

Magnetic properties of hexagonal isotropic polycrystalline $\text{SrFe}_{12}\text{O}_{19}$ ferrites obtained by radiation-thermal sintering

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Abstract

Hexagonal strontium ferrite has found wide application in the fabrication of permanent magnets and active media of UHF electronics and photonics. The performance of hexagonal strontium ferrites depends largely on their synthesis method. Hexagonal polycrystalline isotropic $\text{SrFe}_{12}\text{O}_{19}$ ferrite specimens have been synthesized using fast electron beam radiation-thermal sintering (RTS) in a PLU-6 electron accelerator of G.I. Budker Institute of Nuclear Physics of the Russian Academy of Sciences. The RTS temperature has been varied from 1200 to 1400 °C, and the RTS time, from 10 to 90 min. The phase composition and lattice parameters of the specimens have been studied using X-ray diffraction on a DRON-8 diffractometer in $\text{CoK}_{\alpha 1}$ radiation. The density of the specimens has been measured following Archimedeon law on a UW620H electronic balance with a liquid density measurement attachment. The magnetic hysteresis loop parameters of the specimens have been studied with a VM-07 vibromagnetometer.

The specimens have proven to be single-phase with a $P6_3/mmc$ space group (No. 194), corresponding to a hexagonal ferrite structure. For the first time, changes in the magnetic hysteresis loop parameters of hexagonal $\text{SrFe}_{12}\text{O}_{19}$ strontium ferrite specimens synthesized with fast electron beam RTS have been studied. We show that the width and intensity of the magnetic hysteresis loop decrease noticeably with an increase in the RTS temperature from 1200 to 1350–1400 °C. The magnetization coercive force jH_c decline to the minimum values at RTS temperatures $T_{\text{sint}} \geq 1250$ °C, probably due to recrystallization in the ferrite lattice: the combined impact of RTS temperature and radiation-induced diffusion triggers intense grain growth, significantly reducing the number of domain boundaries and, hence, causing a drop in jH_c . The high energy efficiency of RTS in ferrite ceramics synthesis has been confirmed for the example of $\text{SrFe}_{12}\text{O}_{19}$.

Keywords

radiation-thermal sintering, polycrystalline hexagonal isotropic ferrite $\text{SrFe}_{12}\text{O}_{19}$, X-ray diffraction, fast electrons, electron accelerator, density, lattice magnetic hysteresis loop parameters, magnetization, coercive force

1. Introduction

M-type hexagonal $\text{SrFe}_{12}\text{O}_{19}$ strontium ferrite has a crystalline structure that is isomorphic to that of magnetoplumbite ($\text{PbFe}_{12}\text{O}_{19}$) [1]. Due to the difference in the ionic radii of barium and strontium, a substitution of the former for the latter in the hexagonal ferrite lattice increases the magnetic crystallographic anisotropy constant K by 10 % [2]. Furthermore, SrM hexaferrites have better processability as compared to $\text{BaFe}_{12}\text{O}_{19}$ hexaferrites [2]. Due to its combination of magnetic properties and performance, SrM ferrite has found wide application in the fabrication of permanent magnets [1, 2], active media of

millimeter-wavelength UHF electronics devices [3], and THz photonics devices [4]. In science and engineering, there is still great interest in the development of UHF electronics devices based on thick hexagonal ferrites films [5, 6]. Today, the main industrial synthesis process for the above materials is the ceramic technology [1, 2, 5]. Typical process diagram of polycrystalline hexagonal $\text{SrFe}_{12}\text{O}_{19}$ ferrites is shown in Fig. 1. Along with the commonly known advantages, the ceramic technology has a number of drawbacks. One of the main drawbacks is the high energy consumption. Alternative $\text{SrFe}_{12}\text{O}_{19}$ hexaferrite technology can be radiation-thermal sintering (RTS) which has been well tested for a wide range of ferrites [7–9], including BaM [7]. The difference of the RTS process from the conventional ceramic one is that the thermal sintering of raw billets is replaced for fast electron beam sintering in an electron accelerator [7–9]. The aim of this work is to explore the possibility of synthesis of high-quality isotropic polycrystalline $\text{SrFe}_{12}\text{O}_{19}$ hexaferrites using the RTS technology and to study the magnetic properties of synthesized hexaferrite specimens.

2. Experimental

The iron-containing raw material for the preparation of the test specimens was MM-2 Grade Fe_2O_3 iron oxide (TU6-09-4816–80, impurity contents (wt.%) 0.01 SiO_2 , 0.01 Al_2O_3 , 0.01 Cr_2O_3 , 0.01 Na_2O). The strontium containing raw material was Ch Grade (99.0% purity) crystalline strontium carbonate from Isfara Chemical Factory (Tajikistan). The raw billets were prepared in accordance with the diagram presented in Fig. 1. The preparation route included all conventional operations except thermal sintering. The final operation was replaced for RTS. The replacement of conventional sintering for fast electron beam RTS was chosen due to the far lower energy consumption and higher sintering quality delivered by fast electron beam RTS [7–9]. For RTS, along with the high-temperature treatment, radiation-enhanced diffusion contributes significantly to the process. The combination of the above factors delivers sintering at lower temperatures and in a shorter time [7–9]. Radiation-thermal sintering of the specimens was carried out in a fast electron beam of an ILU-6 electron accelerator used for radiation technologies (maximum fast electron energy 2.5 MeV) at the G.I. Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences [10]. Fast electron beam sintering of hexagonal ferrites was carried out in a cell for ferrite ceramic sintering designed at the Chair of Electronics Materials of the MISIS Research and Technology University. Table 1 summarizes data on the SrM specimens.

X-ray structural analysis of the test specimens was carried out on a DRON-8 X-ray diffractometer (NPP Burevestnik JSC, St. Petersburg, Russia) in $\text{CoK}_{\alpha 1}$ radiation ($\lambda = 0.178897$ nm) with Bragg-Brentano focusing by two Soller slots at room temperature.

