

Description

Background of the invention

Permanent magnet materials are one of the important electric and electronic materials in wide ranges from various electric appliances for domestic use to peripheral terminal devices for large-scaled computers. In view of recent needs for miniaturization and high efficiency of electric and electronic equipment, there has been an increasing demand for upgrading of permanent magnet materials.

Major permanent magnet materials currently in use are alnico®, hard ferrite and rare earth-cobalt magnets. Recent advance in electronics has demanded particularly small-sized and light-weight permanent magnet materials of high performance. To this end, the rare earth-cobalt magnets having high residual magnetic flux densities and high coercive forces are being predominantly used.

However, the rare earth-cobalt magnets are very expensive magnet materials, since they contain costly rare earth such as Sm and costly cobalt in larger amounts of up to 50 to 60% by weight. This poses a grave obstacle to the replacement of alnico and ferrite for such magnets.

In an effort to obtain such permanent magnets, RFe base compounds were proposed, wherein R is at least one of rare earth metals. Regarding the following explanations, it is to be noted that the unit "1 G=10⁻⁴T", that the unit "1 Oe=0.0796 k·A/m" and that the unit "1 MGOe=7.96 kJ/m³". A. E. Clark discovered that sputtered amorphous TbFe had an energy product of 29.5 MGOe at 4.2 K, and shows a coercive force Hc=3.4 kOe and a maximum energy product (BH) max=7 MGOe at room temperature upon heat-treated at 300—500°C. Reportedly, similar studies of SmFe₂ indicated that 9.2 MGOe was reached at 77 K.

In addition, N. C. Koon et al discovered that, with melt-quenched ribbons of (Fe_{0.82}B_{0.18})_{0.9}Tb_{0.05}La_{0.05}, Hc of 9 kOe or more was reached upon annealed at about 875 K. However, the (BH) max of the obtained ribbons are then low because of the unsatisfactory loop rectangularity of the demagnetization curves thereof (N. C. Koon et al, Appl. Phys. Lett. 39(10), 1981, pp. 840—842, IEEE Transaction on Magnetics, Vol. MAG-18, No. 6, 1982, pp. 1448—1450).

Moreover, J. J. Croat and L. Kabacoff et al have reported that the ribbons of PrFe and NdFe compositions prepared by the melt-quenching technique show a coercive force of nearly 8 kOe at room temperature (L. Kabacoff et al, J. Appl. Phys. 53(3)1981, pp. 2255—2257; J. J. Croat IEEE Vol. 118, No. 6, pp. 1442—1447).

In JP—A—52-50598 a process for producing rare earth cobalt magnets consisting mainly of Sm, Co and an additional element by compacting and sintering at elevated temperatures is described, whereby the magnetic properties are improved.

In addition, JP—A—56-47538 discloses an improvement of the magnetic properties by adding Cu, Hf and B to the low rare earth (mainly Sm and/or Ce)-cobalt-type permanent magnet alloy.

In EP—A—101552 an alloy is disclosed which contains at least one stable compound of the ternary Fe-B-R type having a tetragonal structure and which can be magnetized to become a permanent magnet at room temperature or above. The process of preparing such alloy comprises melting and casting a special composition and in which the casting is pulverized to prepare a metallic powder having a mean particle size of 3—10 μm.

EP—A—106498 discloses a magnetic material comprising Fe, B, R and Co having a major phase of a Fe-Co-B-R intermetallic compound having a tetragonal, crystal structure, and wherein the process of preparing such magnetic material includes the pulverization of the crystalline product to 3—10 μm.

In EP—A—108474 high energy product melt-quenched rare earth transition metal magnet alloys are disclosed having high values of coercivity, remanence and energy product. The magnetic alloys are characterized by amorphous to very finely crystalline microstructures.

Melt-quenched ribbons or sputtered thin films are not any practical permanent magnets (bodies) that can be used as such, and it would be impossible to obtain therefrom practical permanent magnets. In other words, it is impossible to obtain bulk permanent magnets of any desired shape and size from the conventional melt-quenched ribbons based on FeB and sputtered thin films based on RFe. Due to the unsatisfactory loop rectangularity or squareness of the magnetization curves, the FeB base ribbons heretofore reported are not taken as any practical permanent magnets comparable with the ordinarily used magnets. Since both the sputtered thin films and the melt-quenched ribbons are magnetically isotropic by nature, it is indeed almost impossible to obtain therefrom any magnetically anisotropic permanent magnets of high performance (hereinafter called the anisotropic permanent magnets) for the practical purpose.

As mentioned above, many researchers have proposed various processes to prepare permanent magnets from alloys based on rare earth elements and iron, but none have given satisfactory permanent magnets for the practical purpose.

Summary of the invention

An object of the present invention is to provide processes for the production of rare earth-iron and rare earth-iron-cobalt practical permanent magnet materials.

Another object of the present invention is to provide a process for the production, of practical permanent magnet materials which possess good magnetic properties at room temperature or elevated



temperature, can be formed into any desired shape and size, and show good loop rectangularity of demagnetization curves as well as magnetic anisotropy or isotropy, and in which as R resourceful light rare earth elements can effectively be used. The invention is indicated in the independent claims 1 and 2.

The FeBR base magnetic materials can be obtained by preparing basic compositions consisting essentially of, in atomic ratio, 8 to 30% R representing at least one of rare earth elements inclusive of Y, 2 to 28% B and the balance being Fe with inevitable impurities, forming and compacting powders of those alloys having a particle size of 0.3 to 80 μm , and sintering said alloy powders under conditions such that said body is densified up to at least 95% of the theoretical density at a temperature of 900 to 1200°C in a reducing or non-oxidizing atmosphere.

The magnet materials in which as R, resourceful light rare earth elements such as Nd and/or Pr are mainly used, do not necessarily contain expensive Co, and show (BH)_{max} of as high as 36 MGOe or more exceeding by far the maximum value, (BH)_{max}=31 MGOe, of the conventional rare earth-cobalt magnets.

It has further been found that the compound magnets based on FeBR exhibit crystalline X-ray diffraction patterns distinguished entirely over those of the conventional amorphous thin films and melt-quenched ribbons, and contain as the major phase a crystal structure of the tetragonal system. In this respect, the disclosure in EP—A—101 552 is herewith incorporated. In accordance with the present invention, the Curie points of the magnet materials can be increased by the incorporation of Co in an amount of 50 at % or below. Furthermore, the magnetic properties of the magnet materials can be enhanced and stabilized by the incorporation of one or more of additional elements (M) in specific at %.

In the following the present invention will be described based on the accompanying Drawings which, however, are presented for illustrative purpose.

Brief description of the drawings

Fig. 1 is a graph showing changes of Br and iHc depending upon the amount of B (x at %) in a system of (85-x)Fe-xB-15Nd.

Fig. 2 is a graph showing changes of Br and iHc depending upon the amount of Nd (x at %) in a system of (92-x)Fe-8B-xNd.

Fig. 3 is a graph showing a magnetization curve of a 75Fe-10B-15Nd magnet.

