

Experimental study of the transport properties of Nd-Fe-B and Sm-Co magnets

Dmitrii Samoshkin*, and Alibek Agazhanov

Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences,
630090 Novosibirsk, Russia

Abstract. The article adduces new reliable experimental data on the thermal conductivity and the thermal diffusivity of hard magnetic materials of brands N35M, N35H, N35SH, as well as YX18, YX24 and YXG22, YXG30 with main components represented by the crystalline phases of $\text{Nd}_2\text{Fe}_{14}\text{B}$, SmCo_5 and $\text{Sm}_2\text{Co}_{17}$ type, respectively. The temperature range from 293 to 773...1273 K has been investigated by laser flash technique with an error of 3–4%. The reference tables of the thermal diffusivity and thermal conductivity coefficients have been developed. The character of the thermal diffusivity changes near the Curie point has been determined. The critical indices and the critical amplitudes have been defined.

1 Introduction

It is hard to imagine modern technology without the use of powerful permanent magnets. Work on the creation of new hard magnetic materials with unique properties is continuously carried out. Alloys based on rare-earth metals (REM), including REM alloys with 3d-transition metals, are one of the most interesting and promising classes of magnetic materials. Modern permanent magnets based on Nd-Fe-B and Sm-Co compounds have to date the highest characteristics, such as coercive force, residual magnetic induction and maximum magnetic product. However, information about the properties of materials, used for the production of advanced permanent magnets, is very limited. The information on magnetic characteristics in technically important intervals of state variables is often given in the literature, but there are practically no reliable data on the thermophysical properties of magnetic materials, including on transport properties. In this regard the aim of the present work was to conduct an experimental study of heat transfer coefficients, such as thermal conductivity and thermal diffusivity, of some magnetic compounds of Nd-Fe-B and Sm-Co systems in a wide temperature range of a solid state, including the region of the magnetic phase transition.

2 Experimental technique

Thermal diffusivity (a) of magnets was measured by the laser flash method on an automated experimental setup LFA-427 [1] according to the technique described in [2, 3].

* Corresponding author: d.a.samoshkin@gmail.com

Measurements were carried out on samples of hard magnetic materials of brands N35M, N35H, N35SH, as well as YX18, YX24 and YXG22, YXG30 containing the crystalline phases of $\text{Nd}_2\text{Fe}_{14}\text{B}$, SmCo_5 and $\text{Sm}_2\text{Co}_{17}$ type, respectively, as a main component. The technology of their manufacture is described in [4] and their technical characteristics are listed in [5, 6]. According to the information provided by the manufacturer the samples of magnets based on Nd-Fe-B compounds have the following chemical structure, namely Fe ~ 71%, Nd ~ 24–27%, Dy ~ 0,5–2,5%, Co ~ 1% and B ~ 1%. According to the composition various brands differ in the content of dysprosium, which is 0,5, 1 and 2,5% for brands N35M, N35H and N35SH, respectively. From the viewpoint of the known properties, the specimens of different grades differ in the range of operating temperatures and the value of the coercive force. For the studied compounds we have that the more dysprosium is in the sample, the higher the coercive force and the upper limit of the permitted temperature interval are. For the magnets of Sm-Co system according to the manufacturer's data [6] the samples of various brands differ in the value of the maximum magnetic product, and from the point of view of chemistry the differences are due to small additions of Pr, Fe, Cu and Zr. The samples had the shape of a disc with a diameter of 12,6 mm and thickness of 2 mm with plane-polished ends.

Experiments were performed in the temperature interval of 293–773...1273 K in a high-purity argon atmosphere (99,992 vol. %). Before the experiments the working volume of the unit was evacuated to a vacuum of 1 Pa and several times washed with argon. The lower side of the sample was heated by a short (0,8 ms) pulse with energy up to 4 J from a Nd:YAG laser. Temperature changes of the upper sample side were recorded with an IR detector based on InSb, which was cooled with liquid nitrogen. Measurements were made at a constant temperature after long-term thermostating of samples in a series of three "shots". The time interval between "shots" was 5 min. Calculation of the thermal diffusivity coefficient was implemented taking into account the heat losses from all surfaces of the sample according to the model [7]. Corrections to the finite duration of the laser pulse and its real shape were introduced [8]. The estimated error of the obtained data, confirmed by experiments with standard inconel and pyroceram samples and well-studied transition *d* metals (nickel, cobalt and iron), was 3–4%.

