Journal of Magnetism and Magnetic Materials 411 (2016) 1–6

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Relation between the alignment dependence of coercive force decrease ratio and the angular dependence of coercive force of ferrite magnets

Yutaka Matsuura [a,*], Nobuyuki Kitai [b], Seiichi Hosokawa [b], Jun Hoshijima [b]

[a] Osaka Prefecture University, 1-1 Gakuencho, Nakaku, Sakai, Osaka 599-8266, Japan
[b] Hitachi Metals Ltd., Magnetic Materials Company, 2-15-17 Egawa, Shimamotocho, Mishimagun, Osaka 618-0013, Japan

ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form
30 January 2016
Accepted 2 March 2016
Available online 3 March 2016

Keywords:
Ferrite magnets
Coercive force
Alignment
Coercive force mechanism

ABSTRACT

The relation of the coercive force decrease ratio (CFDR) and the angular dependence of the coercive force (ADCF) of ferrite magnets and their temperature properties were investigated.

When we compared that against the angle of the magnetization reverse area obtained from these calculation results, which was obtained from the Gaussian distribution of the grain alignment and the postulation that every grain follows the Kondorskii law or the $1/\cos\theta$ law, and against the angle of the reverse magnetization area calculated from the experiment CFDR data of these magnets, it was found that this latter expanded at room temperature, to 36° from the calculated angle, for magnet with $\alpha=0.96$. It was also found that, as temperature increased from room temperature to 413 K, the angle of the reverse magnetization area of ferrite magnets obtained from the experiment data expanded from 36° to 41°.

When we apply these results to the temperature properties of ADCF, it seems that the calculated ADCF could qualitatively and reasonably explain these temperature properties, even though the difference between the calculated angular dependence and the experimental data still exists in the high angle range.

These results strongly suggest that the coercive force of these magnets is determined by the magnetic domain wall motion. The magnetic domain walls are strongly pinned at tilted grains, and when the domain walls are de-pinned from their pinning sites, the coercive force is determined.

1. Introduction

Ferrite magnets such as Sr ferrite and Ba ferrite are used in a wide range of applications such as automobile motors and electric appliance motors. Recently, the magnetic properties of ferrite magnets have been improved with La–Co and Ca–La ferrites magnets [1–3]. It was also reported that the coercive force of these magnets improves the temperature properties of the coercive force compared with conventional Sr-ferrite magnets.

In regards to ferrite magnets, the microstructure and coercive force mechanism are not clear compared with NdFeB sintered magnets.

With NdFeB sintered magnets, the coercive force is determined by coherent rotation [4] or by the magnetic domain wall caused from nucleus of the reverse magnetization nucleated under thermal fluctuation in the weak anisotropy area near the grain boundary [5].

To check the validity of these theories, the angular dependence of the coercive force (ADCF) at room temperature was used for the discussion of the coercive force mechanism, but there are no discussions as to its temperature dependence.

But, a recent study of grain boundaries of NdFeB sintered magnets using an atom probe showed that the grain boundaries contain more Fe than what we considered before and are of ferromagnetic phase in terms of their compositions [6]. On the other hand, it seems that the study of the microstructure of ferrite magnets is insufficient compared with NdFeB sintered magnets. There are no reports of the grain boundary phase being similar to NdFeB sintered magnets. With ferrite magnets, the coercive force mechanism is also discussed using the coherent rotation model that is based on a magnetic anisotropy field of magnetoplumbite crystal structure, which is the basic crystal structure of ferrite magnets, and a demagnetization field that is generated by the grain shape of ferrite magnets [7,8].

In our previous paper [9,10,11], we reported that the coercive forces of NdFeB sintered magnets decrease as the alignment (α=Br/Js) of $Nd_2Fe_{14}B$ grains improves. Especially, coercive force

* Corresponding author.
E-mail address: monopole.matt.27010@gmail.com (Y. Matsuura).

http://dx.doi.org/10.1016/j.jmmm.2016.03.007
0304-8853/

decreases steeply in high alignment area ($\alpha > 0.95$). These phenomena are not limited to NdFeB sintered magnets, as we also detected and reported similar phenomena occurring even in ferrite magnets. To compare various grades of coercive force for magnets, we also defined the coercive force decrease ratio (CFDR) [9,10,11].

It was elucidated that the CFDR line extrapolated from highly aligned Nd(Dy)FeB sintered magnets, which have alignments over 0.95, to a perfectly aligned magnet reaches −30% from that of isotropically oriented magnets. This results shows that the coercive force decreases as the alignment improves and decreases 30% from that of isotropically oriented magnets at the perfect aligned magnet. We also reported this phenomena is not limited in NdFeB sintered magnets. Even in ferrite magnets, CFDR has similar properties to NdDyFeB sintered magnets; we found that the coercive force of ferrite magnets also decreases as the alignment improves [10,11].

In our previous paper we pointed out that it would be difficult to explain our experiment results by the Stoner–Wohlfarth model, which shows that the coercive force increases as the alignment improves [10,11]. This result contradicts the experiment results. Instead, it can be qualitatively explained by the magnetic domain wall motion being governed by the $1/\cos\theta$ law or Kondorskii law [14], that the coercive force reaches $1/\sqrt{2}$ which is close to our experiment data [9,10,11].

