Origins of Radial and Axial Inhomogeneity of Magnetic Performance in Cylindrical Nd-Fe-B Magnet Prepared by Hot Deformation Postprint

Authors: Yin, WZ, Chen, RJ, Tang, X, Tang, X, Lee, D, Yan, A

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Abstract

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Full Text

Origins of Radial and Axial Inhomogeneity of Magnetic Performance in Cylindrical Nd-Fe-B Magnets Prepared by Hot Deformation

Wen-Zong Yin, Ren-Jie Chen, Xu Tang, Xin Tang, Don Lee, and Aru Yan
Key Laboratory of Magnetic Materials and Devices, Ningbo Institute of Material Technology and Engineering, Chinese Academy of Sciences, Zhenhai, Ningbo, Zhejiang 315201, P. R. China
Zhejiang Province Key Laboratory of Magnetic Materials and Application Technology, Ningbo Institute of Material Technology and Engineering, Chinese Academy of Sciences, Zhenhai, Ningbo, Zhejiang 315201, P. R. China

Cylindrical Nd-Fe-B magnets with different height reductions were prepared by hot deformation. The inhomogeneity of magnetic performance along the radial direction was revealed using a closed-circuit B-H apparatus, while axial inhomogeneity was characterized with a vibrating sample magnetometer. Microstructural examination via scanning electron microscopy suggests that orientation variation and grain coarsening of $Nd_2Fe_{14}B$ platelets cooperate to cause deterioration of remanence from the center to the edge along the radial direction. X-ray diffractometry performed over the end surfaces and axially across the

middle cross-section of the cylindrical magnet demonstrates the critical role of texture in determining remanence along the axial direction. Further investigations of intermediate hot-deformed magnets reveal uneven deformation degree in the axial direction during hot deformation, which accounts for the axial variation of texture and consequent remanence.

Index Terms–Hot deformation, inhomogeneity, Nd-Fe-B, texture.

I. Introduction

Hot-deformed (HD) Nd-Fe-B magnets exhibit excellent magnetic performance [?, ?], corrosion resistance [?, ?], and thermal stability [?]. Consequently, they have attracted increasing attention in both fundamental and applied research [?], with primary focus on ring-shaped and cylindrical HD magnets [?]. Today, ring-shaped HD magnets can be readily prepared by a specialized hot deformation technique known as backward extrusion. Detailed investigations have revealed that their magnetic performance is inhomogeneous along both axial and radial directions [?]. In the axial direction, remanence (B_r) increases monotonically from the top to bottom of the ring-shaped HD magnet while coercivity (H_{ci}) decreases simultaneously [?, ?]. In the radial direction, ring-shaped HD magnets display approximately linear enhancement of B_r from the outer to inner surface [?, ?].

For cylindrical HD magnets, Guruswamy et al. presented a theoretical investigation of deformation inhomogeneity via simulation using a finite-element-based software called "ANTARES" [?]. However, systematic experimental investigations of magnetic performance homogeneity in cylindrical HD magnets along either radial or axial directions have not been reported.

For metals and alloys with cylindrical geometry, material flow during plastic deformation is known to be uneven in the axial direction due to friction at both end surfaces in contact with punches [?]. Consequently, material flow at the axially middle cross-section is easier than at the end surfaces. As a ternary alloy, Nd-Fe-B can be deformed from a thin cylinder into a flat one at 650-850°C [?, ?]. The unevenness of material flow in Nd-Fe-B magnets during this deformation was merely mentioned in [?], and to the best of our knowledge, no further experimental investigation has been conducted.

In this paper, we demonstrate magnetic performance inhomogeneities in both axial and radial directions and reveal their origins in terms of microstructure and material flow during deformation.

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II. Experimental Work

Melt-spun powder (MQU-F) was purchased from Magnequench International, Inc. and used as raw material without any treatment. The powder was first compacted into a green body (ϕ 15 mm × 15 mm) under vacuum at 943 K and a pressure of 200 MPa. The green body was then deformed in a tungsten carbide (WC) die at 1113 K under argon atmosphere. Illustrations of the compaction and deformation processes were presented in [**?**]. HD magnets with height reductions (HR) of 28.1%, 53.2%, and 70% were prepared using WC dies with diameters of 15.3 mm, 19.0 mm, and 24 mm, denoted as HDM-1, HDM-2, and HDM-3, respectively.

