

Novel powder processing technologies for production of rare-earth permanent magnets

Kenta Takagi, Yusuke Hirayama, Shusuke Okada, Wataru Yamaguchi and Kimihiro Ozaki

Magnetic Powder Metallurgy Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Nagoya, Japan

ABSTRACT

Post-neodymium magnets that possess high heat resistance, coercivity, and $(BH)_{max}$ are desired for future-generation motors. However, the candidate materials for post-neodymium magnets such as $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ and metastable magnetic alloys have certain process-related problems: low sinterability due to thermal decomposition at elevated temperatures, deterioration of coercivity during sintering, and the poor coercivity of the raw powder. Various developments in powder processing are underway with the aim of overcoming these problems. So far, the development of advanced powder metallurgy techniques has achieved $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ anisotropic sintered magnets without coercivity deterioration, and advances in chemical powder synthesis techniques have been successful in producing $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ fine powders with huge coercivity. The challenge of a new powder process is expected to open the way to realizing post-neodymium magnets.

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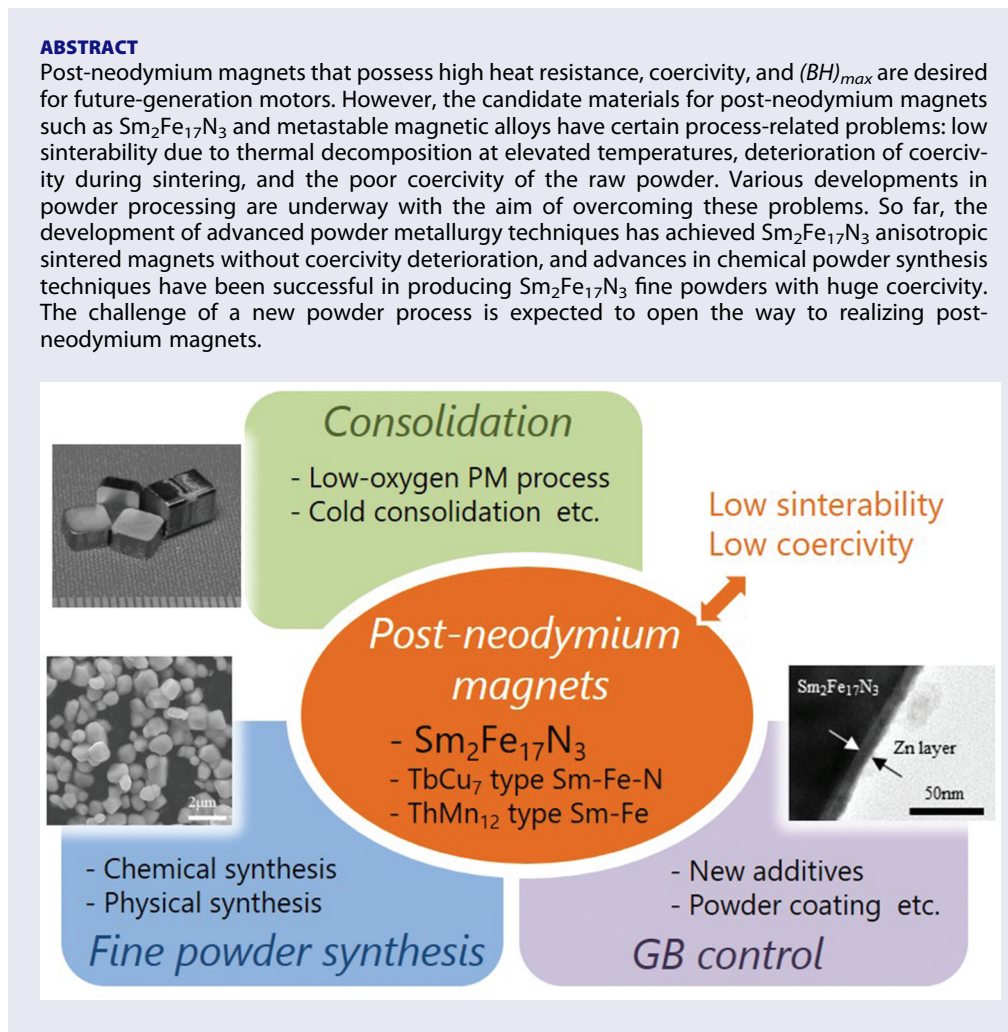
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1. Introduction

Electric vehicles and eco-friendly home appliances, which have become indispensable in modern society, were made possible by the advent of interior permanent magnet motors with dramatically higher efficiency. Since motor performance largely depends on the properties of the permanent magnet, higher performance magnets are required for next-generation motors. $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets (neodymium magnets), which are now widely used, are always affected by resource problems [1,2]. In particular, the prices of Nd, the main raw material, and Dy, an additive used to

enhance magnetic properties, are easily affected by the international situation because their crustal abundances are very low and production area are eccentrically localized. In view of these problems, the development of a post-neodymium magnet with high performance exceeding the current level and stable raw material procurement conditions has been strongly desired.