These results strongly suggested that magnetic domain walls or the reverse magnetization grains already exist in NdFeB sintered magnets.

Micro-magnetics simulations on the "K" supercomputer, which was developed by Riken and Fujitsu, also supported our conclusions [10,11,12] and strongly support how the magnetization reversal process relates with the magnetic domain wall motion [15]. But even by the micro-magnetics simulations, it is still difficult to explain our experiment results that show that the coercive force steeply decreases in the highly aligned area ($\alpha > 0.95$). And, it is also difficult to explain that the coercive force decreases 30% from isotropically aligned magnets in a perfectly aligned magnet.

A comparison of the magnetic measurement results and the calculation results of the alignments and CFDR showed that alignments obtained from the calculation agreed well with the magnetic measurements. But, regarding CFDR, a big difference was found between the calculation results and the magnetic measurements [12,13].

We are considering that this difference in CFDR does not require the other mechanism as it comes from the postulation that each grain independently follows the $1/\cos\theta$ law.

The coercive force of aligned magnets obtained from experiments was closer to that of isotropically oriented magnets than our calculations, in a wide range of alignments [12].

In our previous paper [16,17], the temperature dependence of CFDR and ADCF of NdDyFeB sintered magnets were reported. We also pointed out the relation between the temperature properties of CFDR and ADCF of NdFeB sintered magnets and calculated the reverse magnetization area from the experiment data of CFDR. From the reverse magnetization area, which is obtained from the experiment data, it was found that the reverse magnetization area of the experiment data expanded from the calculation based on the Gaussian distribution of the alignment distribution and the Kondorskii law.

When these results are applied to the angular dependence of the coercive force, the experiment data for ADCF and its temperature dependence qualitatively and reasonably agree well with the calculation results [17].

These results strongly supported that the coercive force of aligned magnets can be reasonably explained when we postulate that, in aligned magnets, magnetic domain walls are pinned at tilted grains, and the coercive force is determined when the magnetic domain walls are de-pinned from these strong pinning sites at the tilted grains. This means that the domain walls jump through a number of grains when magnetic domain walls de-pin at the pinning sites. This mechanism could explain why the demagnetization curves of ferrite magnets and NdFeB sintered magnets have good rectangularity. It is also reasonably explained that the coercive forces of aligned magnets are close to those of an isotropically oriented magnet.

There are no reports on the temperature dependence of CFDR and on the relation between CFDR and ADCF in ferrite magnets. It is not clear whether ADCF could also be explained when applying this idea to ferrite magnets or not. The comparison of temperature properties of CFDR and ADCF of these magnets is interesting and reinforces our postulation of the coercive force mechanism.

In this paper, we report the relation between CFDR and ADCF and discuss the coercive force mechanism of ferrite magnets.

2. Experiment

$SrCO_3$ and Fe_2O_3 powders were weighed and mixed with water in the predetermined composition ($SrFe_{11.6}O_{19}$) by ball milling. Then, the mixtures were dried at 423 K in the air, then calcined at 1573 K. These calcined blocks were crushed and milled to about 0.8 μm using the ball milling with water. Then, the obtained slurry was injected into the cavities, and pressed into 0 T, 0.1 T and 1.87 T magnetic fields. A 0.85 grain alignment (α=0.85) was obtained using a 0.1 T magnetic field and a 0.96 grain alignment was obtained using a 1.87 T magnetic field. After pressing, magnets were sintered at 1473 K.

The alignment of these magnets was evaluated from the alignment distribution obtained by EBSD.

The coercive force was measured by permeameter. With ferrite magnets, the coercive force is defined by a magnetic field having a maximum value of (dI/dH), where dI is the magnetization change and dH means the change in magnetic field.

For elevated temperatures, a permeameter, which was installed in the magnetic circuit inside an oven, was used. Demagnetization was measured at room temperature, 333 K, 373 K, 413 K and 453 K.

We measured $H_{cJisotropic}$ for isotropically oriented magnets and H_{cJ} for aligned magnets at the same temperature which is shown in Fig. 1 and the difference of H_{cJ} and $H_{cJisotropic}$ was divided by $H_{cJisotropic}$.

Magnets with α=0.96 were also used for the angular

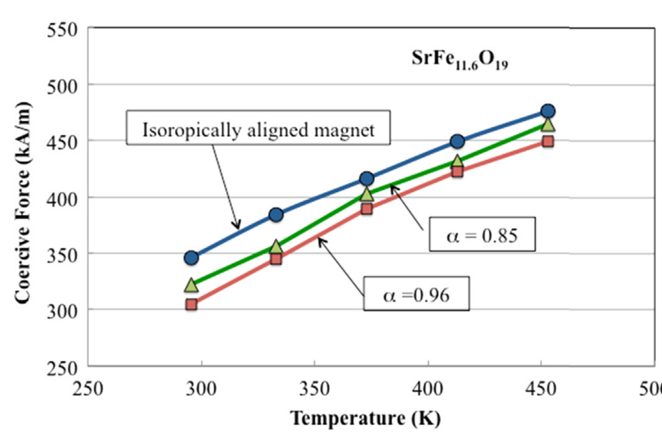

Fig. 1. Temperature dependence of coercive force of ferrite magnets of isotropically oriented ferrite magnets and oriented ferrite magnets with α=0.85 and α=0.96.