Comparison of microstructure and magnetic properties of gas-atomized and melt-spun MRE-Fe-Co-M-B (MRE=Y+Dy+Nd,M=Zr+TiC).

Tang, W.; Wu, Y. Q.; Dennis, K. W.; Kramer, M. J.; Anderson, I. E.; McCallum, R. W

Journal of Applied Physics (2007), 101(9, Pt. 2), 09K510/1-09K510/3

An MRE2(Fe,Co)14B alloy with Zr substitution and TiC additions was systematically studied. It was found by x-ray diffraction, TEM and magnetic measurements that the combination of Zr substitution and TiC addn. yields adequate microstructural control in both gas atomization (GA) and melt spinning (MS) techniques. For MS ribbons, an Hcj of 11.7 kOe and (BH)max of 11.9 MGOe at 27° were obtained in the ribbons spun at 16 m/s and annealed at 700° for 15 min. For GA powders, an Hcj of 9.1 kOe and (BH)max of 9.2 MGOe at 27° were obtained in 20-25 μm GA powder annealed at 700° for 15 min. The temperature coefficients of Br and Hcj are 0.06 and 0.36%/°C for the MS ribbon and 0.09 and 0.4%/°C for the GA powder at 27-100°, resp. TEM images revealed that the MS ribbon consists of a fine and uniform microstructure with an average size of 30 nm, while the GA spherical powder consists of an interior coarsened microstructure with a grain size of 80 nm and a rim area with a grain size of 10 nm.

Microstructural and magnetic studies of gas atomized powder and melt spun ribbon for improved MRE2Fe14B.

Sokolowski, P. K.; Anderson, I. E.; Tang, W.; Wu, Y. Q.; Dennis, K. W.; Kramer, M. J.; McCallum, R. W.

Advances in Powder Metallurgy & Particulate Materials (2006), 9/152-9/167

Rapid solidification of novel mixed rare earth-iron-boron (MRE2Fe14B) alloys via high pressure gas atomization (HPGA) can promote similar properties and structures as closely related alloys produced by melt spinning at low wheel speeds. Recent additions of titanium carbide and zirconium to the permanent magnet (PM) alloy design in HPGA powder (using He atomization gas) have made it possible to achieve highly refined microstructures with magnetic properties approaching melt spun particulate at cooling rates of 105-106K/s. By producing HPGA powders with the desirable qualities of melt spun ribbon, the need for crushing ribbon is eliminated. The spherical geometry of HPGA powders is more ideal for processing of bonded permanent magnets since higher loading fractions can be obtained during compression and injection molding. This increased vol. loading of spherical PM powder can yield a higher maximum energy product (BH)max for magnets to be used in high performance applications.

Microanalytical characterization of multi-rare-earth nanocrystalline magnets by transmission electron microscopy and atom probe tomography.

Wu, Y. Q.; Tang, W.; Miller, M. K.; Anderson, I. E.; McCallum, R. W.; Dennis, K. W.; Kramer, M. J.

Journal of Applied Physics (2006), 99(8, Pt. 2), 08B515/1-08B515/3.

The partitioning behavior of various rare-earth (RE) elements during solidification and their segregation behavior at the grain boundaries were studied in nanocrystaline (Y0.5Dy0.5)2.2Fe14B and (Nd0.5Y0.25Dy0.25)1.8Zr0.4Co1.5Fe12.5B alloys by TEM and atom probe tomog. The best hard magnetic properties obtained are Hcj = 22 kOe, Br = 5.10 kG, and (BH)max=5.97 MG Oe for the Y-Dy-based alloy and Hcj = 10.6 kOe, Br = 6.64 kG, and (BH)max=9.56 MG Oe for the Y-Nd-Dy based alloy. The grain size of the Y-Dy based alloy was .apprx.50 nm. The Y-Nd-Dy based alloy had an overall finer, bimodal grain size. An intergranular (Y0.36Dy0.64)6Fe23 phase was detected in the Y-Dy based alloy. A uniform distribution of RE elements was found within the 2-14-1 grains in both alloys. The Y:(Dy+Nd) ratio in the Y-Nd-Dy alloy was lower than its nominal composition, indicating that the Y is segregating to grain boundaries or forming a 2nd phase.