Fig. 4 is a graph showing the relationship of the sintering temperature with the magnetic properties and the density for an Fe-B-R basic system.

Fig. 5 is a graph showing the relationship between the mean particle size (μm) of alloy powders and iHc (kOe) for Fe-B-R basic systems.

Fig. 6 is a graph showing the relationship between the Co amount (at %) and the Curie point T_c for a system (77-x)Fe-xCo-8B-15Nd.

Fig. 7 is a graph showing the relationship of the sintering temperature with the magnetic properties and the density for an Fe-Co-B-R system.

Fig. 8 is a graph showing the relationship between the mean particle size (μm) of alloy powders and iHc for Fe-Co-B-R systems.

Figs. 9—11 are graphs showing the relationship between the amount of additional elements M (x at %) and Br (kG) for an Fe-Co-B-M system.

Fig. 12 is a graph showing initial magnetization and demagnetization curves for Fe-B-R and Fe-B-R-M systems.

Fig. 13 is a graph showing the relationship of the sintering temperature with magnetic properties and the density for an Fe-B-R-M system.

Fig. 14 is a graph showing the relationship between the Co amount (x at %) and the Curie point T_c for Fe-Co-B-Nd-M systems.

Fig. 15 is a graph showing demagnetization curves typical Fe-Co-B-R and Fe-Co-B-R-M systems (abscissa H (kOe)).

Fig. 16 is a graph showing the relationship between the mean particle size (μm) and iHc (kOe) for an Fe-Co-B-R-M system.

Fig. 17 is a graph showing the relationship of the sintering temperature with the magnetic properties and the density for an Fe-Co-B-R-M system.

Detailed description of the preferred embodiments

The present invention will now be explained in detail. The present invention provides a process for the production of practical permanent magnets based on FeBR on an industrial scale.

In accordance with the present invention, the alloy powders of FeBR base compositions are first prepared.

While the present invention will be described essentially with respect to the anisotropic permanent magnets, it is understood that the present invention is not limited thereto, and can alike be applied to the isotropic permanent magnets.

As illustrated in Fig. 1 showing (85-x)Fe-xB-15Nd as an example, the amount of B to be used in the present invention should be no less than 2 at % in order to comply with a coercive force, iHc, of 1 kOe or more required for permanent magnets, and no more than 28% in order to exceed the residual magnetic flux density, Br, of hard ferrite which is found to be 4 kG. Hereinafter, % means atomic % unless otherwise



specified. The more the amount of R, the higher the iH_c and, hence, the more favorable results are obtained for permanent magnets. However, the amount of R has to be no less than 8% to allow iH_c to exceed 1 kOe, as will be appreciated from Fig. 2 showing $(92-x)Fe-8B-xNd$ as an example. However, the amount of R is preferably no more than 30%, since the powders of alloys having a high R content are easy to burn and difficult to handle due to the susceptibility of R to oxidation.

Boron B used in the present invention may be pure- or ferro-boron, and may also contain impurities such as Al, Si and C. As the rare earth elements represented by R use is made of one or more of light and heavy rare earth elements including Y. In other words, R includes Nd, Pr, La, Ce, Tb, Dy, Ho, Er, Eu, Sm, Gd, Pm, Tm, Yb, Lu and Y. The use of light rare earth as R may suffice for the present invention, but particular preference is given to Nd and Pr. The use of one rare earth element as R may also suffice, but admixtures of two or more elements such as mischmetal and didymium may be used due to their ease in availability and like factors. Sm, Y, La, Ce, Gd may be used in combination with other rare earth elements, particularly Nd and/or Pr. The rare earth elements R are not always pure elements, and may contain impurities which are inevitably entrained in the course of production, as long as they are commercially available.

As the starting materials alloys of any elements Fe, B and R may be used.

The permanent magnet materials permit the presence of impurities which are inevitably entrained in the course of production, and may contain C, S, P, Cu, Ca, Mg, O, Si, etc. within the predetermined limits. C may be derived from an organic binder, and S, P, Cu, Ca, Mg, O, Si and so on may originally be present in the starting materials or come from the course of production. Preferably the amounts of C, P, S, Cu, Ca, Mg, O and Si are respectively no more than 4.0%, 3.5%, 2.5%, 3.5%, 4.0%, 4.0%, 2.0% and 5.0%, with the proviso that the combined amount thereof shall not exceed the highest upper limit of the elements to be actually contained. These total limit is preferred to obtain, $(BH)_{max}$ of at least 4 MGOe. For higher $(BH)_{max}$, e.g., 20 MGOe, the limits are set, particularly for Cu, C and P, at each no more than 2%. It is noted in this connection that the amounts of P and Cu each are preferably no more than 3.3% in the case of the isotropic permanent magnets (materials) for obtaining $(BH)_{max}$ of 2 MGOe or more.

A composition comprising, by atomic percent, 8 to 30% R representing at least one of rare earth elements inclusive of Y, 2 to 28% B and the balance being Fe with inevitable impurities, provides permanent magnet materials with magnetic properties as expressed in terms of a coercive force, iH_c , of 1 kOe or more and a residual magnetic flux density, B_r , of 4 kG or more, and exhibit a maximum energy product, $(BH)_{max}$, on the order of 4 MGOe that is at least equivalent to that of hard ferrite or more. It is preferred that the permanent magnet materials comprises of 11 to 24% R composed mainly of light rare earth elements (namely, the light rare earth elements amount to 50% or more of the entire R), 3 to 27% B and the balance being Fe with impurities, since a maximum energy product, $(BH)_{max}$, of 7 MGOe or more is achieved. It is more preferred that the permanent magnet materials comprises 12 to 20% R composed mainly of light rare earth elements, 4 to 24% B and the balance being Fe with impurities, since a maximum energy product, $(BH)_{max}$, of 10 MGOe or more is then obtained. Still more preferred is the amounts of 12.5–20% R and 4–20% B for $(BH)_{max}$ of 20 MGOe or more, most preferred is the amounts of 13–19% R and 5–11% B for $(BH)_{max}$ of 30 MGOe or more.

The permanent magnet materials are obtained as sintered bodies, and the process of their preparation essentially involves powder metallurgical procedures.

Typically, the magnetic materials may be prepared by the process constituting the preceding stage of the forming and sintering process for the preparation of the permanent magnets of the present invention. For example, various elemental metals are melted and cooled under such conditions that yield substantially crystalline state (no amorphous state), e.g., cast into alloys having a tetragonal system crystal structure, which are then finely ground into fine powders.

As the magnetic material use may be made of the powdery rare earth oxide R_2O_3 (a raw material for R). This may be heated with, e.g., powdery Fe, powdery FeB and a reducing agent (Ca, etc.) for direct reduction (optionally also with powdery Co). The resultant powder alloys show a tetragonal system as well.