Cylindrical samples (type-I) with dimensions of ϕ 3 mm × 3 mm were cut from the HD magnet with 70% HR, as shown in Fig. 1. The magnetic performance of type-I samples was measured along the easy direction (parallel to the pressing direction) using a closed-circuit B-H apparatus at room temperature. Samples were premagnetized with a DC pulse field of 29 kOe. Rectangular samples (type-II) with dimensions of 2 mm × 2 mm × 3 mm were cut from HD magnets with HR of 28.1% and 53.2%, as shown in Fig. 2. Their magnetic performance was measured along the easy axis using a Lakeshore 7400 vibrating sample magnetometer (VSM) in an applied field up to 23 kOe without demagnetization field correction.

Phase composition was identified using an X-ray diffractometer (XRD, Bruker AXS D8 Advance) with Cu Kα radiation. Microstructures were examined using a field emission scanning electron microscope (FE-SEM, Hitachi S-4800).

* * *

III. Results and Discussion

Table I presents the magnetic performance of type-I samples cut from different radial positions of HDM-3. Both remanence (B_r) and maximum energy product ($(BH)_{max}$) decrease from positions a to c, with maximum differences of about 0.53 kGs and 3.4 MGOe, respectively. However, coercivity (H_{ci}) first increases from 14.72 kOe at position a to 15.56 kOe at position b, then decreases to 15.08 kOe at position c. These results reveal that magnetic performance in cylindrical HD magnets is inhomogeneous along the radial direction, with higher B_r and $(BH)_{max}$ at the center than at the edge.

To understand the reasons for declining B_r along the radial direction, microstructures were examined via SEM on cross-sections of type-I samples. At position a, $Nd_2Fe_{14}B$ grains exhibit platelet shape with good alignment [Fig. 1(a)], with grain thickness of about 100–150 nm. At position b, some coarse grains appear while most retain platelet morphology [Fig. 1(b)]. At position c [Fig. 1(c)], the number of coarse grains increases remarkably, and importantly, the alignment orientation of $Nd_2Fe_{14}B$ grains differs from that at positions a and b. While grain coarsening was reported to be an important factor for crystal alignment decline in HD magnets [?], these results further reveal the key role of orientation variation in deteriorating crystal alignment and consequent magnetic performance.

Fig. 2 shows the magnetic performance of type-II samples cut from different axial positions of HDM-1 and HDM-2. Both magnets exhibit inhomogeneous magnetic performance along the axial direction. Specifically, B_r and $(BH)_{max}$ at positions 2 and 3 are much higher than at positions 1 and 4. For HR = 28.1% [Fig. 2(a)], the highest B_r and $(BH)_{max}$ are 10.4 kGs and 25.0 MGOe at position 3, while the lowest values are 9.1 kGs and 19.0 MGOe at position 1, representing differences of 1.3 kGs and 6.0 MGOe, respectively. For HR = 53.2% [Fig. 2(b)], the highest B_r and $(BH)_{max}$ increase to 13.0 kGs and 38.1 MGOe at position 3, while the lowest values are 10.2 kGs and 23.2 MGOe at position 1, with differences enlarged to 2.8 kGs and 14.9 MGOe, respectively. These results demonstrate that the axially middle region of cylindrical HD magnets exhibits higher B_r and $(BH)_{max}$ than both end regions.

Coercivity (H_{ci}) shows opposite variation with axial position at HR = 28.1%, with significantly lower values at positions 2 and 3 than at positions 1 and 4. However, at HR = 53.2%, H_{ci} decreases monotonically from 17.3 kOe at position 1 to 15.7 kOe at position 4. The reason for this phenomenon requires further investigation.

Since B_r of HD magnets is determined largely by texture, the texture of HDM-3 was evaluated using XRD over both end surfaces and the interface between samples 2 and 3. At the interface between samples 2 and 3, intensities of (004), (006), and (008) crystal planes are much higher than others, indicating good texture. Both end surfaces, however, exhibit weak texture. This substantial texture difference along the axial direction accounts for the axial inhomogeneity of magnetic performance in HD magnets.

