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Influence of deposition angle on the magnetic properties of Sm–Fe–N films fabricated by aerosol deposition method

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Abstract

In this paper, we studied the influence of deposition angle during the aerosol deposition (AD) method. The deposition angle was changed from 0° to 45°. The density of films did not change, but the surface roughness was improved by the inclination of deposition angle. This tendency was considered as one of advantages in manufacture of film magnets. However, the magnetization measured along the direction perpendicular to the film plane was decreased by the inclination. Referring to our previous work that the *c*-axis in Sm–Fe–N AD films has a tendency to align in the direction perpendicular to the film plane, it is satisfactory to consider that the increase in deposition angle weakened the alignment of *c*-axis.

Keywords: Permanent magnets; Aerosol deposition; Sm–Fe–N; Surface roughness; Remanence

1. Introduction

Rare earth magnets with thickness about 100–300 μm are demanded in the trend of downsizing motors and electromagnetic devices. Nd–Fe–B sintered magnets [1] and Sm–Fe–N bonded magnets [2] have been reported to have thickness of 200 and 400 μm, respectively. However, the influence of defects introduced to the surface by mechanical methods on magnetic properties becomes a serious problem in film magnets. On the other hand, sputtering is convenient to obtain film magnets [3–6], but it is difficult to obtain a high deposition rate. Recently, pulsed laser deposition (PLD) has been reported in preparing rare earth film magnets because of its high deposition rate [7–9]. However, its deposition rate has been not sufficiently high for manufacturing film magnets.

The aerosol deposition method (ADM) is an attractive method with high deposition rate [10]. In our previous papers [11–13], we applied this method for the fabrication of Sm–Fe–N thick film magnets, and high deposition rate and high coercivity were obtained. In addition, it was found that anisotropic film magnets were capable of fabricating by applying magnetic field during the aerosol deposition [14,15]. However, the remanences were low because of their low film densities. Up to date, we have changed AD conditions of gas flow rate and deposition time, and studied magnetic properties and microstructures [11–13]. However, the influence of deposition angle on fabricating Sm–Fe–N AD film has not been studied yet. In this paper, we changed variously the deposition angle during AD method and studied the influence on magnetic properties of Sm–Fe–N AD films.

2. Experimental procedure

The Sm–Fe–N powder in AD method was provided from the Sumitomo Metal Mining Co. Ltd., which was produced by a reduction and diffusion method. The principle and details of the AD method were described in our previous paper [11]. Helium gas was used as a carrier gas. The AD conditions were

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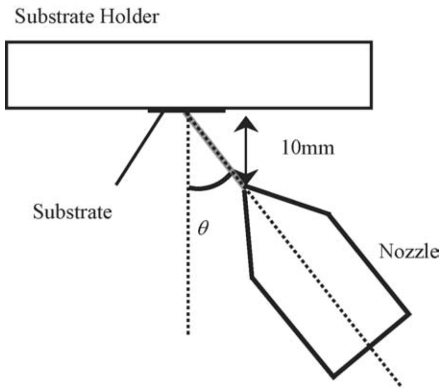

Fig. 1. The illustration of the deposition substrate with deposition angle (θ).

fixed as gas flow rate (gfr) of 6 l/min and deposition time (t) of 4 min. The substrates used in this investigation were SiO_2 and brass plates with the size of 10 mm × 10 mm × 1 mm. The cellophane mask with the opening area of 8 mm × 8 mm was also used. They were placed at a distance of 10 mm from the tip of nozzle, and were maintained at room temperature. The deposition angle (θ) was changed from 0° to 45° by inclining the nozzle, as shown in Fig. 1.

Area, thickness and surface profile of films were measured by a surface profilometer. The magnetic properties were measured by a vibrating sample magnetometer (VSM) after applying a pulsed field near 4 T. The magnetization values were calculated using film density and the X-ray density of the $Sm_2Fe_{17}N_3$ compound (7.67 Mg m^{-3}) reported [16]. For the evaluation of AD films, the magnetization values were compared with that of the host powder derived from its weight and the X-ray density of the $Sm_2Fe_{17}N_3$ compound (rhombohedral Th_2Zn_{17}-type structure (space group $R\bar{3}m$), lattice constants $a = 0.8557$ nm, $c = 1.2437$ nm [17]). The microstructure was observed using an X-ray diffraction (XRD) apparatus and a scanning electron microscopy (SEM).