In view of magnetic properties, the density of the sintered bodies is preferably 95% or more of the theoretical density (ratio). As illustrated in Fig. 4, for instance, a sintering temperature of from 1060 to 1160°C gives a density of 7.2 g/cm³ or more, which corresponds to 96% or more of the theoretical density. Furthermore, 99% or more of the theoretical density is reached with sintering of 1100 to 1160°C. In Fig. 4, although density increases at 1160°C, there is a drop of $(BH)_{max}$. This appears to be attributable to coarser crystal grains, resulting in a reduction in the iH_c and loop rectangularity ratio.

Referring to (anisotropic) 75Fe-10B-15Nd typical of the magnetic materials based on FeBR, Fig. 3 shows the initial magnetization curve 1 and the demagnetization curve 2 extending through the first to the second quadrant. The initial magnetization curve 1 rises steeply in a low magnetic field, and reaches saturation, and the demagnetization curve 2 has very high loop rectangularity. It is thought that the form of the initial magnetization curve 1 indicates that this magnet is a so-called nucleation type permanent magnet, the coercive force of which is determined by nucleation occurring in the inverted magnetic domain. The high loop rectangularity of the demagnetization curve 2 exhibits that this magnet is a typical high-performance magnet.

For the purpose of reference, there is shown a demagnetization curve 3 of a ribbon of a 70.5Fe-15.5B-7Tb-7La amorphous alloy which is an example of the known FeBR base alloys. (660°C×15 min



heat-treated. J. J. Beckev IEEE Transaction on Magnetics Vol. MAG-18 No. 6, 1982, p1451—1453). The curve 3 shows no loop rectangularity whatsoever.

To enhance the properties of the permanent magnet materials resulting from the present invention, the process of their preparation is essential.

The process of the present invention will now be explained in further detail.

In general, rare earth metals are chemically so vigorously active that they combined easily with atmospheric oxygen to yield rare earth oxides. Therefore, various steps such as melting, pulverization, forming (compacting), sintering, etc. have to be performed in a reducing or non-oxidizing atmosphere.

First of all, the powders of alloys having a given composition are prepared. As an example, the starting materials are weighed out to have a given composition within the above-mentioned compositional range, and melted in a high-frequency induction furnace or like equipment to obtain an ingot which is in turn pulverized. Obtained from the powders having a mean particle size of 0.3 to 80 μm , the magnet has a coercive force, iH_c , of 1 kOe or more (Fig. 5). A mean particle size below 0.3 μm is unpreferable for the stable preparation of high-performance products from the permanent magnet materials, since oxidation then proceeds so rapidly that difficulty is encountered in the preparation of the end alloy. On the other hand, a mean particle size exceeding 80 μm is also unpreferable for the maintenance of the properties of permanent magnet materials, since iH_c then drops to 1 kOe or below. When a mean particle size of from 40 to 80 μm is applied, there is a slight drop of iH_c . Thus, a mean particle size of from 1.0 to 20 μm is most preferable to obtain excellent magnetic properties. Two or more types of powders may be used in the form of admixtures for the regulation of compositions or for the promotion of intimation of compositions during sintering, as long as they are within the above-mentioned particle size range and compositional range.

Also the ultimate composition may be obtained through modification of the base Fe-B-R alloy powders by adding minor amount of the componental elements or alloys thereof. This is applicable also for FeCoBR-, FeBRM-, and FeCoBRM systems wherein Co and/or M are part of the componental elements. Namely, alloys of Co and/or M with Fe, B and/or R may be used.

It is preferable that pulverization is of the wet type using a solvent. Used to this end are alcoholic solvents, hexane, trichloroethane, xylenes, toluene, fluorine base solvents, paraffinic solvents, etc.

Subsequently, the alloy powders having the given particle size is compacted preferably at a pressure of 4.9×10^7 to 78.5×10^7 Pa (0.5 to 8 ton/cm²). At a pressure of below 4.9×10^7 Pa (0.5 ton/cm²), the compacted mass or body has so insufficient strength that the permanent magnet to be obtained therefrom is practically very difficult to handle. At a pressure exceeding 78.5×10^7 Pa (8 ton/cm²), the formed body has so increased strength that it can advantageously be handled, but some problems arise in connection with the die and punch of the press and the strength of the die, when continuous forming is performed. However, it is noted that the pressure for forming is not critical. When the materials for the anisotropic permanent magnets are produced by forming-under-pressure, the forming-under-pressure is usually performed in a magnetic field. In order to align the particles, it is then preferred that a magnetic field of about 7 to 13 kOe is applied. It is noted in this connection that the preparation of the isotropic permanent magnet materials is carried out by forming-under-pressure without application of any magnetic field.

The thus obtained formed body is sintered up to at least 95% of the theoretical density thereof. Preferably sintering is effected at a temperature of 900 to 1200°C, preferably 1000 to 1180°C.

When the sintering temperature is below 900 degrees C, it is difficult to obtain the sufficient density required for permanent magnet materials and the given magnetic flux density. A sintering temperature exceeding 1200 degrees C is unpreferable, since the sintered body deforms and the particles mis-align, thus giving rise to decreases in both the residual magnetic flux density, B_r , and the loop rectangularity of the demagnetization curve. A sintering period of 5 minutes or more gives good results. Preferably sintering period ranges from 15 minutes to 8 hours. The sintering period is determined considering the mass productivity.

Sintering is carried out in a reducing or non-oxidizing atmosphere. For instance, sintering is performed in vacuum of 1.33 Pa (10^{-2} Torr), or in a reducing or inert gas of a purity of 99.9 mole % or more at 133.3 to 101325 Pa (1 to 760 Torr). When the sintering atmosphere used is an inert gas atmosphere, sintering may be carried out at a normal or reduced pressure. However, sintering may be effected in reducing atmosphere or inert atmosphere under a reduced pressure to make the sintered bodies more dense. Alternatively, sintering may be performed in a reducing hydrogen atmosphere to increase the sintering density. The magnetically anisotropic (or isotropic) permanent magnet materials having a high magnetic flux density and excelling in magnetic properties can be obtained through the above-mentioned steps. For one example of the correlations between the sintering temperature and the magnetic properties, see Fig. 4.

While the present invention has been described mainly with reference to the anisotropic magnet materials, the present invention is also applicable to the production of isotropic magnet materials. In this case, the isotropic materials are by far superior in various properties to those known so far in the art, although there is a drop of the magnetic properties, compared with the anisotropic materials.

It is preferred that the isotropic permanent magnet materials comprise alloy powders consisting of 10 to 25% R, 3 to 23% B and the balance being Fe with inevitable impurities, since they show preferable properties.

The term "isotropic" means that the magnet materials are substantially isotropic, i.e., in a sense that no magnetic fields are applied during forming. It is thus understood that the term "isotropic" includes any



magnet materials exhibiting isotropy as by pressing. As is the case with the anisotropic magnet materials, as the amount of R increases, iH_c increases, but B_r decreases upon showing a peak. Thus the amount of R ranges from 10 to 25% inclusive to comply with the value of $(BH)_{max}$ of 2 MGOe or more which the conventional isotropic magnets of alnico or ferrite. As the amount of B increases, iH_c increases, but $(BH)_{max}$ decreases upon showing a peak. Thus the amount of B ranges from 3 to 23% inclusive to obtain $(BH)_{max}$ of 2 MGOe or more.

