

THERMAL STABILITY OF THE MAGNETIC PARAMETERS OF ANISOTROPIC AND ISOTROPIC STRONTIUM FERRITE MAGNETS

¹Vojtěch KRMELA, ¹Kamila HRABOVSKÁ, ¹Lucie GEMBALOVÁ, ²Dalibor MATÝSEK,
¹Ondřej ŽIVOTSKÝ

¹VSB - Technical University of Ostrava, Department of Physics, Ostrava, Czech Republic, EU,
vojtech.krmela.st@vsb.cz, kamila.hrabovska@vsb.cz, lucie.gembalova@vsb.cz, ondrej.zivotsky@vsb.cz

²VSB - Technical University of Ostrava, Faculty of Mining and Geology, Ostrava, Czech Republic, EU,
dalibor.matysek@vsb.cz

<https://doi.org/10.37904/metal.2026.5299>

Abstract

The study focuses on a comprehensive analysis of the structure and thermal stability of the magnetic parameters of two commercial ring-shaped strontium ferrite magnets, for which the manufacturing conditions were unknown. Structural characterization was carried out using powder X-ray diffraction (XRD) and scanning electron microscopy (SEM) with EDX analysis. XRD confirmed the magnetoplumbite-type structure $\text{SrFe}_{12}\text{O}_{19}$ in both samples. Evaluation of the March parameter revealed a pronounced preferential grain orientation in the (001) plane for the anisotropic sample, while the isotropic sample exhibited no significant texture.

Magnetic properties were determined from the J - H and B - H magnetization curves measured using the hysteregraph in the temperature range of 25-190 °C. Anisotropic sample exhibited a rectangular magnetization curve with a remanence-to-saturation ratio of 0.951-0.923, which decreased only by a few hundredths with increasing temperature. In the isotropic sample, this ratio was lower (0.663–0.649), and the corresponding curves displayed a significantly more rounded shape. With increasing temperature, both samples showed a linear decrease in remanent induction, saturation polarization, and the maximum energy product BH_{max} (Pearson correlation coefficient ≈ 0.99). The slope of the remanent induction decrease was $-1.178 \text{ mT} \cdot \text{K}^{-1}$ for anisotropic and approximately $-0.423 \text{ mT} \cdot \text{K}^{-1}$ for isotropic sample. A similar trend was observed for saturation polarization and BH_{max} . In contrast, the coercive field H_{cJ} increased linearly, with slopes of $0.908 \text{ kA} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for anisotropic and $0.735 \text{ kA} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for isotropic sample. The Curie temperature of both samples was determined to be approximately 450 °C. The results confirm higher remanent induction and energy product values for the anisotropic ferrite; however, these are accompanied by a more pronounced temperature dependence of the magnetic parameters.

Keywords: Ferrites, hysteregraph, crystal structure, magnetization curve, March parameter

1. INTRODUCTION

Strontium ferrite magnets are the most widely used permanent magnets due to their favourable magnetic properties, low price and simple manufacturing process. They are ferrimagnetic materials produced by powder metallurgy. Base materials are Fe_2O_3 and SrO . They are milled together and subsequently calcinated to create magnetoplumbite structure responsible for their magnetic behaviour. The calcinated powder is then milled again, homogenized and pressed into shape. A strong magnetic field may be applied during pressing to induce magnetic anisotropy. The next step is sintering in controlled atmosphere. Finally, the magnets can be ground and cut to meet application requirements. These magnets are typically used in electromotors, generators, hard drives, reproducers or general home use [1-5].

Quality control is an essential part of every manufacturing process, as numerous variables can influence the final product. The effects of these variables, as well as the overall quality of the process, can be assessed through the structural and magnetic properties of magnets. Samples investigated in this study were ring-shaped magnets (see insets of **Figure 1**) with undisclosed manufacturing process. It is demonstrated in detail how differences in the structure of ferrite magnets influence magnetic anisotropy and high-temperature magnetic characteristics. Structural characterization was performed using Bruker D8 Advance diffractometer for X-ray powder diffraction (XRD) and an FEI Quanta 650 FEG for scanning electron microscopy (SEM) equipped with energy dispersive X-ray analysis (EDAX). Magnetic properties were examined in the temperature range from 25 °C to 190 °C, in 25 °C increments, using Brockhaus hystergaph HG 200 with heated poles [5-7].

