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STUDY OF REVERSIBILITY OF COERCIVITY UNDER HEAT TREATMENT IN PERMANENT MAGNETS

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Abstract. This article is aimed at observation all discussion and results that have ever been found about the phenomenon of reversibility of coercivity under heat treatments in permanent magnets including the latest researches. Despite the fundamental differences in the nature of coercivity as sensitive to structure property and magnetization reversal processes all works illustrate no changes in structure under heat treatment that causes doubts about this phenomenon.

Introduction

The phenomenon of reversibility of coercivity under heat treatments in permanent magnets have known for a long time. Short time heating of the magnets at a high temperature after the complete technological cycle leads to a sharp reduction of magnetic properties, especially the coercivity. Low-temperature aging reverses alloys to initial magnetic properties. Analysis of previous investigations and additional experiments show that reversibility of coercivity is characteristic of almost all magnets. This phenomenon occurs in almost all alloys for permanent magnets, despite the fundamental differences in the nature of coercivity as sensitive to structure property and magnetization reversal processes. Present work based on studies of changes and the reversibility of magnetic properties under different heat treatments attempted to explain this phenomenon in different magnetic alloys.

Comparative study of reversibility of coercivity

Reversibility of coercivity of the permanent magnets under heat treatments discovered in current research and previous works remains unclear and ambiguous because of many issues of this phenomenon at present. In current research, the results of studies and literature data describe the samples of alloys obtained from industrial enterprises using a standard, common technology, and the measurements were performed with standard equipment.

Table 1 Reversibility of coercivity under heat treatments in permanent magnets

Year	Material	Hc optimal кA/m(kOe)	Hc spoiling кA/m (kOe)	Hc reconditioning кA/m (kOe)	Source
1964	Alnico	48 (0.6)	32 (0.4)	48 (0.6)	[1]
1973	Ticonal	116 (1.45)	36 (0.45)	116 (1.45)	[2]
1975	$SmCo_5$	1840 (23.0)	1240 (15.0)	1840 (23.0)	[3]
1979	Sm-Co-Cu-Fe-Zr	1120 (14.0)	720 (9.0)	1120 (14.0)	[4]
2014	$Sm(Co_{0.65}Fe_{0.26}Cu_{0.07}Zr_{0.02})_7$	2360 (29.5)	96 (1.2)	2360 (29.5)	[5]
2014	$Nd_2Fe_{14}B$ (1050°C)	1520 (19.0)	1190 (14.9)	1520 (19.0)	[6]
2016	$Nd_2Fe_{14}B$ (1000°C)	1740 (21.8)	1247 (15.7)	1662 (20.9)	present research
2015	$Nd_2Fe_{14}B$ (900 °C)	1740 (21.8)	1340 (16.9)	1740 (21.8)	[7]
2017	$Nd_2Fe_{14}B$ (800 °C)	1740 (21.8)	1367 (17.2)	1740 (21.8)	present research
2017	$Nd_2Fe_{14}B$ (700 °C)	1740 (21.8)	1332 (16.7)	1740 (21.8)	present research
2017	FeCrCo	44 (0.55)	2.0 (0.025)	44 (0.55)	present research

Table summarizes data for a reversible change of the coercivity of the magnets under heat treatments obtained on the various alloys with reference to authors (the coercivity in the initial condition – “Hc optimal”, after high-temperature heating of the initial state – “Hc spoiling” and after the low temperature aging – “Hc reconditioning”).

This table shows only values of the coercivity on the magnetization as this property is sensitive to structure and determined by the mechanism of magnetization reversal. High temperature range that leads to reduction of properties (‘spoiling’) and low temperature aging that reverses initial properties (‘reconditioning’) are described in details later. The essential point is the reversible changes of the coercivity, as the structure of the alloy is not changed reversibly by heat treatment. The aim of the present work is to analyse studies of magnetization reversal processes in real permanent magnets for the possibility of further improvement of technology.

The analysis starts with the system Fe-Co-Ni-Al-Ti (Alnico and ticonal), in which the coercivity is determined by the rotation process of the magnetization vector in the elongated single-domain particles of the ferromagnetic phase. Heating of the samples with coercivity 116 kA/m (1.45 kOe) at a temperature of 800 °C for 1-3 minutes causes it to reduce to 36 kA/m (0.45 kOe). Aging at 650 °C within 5 hours and 560 °C in 24 hours reverse of coercivity to the initial value.