The isotropic permanent magnets show high magnetic properties exemplified by a high $(BH)_{max}$ on the order of 4 MGOe or more, if comprised of 12 to 20% R composed mainly of light rare earth (amounting to 50 at % or more of the entire R), 5 to 18% B and the balance being Fe. It is most preferable that the permanent magnets comprised of 12 to 16% R composed mainly of light rare earth such as Nd and Pr, 6 to 18% B and the balance being Fe, since it is then possible to obtain the highest properties ever such as $(BH)_{max}$ of 7 MGOe or more.

The present invention will now be explained in the following non-restrictive examples.

The samples used in the examples were generally prepared by the following steps.

(1) The starting rare earth used had a purity, by weight ratio, of 99% or higher and contained mainly other rare earth metals as impurities. In this disclosure, the purity is given by weight. As iron and boron use was made of electrolytic iron having a purity of 99.9% and ferroboration containing 19.4% of B and as impurities Al and Si, respectively. The starting materials were weighed out to have the predetermined compositions.

(2) The raw material for magnets was melted by high-frequency induction. An alumina crucible was then used. The obtained melt was cast in a water-cooled copper mold to obtain an ingot.

(3) The thus obtained ingot was crushed to -0.42 mm (-35 mesh), and subsequently finely divided in a ball mill until powders having a particle size of 0.3 to 80 μ m were obtained.

(4) The powders were compacted at a pressure of 4.9×10^7 to 78.5×10^7 Pa (0.5 to 8 ton/cm²) in a magnetic field of 7 to 13 kOe. However, no magnetic field was applied in the case of the production of isotropic magnets.

(5) The compacted body was sintered at a temperature of 900 to 1200°C in a reducing gas or inert gas atmosphere, or in vacuum for 15 minutes to 8 hours.

The embodiments of the sintered bodies obtained through above-mentioned steps are shown in Table

1.

As will be understood from the embodiments, the FeBR base permanent magnets of high performance and any desired size can be prepared by the powder metallurgical sintering procedures according to the present invention. It is also possible to attain excellent magnetic properties that are by no means obtained through the conventional processes such as sputtering or melt-quenching. Thus, the present invention is industrially very advantageous in that the FeBR base high-performance permanent magnets of any desired shape can be prepared inexpensively.

These FeBR base permanent magnets have usually a Curie point of about 300°C and reaching 370°C at most, as disclosed in EP—A—101 552. However, it is still desired that the Curie point be further enhanced.

As a result of detailed studies, it has further been found that the temperature-depending properties of such FeBR base magnets can be improved by adding Co to the permanent magnet materials based on FeBR ternary systems, provided that they are within a constant compositional range and produced by the powder metallurgical procedures under certain conditions. In addition, it has been noted that such FeBR base magnets do not only show the magnetic properties comparable with, or greater than, those of the existing alnico®, ferrite and rare earth magnets, but can also be formed into any desired shape and practical size.

In general, Co additions to alloy systems incur complicated and unpredictable results in respect of the Curie point and, in some cases, may bring about a drop of that point. The Curie points of the FeBR base alloys (magnets) can be increased by substituting a part of the iron, a main component thereof, with Co (refer to Fig. 6).

In the FeBR base alloys, similar tendencies were observed regardless of the type of R. Even when used in a slight amount of, e.g., 1%, Co serves to increase T_c . Alloys having any T_c ranging from about 300 to 750°C can be obtained depending upon the amount of Co to be added. (The Co incorporation provides similar effect in the FeCoBRM system, see Fig. 14).

Due to the presence of Co, the temperature-depending properties equivalent with those of the existing alnico® and RCo base magnets and, moreover, offer other advantages. In other words, high magnetic properties can be attained by using as the rare earth elements R light rare earth such as resourceful Nd and Pr. For this reason, the Co-containing magnets based on FeBR are advantageous over the conventional RCo magnets from the standpoints of both resource and economy, and offer further excellent magnetic properties.

Whether anisotropic or isotropic, the present permanent magnets based essentially on FeBR can be prepared by the powder metallurgical procedures, and comprise sintered bodies.

Basically, the combined composition of B, R and (Fe+Co) of the FeCoBR base permanent magnets is similar to that of the FeBR base alloys (free from Co).

Comprising, by atomic percent, 8 to 30% R, 2 to 28% R, 50% or less Co and the balance being Fe with inevitable impurities, the permanent magnets show magnetic properties exemplified by a coercive force,



iHc, of 1 kOe or more and a residual magnetic flux density, Br, of 4 kG or more, and exhibit a maximum energy product, (BH)max, equivalent with, or greater than, 4 MGOe of hard ferrite.

Table 2 shows the embodiments of the FeCoBR base sintered bodies as obtained by the same procedures as applied to the FeBR base magnet materials, and Fig. 7 illustrates one embodiment for sintering.

Like the FeBR systems, the isotropic magnets based on FeCoBR exhibit good properties (see Figs. 2 to 6).

As stated in the foregoing examples, the FeCoBR base permanent magnets materials can be formed into high-performance permanent magnets of practical Curie points as well as any desired shape and size.

Recently, the permanent magnets have increasingly been exposed to severer circumstances—strong demagnetizing fields incidental to the thinning tendencies of magnets, strong inverted magnetic fields applied through coils or other magnets, and high temperatures incidental to high processing rates and high loading of equipment—and, in many applications, need to possess higher and higher coercive forces for the stabilization of their properties.

Owing to the inclusion of one or more of the aforesaid certain additional elements M, the permanent magnets based on FeBRM can provide iHc higher than do the ternary permanent magnets based on FeBR (see Fig. 12). However, it has been revealed that the addition of these elements M causes gradual decreases in residual magnetization, Br, when they are actually added. Consequently, the amount of the elements M should be such that the residual magnetization, Br, is at least equal to that of hard ferrite, and a high coercive force is attained.

To make clear the effect of the individual elements M, the changes in Br were experimentally examined in varied amounts thereof. The results are shown in Figs. 9 to 11. As illustrated in Figs. 9 to 11, the upper limits of the amounts of additional elements M (Ti, V, Nb, Ta, Cr, Mo, W, Al, Sb, Ge, Sn, Zr, Hf) other than Bi, Mn and Ni are determined such that Br equal to, or greater than, about 4 kG of hard ferrite is obtained. The upper limits of the respective elements M are given below:

4.5% Ti,	8.0% Ni,	5.0% Bi,
9.5% V,	12.5% Nb,	10.5% Ta,
8.5% Cr,	9.5% Mo,	9.5% W,
8.0% Mn,	9.5% Al,	2.5% Sb,
7.0% Ge,	3.5% Sn,	5.5% Zr,
and 5.5% Hf.		

Further preferable upper limits can clearly be read from Figs. 9 to 11 by dividing Br into several sections such as 6.5, 8, 9, 10 kG and so on. E.g., Br of 9 kG or more is necessary for obtaining (BH)max of 20 MGOe or more.