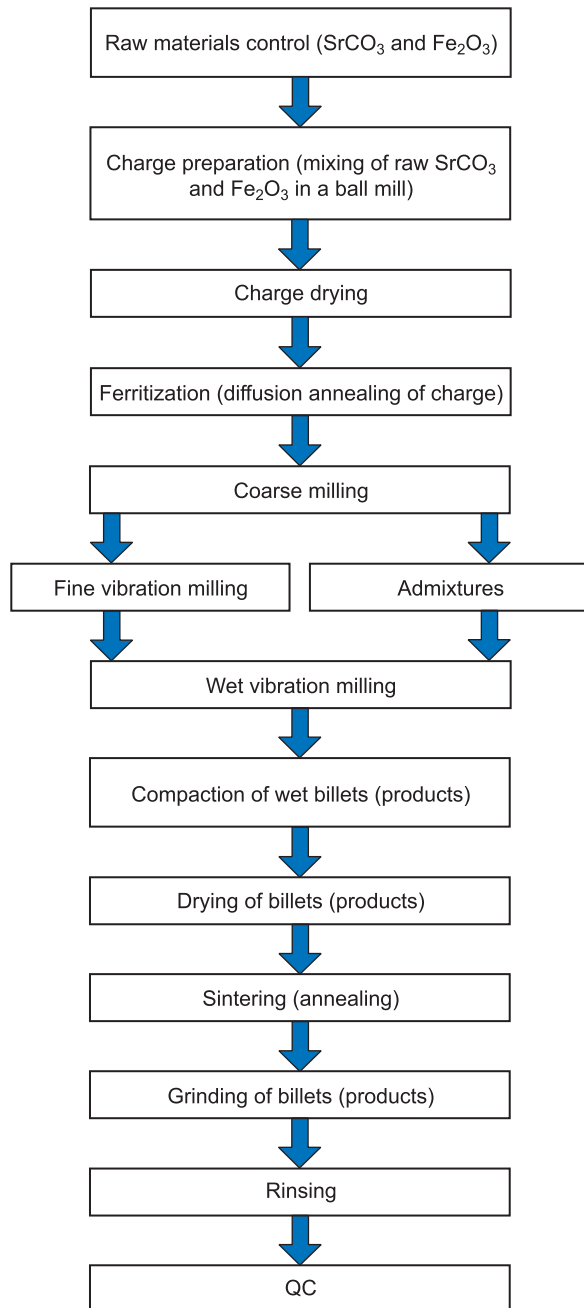


Figure 1. Typical synthesis process route of isotropic polycrystalline hexagonal ferrites using ceramic technology

Table 1. Radiation-thermal sintering parameters for SrFe₁₂O₁₉ specimens

#	Raw billet No.	Specimen	RTS temperature (°C)	RTS time (min)
1	8-p6	GSI_# 8	1200	60
2	9-p6	GSI_# 9	1250	60
3	11-p6	GSI_# 11	1300	10
4	12-p6	GSI_# 12	1300	30
5	10-p6	GSI_# 10	1300	60
6	13-p6	GSI_# 13	1300	90
7	14-p6	GSI_# 14	1350	40; 60
8	30-p6	GSI_# 30	1400	30; 60

The density of the specimens was measured using Archimedeian law on a UW620H electronic balance with a liquid density measurement attachment and calculated using the following formula:

$$\rho = \rho_0 \left(\frac{W_a}{W_a - W_l} \right), \quad (1)$$

where ρ is the specimen density (g/cm³), ρ_0 is the known liquid density (g/cm³), W_a is the specimen weight in air (g), and W_l is the liquid sample weight (g).

The X-ray density of the ferrites was calculated based on X-ray analysis data using the following formula:

$$\rho_{\text{X-ray}} = \frac{2M_A}{VN_A} = \frac{2M_A \cdot 2}{ca^2 3\sqrt{3}N_A}, \quad (2)$$

where M_A is the molecular weight of hexaferrite, c and a are the lattice parameters of hexaferrite, N_A is the Avogadro number, and V is the unit cell volume. The average density proved to be 5.1 g/cm³.

The hysteresis loops of the 1.0–3.0 mm diam. spherical sintered hexaferrite specimens were recorded using a VM-07 vibromagnetometer.

3. Results and discussion

Analysis of the X-ray diffraction spectra showed that the synthesized specimens were single-phase (space group $P6_3/mmc$ (No. 194), i.e., hexagonal ferrites. Figure 2 shows RTS-synthesized SrFe₁₂O₁₉ hexagonal ferrite specimen density as a function of (a) sintering time at $T = 1300$ °C and (b) of RTS temperature for sintering time 30 and 60 min.

The density of SrFe₁₂O₁₉ decreases with an increase in the RTS time at 1300 °C (Fig. 2a) and increases with the RTS temperature (Fig. 2b). It can be seen from Fig. 2 that the optimum RTS mode for SrFe₁₂O₁₉ is 1250–1300 °C for 30–60 min.

The decrease in the polycrystal density for RTS beginning from a certain time seems to be accounted for by the fact that, upon reaching the optimum density of the material, the energy of fast electrons starts to exert the contrary impact, i.e., lattice degradation, making the polycrystal structure looser [11–14].

