle size for strontium hexaferrite single domains is reported to be about 650 nm [38]. According to FESEM image of the sample synthesized without CTAB addition, the particle size is lower than the critical single-domain size while there are some particles that approached to the super paramagnetic behavior.

It is known that the iH_c of ferrites is strongly affected by grain or particle sizes [31]. The hysteresis loop of the sample prepared with surfactant addition under calcination temperature of 800 °C represents that the intrinsic coercivity

force (iH_c) of the sample increased to 5.22 kOe which may be as a result of presence of small particles that approached to the super paramagnetic state in the sample, while CTAB additions caused formation of coarse particles in the single-domain range.

Increasing the calcination temperature to 900 °C, in the sample synthesized with CTAB addition, reduced the iH_c from 5.22 to 4.99 kOe which could be as a result of the growth of the particles during calcination, since the coarse particles of hexaferrite in the sample synthesized with surfactant calcined at 900 °C may have a transition from single magnetic domain to multi-magnetic domain by increasing the calcination temperature.

On the other hand, increasing the calcination temperature in the sample synthesized without surfactant addition increases the coercivity force to 5.52 kOe. It seems that the growth of particles causes formation of single-domain particles instead of particles starting to approach the super paramagnetic state and this enhances the coercivity force. Also, reduced amount of α -Fe₂O₃ may affect the coercivity force while there is no known trend for the relationship between the amount of α -Fe₂O₃ and coercivity force values [25, 39, 40]. The step which was present in the demagnetization curves of the second and fourth quadrants of the sample without CTAB addition calcined at 800 °C is flattened in the VSM plots of the samples with CTAB addition.

Fig. 9 Schematic illustration of the relationship between intrinsic coercivity force and the particle size in hexagonal ferrites [35]

4 Conclusion

The SrFe₁₂O₁₉ nanopowders were synthesized by sol-gel auto-combustion method with and without CTAB addition. The results revealed that CTAB additions can improve the magnetic properties of the sample calcined at 800 °C and increase its maximum magnetization from 48.41 to 60.40 emu/g and its iH_c from 4950.89 to 5221.47 Oe. This magnetic properties improvement is as a result of reduced amount of residual α -Fe₂O₃ and presence of some particles with the sizes in the single-domain range. Increasing the calcination temperature to 900 °C in the sample without CTAB addition increases the $M_{\max}$ and iH_c , while in the sample with CTAB addition increasing the calcination temperature diminishes the iH_c as a result of particle coarsening.