Addition of Mn and Ni in larger amounts decreases iHc, but there is no appreciable drop of Br due to the fact that Ni is a ferromagnetic element. For this reason, in view of iHc, the upper limit of Ni is 8%, preferably 6.5%.

The influence of Mn addition upon the decrease in Br is larger than the case with Ni, but not strong. In view of iHc, the upper limit of Mn is thus 8%, preferably 6%.

The upper limit of Bi is fixed at 5%, since it is indeed impossible to produce alloys having a Bi content of 5% or higher due to the high vapor pressure of Bi. In the case of alloys containing two or more of the additional elements, it is required that the sum thereof be no more than the maximum value (%) among the upper limits of the elements to be actually added.

Within the compositional range of FeBRM as mentioned above, for instance, the starting materials were weighed out to have a composition of 15 at % Nd, 8 at % B, 1 at % V and the balance being Fe, and melted into an ingot. The ingot was pulverized according to the procedures as mentioned above, formed at a pressure of 19.6×10^7 Pa (2 ton/cm²) in a magnetic field of 10 kOe, and sintered at 1080°C and 1100°C for 1 hour in an argon atmosphere of 2.66×10^4 Pa (200 Torr).

The relationship between the particle size of the powder upon pulverization and the coercive force, iHc, of the sintered body is substantially the same as illustrated in Fig. 5.

The results are shown in Table 3, from which it is found that the FeBRM base permanent magnet materials are industrially very advantageous in that they can be formed into the end products of high performance and any desired size by the powder metallurgical procedures according to the present invention, and can industrially be produced inexpensively in a stable manner.

It is noted that no magnets of high performance and any desired shape can be obtained by the prior art sputtering or melt-quenching.

According to another embodiment of the present invention, improvements in iHc are in principle intended by adding said additional elements M to FeCoBR quaternary systems as is the case for the FeBR ternary systems. The coercive force, iHc, generally decreases with increases in temperature, but, owing to the inclusion of M, the materials based on FeBR are allowed to have a practically high Curie point and, moreover, to possess magnetic properties equivalent with, or greater than, those of the conventional hard ferrite.



In the FeCoBRM quinary alloys, the compositional range of R and B are basically determined in the same manner as is the case with the FeCoBR quaternary alloys.

In general, when Co is added to Fe alloys, the Curie points of some alloys increase proportionately with the Co amount, while those of another drop, so that difficulty is involved in the prediction of the effect of Co addition.

When a part of Fe is substituted with Co, the Curie point increases gradually with increases in the amount of Co to be added, as illustrated in Fig. 14. Co is effective for increases in Curie point even in a slight amount. As illustrated in Fig. 14, alloys having any Curie point ranging from about 310 to about 750°C depending upon the amount of Co to be added.

When Co is added in an amount of 25% or less, it contributes to increases in Curie points of the FeCoBRM systems without having an adverse influence thereupon, like also in the FeCoBR system. However, when the amount of Co exceeds 25%, there is a gradual drop of (BH)max, and there is a sharp drop of (BH)max in an amount exceeding 35%. This is mainly attributable to a drop of iHc of the magnets. When the amount of Co exceeds 50%, (BH)max drops to about 4 MGOe of hard ferrite. Therefore, the critical amount of Co is 50%. The amount of Co is preferably 35% or less, since (BH)max then exceeds 10 MGOe of the highest grade alnico® and the cost of the raw material is reduced. Presence of Co 5% or more provides the thermal coefficient of Br of about 0.1%/°C or less. Co affords corrosion resistance to the magnets, since Co is superior in corrosion resistance to Fe.

Most of M serve to increase the Hc of the magnets based on both FeBRM and FeCoBRM systems. Fig. 15 illustrates the demagnetization curves of typical examples of the FeCoBRM magnets and the FeCoBR magnets (free from M) for the purpose of comparison. An increase in iHc due to the addition of M leads to an increase in the stability of the magnets, so that they can find use in wider applications. However, since M except Ni is non-magnetic elements, Br decreases with the resulting decreases in (BH)max, as the amount of M increases. Recently, there have been increasing applications for which magnets having slightly low (BH)max but high Hc are needed. Hence, M-containing alloys are very useful, as long as they possess (BH)max of 4 MGOe or higher.

To make clear the effect of the individual elements M, the changes in Br were experimentally examined in varied amounts thereof. The results are substantially similar with those curves for the FeBRM systems as shown in Figs. 9 to 11. As illustrated in Figs. 9 to 11, the upper limits of the amounts of M are principally determined such that Br of about 4 Kg equal to, or greater than, that of hard ferrite is obtained, as is the case for the FeBRM systems.

As seen from the foregoing examples, the FeCoBRM base permanent magnets can be formed into high-performance products of any desired size by the powder metallurgical procedures according to the present invention, and as will be appreciated from Fig. 7, no products of high performance and any desired shape can be obtained by the conventional sputtering or melt-quenching. Consequently, this embodiment is industrially very advantageous in that high-performance permanent magnets of any desired shape can be produced inexpensively.

The preferable ranges of B and R are also given as in the case of FeBR or FeBRM cases.

As the starting metallic powders for the forming (compacting) step, besides alloys with predetermined composition or a mixture of alloys of within such compositions, any elemental metal or alloys of the component elements including Fe, B, R, Co and/or additional elements M may be used for auxiliary material with a complementary composition making up the final compositions.

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TABLE 1

Alloy composition (at %)	Mean particle size (μm)	Pressing pressure ton/cm ² *** in magnetic field of 10 kOe ^a	Sintering atmosphere time	Sintering temperature							
				900°C		1040°C		1120°C		1180°C	
				density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b
(1) 72Fe8B20Nd	3.3	3	Ar atm.* pressure 1 h	6.0	9.5	7.1	23.5	7.4	26.0	7.4	22.0
(2) 77Fe9B9Nd5Pr	2.8	1.5	200 Torr** 4 h	6.1	10.8	7.1	24.7	7.4	31.0	7.3	24.1
(3) 77Fe7B16Pr	4.9	5	1×10 ⁻⁴ Torr** vacuum 2 h	5.7	10.0	7.1	24.5	7.3	22.0	7.3	10.5
(4) 79Fe7B14Nd	5.2	1.5	Ar atmosphere 1 h	5.8	13.5	7.1	31.0	7.4	33.8	7.4	25.5
(5) 68Fe17B15Nd	1.8	2	Ar 200 Torr** 2 h	5.8	6.2	7.2	16.5	7.3	19.0	7.3	15.5
(6) 77Fe8B15Nd	1.5	No magnetic field 2	Ar atmosphere 1 h	5.8	2.4	7.2	8.7	7.4	9.7	7.4	6.2