3. Results and discussion

Fig. 2 (a) shows the variation in thickness (d) of the Sm–Fe–N film deposited in the conditions of gfr = 6 l/min and $t = 4$ min versus deposition angle (θ). The thickness decreased with increasing θ. The average deposition rate at $\theta = 45°$ was 5.9 μm min^{-1}, but this value is still higher than those using the other methods for the production of film magnets. The density of films (ρ) shown in Fig. 2 (b) was around 5.6 Mg m^{-3}. The relative density was about 73% of the X-ray density of $Sm_2Fe_{17}N_3$ compound (7.67 Mg m^{-3}). These densities were not even changed by inclining.

Fig. 3 shows the SEM photographs taken the surface of Sm–Fe–N AD film, deposited with $\theta = 0°$ or 45°. In the film deposited with $\theta = 0°$, many asperities and craters were observed on its surface. However, the film with $\theta = 45°$ had more smooth surface but no crater. Fig. 4 shows the relationship between deposition angle and surface roughness (r/d) of

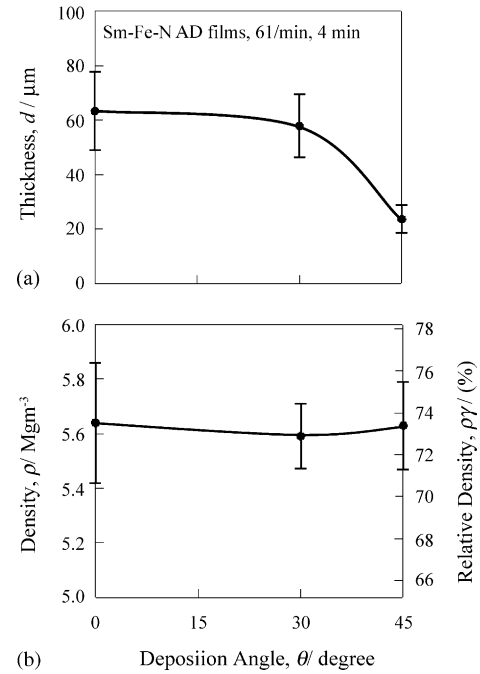

Fig. 2. Variation in thickness d (a) and density ρ (b) of Sm–Fe–N AD films deposited with θ ($\theta = 0$–45°).

the AD films. The surface roughness (r/d) was determined by the normalized ratio of average height of asperity (r) to the film thickness (d). When θ was 30° or 45°, the roughness was smaller than that deposited with $\theta = 0°$. From these results, it

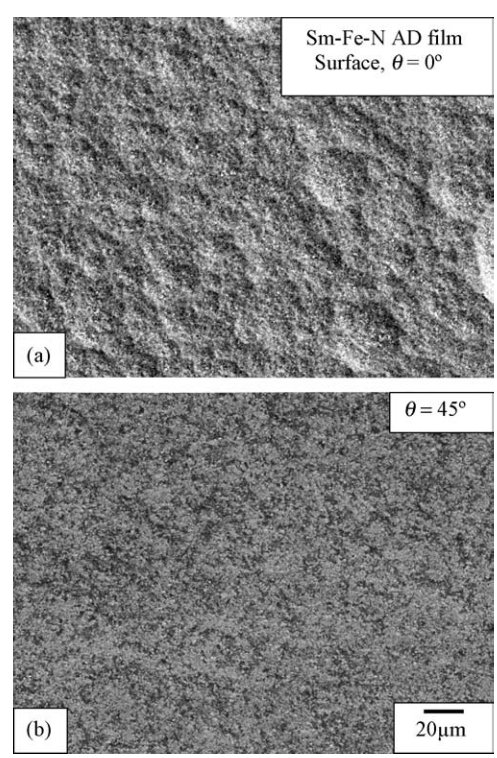

Fig. 3. SEM photographs taken from the surfaces of Sm–Fe–N AD films deposited with (a) $\theta = 0°$ and (b) $\theta = 45°$.

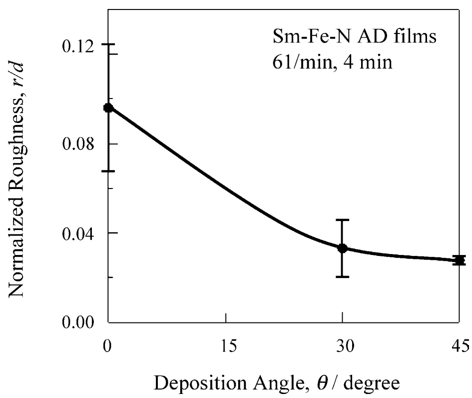

Fig. 4. Variation in the surface roughness of Sm–Fe–N AD films deposited with θ ($\theta = 0$–45°), which was normalized using their average thickness.

is considered that inclination improves the surface roughness of AD films and this is one of advantages for manufacturing film magnets. The reason of improvement in surface roughness is thought to be related to the state of aerosol flow near the substrate. In the case of $\theta = 0°$, the aerosol flow collided with the substrate vertically and the reflected flow dispersed in all directions, which led turbulent flow near the substrate. This turbulent flow prevented uniform deposition of ultrafine powder and resultantly formed asperities. On the other hand, in the case of $\theta = 30°$ or 45° the aerosol flow collided with the substrate obliquely and the reflected flow dispersed in one direction. Therefore, the aerosol flow near the substrate became laminar flow, which led to uniform deposition.