Figure 1 compares the potential of various magnetic compounds using the anisotropic magnetic field H_a and saturation magnetization J_s , and the theoretical maximum energy product $(BH)_{max}$. As saturation

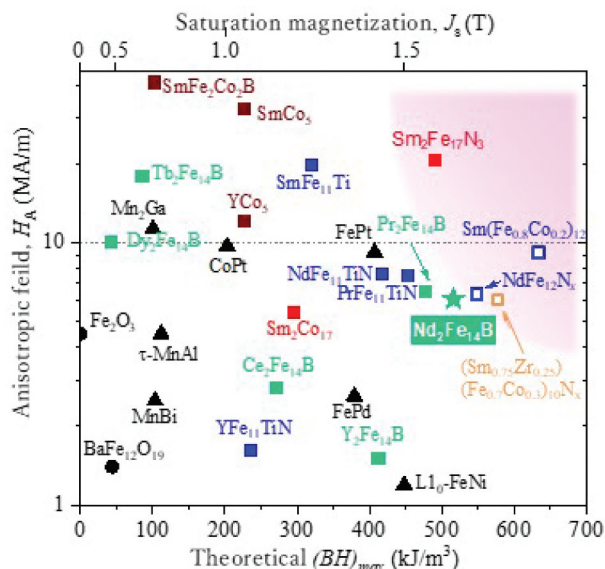


Figure 1. Comparison of magnetic properties of various magnetic compounds. The rectangle, triangle, and circle symbols represent rare-earth alloys, non-rare-earth alloys, and oxides. The same color (except black) means the same crystal structure. Open symbols represent a compound for which a single crystal powder has never been obtained [56].

magnetization and the anisotropic magnetic field increase, higher remanence B_r and coercivity H_c can be expected. The theoretical value of $(BH)_{max}$, which is an important index for motor design, can be calculated by $J_s^2/4\mu_0$, where μ_0 represents permeability in a vacuum. To date, only three types of compounds with saturation magnetization and anisotropic magnetic fields comparable to or higher than those of $Nd_2Fe_{14}B$ have been discovered: $Sm_2Fe_{17}N_3$, $TbCu_7$ type compounds such as $(SmZr)(FeCo)_{10}N_x$, and $ThMn_{12}$ type compounds such as $Sm(FeCo)_{12}$ and $NdFe_{12}N_x$ [3–8]. For example, $Sm_2Fe_{17}N_3$ is a magnetic compound that was firstly reported by Iriyama and Coey in 1990 and possesses saturation magnetization equivalent to that of $Nd_2Fe_{14}B$, together with a huge anisotropic magnetic field of 20.7 MA/m, which is about three times that of $Nd_2Fe_{14}B$ [3,4]. This huge anisotropic magnetic field is very attractive because larger coercivity has been required in recent motors. Moreover, the Curie temperature of $Sm_2Fe_{17}N_3$ is 160 K higher than that of $Nd_2Fe_{14}B$, indicating high heat resistance. The other two candidate compounds have even higher saturation magnetization, as seen in Figure 1. Figure 2 shows the temperature dependencies of the theoretical $(BH)_{max}$ values estimated from the literature values for the four candidate materials. Here, $(BH)_{max}$ is calculated with 0.8 J_s considering some property degradation during processing. $Sm_2Fe_{17}N_3$ is expected to exhibit a higher $(BH)_{max}$ above 120°C than the current $Nd_2Fe_{14}B$ sintered magnets. In addition to its advantage in heat resistance, the resource problem of $Sm_2Fe_{17}N_3$ is far smaller than that of $Nd_2Fe_{14}B$ magnets, since the element Sm

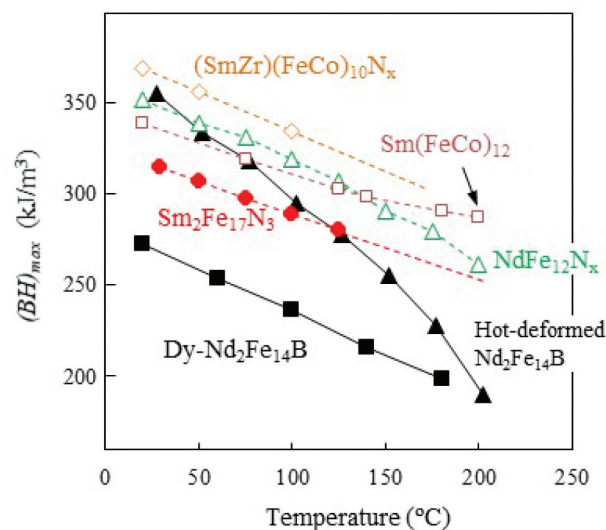


Figure 2. Comparison of temperature dependencies of $(BH)_{max}$. The values of Dy-added and hot-deformed $Nd_2Fe_{14}B$ sintered magnets are experimental [9,10]. The $(BH)_{max}$ of the other materials are theoretical values that are calculated with 0.8 J_s [5,7,8,45,57,5859].

occurs in a wide range of areas, including North America and Australia, and has few other industrial uses. The $TbCu_7$ -type and $ThMn_{12}$ -type compounds are further expected to exhibit much higher $(BH)_{max}$ owing to their large saturation magnetization.