* 1 atm.=1.01×10⁵ Pa

** 1 Torr=133.3 Pa

*** 1 ton/cm²=9.81×10⁷ Pa^a 1 kOe=79.6 kA/m^b 1 MGOe=7.96 kJ/m³

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TABLE 2

Alloy composition (at %)	Mean particle size (μm)	Pressing pressure in magnetic field of 10 kOe ^a	Sintering atmosphere time	Sintering temperature							
				900°C		1040°C		1100°C		1160°C	
				density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b
(1) 71Fe-5Co-7B-17Nd	3.1	3	Ar atm.* pressure 1 h	6.0 (950°C)	13.0	7.3	30.1	7.4 (1080°C)	32.5	7.4	33.0
(2) 67Fe-10Co-9B-9Nd-5Pr	3.5	1.5	Ar 200 Torr** 4 h	6.0 (950°C)	11.5	7.3	29.5	7.4 (1080°C)	30.3	7.4	30.5
(3) 57Fe-20Co-10B-13Nd	5.2	1.5	Ar atmosphere 1 h	6.0	13.5	7.4	28.0	7.5	31.0	7.5 (1180°C)	31.5
(4) 65.5Fe-2.5Co-17B-15Nd	2.8	2	Ar 200 Torr** 2 h	6.0	6.5	7.2	16.8	7.3	19.5	7.3 (1180°C)	15.5
(5) 45Fe-30Co-10B-15Nd	1.5	2	Ar 200 Torr** 2 h	6.0	10.5	7.3	28.0	7.4	28.3	7.4 (1140°C)	27.5
(6) 67Fe-10Co-8B-15Nd	2.0	No magnetic field ²	Ar atmosphere 1 h	6.1	2.3	7.2	8.7	7.4	9.7	7.4 (1140°C)	6.2

for *, **, ***, ****, ^a, ^b see Table 1.

TABLE 3-1

Alloy composition (at %)	Mean particle size (μm)	Pressing pressure ton/cm ² *** in magnetic field of 10 kOe ^a	Sintering atmosphere time	Sintering temperature							
				900°C		1000°C		1080°C		1160°C	
				density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b
(1) 76Fe-8B-15Nd-1Ti	3	3	Ar atm.* pressure 2 h	6.0	14.1	6.8	24.8	7.4	33.2	7.4	34.0
(2) 73Fe-10B-15Nd-2V	5	1.5	vacuum 1x10 ⁻⁴ Torr** 1 h	5.9	11.3	6.7	21.0	7.3	28.0	7.4	28.0
(3) 76Fe-8B-15Nd-1Nb	2	2	Ar 200 Torr** 1 h	6.0	14.6	6.9	25.2	7.4	32.9	7.4	33.0
(4) 74Fe-8B-17Nd-1Ta	3	1.5	Ar atm.* pressure 3 h	6.1	10.8	7.0	23.5	7.6	29.5	7.6	29.0
(5) 75.5Fe-10B-14Nd-0.5Cr	2.8	2	vacuum 1x10 ⁻⁴ Torr** 4 h	5.9	12.0	6.9	25.0	7.45	32.5	7.5	33.0
(6) 76Fe-8B-15Nd-1Mo	3.5	3	Ar 60 Torr** 2 h	5.9	13.5	6.8	23.5	7.4	31.0	7.4	31.5
(7) 75.5Fe-7B-17Nd-0.5W	3.6	3	Ar atm.* pressure 1 h	6.1	10.8	7.0	24.0	7.5	28.5	7.5	28.0

for *, **, ***, ^a, ^b see Table 1.

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TABLE 3-2

Alloy composition (at %)	Mean particle size (μm)	Pressing pressure ton/cm ² *** in magnetic field of 10 kOe ^a	Sintering atmosphere time	Sintering temperature							
				900°C		1000°C		1080°C		1160°C	
				density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b
(8) 76Fe-9B-14Nd-1Mn	4.0	1.5	Ar 200 Torr** 2 h	5.9	12.4	6.9	23.6	7.45	29.0	7.5	29.5
(9) 76.5Fe-7B-16Nd-0.5Ni	4.0	2	1×10 ⁻⁴ Torr** vacuum 1 h	5.8	12.0	6.8	23.5	7.3	29.5	7.4	30.0
(10) 76Fe-8B-15Nd-1Al	2.5	1.5	Ar 400 Torr** 2 h	5.8	13.5	6.8	24.5	7.3	30.5	7.4	31.0
(11) 74.5Fe-9B-16Nd-0.5Ge	3.5	7.5	Ar atm.* pressure 2 h	5.8	10.8	6.7	19.5	7.2	25.5	7.4	27.0
(12) 76Fe-9B-14Nd-1Sn	4.0	2.5	Ar 60 Torr** 1 h	5.9	5.8	6.9	13.0	7.4	20.1	7.4	21.0
(13) 75Fe-9B-15Nd-1Sb	3.1	1.5	1×10 ⁻⁴ Torr** vacuum 1.5 h	5.8	8.5	7.0	13.0	7.4	20.5	7.4	20.5

for *, **, ***, ^a, ^b see Table 1.

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TABLE 3-3

Alloy composition (at %)	Mean particle size (μm)	Pressing pressure ton/cm ² *** in magnetic field of 10 kOe ^a	Sintering atmosphere time	Sintering temperature							
				900°C		1000°C		1080°C		1160°C	
				density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b
(14) 75Fe-7B-14Nd-1Bi	2.1	2.5	Ar 1 Torr** 0.5 h	5.9	13.2	6.9	25.0	7.4	31.8	7.4	32.0
(15) 76Fe-8B-15Pr-1Al	4.0	1.5	Ar 200 Torr** 2 h	5.9	8.4	6.8	15.0	7.4	25.5	7.4	15.0
(16) 73Fe-9B-15Nd-2Dy-1V	3.1	2	Ar 100 Torr** 1 h	6.1	12.5	7.0	23.0	7.5	27.7	7.6	25.0
(17) 76Fe-8B-15Nd-1Al	3.0	No magnetic field ³	Ar atm.* pressure 1.1 h	5.8	2.9	6.8	4.8	7.4	9.3	7.4	9.1

for *, **, ***, ^a, ^b see Table 1.