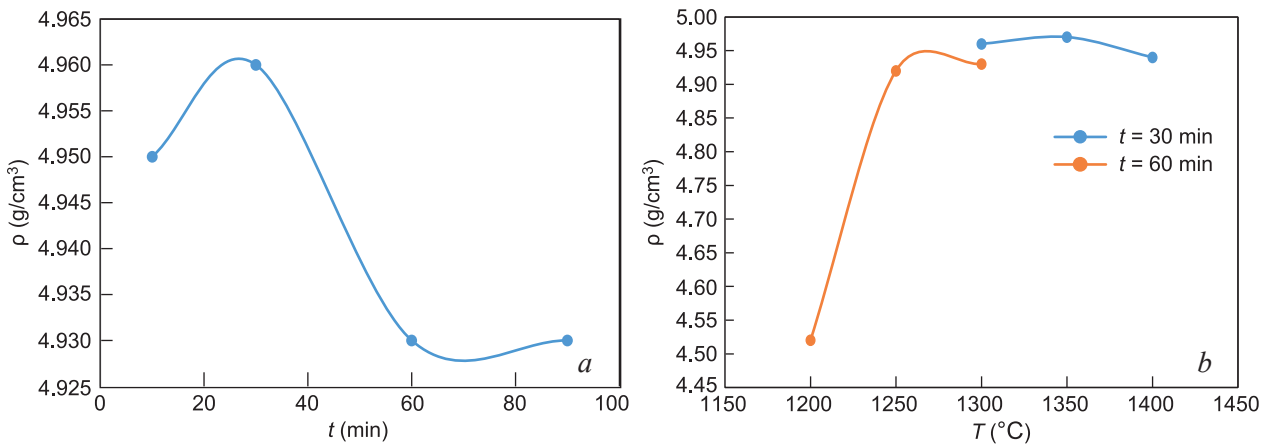
Figure 3 shows magnetic hysteresis loops for the specimens synthesized with 60 min RTS.

Figure 4 shows magnetic hysteresis loops for the specimens synthesized with RTS at 1300 °C for different time.

It can be seen from Figs. 3 and 4 that the intensity and width of the magnetic hysteresis loops decrease with an increase in the sintering temperature and time.

Figure 5 shows specific saturation magnetization σ_s and specific remanent magnetization of the RTS SrFe₁₂O₁₉ specimens as a function of (a and b) RTS temperature for 60 min sintering time and (c and d) sintering time for 1300 °C RTS temperature. Figures 6–9 show coercive force jH_c , magnetic anisotropy field H_k , magnetic hysteresis loop area S_{loop} , and magnetic hysteresis loop rectangularity, respectively, as a function of RTS temperature and time.

As can be seen from Figs. 5–9, the magnetic hysteresis parameters of the SrFe₁₂O₁₉ specimens change in a similar manner during RTS with an increase in the RTS

**Figure 2.** SrFe₁₂O₁₉ hexaferrite specimen density as a function of (a) RTS time at 1300 °C and (b) RTS temperature

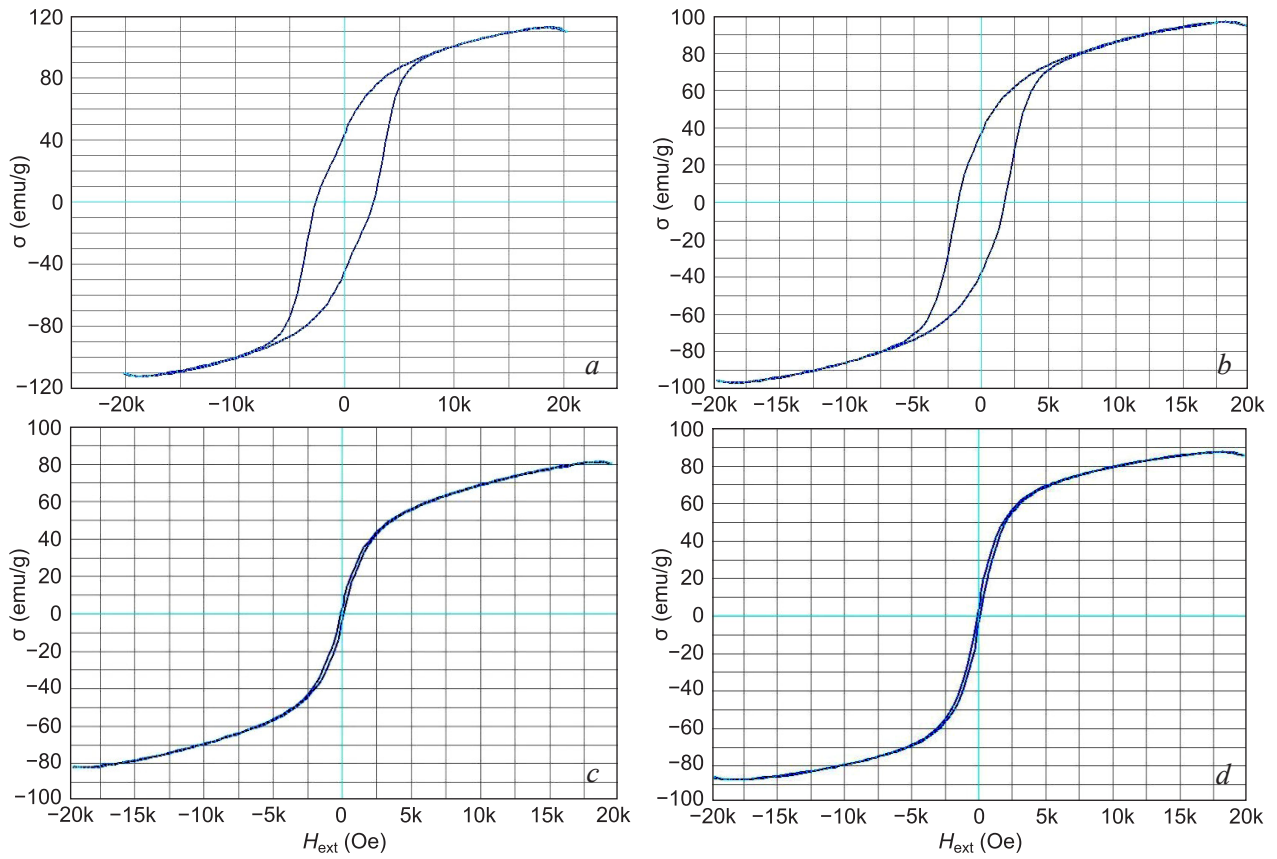


Figure 3. Magnetic hysteresis loops for polycrystalline $\text{SrFe}_{12}\text{O}_{19}$ hexagonal isotropic ferrite specimens synthesized using RTS at different temperatures: (a) 1200 °C, (b) 1250 °C, (c) 1300 °C, and (d) 1400 °C. Sintering time 60 min.