However, there are three major problems in producing practical sintered magnets from these candidate materials. In general, sintered magnets of rare-earth-containing compounds are produced by powder metallurgy processes, that is, preparation of a single crystal fine powder, compaction with a crystalline orientation using an external magnetic field, and sintering. The first problem is the difficulty of sintering while maintaining the performance of the raw powder. In the case of $Nd_2Fe_{14}B$, it is well known that improved coercivity and densification can be obtained because liquid phase sintering can be applied. However, some of candidate materials such as $Sm_2Fe_{17}N_3$ and $(SmZr)(FeCo)_{10}N_x$ are nitrides which undergo thermal decomposition at elevated temperatures [5,9,10], making it difficult to apply liquid phase sintering which requires high temperature heating. Solid-phase sintering at a low temperature must be applied in such cases. However, solid-phase sintering does not produce the effects of improving coercivity and densification, and with some candidate materials, it causes a significant reduction in coercivity. The second problem is that even though the candidate materials have a high anisotropic magnetic field, high coercivity commensurate with that anisotropic magnetic field has not been obtained. Because a coercivity improvement effect cannot be expected with solid-phase sintering, as noted above, raw powder with the highest coercivity possible must be prepared from the beginning, but the current coercivity of powders of

the candidate materials is significantly low. For example, the highest coercivity obtained in $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders is still about 7% of the anisotropic magnetic field [11]. The third problem is the difficulty of producing single-crystal powders of TbCu₇- and ThMn₁₂-type compounds. Since these materials are metastable phases, the powders have been synthesized by quenching methods, mechanical alloying, and HDDR (hydrogen-disproportionation-desorption-recombination) so far [12–16], but these methods produce only polycrystalline powder, which cannot be used as a raw powder for anisotropic sintered magnets.

In order to bring out the potential of candidate materials such as $\text{Sm}_2\text{Fe}_{17}\text{N}_3$, it is necessary to overcome these process-related problems, which do not affect $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets. Therefore, many studies have been carried out to elucidate the phenomena that occur during the processes and to develop new powder processes based on them. This paper presents an overview of research developments related to the powder preparation and powder consolidation processes for the candidate materials. In particular, the focus of this paper is $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ because this material is the most widely studied and the other candidate materials also have common issues.

2. Powder sintering and consolidation technologies

2.1. Powder consolidation techniques for thermally degradable rare-earth magnets

Nitride magnets of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ and $(\text{SmZr})(\text{FeCo})_{10}\text{N}_x$ undergo thermal decomposition at around 600°C and lose their properties as permanent magnets [5,9,10]. Therefore, unlike $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets, it is impossible simply to apply liquid phase sintering to powders of these compounds because their decomposition temperatures are lower than the liquidus temperature of

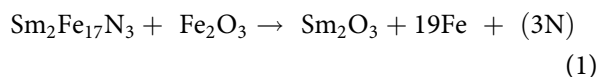
the Sm-Fe system (720°C). This means that these powders must be densified by solid-phase sintering, which has a densification rate far lower than that of liquid phase sintering. In the early stage of research on $\text{Sm}_2\text{Fe}_{17}\text{N}_3$, conventional pressure sintering techniques such as hot-pressing and hot isostatic pressing were applied for densification at temperatures below the decomposition temperature, as indicated in Table 1 [17,18]. Subsequently, spark plasma sintering and current sintering were tried in order to further reduce the thermal load during sintering [19,20]. Even though these approaches achieved good consolidation of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powder without apparent decomposition, the problem of significantly decreased coercivity remained. For example, Zhang et al. reported that when $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powder with a coercivity more than 600 kA/m was sintered, coercivity dropped to 300 kA/m at 500°C, even though this temperature is approximately 100°C lower than the decomposition temperature [19]. Including the other methods, sintering deteriorated coercivity by 35% to 75% in comparison with the raw powder. This phenomenon had long been attributed to thermal decomposition, and thus was thought to be unavoidable. Therefore, some researchers applied cold consolidation methods such as shock compaction, aerosol deposition, and compression shearing [21–27]. Some of these approaches were successful in densification without coercivity deterioration, and in particular, compression shearing has achieved a $(BH)_{\text{max}}$ of 228 kJ/m³, which was the highest for the $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ bulk magnets [27]. However, these cold consolidation processes are not practical techniques due to their low throughput and shape constraints on products.

In contrast to the conventional explanation of coercivity deterioration, a new mechanism was proposed in the recent years: Coercivity decreases due not to thermal decomposition, but due to the existence of an oxide film on the powder surface [20]. The surface oxide film of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powder is usually composed

Table 1. Properties of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ magnets consolidated by various methods. T_{cons} , H_{cj} , and ρ represent the consolidation temperature, coercivity, and density, respectively.