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TABLE 4-1

No.	Alloy composition (at %)	Mean particle size (μm)	Pressing condition		Sintering atmosphere (sintered for 1 h)
			Pressure (ton/cm ²)***	Magnetic field (kOe) ^a	
1	Fe-10Co-8B-15Nd-1Al	3.2	2	10	Ar, 200 Torr**
2	Fe-20Co-12B-16Nd-1Ti	2.4	1.5	8	Ar, atm.* pressure
3	Fe-2Co-8B-16Nd-2V	6.3	2.5	9	vacuum 1×10^{-4} Torr
4	Fe-20Co-8B-15Nd-1Cr	2.8	3	10	Ar, 60 Torr
5	Fe-2Co-8B-14Nd-0.5Mn	3.0	2	7	Ar, 200 Torr
6	Fe-5Co-8B-17Nd-1Zr	3.5	4.0	12	vacuum 1×10^{-4} Torr
7	Fe-20Co-13B-14Nd-0.3Hf	8.3	3.0	13	H ₂ , 0.1 Torr
8	Fe-35Co-7B-15Nd-3Nb	2.5	3.5	12	Ar, 200 Torr
9	Fe-10Co-8B-15Nd-1Ta	1.5	1.5	10	Ar, 460 Torr
10	Fe-2Co-8B-15Nd-1W	4.0	2.0	13	vacuum 1×10^{-4} Torr
11	Fe-20Co-13B-14Nd-1Mo	3.3	2.5	10	Ar, atm. pressure
12	Fe-20Co-8B-13Nd-0.3Ge	3.8	2	12	Ar, 200 Torr
13	Fe-10Co-9B-14Nd-0.5Sn	1.5	3	11	Ar, 1 Torr
14	Fe-5Co-8B-15Nd-0.2Bi	3	2.5	13	Ar, atm. pressure
15	Fe-5Co-8B-15Nd-1Ni	2.1	2.0	11	Ar, 0.1 Torr
16	Fe-10Co-9B-14Pr-1W	3.5	1.5	8	vacuum 1×10^{-4} Torr
17	Fe-5Co-7B-11Nd-4Dy-0.5Al	2.3	2.0	10	Ar, 200 Torr

for *, **, ***, ^a see Table 1.
Fe=balance Fe.

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TABLE 4-2

No.	Alloy composition (at %)	Sintering temperature								
		900°C			1000°C			1080°C		
		density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	density g/cm ³	(BH)max (MGOe) ^b	(BH)max (MGOe) ^b
1	Fe-10Co-8B-15Nd-1Al	5.8	12.5	6.8	20.6	7.4	31.6	7.4	30.2	30.2
2	Fe-20Co-12B-16Nd-1Ti	5.9	6.9	6.8	13.5	7.4	22.1	7.4	18.5	18.5
3	Fe-2Co-8B-16Nd-2V	5.7	8.0	6.8	14.0	7.4	24.0	7.3	23.5	23.5
4	Fe-20Co-8B-15Nd-1Cr	5.9	13.0	6.9	22.5	7.4	30.5	7.4	29.5	29.5
5	Fe-2Co-8B-14Nd-0.5Mn	5.8	7.3	6.8	15.8	7.4	25.5	7.4	25.3	25.3
6	Fe-5Co-8B-17Nd-1Zr	5.9	11.5	6.8	23.0	7.4	30.8	7.4	28.3	28.3
7	Fe-20Co-13B-14Nd-0.3Hf	5.8	9.5	6.9	17.3	7.5	25.4	7.4	24.2	24.2
8	Fe-35Co-7B-15Nd-3Nb	5.8	7.3	6.8	12.3	7.5	21.6	7.5	21.0	21.0
9	Fe-10Co-8B-15Nd-1Ta	5.7	13.5	6.7	23.5	7.5	31.5	7.5	30.8	30.8
10	Fe-2Co-8B-15Nd-1W	5.9	13.6	6.8	25.8	7.5	33.2	7.5	32.5	32.5
11	Fe-20Co-13B-14Nd-1Mo	5.8	12.8	6.9	15.9	7.4	25.4	7.4	24.1	24.1
12	Fe-20Co-8B-13Nd-0.3Ge	6.0	7.1	6.8	13.3	7.4	28.1	7.4	26.5	26.5
13	Fe-10Co-9B-14Nd-0.5Sn	5.9	8.1	6.8	13.8	7.4	26.1	7.4	24.0	24.0
14	Fe-5Co-8B-15Nd-0.2Bi	5.8	11.8	6.8	24.1	7.4	31.5	7.4	30.8	30.8
15	Fe-5Co-8B-15Nd-1Ni	5.8	8.9	6.7	15.8	7.4	25.3	7.4	25.0	25.0
16	Fe-10Co-9B-14Pr-1W	5.9	9.8	6.8	18.0	7.4	26.5	7.4	24.8	24.8
17	Fe-5Co-7B-11Nd-4Dy-0.5Al	5.8	10.3	7.0	18.5	7.6	24.8	7.6	24.3	24.3

for ^b see Table 1.
Fe=balance Fe.

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Claims

1. A process for producing permanent magnet materials of the Fe-B-R type comprising the steps of providing a composition comprising by atomic percent 8—30% R, wherein R is at least one of the rare earth elements including Y, 2—28% boron (B), and the balance being iron (Fe), melting said composition, cooling the resultant alloy, pulverizing it to prepare a metallic powder having a mean particle size of 0.3—80 μm , preferably 1—40 μm , most preferably 2—20 μm , mean particle sizes of 3—10 μm being excluded, compacting said metallic powder, and sintering the resultant body.

2. A process for preparing permanent magnet materials of the Fe-B-R type comprising by atomic percent 8—30% R, wherein R is at least one of the rare earth elements including Y, 2—28% boron (B), and the balance being iron (Fe), by heating a mixture of rare earth oxide and the other metallic materials with a reducing agent to reduce the rare earth oxide, pulverizing the obtained product to a metallic powder having a mean particle size of 0.3—80 μm , preferably 1—40 μm , most preferably 2—20 μm , mean particle sizes of 3—10 μm being excluded, compacting said metallic powder, and sintering the resultant body.

3. A process as defined in claim 1, wherein the sum of Nd and/or Pr amounts to no less than 50 at % of the overall rare earth elements R.

4. A process as defined in claim 1, wherein in said metallic powder Nd and/or Pr amounts to no less than 50 at % of the overall rare earth elements R and a part of the Fe is substituted for by Cobalt (Co), such that the powder comprises no more than 50 at % of Co.

5. A process as defined in one of the preceding claims, wherein said metallic powder optionally comprises at least one of additional elements M of no more than the values by atomic percent as specified hereinbelow provided that, when two or more elements M are added, the total amount thereof shall be no more than the largest value among said specified values of the elements actually added:

25	4.5% Ti,	8.0% Ni,	5.0% Bi,
	9.5% V,	12.5% Nb,	10.5% Ta,
	8.5% Cr,	9.5% Mo,	9.5% W,
	8.0% Mn,	9.5% Al,	2.5% Sb,
	7.0% Ge,	3.5% Sn,	5.5% Zr,
30	and 5.5% Hf.		

6. A process as defined in claim 1, wherein the cooling is done under such a condition as to yield substantially crystalline state.

7. A process as defined in one of the preceding Claims, wherein the compacting is carried out in a magnetic field.

8. A process as defined in any of Claims 1 to 6, wherein said metallic powder comprises, by atomic percent, 10—25% R, preferably 12—20%, most preferably 12—16%, and 3—23% B, preferably 5—18%, most preferably 6—18%, and the compacting is carried out without applying the magnetic field.

9. A process as defined in one of the preceding Claims, wherein the sintering is carried out at 900 to 1200 degrees C.

10. A process as defined in Claim 9, wherein the sintering is carried out at 1000—1180 degrees C.

11. A process as defined in one of the preceding Claims, wherein the sintering is carried out in a non-oxidizing or a reducing atmosphere.