Fig. 5 shows the demagnetization curves of Sm–Fe–N AD films deposited with $\theta = 0°$ and 45°. Both were measured along the direction perpendicular to the film plane. The remanence (B_r) of the film deposited with $\theta = 45°$ was 0.32 T, which was smaller than that with $\theta = 0°$ (0.40 T). Fig. 6 summarizes the remanence of AD films deposited with $\theta = 0$–45°. The B_r measured along the direction parallel to the film plane (para) slightly decreased with increasing θ. On the other hand, the B_r measured along the direction perpendicular to the film plane (perp) drastically decreased with increasing θ. Referring to the result in our previous work [13], in which the c-axis in Sm–Fe–N AD films has a tendency to align along the direction perpendicular to the film plane, it is considered that the increase in deposition angle weakened the alignment of c-axis.

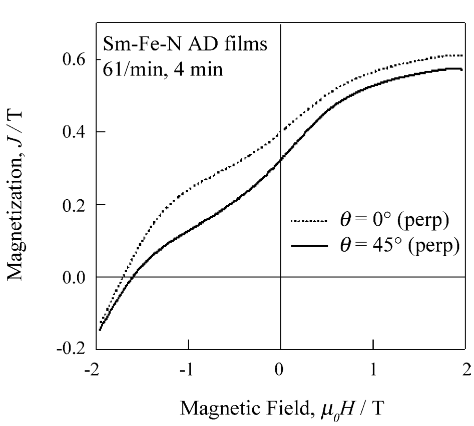

Fig. 5. The demagnetization curves of Sm–Fe–N films deposited with $\theta = 0°$ and 45°, which were measured along the direction perpendicular to the film plane.

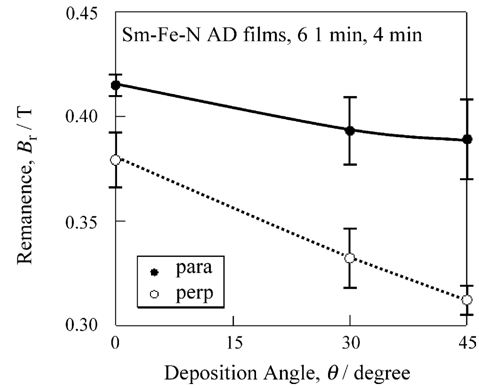

Fig. 6. The remanences B_r of Sm–Fe–N AD films prepared with deposition angle of 0–45°.

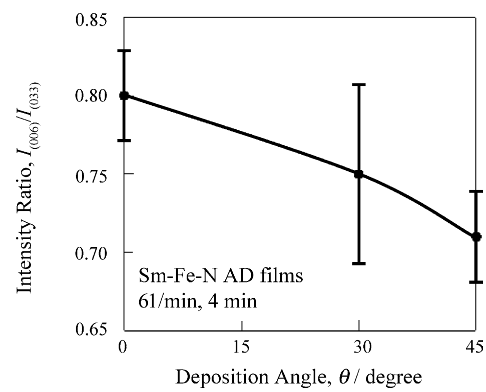

Fig. 7. The ratio of X-ray intensity of (0 0 6) to (0 3 3) reflections in the $Sm_2Fe_{17}N_x$ compound ($I_{(006)}/I_{(033)}$), which was calculated in the AD films prepared with deposition angle of 0–45°.

In order to investigate the directionality of AD films, the XRD analysis was carried out. X-ray intensity of c-axis direction ((0 0 6) reflection) and the maximum intensity direction ((0 3 3) reflection) of $Sm_2Fe_{17}N_x$ compound in the AD films were selected as a measure of the direction. Fig. 7 shows the variation in ratio of (0 0 6) to (0 3 3) reflections ($I_{(006)}/I_{(033)}$) which was measured in the AD films deposited with $\theta = 0$–45°. The average ratio of the film with $\theta = 45°$ was 0.71, which was lower than that of $\theta = 0°$ (0.80). This result suggests that the increase in deposition angle tended to weaken the alignment of c-axis along the direction perpendicular to the film plane.

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