2. STRUCTURAL ANALYSIS

Samples are referred to as anisotropic and isotropic due to results discussed in this part. Elemental composition and surface topography were examined using SEM/EDAX analysis. The weight percentages of the identified elements, along with their approximate oxide compositions, are listed in **Table 1**. The results confirmed that both samples are made from iron and strontium oxides. EDAX analysis also revealed trace amounts of manganese, calcium and aluminium. Aluminum originated from the sample holder, while Mn and Ca are common constituents in ferrite manufacturing. Their concentrations were low and therefore these elements were excluded from **Table 1** for clarity. Weight percentages of elements and corresponding oxides were approximately the same for both samples.

Table 1 EDAX element and oxide composition with estimated uncertainty 3-5 %

Anisotropic sample				Isotropic sample			
Element	wt%	Oxide	wt%	Element	wt%	Oxide	wt%
Fe	60.4	Fe ₂ O ₃	87.3	Fe	64.3	Fe ₂ O ₃	88.9
Sr	7.8	SrO	10.8	Sr	7.1	SrO	9.2
O	30.6			O	27.4		

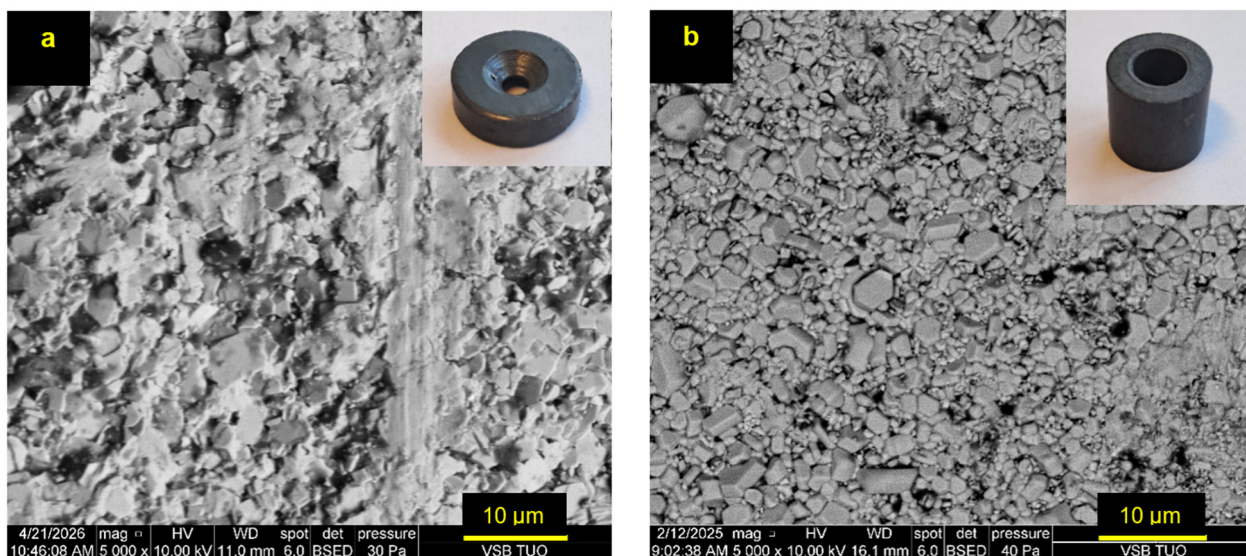


Figure 1 SEM images of ferrite surfaces, a) anisotropic sample, b) isotropic sample

Figure 1 shows the surface topography of the samples at 5000× magnification. **Figure 1a** corresponds to the anisotropic sample, whose surface was ground; as a result, individual grains are poorly resolved. In contrast, the surface of the isotropic sample was not machined, and the grains are therefore clearly visible (**Figure 1b**). The grains in the isotropic sample are randomly oriented, whereas those in the anisotropic sample exhibit a preferred orientation within the grinding plane.