Consolidation method	Tcons (C)	H_{cj} (kA/m)		ρ (%)	(BH)max (kJ/m3)	Ref
		powder	bulk			
<i>Sintering process</i>						
Ultra high pressure sintering	550	700	453	97	88	[17]
Hot isostatic pressing	450	600	300	90	118	[18]
Spark plasma sintering	500	≈680	≈310	89	-	[19]
	420	≈850	≈200	85	50	[28]
Current sintering	450	1162	287	82	-	[20]
Low-oxygen process	420	720	730	85	167	[28]
	500	987	870	91	191	[29]
<i>Cold compaction processes</i>						
Shock explosion/compaction	-	700	34	77	88	[21]
	-	-	300	97	84	[22]
	-	358	454	98	174	[23]
	-	-	-	≈100	191	[24]
Aerosol deposition	-	923	1480	77	-	[25]
Compression shearing	-	860	920	84	-	[26]
	-	-	880	-	228	[27]

of Sm_2O_3 and Fe_2O_3 , and when heated, the following redox reaction occurs between the oxide and the $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ matrix:



Since the rare-earth element Sm has a very strong reducing ability, the above reaction proceeds even under heating to several 100°C. As can be seen from the reaction formula, a large amount of $\alpha\text{-Fe}$ is precipitated even if Fe_2O_3 is slightly reduced, and if soft magnetic $\alpha\text{-Fe}$ exists on the particle surface, it becomes a nucleation site for reverse domains, resulting in a decreased coercivity. According to this hypothesis, if a powder without an oxide film can be sintered, it should be possible to realize a $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ sintered magnet with no decrease in coercivity. The important point here is that the Sm_2O_3 surface oxide film cannot be removed by the usual hydrogen reduction.

Hence, low-oxygen powder metallurgy techniques, which can produce sintered magnets without forming an oxide film, were developed [28,29]. For example, Takagi et al. attempted to perform all the processes from pulverizing to sintering under a very low oxygen environment below 0.5 ppm O_2 in connected glove-boxes, as illustrated in Figure 3 [29]. The oxygen concentration of the fine powder produced by this approach can be suppressed to less than 0.5 wt%, which is from one-half to one-third of the level of air-exposed powders. The powders were sintered below the decomposition temperature while maintaining this low oxygen concentration, and coercivity deterioration was constrained to below 10%, as indicated in Figure 4. This convincingly demonstrated that a $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ anisotropic sintered magnet can be produced by sintering using raw powder with a low surface

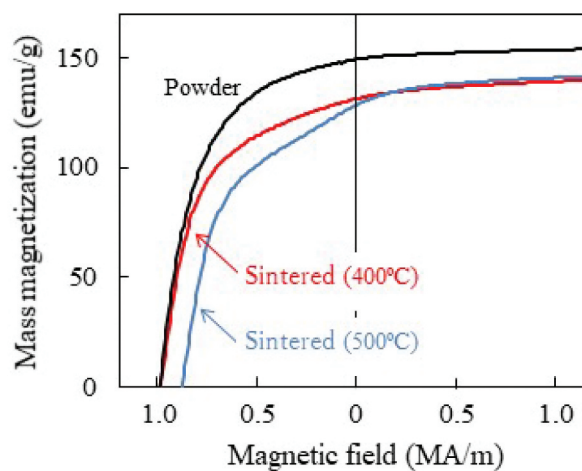


Figure 4. Demagnetization curves of powder and sintered magnets produced by the low-oxygen powder metallurgy process [29].

oxide concentration. Furthermore, this low-oxygen powder metallurgy approach is presumably effective for the other candidate, $(\text{SmZr})(\text{FeCo})_{10}\text{N}_x$, because it is a nitride compound similar to $\text{Sm}_2\text{Fe}_{17}\text{N}_3$.

Other issues have also been clarified in the development of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ sintered magnets so far. As mentioned above, the many low-thermal load consolidation processes studied to date have not yet achieved sufficient densification. For example, the relative density obtained by the sintering approach is 91% at maximum, as indicated in Table 1. In addition, although the significant decrease in coercivity due to the surface oxide film was suppressed, a small decrease in coercivity with increasing sintering temperature was found as seen Figure 4. The possible reason is presumed to be the effect of magnetic coupling due to densification. This needs to be investigated in the future as a new problem. Furthermore, the coercivity is still only about 1 MA/m, which is much lower than

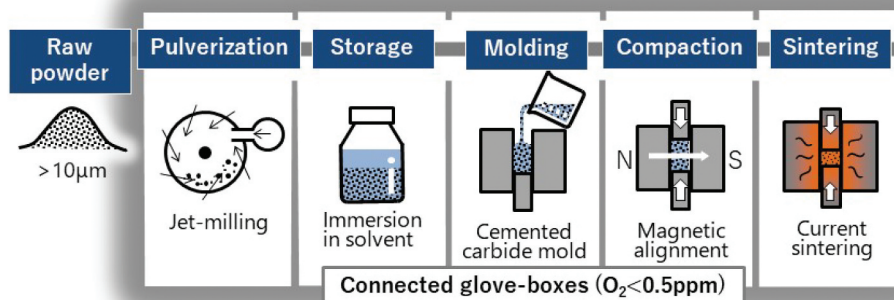


Figure 3. Low oxygen powder metallurgy process for $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ sintered magnets [29].

the anisotropic magnetic field of 20.7 MA/m. Therefore, further development is needed in order to realize the potential of coercivity as much as possible.