3 Results and discussion

The experimental data for thermal diffusivity of magnet of brand N35M obtained in different thermal cycles are shown in Figure 1. It can be seen that the results of three heatings are almost completely reproduced and do not depend on the magnitude of residual magnetization. Before the experiments the magnetic field on the surface of the samples was 126–177 mT and 139–157 mT for Nd-Fe-B and Sm-Co systems, respectively. The samples were completely demagnetized at heating above the region of the Curie temperature (T_C), which is shown in Fig. 1 as a sharp minimum. Similar measurements were made for all the magnets, during which it was established, that for each magnet the results of all the heatings are fully reproduced between each other. This indicates that the magnetization does not affect or has a minimal effect on the thermal diffusivity. The measurement results of thermal diffusivity for all grades of the magnetic systems studied in this work are shown in Figure 2.

In the region of the magnetic phase transition the description of the results was carried out according to the scaling theory [9]. A detailed procedure for finding the critical index (α) and critical amplitude (A) of the thermal diffusivity by scaling theory is described in our earlier work [3]. The calculated α and A values for the ferromagnetic and paramagnetic regions, as well as the experimental values of T_C for all studied hard magnetic materials of Nd-Fe-B and Sm-Co systems are presented in Table 1.

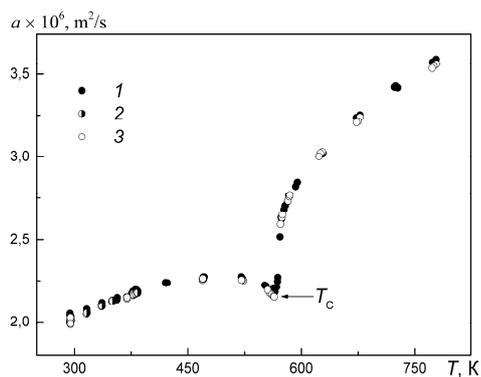


Fig. 1. Thermal diffusivity of Nd-Fe-B magnet of brand N35M: 1 – 1-st heating, 2 – 2-nd heating, 3 – 3-rd heating.

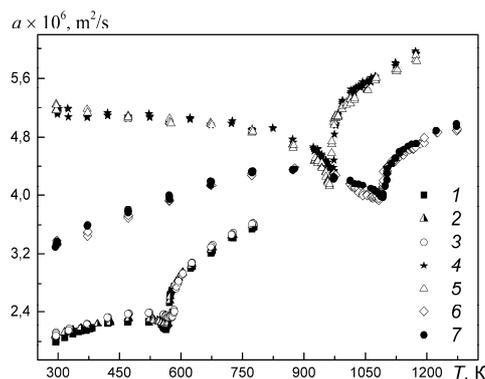


Fig. 2. Comparison of the thermal diffusivity experimental results: 1 – N35M, 2 – N35H, 3 – N35SH, 4 – YX18, 5 – YX24, 6 – YXG22, 7 – YXG30.

It was found that the thermal diffusivity of magnets of the Nd-Fe-B system has a more complex behavior than for magnets of the Sm-Co system in the critical region above the Curie temperature. Therefore, the critical region above the T_C for the magnets N35M, N35H and N35SH was divided into two parts, for each of which the critical indices and critical amplitudes were determined. It was also found that the critical index of the thermal diffusivity takes a positive value, significantly exceeds in absolute value the classical critical index of the heat capacity and has different values in the ferromagnetic and paramagnetic regions.

Table 1. Critical indices and critical amplitudes of Nd-Fe-B and Sm-Co magnets.

Magnets	T_C , K	$T < T_C$		$T > T_C$			
		α'	A'	α_1	α_2	A_1	A_2
N35M	564	1,06	6,192	2,31	0,26	6634,204	1,278
N35H	568	0,98	3,162	1,65	0,25	536,458	1,175
N35SH	578	1,30	8,712	2,72	0,22	23709,569	0,991
YX18	973	0,95	9,492	–	0,30	–	3,023
YX24	962	0,81	6,596	–	0,27	–	2,527
YXG22	1083	0,94	3,517	–	0,48	–	2,466
N35SH	1093	0,79	2,692	–	0,54	–	3,226

With allowance for our data on density ρ [10] and heat capacity C_p [11], and also the known relation $\lambda = a \rho C_p$, we calculated the values of thermal conductivity λ of investigated magnets. The a and λ recommended values of hard magnetic materials of brands N35M, N35H, N35SH, YX18, YX24, YXG22 and YXG30 are presented in Table 2 and Table 3.

Table 2. Recommended values of thermal diffusivity and thermal conductivity of Nd-Fe-B magnets.