XRD was the key measurement that enabled differentiation between the samples due to their distinct grain orientation. XRD spectra were analyzed by Rietveld analysis (**Table 2**). Both samples exhibited only one phase corresponding with magnetoplumbite structure of $\text{SrFe}_{12}\text{O}_{19}$ modelled in **Figure 2 (left subplot)**. The crystallite sizes were also similar, approximately 125.4 nm for the anisotropic sample and 100.1 nm for the isotropic one. However, the diffractograms (**right subplots of Figure 2**) show a clear difference caused by preferred grain orientation along the (0 0 1) direction in the anisotropic sample. In Rietveld refinement, preferred orientation is quantified by the March parameter, which ranges from 1 (random orientation) to 0 (complete alignment). The anisotropic sample exhibited March parameter of 0.382 in the (0 0 1) direction, indicating very strong preferred orientation. Isotropic sample showed a completely random grain orientation with March parameter of 1 [8,9].

Table 2 XRD results from Rietveld analysis

	Phase	W_{Rit} (%)	Lattice	a (nm)	c (nm)	d (nm)	r (-)
Anisotropic sample	$\text{SrFe}_{12}\text{O}_{19}$	100	P63/mmc	0.587	2.304	125.4	0.382
Isotropic sample	$\text{SrFe}_{12}\text{O}_{19}$	100	P63/mmc	0.587	2.306	100.1	1

* W_{Rit} – weight percent from Rietveld analysis, a , c – lattice parameters, d – crystallite size, r – March parameter

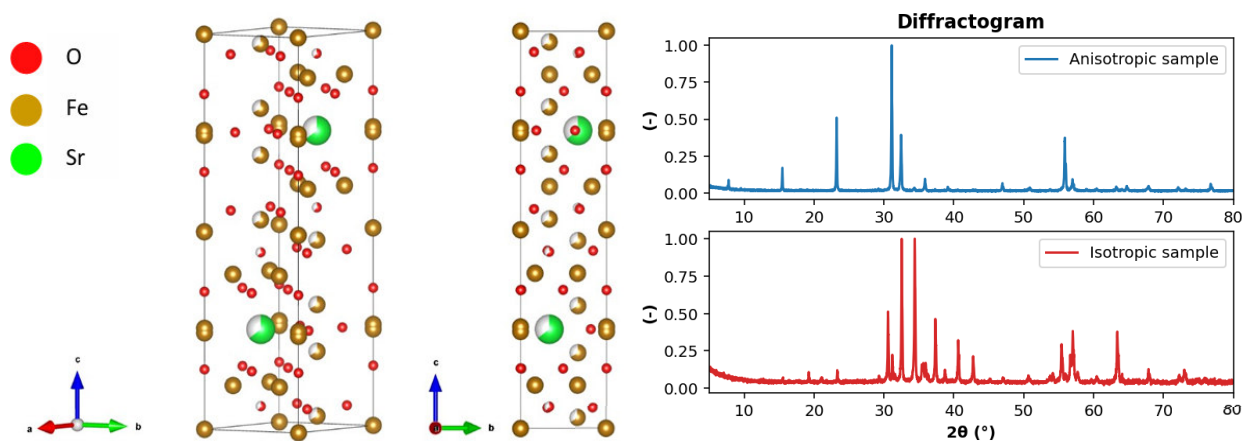


Figure 2 Model of $\text{SrFe}_{12}\text{O}_{19}$ structure [10] and measured diffractograms of the ferrite samples

3. MAGNETIC PROPERTIES

J - H and B - H loops were measured in the temperature range from 25 °C to 190 °C using a Brockhaus HG200 hystergaph. The second quadrants of these loops are plotted in **Figure 3**. The anisotropic sample exhibits significantly more rectangular loops than the isotropic one, which is a consequence of preferred grain orientation. Loop rectangularity is supported by the ratio between remanence and saturation polarization. For the anisotropic sample, this ratio remained around 0.94 across the temperature range, whereas for the isotropic sample it was approximately 0.66.