2.2. Powder techniques exploring sintering additives for coercivity enhancement

It is known that the coercivity of $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets is greatly improved by adding a specific other element to the grain boundaries, suggesting the possibility that the same effect can be obtained in $\text{Sm}_2\text{Fe}_{17}\text{N}_3$. Therefore, many researchers have attempted to improve coercivity by adding various elements to $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders and bulk magnets. In particular, Zn addition is well known to yield a substantial improvement in coercivity [30]. For example, Kuhrt et al. reported that huge coercivity of 3.5 MA/m could be achieved by addition of Zn [31]. However, Zn addition cannot improve $(BH)_{\max}$ because it inevitably decreases the intrinsic saturation magnetization of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powder. Therefore, an alternative additive to Zn is required in order to realize high-coercivity sintered magnets. So far, In, Sn, Al, Bi, etc. have been investigated as alternatives to Zn, but no element has exhibited a certain effect in improving coercivity [32]. Moreover, previous studies had been mostly limited to low melting point metals, because the effect of the additive could not be investigated unless it melts and infiltrates into the interparticle. If the effect of additives is to be investigated purely as a means of improving coercivity, the scope should be expanded to materials with high melting points [33,34]. In addition, because the surface oxide film was not sufficiently controlled in these past studies, it cannot be said that the effect of addition was investigated accurately, under a condition of direct contact between $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ and the additive element. That is, if the low-oxygen powder metallurgy technology described earlier can be adopted, the additive element can be added directly to the grain boundaries without an oxide film. This approach also has the potential to achieve the maximum effect with the minimum amount of addition.

In order to form a metal film on the surface of magnetic powder, Matsuura et al. developed a low-oxygen powder coating technique utilizing plasma deposition [28]. They applied this process to prepare Zn-bonded magnets, and succeeded in improving the coercivity while suppressing the decrease in remanence [35]. As the result, the obtained magnets exhibited a very excellent $(BH)_{\max}$ of 200 kJ/m^{-3} . Yamaguchi et al. also reported a similar coating technique involving sputtering of a metal film [36]. In these techniques, the powder is subjected to coating with mechanical agitation, resulting in a uniform nano-order metal film without any oxide film, as shown by the transmission electron microscopy (TEM) image in the inset in Figure 5. X-ray photoelectron spectroscopy has demonstrated that the obtained powders have an oxide-free

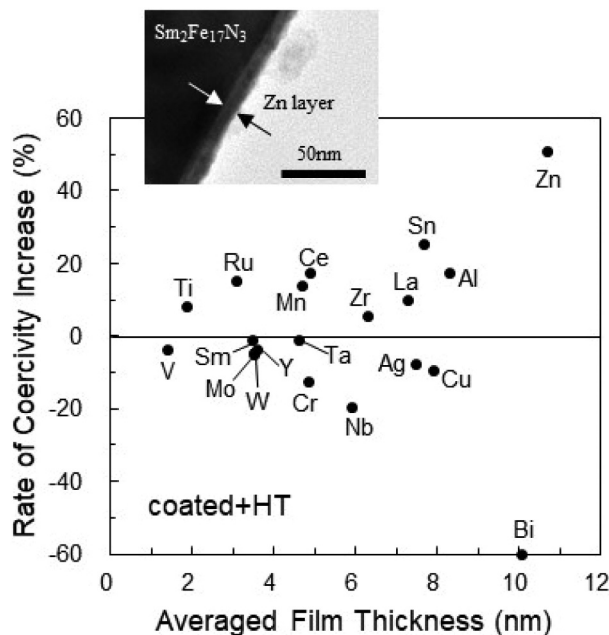


Figure 5. Summary of the effects of coating 20 non-magnetic metals on the coercivity of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders [39]. All coated powders were heat-treated at 500°C. The inset shows a cross-sectional TEM image of a Zn-coated powder [36].

single-phase metal film. Previously, physical and chemical coating methods such as vapor deposition and complex photodecomposition were reported, but those methods had the drawbacks of low coverage and low material selectivity [32,37,38]. The new techniques are able to overcome these problems of the conventional methods.

Figure 5 summarizes the change in coercivity of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders by coating with 20 different non-magnetic metals [39]. At present, nine elements that can improve the coercivity of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ when used in conjunction with the low-oxygen powder coating technique have been discovered: Al, Ti, Mn, etc. are new elements which were not found in previous studies using powders with a surface oxide film. Interestingly, these elements do not coincide with the elements for $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets, such as Dy and Ga, suggesting that further research using the low-oxygen powder coating technique may lead to the discovery of new elements and alloys which are capable of enhancing coercivity. In addition, the mechanism that the effect on coercivity differs greatly depending on the element is of academic interest and is also important from the viewpoint of additive design of sintered magnets. Therefore, the mechanism of the effect of each element should be investigated in the future.