To reveal the origins of texture variation along the axial direction, an intermediate HD magnet with HR = 53.2% was prepared using a WC die with 24 mm diameter (maximum HR = 70%). Fig. 4 shows a photograph and dimensions of this intermediate HD magnet. The intermediate magnet exhibits a barrel shape, with its axially middle region bulging outward [Fig. 4(a)]. Diameters vary along the axial direction [Fig. 4(b)], with the minimum diameter of 17.7 mm at the two end surfaces and the maximum diameter of 21.2 mm at the middle cross-section. The intermediate magnet thickness is 9.8 mm.

This barrel-like shape results from uneven plastic deformation of Nd-Fe-B alloy due to friction at both end surfaces in contact with punches [?]. Deformation degree (ϵ) can be evaluated in two ways. One method uses height reduction (HR) as follows [?]:

$$\epsilon = \ln \frac{h_0}{h}$$

where h_0 is the green body height before hot deformation and h is the HD magnet height. Alternatively, deformation degree can be calculated from the cross-sectional area of the cylindrical HD magnet:

$$\epsilon = \ln \frac{A}{A_0} = 2 \ln \frac{d}{d_0}$$

where d_0 and d are the diameters before and after hot deformation, and A_0 and A are the corresponding cross-sectional areas. Due to constant magnet volume before and after deformation, these two methods are equivalent for cylindrical HD magnets. However, for barrel-shaped intermediate HD magnets, only equation (2) is appropriate for evaluating deformation degree, while equation (1) merely provides an average deformation degree for the entire magnet.

For the as-prepared intermediate magnet, $h_0 = 15$ mm and $h = 9.8$ mm, giving $\epsilon = 53.2\%$ from equation (1). Nevertheless, ϵ is calculated to be 44.4% using equation (2) from the minimum diameter (17.7 mm) at the end surface and 61.2% from the maximum diameter (21.2 mm) at the middle cross-section. This difference in ϵ plays an important role in texture variation and consequent B_r along the axial direction.

Table II lists the magnetic performance of IM series samples (ϕ 3 mm × 3 mm) cut from different axial regions of the intermediate HD magnet (Fig. 5). The B_r of sample IM-2 (13.56 kGs) is much higher than that of IM-1 (10.92 kGs) and IM-3 (9.95 kGs), consistent with B_r variations in Fig. 2 and texture variations in Fig. 3, confirming the key role of ϵ in texture variation along the axial direction.

IV. Conclusion

Cylindrical HD magnets exhibit inhomogeneous magnetic performance in both radial and axial directions. Along the radial direction, B_r at position a is higher than at position c due to orientation variation and grain coarsening at the edge. In the axial direction, the HD magnet shows higher B_r in the axially middle region than near both end surfaces, which is ascribed to texture variation at different axial positions. Furthermore, such texture variation results from uneven deformation degree caused by friction at both end surfaces in contact with punches.

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References

[1] M. Leonowicz, D. Derewnicka, M. Wozniak, and H. A. Davies, "Processing of high-performance anisotropic permanent magnets by die-upset forging," *J. Mater. Process. Technol.*, vol. 153, pp. 860–867, 2004.

[2] S. Liu, D. Lee, M. Huang, and A. Higgins, "Research and development of bulk anisotropic nanograin composite rare earth permanent magnets," *J. Iron. Steel. Res. Int.*, vol. 13, pp. 123–135, 2006.

[3] B. M. Ma, D. Lee, B. Smith, S. Gaffi, B. Owens, H. Bie, and G. W. Warren, "Comparison of the corrosion behavior of die-upset and sintered NdFeB magnets," *IEEE Trans. Magn.*, vol. 37, no. 5, pp. 2477–2479, Oct. 2001.

[4] A. A. El-Moneim, O. Gutfleisch, A. Plotnikov, and A. Gebert, "Corrosion behaviour of hot-pressed and die-upset nanocrystalline NdFeB-based magnets," *J. Magn. Magn. Mater.*, vol. 248, pp. 121–133, 2002.