References

- Zhanyong, W., Liuming Z., Jieli, L., Huichun, Q., Yuli, Z., Yongzheng, F., Minglin, J., Jiayue, X.: Microwave-assisted synthesis of $\text{SrFe}_{12}\text{O}_{19}$ hexaferrites. *J. Magn. Magn. Mater.* **322**, 2782–2785 (2010)
- Xia, A., Zuo, C., Chen, L., Jin, C., Lv, Y.: Hexagonal $\text{SrFe}_{12}\text{O}_{19}$ ferrites: hydrothermal synthesis and their sintering properties. *J. Magn. Magn. Mater.* **332**, 186–191 (2013)
- Wang, Y., Li, Q., Zhang, C., Li, B.: Effect of Fe/Sr mole ratios on the formation and magnetic properties of $\text{SrFe}_{12}\text{O}_{19}$ microtubules prepared by sol-gel method. *J. Magn. Magn. Mater.* **321**, 3368–3372 (2009)
- Singh, P., Babbar, V.K., Razdan, A., Srivastava, S.L., Agrawal, V.K., Goel, T.C.: Dielectric constant, magnetic permeability and microwave absorption studies of hot-pressed Ba-CoTi hexaferrite composites in X-band. *J. Mater. Sci.* **41**, 7190–7196 (2006)
- Kuo, H.M., Hsui, T.e.-Fa., Tuo, Y.S., Yuan, C.L.: Microwave adsorption of core-shell structured $\text{Sr}(\text{MnTi})_x\text{Fe}_{12-2x}\text{O}_{19}/\text{PANI}$ composites. *J. Mater. Sci.* **47**, 2264–2270 (2012)
- Jacobo, S.E., Blesa, M.A., Domingo-Pascual, C., Rodriguez-Clemente, R.: Synthesis of ultrafine particles of barium ferrite by chemical coprecipitation. *J. Mater. Sci.* **32**, 1025–1028 (1997)
- Calleja, A., Tijero, E., Martinez, B., Pinol, S., Sandiumenge, F., Obradors, X.: Hexaferrite particles by coprecipitation and lyophilization. *J. Magn. Magn. Mater.* **196–197**, 293–294 (1999)
- Barb, D., Diamandescu, L., Rusi, A.: Preparation of barium hexaferrite by a hydrothermal method: structure and magnetic properties. *J. Mater. Sci.* **21**, 1118–1122 (1986)
- Ataie, A., Harris, I.R., Ponton, C.B.: Magnetic properties of hydrothermally synthesized strontium hexaferrite as a function of synthesis conditions. *J. Mater. Sci.* **30**, 1429–1433 (1995)
- Elvin, G., Parkin, I.P.P., Bui, Q.T., Barquin, L.F., Pankhurst, Q.A., Komarov, A.V., Morozov, Y.G.: Self-propagating high-temperature synthesis of $\text{SrFe}_{12}\text{O}_{19}$ from reactions of strontium superoxide, iron metal and iron oxide powders. *J. Mater. Sci. Lett.* **16**, 1237–1239 (1997)
- Ding, J., Miao, W.F., McCormick, P.G., Street, R.: High-coercivity ferrite magnets prepared by mechanical alloying. *J. alloys comp.* **281**, 32–36 (1998)
- Ketov, S.V., Yagodka, Yu.D., Lebed, A.L., Chernopyatova, Yu.V., Khlopkov, K.: Structure and magnetic properties of nanocrystalline $\text{SrFe}_{12}\text{O}_{19}$ alloy produced by high-energy ball milling and annealing. *J. Magn. Magn. Mater.* **300**, e479–e481 (2006)
- Surig, C., Hempel, K.A., Bonnenborg, D.: Hexaferrite particles prepared by sol-gel technique. *IEEE Trans. Magn.* **30**, 4092–4094 (1994)
- Srivastava, A., Singh, P., Gupta, M.P.: Barium ferrite: preparation by liquid mix technique and its characterization. *J. Mater. Sci.* **22**, 1489–1494 (1987)
- Pullar, R.C., Taylor, M.D., Bhattacharya, A.K.: Novel aqueous sol-gel preparation and characterization of barium M ferrite $\text{BaFe}_{12}\text{O}_{19}$ fibers. *J. Mater. Sci.* **32**, 349–352 (1997)
- Alamolhoda, S., Seyyed Ebrahimi, S.A., Badiei, A.: Optimization of the Fe/Sr ratio in processing of ultrafine strontium hexaferrite powders by a sol-gel auto combustion method. *Phys. Met. Metall.* **102**, S71–S73 (2006)
- Sivakumar, M., Gedanken, A., Zhong, W., Du, Y.W., Bhattacharya, D., Yeshurun, Y., Felner, I.: Nanophase formation of strontium hexaferrite fine powder by the sonochemical method using $\text{Fe}(\text{CO})_5$. *J. Magn. Magn. Mater.* **268**, 95–104 (2004)
- Ghobeiti Hasab, M., Seyyed Ebrahimi, S.A., Badiei, A.: Comparison of the effects of cationic, anionic and nonionic surfactants on the properties of Sr-hexaferrite nanopowder synthesized by a sol-gel auto-combustion method. *J. Magn. Magn. Mater.* **316**, e13–e15 (2007)
- Ghobeiti Hasab, M., Seyyed Ebrahimi, S.A., Badiei, A.: An investigation on physical properties of strontium hexaferrite nanopowder synthesized by a sol-gel auto-combustion process with addition of cationic surfactant. *J. Eur. Ceram. Soc.* **27**, 3637–3640 (2007)
- Rietveld, H.M.: A profile refinement method for nuclear and magnetic structures. *J. Appl. Cryst.* **2**, 65–71 (1969)
- Martell, E., Smith, R.M.: Critical stability constants, vol. 3. Springer, New York (1977)
- Topallar, H., Karadag, B.: Mechanism of micelle formation in sodium dodecyl sulfate and cetyltrimethylammonium bromide. *J. Surfactants Deterg.* **1**, 49–51 (1998)
- Dean, J.A.: Lange's handbook of chemistry. 15th edn. Mc Graw Hill, New York (1999)
- Alamolhoda, S., Seyyed Ebrahimi, S.A., Badiei, A.: A study on the formation of strontium hexaferrite nanopowder by a sol-gel auto-combustion method in the presence of surfactant. *J. Magn. Magn. Mater.* **303**, 69–72 (2006)
- Chen, D.Y., Meng, Y.Y., Zeng, D.C., Liu, Z.W., Yu, H.Y., Zhong, X.C.: CTAB-assisted low-temperature synthesis of $\text{SrFe}_{12}\text{O}_{19}$ ultrathin hexagonal platelets and its formation mechanism. *Mater. Lett.* **76**, 84–86 (2012)
- Singh, I., Bedi, R.K.: Surfactant-assisted synthesis, characterizations, and room temperature ammonia sensing mechanism of nanocrystalline CuO. *Solid State Sci.* **13**, 2011–2018 (2011)
- Pu, Z., Cao, M., Yang, J., Huang, K., Hu, C.: Controlled synthesis and growth mechanism of hematite nanorhomboids, nanorods and nanocubes. *Nanotechnology* **17**, 799–804 (2006)
- Zhang, H., Shen, C., Chen, S., Xu, Z., Liu, F., Li, J., Gao, H.: Morphologies and microstructures of nano-sized Cu_2O particles using a cetyltrimethylammonium template. *Nanotechnology* **16**, 267–272 (2005)
- Kang, S.K., Chah, S., Yun, C.Y., Yi, J.: Aspect ratio controlled synthesis of gold nanorods. *Korean J. Chem. Eng.* **20**, 1145–1148 (2003)
- Mula, S., Mondal, K., Ghosh, S., Pabi, S.K.: Structure and mechanical properties of Al–Ni–Ti amorphous powder consolidated by pressure-less, pressure-assisted and spark plasma sintering. *Mater. Sci. Eng. A* **527**, 3757–3763 (2010)
- Lin, C.S., Hwang, C.C., Huang, T.H., Wang, G.P., Peng, C.H.: Fine powders of $\text{SrFe}_{12}\text{O}_{19}$ with SrTiO_3 additive prepared via a quasi-dry combustion synthesis route. *Mater. Sci. Eng. B* **139**, 24–36 (2007)
- Saravanan, P., Arvindha Babu, D., Chandrasekaran, V.: Microstructure, phase evolution and magnetic properties of melt-spun $\text{SmCo}_{6.8-x}\text{Sn}_x\text{Zr}_{0.2}$ ($x = 0, 0.1$ and 0.3) ribbons. *Intermetallics* **19**, 651–656 (2011)
- Dzyaloshinsky, I.: A thermodynamic theory of weak ferromagnetism of antiferromagnetics. *J. Phys. Chem. Solids* **4**, 241–255 (1958)
- Bødker, F., Hansen, M.F., Koch, C.B., Lefmann, K., Mørup, S.: Magnetic properties of hematite nanoparticles. *Phys. Rev. B* **61**, 6826–6838 (2000)
- Moulson, A.J., Herbert, J.M.: *Electroceramics Materials. Properties. Applications* 2nd edn. John Wiley & Sons, Chichester (2003)
- Spaldin, N.A.: *Magnetic Materials, Fundamentals and Applications* 2nd edn. Cambridge University Press, New York (2010)