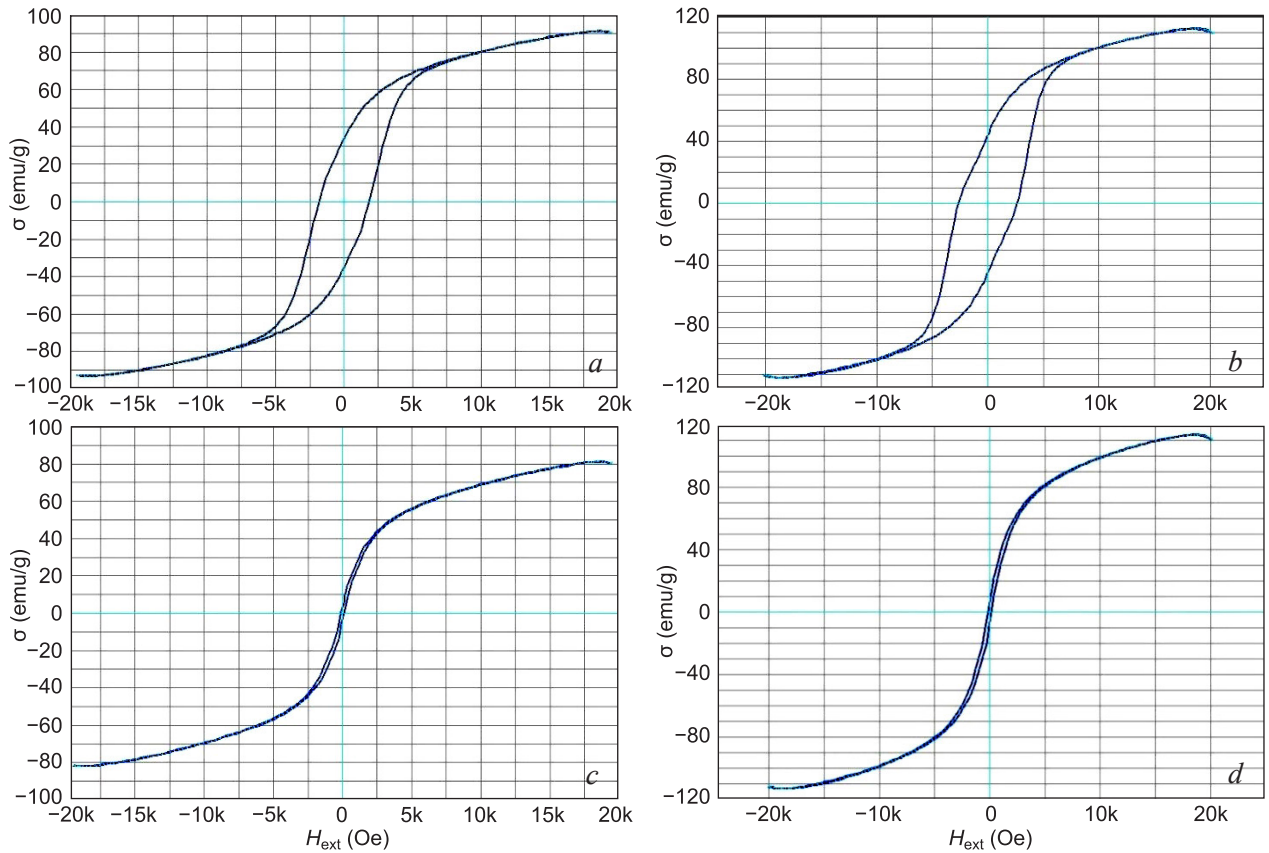


Figure 4. Magnetic hysteresis loops for polycrystalline $\text{SrFe}_{12}\text{O}_{19}$ hexagonal isotropic ferrite specimens synthesized using RTS at different time: (a) 10 min, (b) 30 min, (c) 60 min, and (d) 90 min. Sintering temperature 1300 °C