Effect of TiC addition on microstructure and magnetic properties for MRE2(Fe,Co)14B melt-spun ribbons (MRE=Nd+Y+Dy).

Tang, W.; Wu, Y. Q.; Dennis, K. W.; Kramer, M. J.; Anderson, I. E.; McCallum, R. W.

Journal of Applied Physics (2006), 99(8, Pt. 2), 08B510/1-08B510/3.

Effects of a TiC addn. on microstructure and magnetic properties in [MRE2.2Fe14B](100-2x)/17.2+TixCx(MRE=Nd+Y+Dy,x = 1-5) ribbons, melt spun at a wheel speed of 16 m/s, were systematically studied. X-ray diffraction and DTA data revealed that the addn. of TiC improves the glass formability in the mixed rare earth alloys without Co, resulting in partially amorphous alloys. TEM observations showed that the av. grain size in the as spun samples decreases from 200 to 20 nm with increasing x from 1 to 5, confirming that the addn. of TiC can significantly improve microstructure. For an optimized [MRE2(Fe,Co)14B](100-2x)/17.2+TixCx sample with x = 2, spun at 25 m/s and annealed at 750° for 15 min, the room-temperature magnetic properties of Hcj = 11.8 kOe, Mr = 7.2 kGs, and (BH)max=11.3 MGOe were obtained. Temperature coefficients for Mr and Hcj of -0.06 and -0.37%/°C, respectively, also were measured at 27-100°. The new magnet alloy exhibits more uniform magnetic properties and a usable energy product to nearly 300°.

Effect of Zr substitution on microstructure and magnetic properties of YDy-based R2Fe14B magnets (R=Y+Dy+Nd).

Tang, W.; Wu, Y. Q.; Dennis, K. W.; Kramer, M. J.; Anderson, I. E.; McCallum, R. W,

Journal of Applied Physics (2005), 97(10, Pt. 2), 10H106/1-10H106/3.

The effect of Zr substitution on the microstructure and magnetic properties in [Nd0.5(YDy)0.25]2.2-xZrxCo1.5Fe12.5B (x = 0-0.7) ribbons melt spun at a wheel speed of 10 m/s was systematically studied. For as-spun Zr-free ribbon, a coercivity, Hcj, of 15.5 kOe was obtained but the demagnetization curve exhibits a large shoulder, resulting in a very low maximum energy product (BH)max(3 MGOe). With increasing Zr content (x), Hcj 1st decreases and then increases. When x = 0.4, both Hcj and (BH)max reach their optimized values of 10.6 kOe and 9.6 MGOe, resp. The Hcj and (BH)max for the sample at 200° are 5 kOe and 4.3 MGOe, respectively. TEM characterizations show that the av. grain size is 200, 65, and 50 nm for x = 0, 0.4, and 0.7, resp., indicating that the substitution of Zr can effectively inhibit grain growth. However, an excessive substitution of Zr results in the appearance of the 2:17 phase and thus the reduction of magnetic properties.

New YDy-based R2(Fe,Co)14B melt-spun magnets (R=Y+Dy+Nd).

Tang, W.; Dennis, K. W.; Kramer, M. J.; Anderson, I. E.; McCallum, R. W.
Materials Science Forum (2005), 475-479(Pt. 3, PRICM 5: The Fifth Pacific Rim International Conference on Advanced Materials and Processing, 2004), 2155-2160

The effects of the ratio of Y to Dy as well as the effect of Nd and Co substitutions on magnetic properties in [Ndx(YDy)0.5(1-x)]2.2Fe14-yCoyB ribbons melt-spun at 22 m/s have been systematically studied. (Y1-zDyz)2.2Fe14B ribbons with a ratio z of 0.25 or 0.5 simultaneously obtains a smaller temperature coefficient of remanence (α) and coercivity (β) which are much smaller than those of Nd-based Nd2Fe14B ribbons. In [Ndx(YDy)0.5(1-x)]2.2Fe14-yCoyB ribbons, Nd substitution (x=0 to 0.8) can improve the max. energy product (BH)max of annealed ribbons but degrades the temperature stability of the magnetic properties. The ribbons with x=0.4 and y=0 yield a (BH)max of 8.7 MGOe.