3. Powder preparation technologies for high-coercivity rare-earth magnets

3.1. Chemical synthesis approaches

The coercivity of $\text{Nd}_2\text{Fe}_{14}\text{B}$ sintered magnets is greatly increased by liquid phase sintering, as mentioned

earlier. However, it is not possible to apply liquid phase sintering to thermally degradable and meta-stable materials such as $\text{Sm}_2\text{Fe}_{17}\text{N}_3$. This means that the coercivity of sintered magnets of these materials cannot be increased in sintering unless an effective sintering additive is used, and thus, is basically lower than the coercivity of the raw powder, as indicated in Table 1. Therefore, the key to producing high-coercivity sintered magnets of these materials is to prepare a high-coercivity powder as the raw powder.

A sintered magnet is commonly produced from single crystal powder in order to align the crystalline orientation of the magnet with the axis of easy magnetization. Single crystal magnetic powders are previously prepared through a polycrystalline ingot casting process followed by a mechanical pulverizing process such as ball milling and jet milling. However, as shown in Figure 6, the coercivity of pulverized $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders is about 1 MA/m, which is significantly inferior to that of $\text{Nd}_2\text{Fe}_{14}\text{B}$ sintered magnets (up to 2 MA/m). The pulverized powders have a polygonal shape with sharp corners and surface damage

which are prone to the formation of reverse magnetic domains, resulting in low coercivity.

As an alternative to mechanical pulverization techniques, Nichia Corporation invented a chemical synthesis process for direct preparation of single crystal $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ fine powders based on a conventional reduction diffusion method, which had been used to synthesize coarse polycrystalline powders [11]. As shown in Figure 7, in this advanced reduction diffusion (RD) method, $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders are obtained by sequential H_2 -reduction and Ca-reduction of a complex oxide precursor prepared by a wet synthesis method. This process also includes a water washing step to remove CaO generated as a byproduct in Ca-reduction before the ammonia nitridation step. Because the powders are not pulverized, single crystal powders synthesized by this process have the features of spherical-shaped particles and high crystallinity. Kume et al. synthesized single crystal $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders with a size of 2 μm that significantly increased coercivity to 1.5 MA/m [11]. Nevertheless, further improvement of coercivity should be possible, as this is still only about 7% of the anisotropic magnetic field.

The coercivity of permanent magnets is well known to be dependent on particle size. That is, coercivity increases in inverse proportion to the logarithm of the square of the particle size [40]. This law should naturally apply to $\text{Sm}_2\text{Fe}_{17}\text{N}_3$, and in fact, pulverized $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders display particle size dependency of coercivity, as shown in Figure 6. Hirayama and Okada carried out a development project to reduce the synthesis temperature in the RD process for particle size refinement, and succeeded in reducing the synthesis temperature to 900°C from the conventional temperature of 1050°C [41,42]. As a result, the particle size was refined to the submicron size, as seen in Figure 8, and coercivity was improved by 1.85 MA/m due to the above-mentioned particle size dependency effect. As shown in Figure 8, the obtained powders have an equiaxed shape and narrow particle size distribution, which would also contribute to high coercivity.

Okada et al. found that a Sm-rich Sm-Fe phase forms on the surface of $\text{Sm}_2\text{Fe}_{17}$ particles in the Ca-

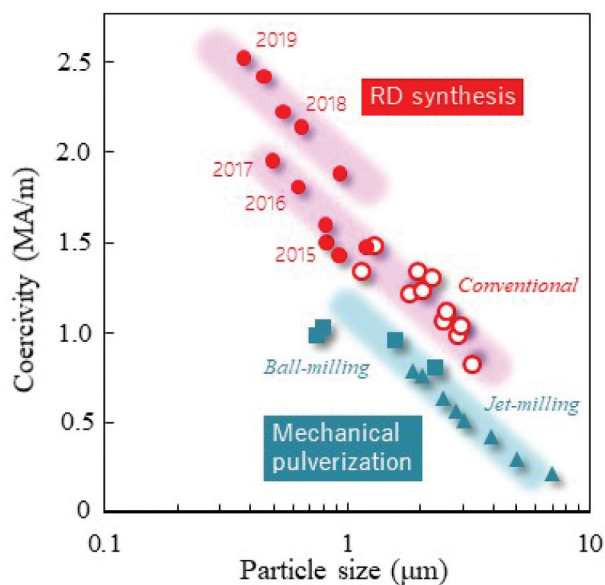


Figure 6. Dependencies of coercivity on particle size for $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ fine powders prepared by the mechanical pulverization and reduction diffusion methods [11,41–43].

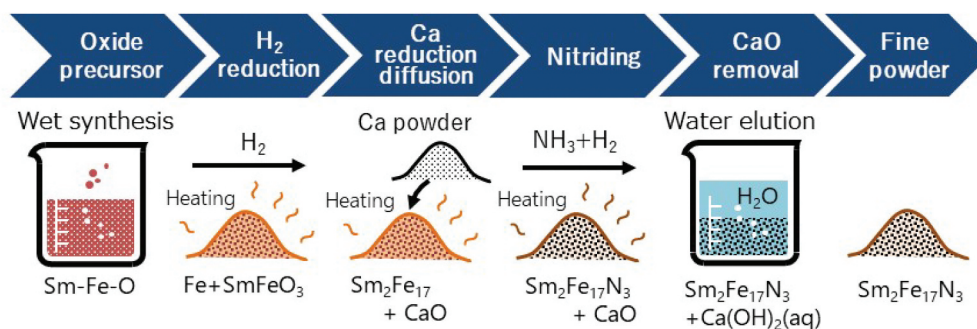


Figure 7. Direct reduction diffusion process for synthesizing $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ fine powder.