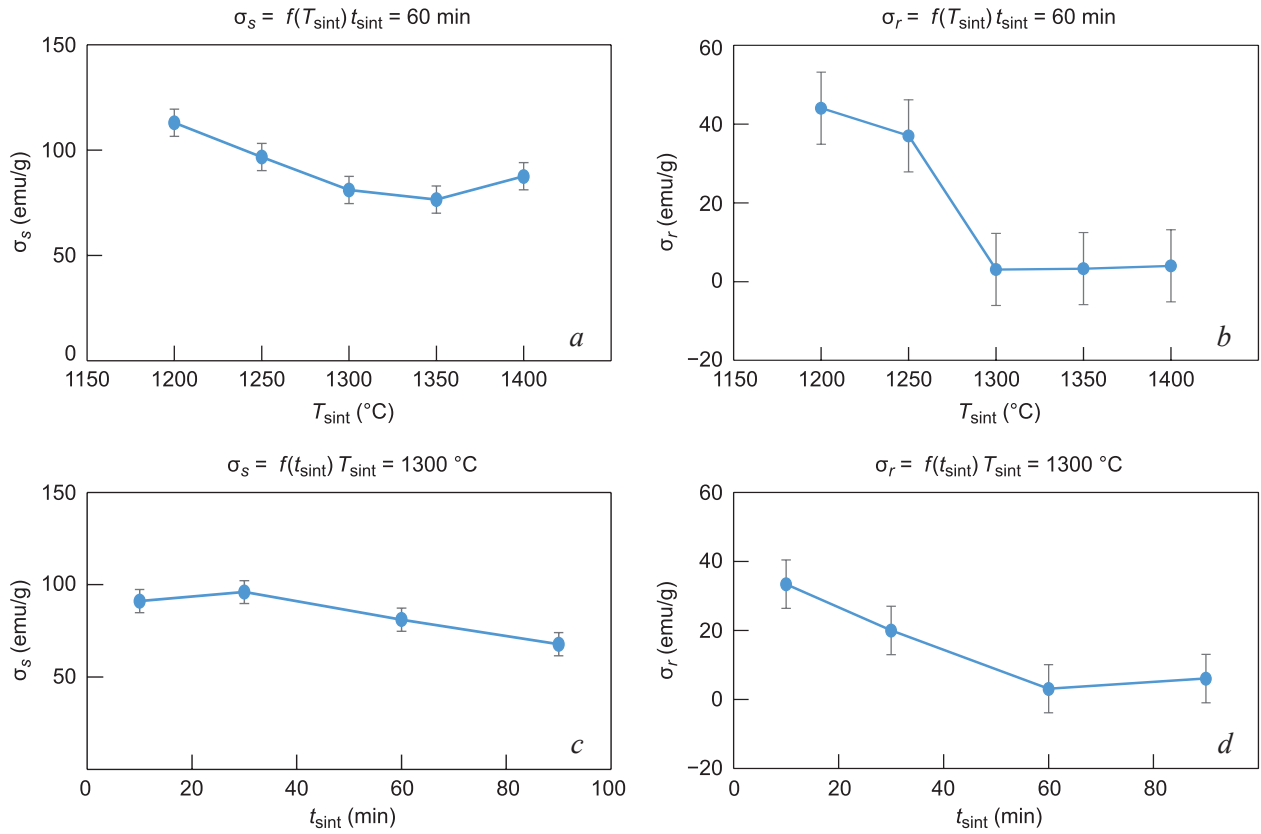


Figure 5. (a and c) Specific saturation magnetization σ_s and (b and d) specific remanent magnetization of RTS $\text{SrFe}_{12}\text{O}_{19}$ specimens as a function of (a and b) RTS temperature and (c and d) RTS time

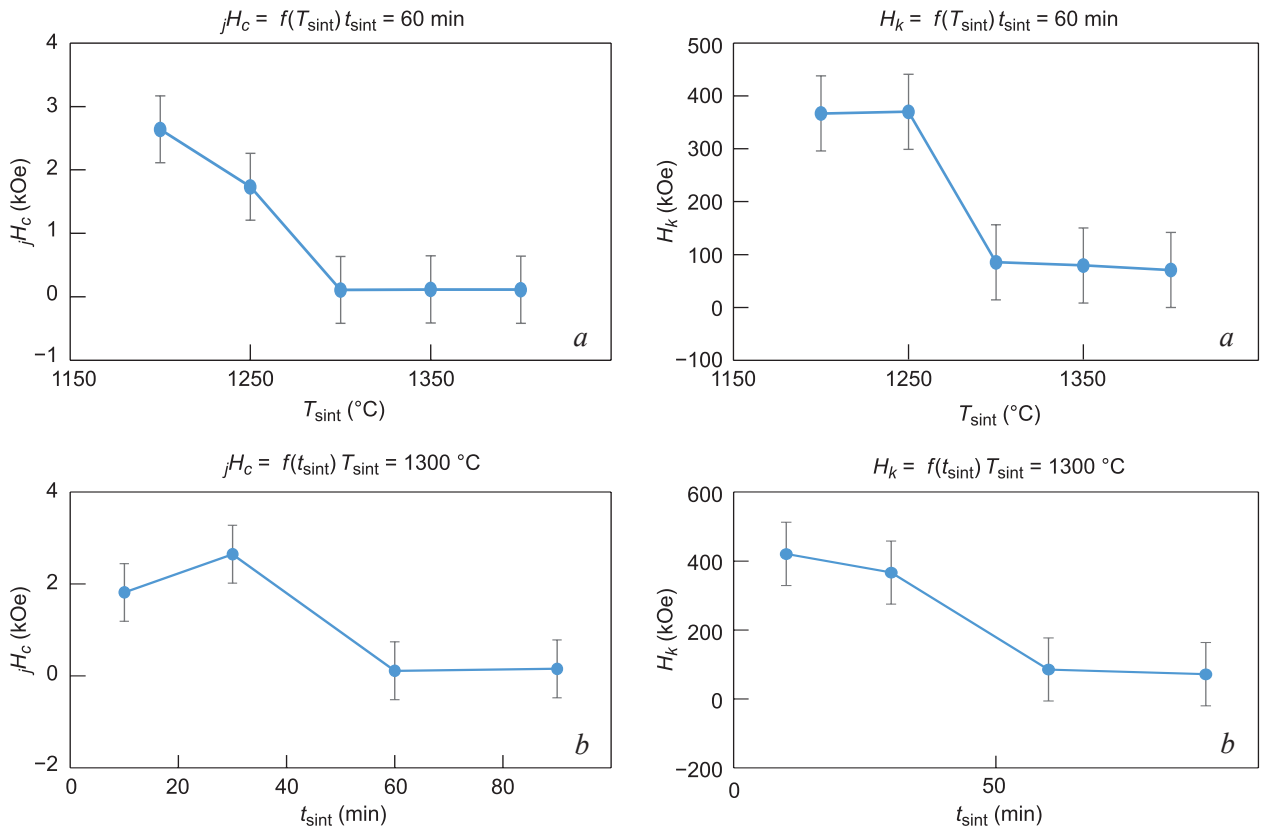


Figure 6. Magnetization coercive force of $\text{SrFe}_{12}\text{O}_{19}$ specimens as a function of (a) RTS temperature and (b) RTS time