For these ribbons, the α and β are -0.07 and -0.31%/°C in the temp. range of 27 to 127°C, resp. Increasing Co (x) from 0 to 3, slightly decreases coercivity Hcj from 21.5 to 16.3 kOe, but keeps the (BH)max in the range of 8.6 to 10.2 MGOe. The optimal sample with x=0.5 and y=1.5 obtains a (BH)max of 10.2 and 5.0 MGOe at 27 and 250°C, resp. Its α and β are -0.11 and -0.30 %/°C, resp. These results show that studied ribbons are very promising to develop into high temp. isotropic bonded magnets capable of operating at or above 180°C.

Studies of new YDy-based R2Fe14B magnets for high temperature performance (R= Y + Dy + Nd).

Tang, W.; Dennis, K. W.; Wu, Y. Q.; Kramer, M. J.; Anderson, I. E.; McCallum, R. W.

IEEE Transactions on Magnetics (2004), 40(4, Pt. 2), 2907-2909

The effect of Nd substitution on microstructure and magnetic properties in [Ndx(YDy)0.5(1-x)]2.2Fe14B ribbons melt-spun at 22 m/s was systematically studied. As-spun ribbons with low Nd content consist of 2:17 and 2:14:1 phases in an amorphous matrix, while as-spun ribbons with high Nd contain 2:14:1 and Fe phases in the amorphous matrix. After annealing at 700° for 15 min, all of the ribbons exhibit only a single 2:14:1 phase in their x-ray diffraction patterns. Nd substitution can improve the max. energy product of annealed ribbons but deteriorate the temp. stability of the ribbons. Increasing Nd (x) from 0 to 0.8, decreases coercivity from 22 to 13.5 kOe, but increases the maximum energy product from 5.87 to 11.2 MGOe. The temperature coefficients for remanence and coercivity increase from -0.045° to -0.106 %/°C, and -0.306 to -0.38 %/°C, respectively for the same substitution range. Transmission electron microscope microstructures show that the samples with less Nd content exhibit a more uniform distribution of grains. Their av. grain size is .apprx.40 nm. The studied results show that the YDy-based R2Fe14B magnets are very promising for high-temperature performance.

Properties of polymer bonded permanent magnets made with melt-spun mixed rare earth iron boron.

Buelow, Nicholas L.; Anderson, Iver E.; McCallum, R. W.; Kramer, Matthew; Tang, Wei; Dennis, Kevin; Constantinides, Steve

Advances in Powder Metallurgy & Particulate Materials (2005), 10/308-10/319

Usage of neodymium-iron-boron permanent magnets in sintered and bonded form is growing rapidly as the price of raw materials has declined relative to alternatives. While sintered magnets offer the highest energy output, bonded magnets offer complex shape and magnetization patterns. Bonded magnets are also net shape and can often reduce subsequent assembly steps through insert and multi-component molding. With improvements to the constituent magnetic powders of polymer bonded magnets, useful energy products can be obtained. Of particular interest is the novel mixed rare earth iron boron system (MRE2Fe14B). Melt spun MRE2Fe14B ribbon can be crushed in an inert environment creating a fine powder that is suitable for polymer bonding. Environmental testing will give insight into the robustness of the magnetic properties and the effect of surface coatings during short and long term exposure to elevated temp.

Microstructure and magnetic properties of gas atomized powders of mixed rare earth iron boron.

Buelow, Nicholas L.; Anderson, Iver E.; McCallum, R. W.; Kramer, Matthew; Tang, Wei; Dennis, Kevin

Advances in Powder Metallurgy & Particulate Materials (2005), 9/74-9/88.