T, K	N35M		N35H		N35SH	
	$a, 10^{-6} \text{ m}^2/\text{s}$	$\lambda, \text{ W}/(\text{m K})$	$a, 10^{-6} \text{ m}^2/\text{s}$	$\lambda, \text{ W}/(\text{m K})$	$a, 10^{-6} \text{ m}^2/\text{s}$	$\lambda, \text{ W}/(\text{m K})$
300	2,02	5,2	2,09	5,4	2,11	5,4
350	2,12	5,8	2,17	6,0	2,20	6,1
400	2,20	6,5	2,24	6,7	2,29	6,8
450	2,26	7,2	2,30	7,4	2,36	7,6
500	2,26	7,8	2,31	8,1	2,39	8,4
550	2,20	8,3	2,26	8,7	2,37	9,0
600	2,84	10,4	2,85	9,4	2,80	9,5
650	3,12	10,0	3,18	10,1	3,21	10,3
700	3,34	10,6	3,41	10,8	3,47	11,1
750	3,49	11,1	3,54	11,4	3,54	11,6
800	3,57	–	3,57	–	3,58	–

Table 3. Recommended values of thermal diffusivity and thermal conductivity of Sm-Co magnets.

T, K	YX18		YX24		YXG22		YXG30	
	$a, 10^{-6} \text{ m}^2/\text{s}$	$\lambda, \text{ W}/(\text{m K})$	$a, 10^{-6} \text{ m}^2/\text{s}$	$\lambda, \text{ W}/(\text{m K})$	$a, 10^{-6} \text{ m}^2/\text{s}$	$\lambda, \text{ W}/(\text{m K})$	$a, 10^{-6} \text{ m}^2/\text{s}$	$\lambda, \text{ W}/(\text{m K})$
300	5,15	16,1	5,19	14,2	3,33	9,7	3,36	10,4
350	5,13	16,4	5,18	14,5	3,45	10,4	3,50	11,2
400	5,11	16,6	5,15	14,7	3,57	11,2	3,62	11,9
450	5,09	16,9	5,13	15,0	3,68	11,9	3,74	12,7
500	5,07	17,4	5,09	15,2	3,79	12,6	3,85	13,5
550	5,05	17,9	5,06	15,3	3,89	13,4	3,95	14,3
600	5,03	18,4	5,01	15,4	3,98	14,1	4,04	15,1
650	5,00	18,8	4,97	15,5	4,07	14,9	4,12	15,8
700	4,97	19,3	4,91	15,6	4,15	15,6	4,19	16,6
750	4,95	19,6	4,86	15,6	4,22	16,4	4,26	17,4
800	4,91	19,8	4,80	15,6	4,29	17,1	4,31	18,2
850	4,88	19,9	4,73	15,6	4,35	17,9	4,35	18,9
900	4,85	20,2	4,66	16,1	4,41	18,6	4,39	19,6
950	4,48	20,1	4,30	15,3	4,28	18,3	4,28	19,6
1000	5,41	19,0	5,33	14,4	4,16	18,6	4,21	20,3
1050	5,54	19,1	5,44	14,1	4,03	19,7	4,11	21,4
1100	5,71	19,5	5,62	14,3	4,28	18,7	4,20	18,8
1150	5,87	–	5,80	14,5	4,65	19,5	4,72	20,8
1200	6,04	–	5,98	–	4,82	19,9	4,85	21,2
1250	–	–	–	–	4,87	20,1	4,93	21,5
1300	–	–	–	–	4,92	–	5,01	–

4 Conclusion

For the first time, it has become possible to obtain new reliable experimental data on the thermal diffusivity and thermal conductivity of hard magnetic materials of brands N35M, N35H, N35SH, as well as YX18, YX24 and YXG22, YXG30 containing the crystalline phases of $\text{Nd}_2\text{Fe}_{14}\text{B}$, SmCo_5 and $\text{Sm}_2\text{Co}_{17}$ type, respectively, as a main component. The measurements were made by laser flash technique with an error of 3–4% in the temperature interval from 293 to 773...1273 K. Tables of the reference data on the thermal diffusivity and thermal conductivity coefficients have been developed. The character of the thermal diffusivity changes in the region near the Curie point has been determined. It has been found that the critical index of the thermal diffusivity takes a positive value, significantly exceeds in absolute value the classical critical index of the heat capacity and has different values in the ferromagnetic and paramagnetic areas. It was shown that the presence of the constant magnetic field did not lead to changes in the thermal diffusivity of investigated materials.

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