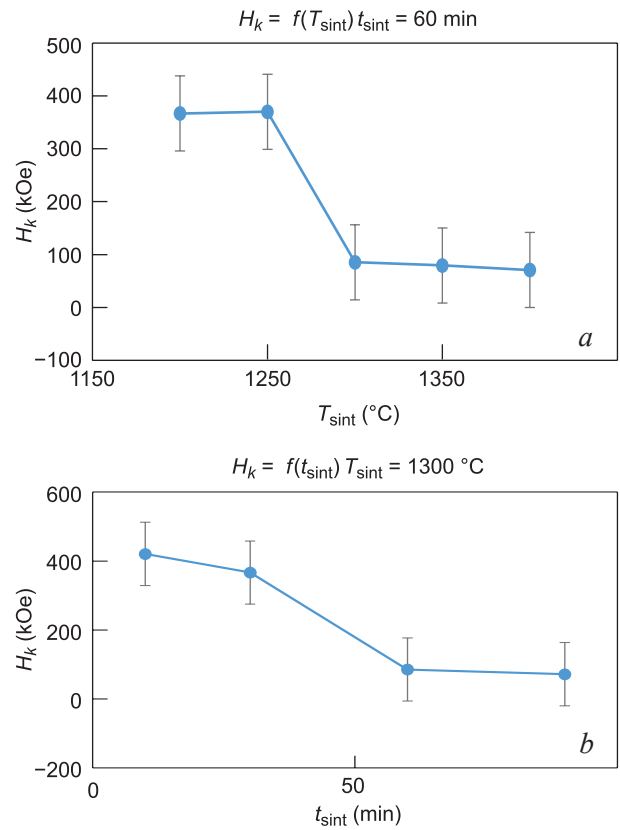


Figure 7. Magnetic anisotropy of $\text{SrFe}_{12}\text{O}_{19}$ specimens as a function of (a) RTS temperature and (b) RTS time

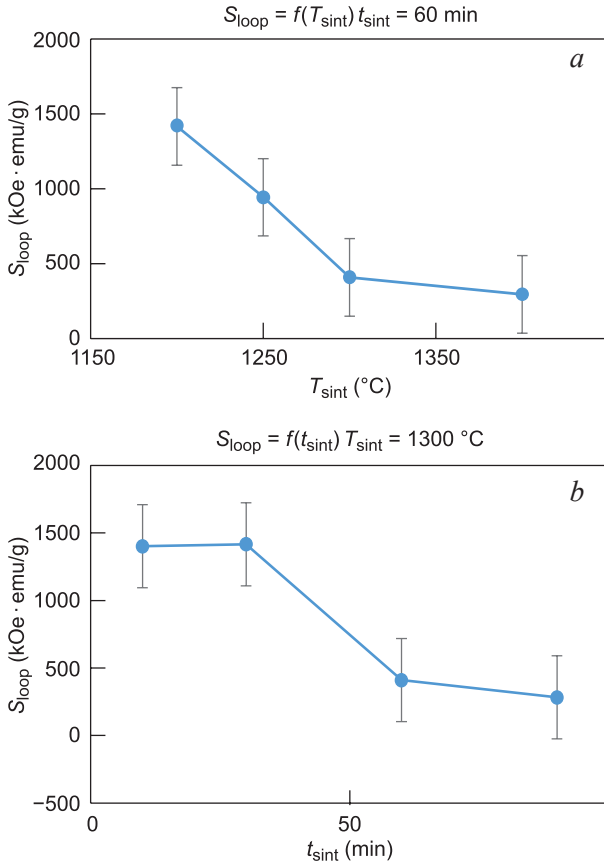


Figure 8. Magnetic energy (magnetic hysteresis loop area) of $\text{SrFe}_{12}\text{O}_{19}$ specimens as a function of (a) RTS temperature and (b) RTS time

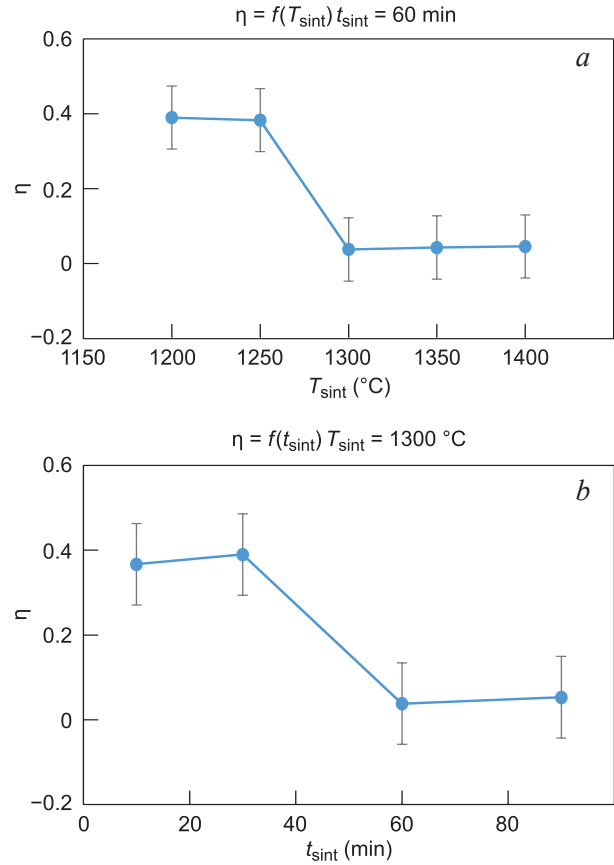


Figure 9. Magnetic hysteresis loop rectangularity coefficient of $\text{SrFe}_{12}\text{O}_{19}$ specimens as a function of (a) RTS temperature and (b) RTS time

temperature and time. RTS temperature determines the shape and parameters of the hysteresis loop. With an increase in the RTS temperature and time, all magnetic hysteresis loop parameters of the test specimens decline in comparison with their parameters for the lowest RTS temperature and shortest time.