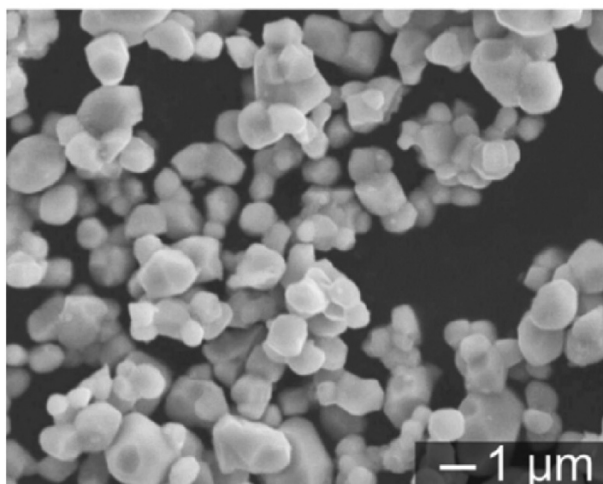


Figure 8. Scanning electron microscopy (SEM) micrograph of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ fine powder synthesized by reduction diffusion process [42].

reduction process and adversely affects coercivity [43], but gentle oxidation treatment before washing is effective to prevent the formation of this Sm-rich phase. This treatment successfully increased the level of particle size dependency of coercivity by 0.4 MA/m, which appears in Figure 7 as a sudden increase in coercivity from 2017 to 2018. At present, $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powder expresses coercivity of up to 2.55 MA/m [44], which is higher than that of state-of-the-art $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets such as hot-deformed magnets [45]. In recent years, KCl salt was mixed as a flux with the reductant Ca in order to dilute the density of reaction atoms in the reaction field, which suppresses particle growth and particle condensation. This new approach resulted in the development of a SmCo_5 powder with a huge coercive force of 5.7 MA/m [46].

As outlined above, the RD process is continuing to evolve year by year, and is expected to lead to powders with even huger coercivity for rare-earth magnets. However, it is not possible to avoid surface oxidation with powders prepared by the current RD process due to the water washing step. Thus, in order to apply RD powder as the raw powder for sintered magnets, it is necessary to develop a technique for suppressing surface oxidation.

3.2. Physical synthesis approaches for nanoparticles

Particle size refinement is very effective for improving coercivity, as indicated in the prior section. Particle size refinement is also expected to be effective for promoting sintering of low-sinterable materials such as $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ and metastable magnets. Therefore, preparation of nanosized particles of rare-earth magnets would overcome both the problems of coercivity and densification at once. Furthermore, nanoparticles of rare-earth magnets are expected to be applied as the

raw powder for hard phases in nanocomposite magnets, which are desired as an ultimate magnet [47].

Several reports have described efforts to prepare nanoparticles of rare-earth magnets. Hadjipanayis' group prepared SmCo_5 and $\text{Nd}_2\text{Fe}_{14}\text{B}$ nanoparticles with a particle size of less than 10 nm by surfactant-assisted ball milling, realizing coercivities of up to 1.48 and 0.3 MA/m, respectively [48,49]. The same group also successfully produced Sm-Co nanoparticles with a size of several nanometers by a physical synthesis approach using a cluster deposition method, but the obtained coercivity was very low [50].

Currently, Hirayama et al. are developing a new synthesis technique to produce rare-earth magnet nanoparticles using a thermal plasma method. In the thermal plasma method, raw coarse powder is evaporated in an induction plasma flame having a temperature of 10 000 K, as shown in Figure 9 [51,52], after which the metal vapor that emerges from the plasma flame due to the downdraft undergoes a nucleus generation/aggregation process and finally forms nanoparticles. Here, the nanodroplets emitted from the plasma flame solidify under ultra-fast quenching at 10^5 K/s. Since this cooling rate is close to that of melt-spinning (10^4 to 10^6 K/s) [53], metastable phase nanoparticles can also be expected. When producing easily oxidizable rare-earth alloy nanoparticles, it is essential to avoid exposure to even a small amount of oxygen.

Previous study demonstrated that it is possible to prevent surface oxidation of nanoparticles by covering part of the thermal plasma device with a glovebox to create an extremely low-oxygen atmosphere [54]. Figure 10 shows an example of the rare-earth magnet

