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Research Progress on High Performance Nd-Fe-B Permanent Magnet

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We have systemically investigated the correlation among the magnetic characterization and the lattice distortion effect and the multiphase couplings during the fabrication process of the high performance Nd-Fe-B magnetusing X-ray diffraction(XRD), scanning electron microscopy (SEM), magnetic force microscopy (MFM), and magnetic measurements.Rietveld structural refinement is employed to determine the atomic occupations in even structure and the phase contents in Nd-Fe-B alloy. The Diamond soft ware is used to measure lattice distortion (bond length and bond angle). The magnetism of Nd-Fe-B alloys was studied with a modified magnetic valence model. The demagnetic process is fitting with an empirical model.

The XRD analysis exhibits the phase evolution process from four phases ($Nd_2Fe_{14}B$ phase, Nd_2Fe_{17} (B), α-Fe , and Nd rich phase) coexistence in the initial NdFeB alloy to the $Nd_2Fe_{14}B$ phase and Nd rich phase in the terminal magnet. The annealing process drives the heavy rare earth doping from the grain boundary phase to the $Nd_2Fe_{14}B$ main phase, it causes the lattice concentration. The $Nd_2Fe_{14}B$ main phase concentration is near 95wt % in the terminal magnet. MFM measurement shows the strip magnetic domain content of the $Nd_2Fe_{14}B$ phase tends to enhance with increasing the main $Nd_2Fe_{14}B$ content induced by the annealing process. The ordered strip magnetic domains homogeneously disturb in the final magnet. The temperature dependence of magnetization shows three ferromagnetic phase ($Nd_2Fe_{14}B$, Nd_2Fe_{17} (B) and α-Fe) coexist in the strip cast alloy. After annealing heat treatment, the α-Fe disappears and the magnetic phase transition from Nd_2Fe_{17} (B) to $Nd_2Fe_{14}B$ occurs, which results in a significant decrease of the content of the Nd_2Fe_{17} (B) phase. Curie temperature is sensitive to the Fe-Fe and Nd-Fe bond lengths, a short bond distance is beneficial for the high Curie temperature. The magnetism of Nd-Fe-B intermetallics reveals that the essential fact of the existence of gaps or deep minima in the density of states for 3d bands. Such band gaps *provide a necessary conduction for strong magnetism in the framework* of Stoner's 'collective electron ferromagnetism' theory and give rise to the important conservation law for the integrated density of states under alloying. The magnetic moment depends only on the total number ofd and s-p as well as f electrons, not on the band shape. Finally we have discussed the physical picture of the Nd rich phase playing role in the high performance permanent magnet by analyzing structural frame. The coercivity is related to the Nd-Fe bond angle. It implies that hard magnetic characteristics of $Nd_2Fe_{14}B$ is derivedfrom the Nd-B layers. As for the Fe-Fe layers and their atomic clusters, the extra Nd atom is necessary to be arranged near to these layers for forming Nd-Fe coupling, which enhances the coercivity, that is the reason why the Nd-rich phase is necessary in the synthesis of high performance NdFeB magnet.

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EB04

Effect of High Magnetic Field Applied during Annealing on the Coercivity in Sintered Nd-Fe-B Magnets

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These is an imperative need to develop a nature-friendly electric vehicle (EV) as an alternative transportation. Sintered Nd-Fe-B magnets are the most promising materials for a driving motor of the hybrid EV and the forthcoming pure EV. Since the operating temperature of magnets in these high-power motor applications reaches beyond 200°C, a very large value of coercivity H_c is necessary at room temperature. Current Nd-Fe-B magnets commercially available for such high H_c applications, therefore, contain a huge amount (~10 wt.%) of Dy to enhance H_c. But, this method has at least two crucial disadvantages. First problem is an estimated short supply of Dy in the EV mass-production stage owing to its low natural abundance as compared with that of Nd. The second inferiority in using Dy arises from the antiparallel coupling of Dy and Fe moments, which results in smaller magnetization and much-reduced energy product values. It is well known that a heat treatment around 600°C is indispensable to obtain a high coercivity in the sintered Nd-Fe-B magnets. We have been investigating an effect of high magnetic field in this annealing process on the magnetic properties. The characteristic value of this experiment is the Field-enhanced Coercivity Ratio (FCR), which is defined to be a difference of H_c with and without annealing field, divided by an original H_c value. We already reported that the FCR value of 37% can be achieved, when the sample containing 3.1 wt.% Dy and 0.13 wt.% Al was annealed at T_a = 550°C under a magnetic field of H_a = 140 kOe [1]. However, detailed mechanism of such coercivity enhancement phenomena has been left unclarified. In this work, we present a more systematic study for a *series of Nd-Fe-B magnets with and without Dy, containing* a small amount of Al and Cu.

The heat treatments were carried out by using a furnace installed in a cryocooled superconducting magnet which generates magnetic fields of up to H_a=140 kOe. In the present study, eight samples with different amounts of Dy, Cu and Al were prepared. All these samples were annealed at 800°C in zero field prior to the field annealing. The annealing temperature T_a was selected between 475°C and 625°C, while the duration at T_a was fixed to be 3 h.

In a series of Dy-free Nd-Fe-B magnets, we obtained the following results. The room temperature values of H_c for samples without Cu additive were less than 5 kOe even after annealing at T_a = 500°C~625°C. The effect of magnetic field of up to 140 kOe on the H_c was negligibly small. On the other hand, Cu-containing samples showed much higher H_c values (>12 kOe) and an appreciable change in H_c by the magnetic annealing. Highest H_c value of 14.7 kOe was obtained when the sample containing Al 0.13 wt.% and Cu 0.13 wt.% was annealed at T_a=550°C under the applied field of H_a=140 kOe. This value of H_c is 16% larger than that of the control sample (T_a=550°C and H_a=0).

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