The RTS temperature growing from 1200 to 1350–1400 $^{\circ}\text{C}$ (sintering time 60 min), the specific saturation magnetization σ_s declines by 32 %; the RTS time increasing from 10 to 90 min (sintering temperature 1300 $^{\circ}\text{C}$), σ_s drops by 29.5 %. The specific remanent magnetization σ_r for the same RTS modes drops by 93 and 91 %, respectively; the magnetization coercive force H_c declines by 96 % in both cases; the magnetic field anisotropy H_k decreases by 81 and 82 %, respectively; the magnetic energy (magnetic hysteresis loop area) drops by 79 and 80 %, respectively; the magnetic hysteresis loop rectangularity coefficient drops by 88 and 90 %, respectively. Similar changes, though less intense, were observed [15] for RTS-synthesized hexagonal $\text{BaFe}_{12}\text{O}_{19}$ ferrites.

It was shown that the RTS technology allows ferrite sintering in several decades of minutes. The predominant factor was the RTS temperature, differing for each type of ceramics. The physical mechanism of ceramic sintering process acceleration by fast electrons is not yet clear [16–23]. Most researchers believe that the predominant

mechanism of radiation acceleration of mass transport in ferrite ceramics is surface recombination. Irradiation of ceramics billets induces electron excitation in grains and powder compacts. Excited electrons tend to localize at grain boundaries and recombine, releasing energy. This results in the formation of temperature gradients, causing thermal diffusion flows which significantly accelerate solid state reactions of ferrite synthesis.

The results reported herein show that, for the RTS modes used, the highest $\text{SrFe}_{12}\text{O}_{19}$ hexaferrite density was obtained for sintering temperature $T_{\text{sint}} = 1200\div1300 ^{\circ}\text{C}$ and sintering time $t_{\text{sint}} = 60 \text{ min}$, and at sintering temperature $T_{\text{sint}} = 1300\div1400 ^{\circ}\text{C}$ and sintering time $t_{\text{sint}} = 30 \text{ min}$. However, at RTS temperature $\geq 1350 ^{\circ}\text{C}$, even for a sintering time of 30 min, the magnetization drops by 30 % and the coercive force, by 96 %. Thus, strontium hexaferrite, in fact, becomes low-magnetization and low-coercive force hexaferrite, i.e., a magnetically soft material. This material cannot be used for the fabrication of high-quality permanent magnets. The problem of its applications in other conventional application domains of hexagonal ferrites requires further study. The experiments carried out in this work showed that the existing RTS process modes for polycrystalline $\text{SrFe}_{12}\text{O}_{19}$ require improvement. Yet it is obvious that the RTS temperature should be within 1250–1300 $^{\circ}\text{C}$.

The abrupt decline of JH_c at RTS temperatures of above $\geq 1250^\circ\text{C}$ can be accounted for by recrystallization in the material. Elevated RTS temperatures cause intense grain growth. The overall quantity of domain boundaries decreases abruptly, also leading to a significant decrease in the coercive force [24].

Conclusion

Changes in the parameters of magnetic hysteresis loop parameters in hexagonal $\text{SrFe}_{12}\text{O}_{19}$, strontium ferrite synthesized using fast electron beam RTS were studied for the first time.

The high energy efficiency of RTS technology of ferrite ceramics was confirmed for the example of *M*-type hexagonal strontium ferrite.

We showed that the RTS modes tested are not suitable for the synthesis of high-quality polycrystalline $\text{SrFe}_{12}\text{O}_{19}$ hexaferrites and require improvement.

The significant decline of JH_c of the $\text{SrFe}_{12}\text{O}_{19}$ specimens at $T_{\text{sint}} \geq 1250^\circ\text{C}$ is accounted for by recrystallization and intense grain growth due to high temperatures and radiation-enhanced diffusion.

References

1. Letyuk L.M., Kostishin V.G., Gonchar A.V. Technology of ferrite materials for magnetoelectronics. Moscow: MISIS; 2005. 352 p. (In Russ.)
2. Al'tman A.B., Gerber A.N., Gladyshev P.A., Gratsianov Yu.A., Zein E.N. Permanent magnets. Moscow: Ehnergiya; 1980. 488 p. (In Russ.)
3. Ustinov A., Kochemasov V., Khasyanova E. Ferrite materials for microwave electronics. selection prime criterions. *Electronics: Science, Technology, Business*. 2015;(8):86–92. (In Russ.). https://www.electronics.ru/files/article_pdf/4/article_4907_795.pdf
4. Shalaby M., Peccianti M., Ozturk Y., Morandotti R. A magnetic non-reciprocal isolator for broadband terahertz operation. *Nature Communications*. 2013; 4(1558): 1–7. <https://doi.org/10.1038/ncomms2572>
5. Pullar R. Hexagonal ferrites: A review of the synthesis, properties and applications of hexaferrite ceramics. *Progress in Materials Science*. 2012; 57(7): 1191–1334. <https://doi.org/10.1016/j.pmatsci.2012.04.001>
6. Harris V.G. Modern microwave ferrites. *IEEE Transactions on Magnetics*. 2012; 48(3): 1075–1104. <https://doi.org/10.1109/TMAG.2011.2180732>
7. Kostishin V., Isaev I., Shcherbakov S., Nalogin A., Belokon E., Bryazgin A. Obtaining anisotropic hexaferrites for the base layers of microstrip SHF devices by the radiation-thermal sintering. *Eastern-European Journal of Enterprise Technologies*. 2016; (83): 32–39. <https://doi.org/10.15587/1729-4061.2016.80070>
8. Kostishin V.G., Nalogin A.G., Shcherbakov S.V., Mezentsева M.P., Mikhaylenko M.A., Korobeinikov M.V., Salogub D.V., Bryazgin A.A. Magnetic properties of polycrystalline $\text{Y}_3\text{Fe}_5\text{O}_{12}$ obtained by the method of radiation-thermal sintering. *Proceedings of*