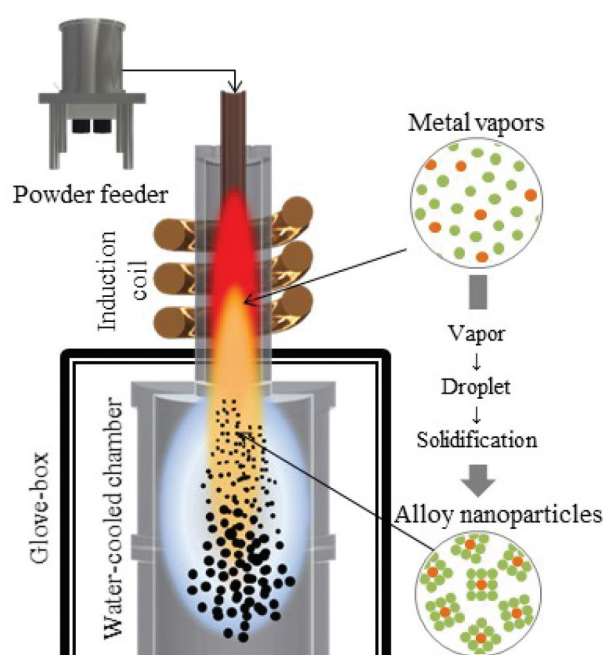


Figure 9. Schematic of low-oxygen thermal plasma system for synthesizing rare-earth magnet powders [54].

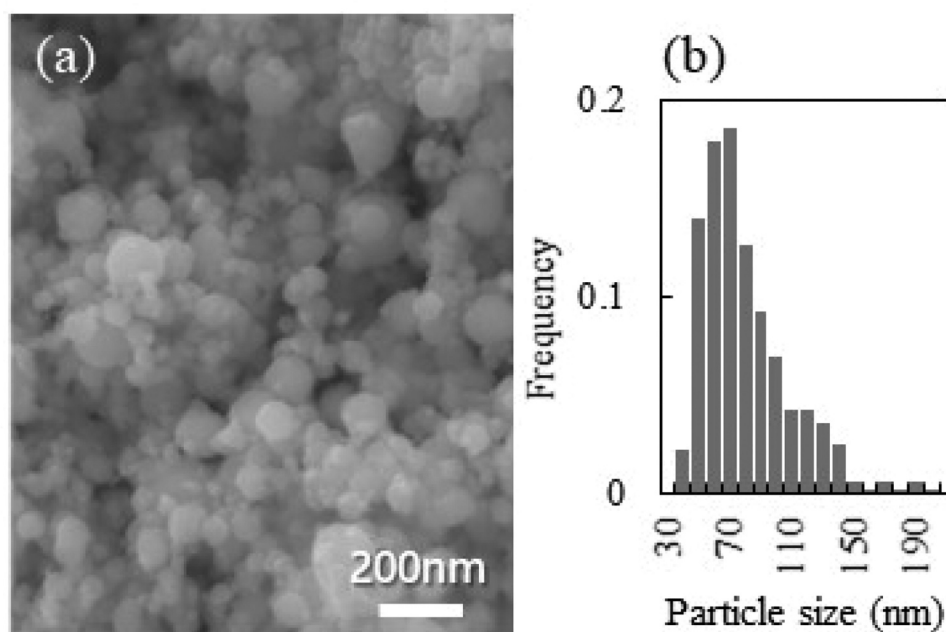


Figure 10. Sm-Co nanoparticles synthesized by low-oxygen thermal plasma system. (a) SEM image and (b) particle size distribution [59].

nanoparticles synthesized by this method, in this case, Sm-Co alloy nanoparticles having an average particle size of 70 nm. In addition, nanoparticles of Y-Fe, Nd-Fe, and Sm-Fe alloys have been also produced. In particular, synthesis of metastable phase nanoparticles of a TbCu_7 type alloy has been confirmed [55].

4. Summary

$\text{Sm}_2\text{Fe}_{17}\text{N}_3$ and metastable materials such as TbCu_7 type compounds have attracted attention as alternatives to $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets, but in order to realize practical magnets of these materials, it is necessary to overcome process-related problems such as the difficulty of sintering and low coercivity. Various powder preparation and powder metallurgy approaches have been attempted to overcome these problems. Although efforts to develop a sintering technique for $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ have struggled against thermal decomposition and coercivity deterioration for many years, low-oxygen powder metallurgy approaches for overcoming coercivity deterioration have been discovered recently, opening up the possibility of realizing $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ sintered magnets. However, a high-coercivity powder is required for production of sintered magnets of these magnetic materials because liquid phase sintering is not possible. As new fine powder preparation techniques, chemical and physical synthesis approaches such as reduction diffusion and thermal plasma processes are being developed, with results surpassing the conventional mechanical pulverization process. In particular, the reduction diffusion process enables direct production of high-quality fine powders of

$\text{Sm}_2\text{Fe}_{17}\text{N}_3$ which exhibit a huge coercivity of 2.5 MA/m.

Thus, the development of new powder processes is creating the high coercive $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ powders and bulk magnets which have been difficult so far. In addition, these new processes can also be expected to be applied to metastable TbCu_7 -type magnets. On the other hand, problems such as insufficient sintering densification still remain to be solved, but the challenge of a new powder process is expected to open up new paths for high-performance rare-earth permanent magnets.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributor

Kenta Takagi is a senior researcher at the National Institute of Advanced Industrial Science and technology. He obtained his bachelor's degree and master's degree in Materials Science from Tohoku University in 1995 and 1997, respectively. Later he obtained his Doctor of Engineering from Tohoku University in 2003. His latest research interests revolve around permanent magnets. In particular, he is motivated in studying on powder processing for lowsinterable and metastable magnetic alloys.

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