In this case, the reversible changes $_IH_C$ were about 70 % connected with reversible local change in the composition of α_1 and α_2 – phases and possible atomic ordering in one of the phases [2], so the quantitative changes are not explained only by the composition changes. However, in these studies it is ignored the fact of changes in magnetostatic interaction between particles that is related to changes of the magnetic moment connected with changes in the composition of the phases.

In the magnets of system Fe-Co-Cr coercivity is also associated with the rotation process of the magnetization vector in single-domain particles. The coercivity after the full treatment cycle – 620 °C 45 minutes TMT (Thermomagnetic Tempering) and step aging 610 °C in 2 hours, 580 °C in 3 hours, 560 °C in 4 hours and 540 °C in 6 hours) is 44.9 kA/m. The "spoiling" (620 °C for 15 minutes) reduces the coercivity to 0.6 kA/m. Step aging reverse the coercivity to 43.7 kA/m. Reversibility of 95 % of coercivity is not able to be explained by local changes of structure. Even accounting for the extended partition of particles, which is observed in these alloys does not eliminate the problem of understanding the phenomenon. These results were obtained for the first time and there was no a detailed study of the influence of temperature and duration of the "spoiling", but the result deserves attention.

In sintered magnets based on $SmCo_5$ and Nd-Fe-B coercivity is determined by the difficulty of nucleation in highly anisotropic phase. In [3] a sintered permanent magnet $SmCo_5$ with the coercivity 1840 kA/m (23.0 kOe) was heated to a temperature 700 °C for 1 minute that reduced the coercivity to 1240 kA/m (15.0 kOe). Aging at 400 °C for 60 minutes reverses the value of the coercivity. Reversible changes was about 30 %.

In [6] “spoiling” sintered magnets Nd-Fe-B of different composition at high temperature 1050 °C within 30 minutes was performed, and then spent the cooling at 500 °C for 1 hour. Reversible changes of the coercivity were about 30 %.

In [7] and in subsequent studies, experiments of ‘spoiling’ were performed at temperatures of 1000, 900, 800 and 700 °C. Aging at 500 °C for 1 hour reversed the value of the coercivity to the initial. Reversible changes of the coercivity were about 30%.

It is difficult to explain the reversibility of changes of structural properties in single-phase materials. In several papers it is assumed that the process of aging at 500 °C makes grain boundaries smooth which leads to increase of coercivity. However, it is difficult to suppose explanation of the phenomenon of reversibility. There is hypothesis that excess phases occur transformation at the boundary of cell phase [8].

The most interesting results and discussions are related to the reversibility of coercivity that exists in system of Sm-Co-Fe-Cu-Zr, in which the coercivity is determined by pinning of domain walls at the boundaries of cells phase 2:17. The boundary cells similar to phase 1:5 [9]. In [5] a study of the "spoiling" at a temperature of 800 °C within 16 hours at which the structure of the alloy is formed, followed by controlled cooling from 400 °C to 800 °C for 4 hours. Heating of the samples with coercivity of 2360 kA/m (29.5 kOe) for 5 minutes reduces the coercivity to 96 kA/m (1.2 kOe). Controlled cooling reverses coercivity and a reversible change is 95 % or almost 30-fold change compared to the state with zero coercivity. It is important to mention that there are no changes in value of reversal coercivity with increasing aging time at 800 °C up to 22 hours.

In [9-11] detailed chemical analysis was performed with using 3D atom probe of the boundary-phase 1:5 in the state after rapid cooling from 800 °C and after controlled cooling. It is shown that on the border there is a redistribution of Cu and Zr, and changes the nature of the distribution of the components. In [11] the calculation of the distribution constants of anisotropy in the phase boundary takes into account the changing nature of the distribution of the components. However, the question how the changing nature of distribution of the constants of anisotropy can affect multiple changes in the coercivity is not solved.

As can be seen from the listed examples of reversible changes of the coercivity under heat treatments, many questions are related not only to the formation of the alloy structure, but also to the nature of coercivity and magnetization reversal processes.

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