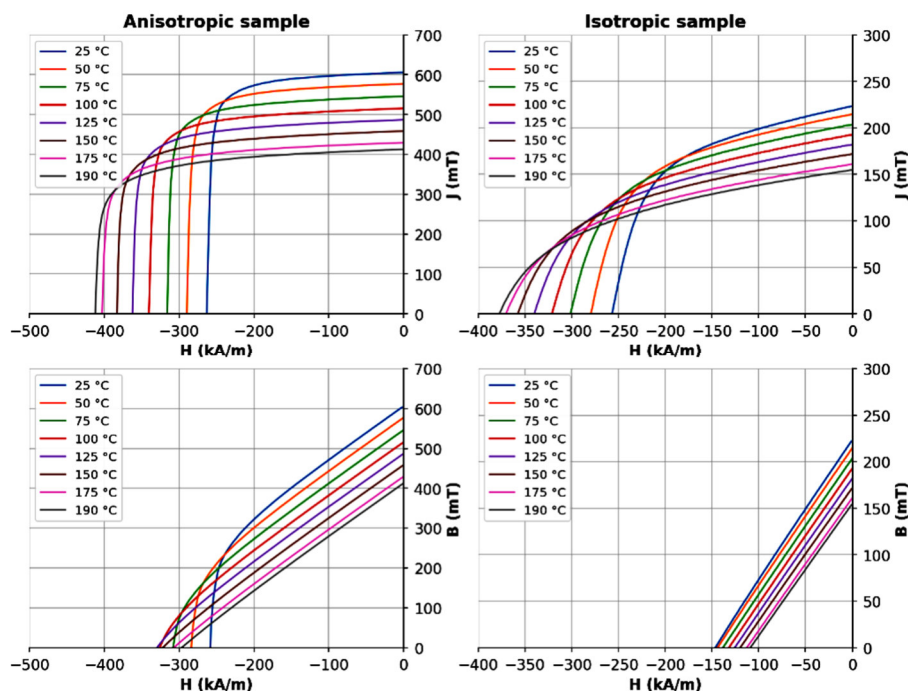


Figure 3 Second quadrants of J - H and B - H loops

The main magnetic parameters used to characterize the permanent magnets are saturation polarization J_s , remanence induction (polarization) B_r (J_r), maximum energy product $BH_{\max}$, and coercive field H_{cJ} . Their dependences on the temperature are shown in **Figure 4**. Values of all mentioned parameters were significantly higher in the anisotropic sample compared to the isotropic one. Additional thermomagnetic measurements performed using a vibrating sample magnetometer (VSM EZ9 Microsense) revealed that the Curie temperatures of both magnets are identical and are approximately 450 °C.