[5] N. Yoshikawa, Y. Kasai, T. Watanabe, S. Shibata, V. Panchanathan, and J. J. Croat, "Effect of additive elements on magnetic properties and irreversible loss of hot-worked Nd-Fe-Co-B magnets," *J. Appl. Phys.*, vol. 69, pp. 6049–6051, 1991.

[6] W. Grunberger, D. Hinz, A. Kirchner, K. H. Muller, and L. Schultz, "Hot deformation of nanocrystalline Nd-Fe-B alloys," *J. Alloy. Compd.*, vol. 257, pp. 293–301, 1997.

[7] K. Khlopkov, O. Gutfleisch, D. Hinz, K. H. Muller, and L. Schultz, "Evolution of interaction domains in textured fine-grained NdFeB magnets," *J. Appl. Phys.*, vol. 102, p. 023912, 2007.

[8] D. Hinz, A. Kirchner, D. N. Brown, B. M. Ma, and O. Gutfleisch, "Near net shape production of radially oriented NdFeB ring magnets by backward extrusion," *J. Mater. Process. Technol.*, vol. 135, pp. 358–365, 2003.

[9] S. Sugimoto, "Current status and recent topics of rare-earth permanent magnets," *J. Phys. D: Appl. Phys.*, vol. 44, p. 064001, 2011.

[10] A. H. Li, W. Li, B. Lai, H. J. Wang, M. G. Zhu, and W. Pan, "Investigation on microstructure, texture, and magnetic properties of hot deformed Nd-Fe-B ring magnets," *J. Appl. Phys.*, vol. 107, p. 09A725, 2010.

[11] O. Gutfleisch, A. Kirchner, W. Grunberger, D. Hinz, R. Schafer, L. Schultz, and I. R. Harris, "Backward extruded NdFeB HDDR ring magnets," *J. Magn. Magn. Mater.*, vol. 183, pp. 359-364, 1998.

[12] H. T. Kim and Y. B. Kim, "Microstructure and magnetic properties of backward extruded NdFeB ring magnets by the CAPA process," *Phys. Status. Solidi. A*, vol. 201, pp. 1926-1929, 2004.

[13] W. Grunberger, D. Hinz, D. Schlafer, and L. Schultz, "Microstructure, texture, and magnetic properties of backward extruded NdFeB ring magnets," *J. Magn. Magn. Mater.*, vol. 157, pp. 41-42, 1996.

[14] S. Guruswamy, Y. R. Wang, and V. Panchanathan, "Plastic deformation modeling of die-upset process for magnequench NdFeB magnets," *J. Appl. Phys.*, vol. 83, pp. 6393-6395, 1998.

[15] V. Boljanovic, *Metal Shaping Processes: Casting and Molding, Particulate Processing, Deformation Processes, and Metal Removal.* New York, NY, USA: Industrial Press, 2009.

[16] Z. H. Hu, J. Li, L. H. Chu, and Y. Liu, "Effect of hot deformation temperature on the magnetic and mechanical properties of Nd-Fe-B magnets prepared by spark plasma sintering," *J. Magn. Magn. Mater.*, vol. 323, pp. 104-107, 2011.

[17] M. Lin, H. J. Wang, P. P. Yi, and A. R. Yan, "Effects of excessive grain growth on the magnetic and mechanical properties of hot-deformed NdFeB magnets," *J. Magn. Magn. Mater.*, vol. 322, pp. 2268-2271, 2010.

[18] L. Li and J. C. D. Graham, "Mechanism of texture formation by hot deformation in rapidly quenched FeNdB," *J. Appl. Phys.*, vol. 67, pp. 4756-4758, 1990.

[19] P. P. Yi, M. Lin, H. J. Wang, A. Yan, and D. Li, "Effect of hot-pressed progress on the magnetic properties of die-upset Nd-Fe-B magnets," *Rare Metal Mat. Eng.*, vol. 38, pp. 576-578, 2009.

[20] H. T. Kim, S. H. Cho, Y. B. Kim, K. S. Ryu, G. A. Kapustin, and H. S. Kim, "NdFeB thin anisotropic magnets obtained by hot working process," *J. Magn. Magn. Mater.*, vol. 272, pp. e1925-e1927, 2004.

Note: Figure translations are in progress. See original paper for figures.