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Conflict of interests

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- the Southwest State University. Series: Engineering and Technology. 2018; 8(1(26)): 124–133. (In Russ.)
9. Vlasov V.A., Vasendina E.A., Galtseva O.V., Nikolaev E.V. The magnetic properties lithium-substituted ferrosphinel synthesis in the electron beam. *Modern Problems of Science and Education*. 2013; (5): 581. (In Russ.)
10. Auslender V.L., Bezuglov V.V., Bryazgin A.A., Voronin L.A., Gorbunov V.A., Korobeynikov M.V., Nekhaev V.E., Panfilov A.D., Podobayev V.S., Tkachenko V.O., Tuvik A.A., Faktorovich B.L. Pulse linear electron accelerators of the ilu series produced by the Budker Institute of Nuclear Physics. *Vestnik Novosibirskogo gosudarstvennogo universiteta. Seriya: Fizika*. 2006; 2(1): 89–96. (In Russ.)
11. Lysenko E.N., Surzhikov A.P., Vlasov V.A., Nikolaev E.V., Malyshov A.V., Bryazgin A.A., Korobeynikov M.V., Mikhailenko M.A. Synthesis of substituted lithium ferrites under the pulsed and continuous electron beam heating. *Nuclear Instruments & Methods in Physics Research Section B-beam Interactions with Materials and Atoms*. 2017; 392: 1–7. <https://doi.org/10.1016/j.nimb.2016.11.042>
12. Surzhikov A.P., Pritulov A.M., Lysenko E.N., Vlasov V.A., Vasendina E.A. Kinetic analysis of radiation-thermal synthesis of lithium-zinc ferrites. *Modern Problems of Science and Education*. 2012; (3): 412. (In Russ.)
13. Surzhikov A.P., Pritulov A.M., Lysenko E.N., Galtseva O.V., Sokolovsky A.N., Vlasov V.A., Vasendina E.A. Study of the synthesis of lithium ferrites by thermoanalysis. In: *Proceed. of the XIX Inter. conf. meeting "Radiation Physics of Solids": Sevastopol', August 31 – September 5, 2009*. Moscow: NII PMT; 2009. P. 193–199. (In Russ.)

14. Surzhikov A.P., Sokolovskiy A.N., Vlasov V.A., Vasendina E.A. Synthesis of lithium-zinc ferrite in bunch of accelerated electrons. *Rare Metals*. 2009; 28: 418–420. <https://doi.org/10.1109/IF-OST.2012.6357503>
15. Isaev I.M. Radiation-thermal sintering in a beam of fast electrons of polycrystalline hexagonal ferrites $\text{BaFe}_{12}\text{O}_{19}$ and $\text{BaFe}_{12-x}(\text{Al}, \text{Ni}, \text{Ti}, \text{Mn})_x\text{O}_{19}$ for permanent magnets and substrates of microstrip devices of microwave electronics. Summ. Diss. ... Cand. Sci. (Eng). Moscow; 2017. 30 p. (In Russ.)
16. Annenkov Yu.M., Ivashutenko A.S. Physical model of sintering and modification of ceramics in high-frequency and ultra-high-frequency fields. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*. 2005; 308(7): 30–36. (In Russ.)
17. Surzhikov A.P., Lysenko E.N., Malyshev A.V., Petrova A., Ghyn-gazov S.A., Aimukhanov A.K. Phase transformations in ferrites during radiation-thermal sintering. *Eurasian Physical Technical Journal*. 2020; 17(1(33)): 26–34. <https://doi.org/10.31489/2020No1/26-344>
18. Sary O., Malyshev A.V., Lysenko E.N., Petrova A. Formation of magnetic properties of ferrites during radiation-thermal sintering. *Eurasian Journal of Physics and Technology*. 2020; 17(2(34)): 6–10. <https://doi.org/10.31489/2020No2/6-10>
19. Komlev A.S. Physical model of radiation-thermal technology for producing ferrite ceramics. *Tavricheskii nauchnyi obozrevatel*. 2016; (12(17)). (In Russ.)
20. Malyshev A.V., Lysenko E.N., Sheveleva E.A., Surzhikova O.A., Aringazin A.K. Relationship between magnetic properties and microstructure of ferrites during sintering in radiation and radiation-thermal conditions. *Materials Science*. 2021; (3): 3–7. <https://doi.org/10.31489/2021No1/3-8>
21. Sary O., Surzhikov A.P., Malyshev A.V., Lysenko E.N., Sheveleva E.A. Effect of normalizing heating of ferrite copacts on compaction during radiation-thermal sintering. *Eurasian Physical Technical Journal*. 2021; 18(3(37)): 11–14. <https://doi.org/10.31489/2021No3/11-14>
22. Surzhikov A.P., Malyshev A.V., Lysenko E.N., Sary O. Temperature dependences of initial permeability of lithium-titanium ferrites produced by solid-state sintering in thermal and radiation-thermal modes. *Materials Science*. 2022; (5): 5–9. <https://doi.org/10.31489/2022No1/5-9>
23. Lysenko E.N. Obtaining and shaping the properties of lithium-group ferrites under high-energy mechanical and electron-beam effects. Summ. Diss. ... Dr. Sci. (Eng.). Tomsk; 2019. 44 p. (In Russ.)
24. Gorelik S.S., Babich E.A., and Letyuk L.M. Formation of the microstructure and properties of ferrites during recrystallization. Moscow: Metallurgiya; 1984. 111 p. (In Russ.)