Novel mixed rare earth iron boron (MRE2Fe14B) permanent magnet alloys have the desirable ability to be gas atomized into powders with competitive magnetic properties. Current stoichiometric Nd2Fe14B permanent magnets (having high flux d.) are typically melt-spun to achieve the cooling rates necessary to create the amorphous or nanocryst. phases desired for permanent magnets. Gas atomized powders have a spherical shape which is preferred for polymer bonded magnets as compared to the flake geometry of melt-spun powder. The most beneficial magnetic property of MRE2Fe14B is the stabilization of coercivity, remanence and therefore energy product (BHmax) over a range of elevated operating temps. (>150°C). With the use of glass formers the microstructure can be modified creating a fine dendritic structure, microcrystaline structure, and amorphous structure depending on particle size. Similar to flake particulate, as-atomized powders often need annealing treatments to modify the microstructure for optimal magnetic properties.

Mixed rare earth iron boride powders for bonded isotropic permanent magnets.

Buelow, Nicholas L.; Anderson, Iver E.; McCallum, R. W.; Kramer, Matthew; Tang, Wei; Dennis, Kevin.

TMS Letters (2004), 1(5), 91-92

Bonded isotropic permanent magnets (BPMs) formed by injection or compression molding offer good corrosion resistance and net shape manufacturing. Substituting Y and Dy for Nd in Nd2Fe14B results in a mixed rare earth iron boride (MRE-Fe-B) for use in BPMs. MRE-Fe-B alloys exhibit decreased remanence and coercivity loss to temps. over 200°, in a marked improvement over Nd2Fe14B results. Since BHmax is improved by increasing the fill factor (f) of BPMs, which is directly proportional to f2, spherical powders with high fill factors are being explored. Gas atomization offers rapid solidification effects that promote glass formation or uniform fine microsegregation to the spherical particulate. Microstructures of MRE-Fe-B powders directly affect the magnetic properties of the BPMs.

Comparison of mixed rare earth iron boride gas atomized powders to melt spun ribbon for bonded isotropic permanent magnets.

Buelow, Nicholas L.; Anderson, Iver E.; McCallum, R. W.; Kramer, Matthew; Tang, Wei; Dennis, Kevin.

Advances in Powder Metallurgy & Particulate Materials (2004), 10/230-10/243.

Bonded isotropic permanent magnets (BPMs) formed by injection or compression molding offer good corrosion resistance and the capability for net shape manufacturing. Substituting Y and Dy for Nd in Nd2-Fe14B results in a mixed rare earth iron boride (MRE-Fe-B) for use in BPMs. Microstructures of MRE-Fe-B powders directly affect the magnetic properties of the BPMs. Melt spinning was used to process Nd-Fe-B alloys to achieve the necessary grain structure to maximize the magnetic properties. Due to the plate-like particulate that results from melt spinning the max. energy product may not exceed that achieved by spherical powders in an injection molded bonded magnet due to polymer compd. viscosity and fill factor considerations. Producing spherical powders allows for a higher fill factor, increasing the max. energy product. Gas atomization offers rapid solidification effects that promote glass formation or uniform fine microsegregation to the particulate and produces spherical particles. Comparisons of melt spun and gas atomized MRE-Fe-B powder will be discussed.

Particulate processing and properties of high-performance permanent magnets.

Anderson, Iver E.; Tang, Wei; McCallum, R. William

International Journal of Powder Metallurgy (Princeton, New Jersey) (2004), 40(6), 37-60.

A review. High-performance permanent magnets (HPPM) are based on several intermetallic compounds of rare earth and transition metals, along with metalloid additions. This review will focus on magnetic materials based on Sm-Co ($SmCo_5$ and Sm_2Co_{17}) and $Nd_2Fe_{14}B$ intermetallics, the most known and well-commercialized representatives. These useful compdounds generally have extremely high crystallographic anisotropy and are brittle. Not generally acceptable properties for most metallurgical applications. However, their outstanding intrinsic magnetic properties and well-tailored microstructures were developed from extensive work on alloy design and advanced materials processing methods and prospects for their continued com. development are strong. This review 1st gives a brief introduction to the basics of ferromagnetism to provide an understanding for the design foundations of HPPM materials. Next, the complex relations between processing methods, resulting microstructures, and magnetic property responses will be examined for the two families of compounds cited. Brief descriptions of recent research activity in this field will also be presented.