Development of high coercivity Nd-Fe-B permanent magnets with improved thermal stability

H. Sepehri-Amin, J. Li, Xin Tang, T. Ohkubo, K. Hono
(ESICMM-NIMS)

(Nd,HRE)-Fe-B based permanent magnets (HRE : heavy rare-earth) are utilized in the traction motors of (hybrid) electric vehicles which are resistive against demagnetization at the operating temperatures up to 200°C. However, due to the limited natural resources of HRE elements such as Dy and Tb, the development of HRE-free Nd-Fe-B based magnets with sufficiently large coercivity is needed. To meet this demand, the improvement of the thermal stability of coercivity is desired. It is well known that the temperature dependence of coercivity in commercial Nd-Fe-B sintered magnets deviates from temperature dependence of the anisotropy field of $Nd_2Fe_{14}B$ (Fig. 1a). In this study, we investigated the mechanism of pronounced thermal degradation of coercivity of Nd-Fe-B magnets by combining micromagnetic simulations, magnetic domain observations, and multi-scale microstructure characterizations using scanning transmission electron microscopy and atom probe tomography [1-6].

In this talk, we first discuss the reason for the poor thermal stability of coercivity in Nd-Fe-B based permanent magnets. In previous micromagnetic simulation studies, the temperature dependent magnetization of intergranular phase has not been considered. In this work, we found that the concavity of H_c-T can be reproduced by incorporating the temperature dependent magnetization of ferromagnetic intergranular phase (Fig. 1b) [6]. Decrease of saturation magnetization and Curie temperature of the grain boundary phase were found to be crucial to improve the thermally stability of the coercivity of Nd-Fe-B magnets. Based on this simulation results, we demonstrated excellent hard magnetic properties of μ_0H_c=2.5 T, μ_0M_r=1.4 T, and an excellent thermal stability of coercivity of -0.33 %/°C by infiltrating low-melting-temperature Nd-HRE-Cu alloy into hot-deformed Nd-Fe-B magnets (Fig. 2). Based on the microstructure studies and micromagnetic simulations, we will discuss how the formation of non-ferromagnetic grain boundary phase and HRE-rich shell are beneficial to achieve high coercivity with excellent thermal stability (Fig. 2).

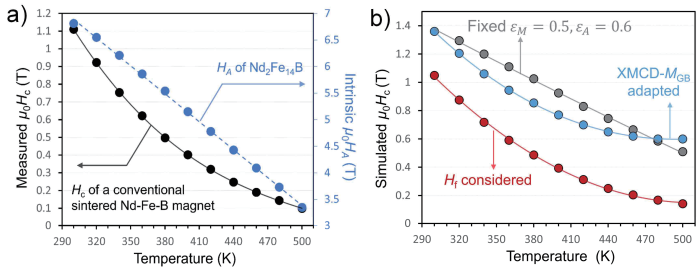

Fig. 1 (a) Comparison of the temperature dependence of coercivity of conventional Nd-Fe-B sintered magnet and intrinsic anisotropy field of $Nd_2Fe_{14}B$ [6]. (b) Simulated temperature dependence of coercivity when grain boundary is ferromagnetic with and without consideration of temperature dependence of M_s^{GB}, A^{GB}, and thermal activation [6].

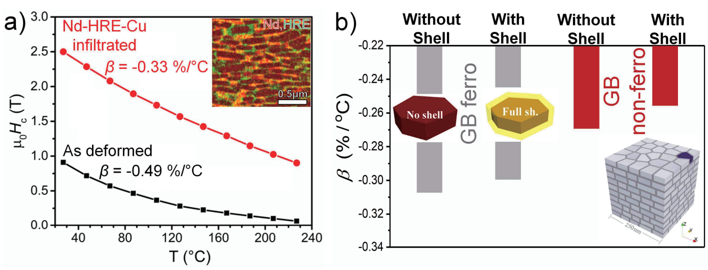

Fig. 2 Coercivity as a function of temperature obtained from as hot-deformed and Nd-HRE-Cu infiltrated magnet. STEM-EDS map of Nd and HRE is shown in inset. (b) Simulated temperature coefficient of coercivity for the hot-deformed model with $Nd_2Fe_{14}B$ grains covered with and without HRE-rich shell and different GB magnetism [5].

[1] H. Sepehri-Amin *et al.* Acta Mater. 99 (2015) 297.
[2] M. Soderžnik *et al.* Acta Mater. 135 (2017) 68-76.
[3] Xin Tang *et al.* Scripta Mater. 147 (2018) 108.
[4] Lihua Liu *et al.* AIP Advances 8 (2018) 056205.
[5] J. Li et al. Acta Mater. 187 (2020) 66.
[6] J. Li et al. Acta Mater. 199 (2020) 288.