37. Pullar, R.C.: Hexagonal ferrites: a review of the synthesis, properties and applications of hexaferrite ceramics. *Prog. Mater. Sci* **57**, 1191–1334 (2012)
38. Zi, Z.F., Sun, Y.P., Zhu, X.B., Yang, Z.R., Dai, J.M., Song, W.H.: Structural and magnetic properties of $\text{SrFe}_{12}\text{O}_{19}$ hexaferrite synthesized by a modified chemical co-precipitation method. *J. Magn. Mater.* **320**, 2746–2751 (2008)
39. Nga, T.T.V., Duong, N.P., Loan, T.T., Hien, T.D.: Key step in the synthesis of ultrafine strontium ferrite powders ($\text{SrFe}_{12}\text{O}_{19}$) by sol–gel method. *J. Alloys Comp.* **610**, 630–634 (2014)
40. Xu, Y.F., Ma, Y.Q., Xu, S.T., Zan, F.L., Zheng, G.H., Dai, Z.X.: Effects of vacancy and exchange-coupling between grains on magnetic properties of $\text{SrFe}_{12}\text{O}_{19}$ and $\alpha\text{-Fe}_2\text{O}_3$ composites. *Mater. Res. Bull.* (2014). doi:[10.1016/j.materresbull.2014.05.017](https://doi.org/10.1016/j.materresbull.2014.05.017)