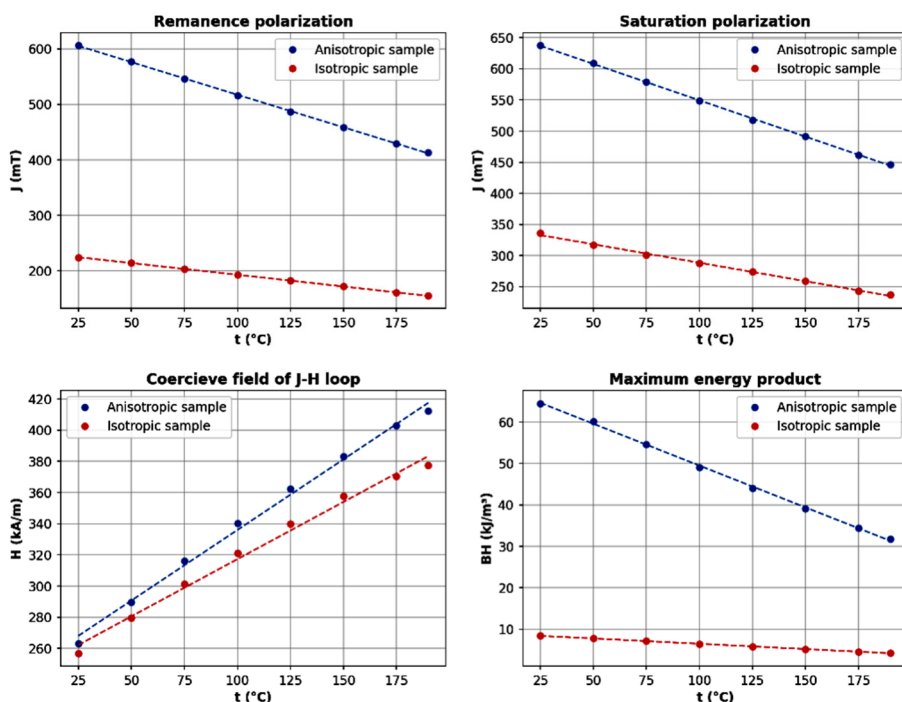


Figure 4 Change of magnetic parameters with increasing temperature

On the other hand, the thermal stability of these parameters appears to be higher for the isotropic sample. The data shown in **Figure 4** were approximated by linear regression, and the corresponding slopes are summarized in **Table 3**, indicating larger changes in the parameters with increasing temperature for the anisotropic sample. The linear regression yielded a very good fit, with a Pearson correlation coefficient close to 0.99. As generally expected, the saturation polarization, remanent polarization, and maximum energy product exhibited an approximately linear decrease with increasing temperature. Interestingly, the coercive field showed an approximately linear increase over the investigated temperature range. This behaviour suggests an increased resistance to demagnetization with rising temperature in this range. It should be noted, however, that this trend is expected to reverse at higher temperatures; the hysteresis measurements do not extend to a sufficiently high temperature range (above 200 °C) to capture this effect.

Table 3 Linear regression slopes of magnetic parameters

	k_{Jr} (mT·K ⁻¹)	k_{Js} (mT·K ⁻¹)	k_{HcJ} (kA·m ⁻¹ ·K ⁻¹)	k_{BH} (kJ·m ⁻³ ·K ⁻¹)
Anisotropic sample	-1.178	-1.165	0.908	-0.203
Isotropic sample	-0.423	-0.591	0.735	-0.024

4. CONCLUSION

Strontium ferrites are widely used permanent magnets that offer sufficient magnetic performance for low-cost applications. Their magnetic properties are strongly dependent on the microstructure of the magnet. Results of this study confirm that inducing magnetic anisotropy in ferrite magnets is highly beneficial, as it enhances remanent polarization, saturation polarization, maximum energy product, and coercive field. However, these improvements are accompanied by reduced thermal stability. It is shown that the magnetic parameters of anisotropic ferrites vary linearly with increasing temperature up to 190 °C and are more sensitive to temperature changes. Therefore, the choice of specific applications for anisotropic and isotropic ferrite magnets is determined by the required magnetic performance and the conditions in which the magnet operates.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Environment under the project CZ.10.03.01/00/22_003/0000045 (CirkArena) and by the Ministry of Education, Youth and Sports under the project SP2026/022

REFERENCES

- [1] HARRIS, Vincent G. (ed.). *Modern Ferrites, Volume 1: Basic principles, processing and properties*. Hoboken: John Wiley & Sons, 2022.
- [2] HARRIS, Vincent G. (ed.). *Modern Ferrites, Volume 2: Emerging technologies and applications*. Hoboken: John Wiley & Sons, 2022.
- [3] RAHMAN, Md Lutfor, et al. *Investigation of structural, morphological and magnetic properties of nanostructured strontium hexaferrite through co-precipitation technique: Impacts of annealing temperature and Fe/Sr ratio*. *Heliyon*, 2023, vol. 9, no. 3, e14532.
- [4] LIAO, Yan, et al. A comprehensive investigation into the structural, thermal, and magnetic properties of terbium- and cobalt-codoped strontium hexaferrite SrFe₁₂O₁₉. *Physica B: Condensed Matter*, 2026, vol. 735, 418691.
- [5] GOLDMAN, Alex. *Modern ferrite technology*. 2nd ed. New York: Springer, 2006.
- [6] TRECHA, Vojtěch. *Study of structural and magnetic properties of Heusler alloys based on Mn*. Ostrava, 2023. Bachelor thesis. VSB – Technical University of Ostrava.

- [7] CHOVANCOVÁ, Ludmila. *Methods for evaluation of the structure of magnetically soft ferrite by scanning electron microscopy*. Ostrava, 2023. Bachelor thesis. VSB – Technical University of Ostrava.
- [8] ZOLOTAYABKO, Emil. *Determination of the degree of preferred orientation within the March–Dollase approach*. *Journal of Applied Crystallography*, 2009, vol. 42, no.3, pp. 513-518.
- [9] LI, Taotao, et al. *Determining the preferred orientation of silver-plating via X-ray diffraction profile*. *Nanomaterials*, 2021, vol. 11, no. 9, 2417.
- [10] MOMMA, Koichi, IZUMI, Fujio. *VESTA 3 for three-dimensional visualization of crystal, volumetric and morphology data*. *Journal of Applied Crystallography*, 2011, vol. 44, no. 6, pp. 1272-1276.