12. A process as defined in one of the preceding Claims, wherein the sintering is carried out under reduced pressure.

13. A process as defined in Claim 12, wherein the pressure is 1,33 Pa (10^{-2} Torr) or less.

14. A process as defined in one of the preceding Claims, wherein R is 12—24%, and B is 3—27%.

15. A process as defined in Claim 14, wherein R is 12—20%, and B is 4—24%.

16. A process as defined in one of Claims 2 to 15, wherein Co is no more than 35%, preferably no more than 25%.

17. A process as defined in one of Claims 2 to 16, wherein Co is 5% or more.

18. A process as defined in one of the preceding Claims, wherein the light rare earth element(s) amounts to no less than 50 at % of the overall rare earth elements R.

19. A process as defined in one of the preceding Claims, wherein said metallic powder is selected so that the sum of Cu, C, P, Ca, Mg, O, Si, and S is no more than 5% by atomic percent.

20. A process as defined in Claim 8, wherein said additional elements M amount to no more than the values specified below:

60	4.7% Ti,	4.7% Ni,	5.0% Bi,
	10.5% V,	12.5% Nb,	10.5% Ta,
	8.5% Cr,	9.5% Mo,	8.8% W,
	8.0% Mn,	9.5% Al,	2.5% Sb,
	6.0% Ge,	3.5% Sn,	5.5% Zr,
65	and 5.5% Hf,		

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provided that, when two or more elements M are added, the total amount thereof shall be no more than the largest value among said specified values.

21. A process as defined in any of the preceding Claims 1, 3 to 5 and 7 to 20, wherein the metallic powder is an alloy powder or a mixture of alloy powders having said respective composition.

22. A process as defined in one of Claims 1, 3—5 and 7—20 wherein the metallic powder is a mixture of an alloy or alloys having an Fe-B-R base composition and a powder metal having a complementary composition making up the respective final composition of said metallic powder.

23. A process as defined in Claim 22, wherein said powder metal comprises an alloy or alloys of the componental elements of said final composition.

24. A process as defined in Claim 22, wherein said powdery metal comprises a componental element(s) of said final composition.

25. A process according to one of the preceding Claims, wherein sintering is effected to a density higher than 95% of the theoretically possible density.

15 Patentansprüche

1. Verfahren zum Herstellen von Permanentmagnet-Werkstoffen des Typs Fe-B-R, gekennzeichnet durch Verfahrensschritte, bei denen eine Zusammensetzung, angegeben in Atom-%, aus 8—30% R, wobei R mindestens ein Seltenerdelement einschließlich Y bedeutet, 2—28% Bor (B), und als Rest Eisen (Fe) bereitgestellt wird, die Zusammensetzung geschmolzen wird, die erhaltene Legierung gekühlt wird, die Legierung pulverisiert wird, um ein Metallpulver mit einer mittleren Teilchengröße von 0,3—80 µm, vorzugsweise 1—40 µm, insbesondere 2—20 µm, wobei eine mittlere Teilchengröße von 3—10 µm ausgeschlossen ist, herzustellen, das Metallpulver verdichtet wird und der erhaltene Körper gesintert wird.

2. Verfahren zum Herstellen von Permanentmagnet-Werkstoffen des Typs Fe-B-R mit einem Gehalt, angegeben in Atom-%, von 8—30% R, wobei R mindestens ein Seltenerdelement einschließlich Y bedeutet, 2—28% Bor (B) und als Rest Eisen (Fe), durch Erhitzen eines Gemisches aus Seltenerdmetalloxid und den anderen metallischen Stoffen mit einem Reduktionsmittel, um das Seltenerdmetalloxid zu reduzieren, sowie durch Pulverisieren des erhaltenen Produkts zu einem Metallpulver mit einer mittleren Teilchengröße von 0,3—80 µm, vorzugsweise 1—40 µm, insbesondere 2—20 µm, wobei eine mittlere Teilchengröße von 3—10 µm ausgeschlossen ist, Verdichten des Metallpulvers und Sintern des erhaltenen Körpers.

3. Verfahren nach Anspruch 1, worin die Summe aus Nd und/oder Pr nicht weniger als 50 Atom-% der gesamten Seltenerdelemente R beträgt.

4. Verfahren nach Anspruch 1, worin in dem Metallpulver Nd und/oder Pr nicht weniger als 50 Atom-% der gesamten Seltenerdelemente R betragen und ein Teil des Fe durch Cobalt (Co) derart ersetzt ist, daß das Pulver nicht mehr als 50 Atom-% Co enthält.

5. Verfahren nach einem der vorstehenden Ansprüche, worin das Metallpulver gegebenenfalls mindestens ein zusätzliches Element M mit einem Atom-%wert, der nicht höher ist, als nachfolgend angegeben ist, mit der Maßgabe, daß bei der Zugabe von zwei oder mehr Elementen M deren Gesamtmenge nicht größer ist als der größte Wert, der für die tatsächlich eingesetzten Elemente angegeben ist:

4,5% Ti,	8,0% Ni,	5,0% Bi,
9,5% V,	12,5% Nb,	10,5% Ta,
8,5% Cr,	9,5% Mo,	9,5% W,
8,0% Mn,	9,5% Al,	2,5% Sb,
7,0% Ge,	3,5% Sn,	5,5% Zr,
und 5,5% Hf.		

6. Verfahren nach Anspruch 1, worin das Kühlen unter Bedingungen erfolgt, bei denen ein im wesentlichen kristalliner Zustand erhalten wird.

7. Verfahren nach einem der vorstehenden Ansprüche, worin das Verdichten in einem Magnetfeld durchgeführt wird.

8. Verfahren nach einem der Ansprüche 1 bis 6, worin das Metallpulver, jeweils in Atom-%, R in einer Menge von 10—25%, vorzugsweise 12—20%, insbesondere 12—16%, und B in einer Menge von 3—23%, vorzugsweise 5—18%, insbesondere 6—18%, enthält sowie das Verdichten ohne Anwendung eines Magnetfeldes durchgeführt wird.

9. Verfahren nach einem der vorstehenden Ansprüche, worin das Sintern bei 900 bis 1200°C durchgeführt wird.

10. Verfahren nach Anspruch 9, worin das Sintern bei 1000—1180°C durchgeführt wird.

11. Verfahren nach einem der vorstehenden Ansprüche, worin das Sintern in einer nichtoxidierenden oder in einer reduzierenden Atmosphäre durchgeführt wird.

12. Verfahren nach einem der vorstehenden Ansprüche, worin das Sintern unter vermindertem Druck durchgeführt wird.

13. Verfahren nach Anspruch 12, worin der Druck 1,33 Pa (10^{-2} Torr) oder weniger beträgt.





14. Verfahren nach einem der vorstehenden Ansprüche, worin für R ein Wert von 12—24% und für B ein Wert von 3—27% gilt.
15. Verfahren nach Anspruch 14, worin für R ein Wert von 12—20% und für B ein Wert von 4—24% gilt.
16. Verfahren nach einem der Ansprüche 2 bis 15, worin der Wert für Co nicht mehr als 35%,
5 vorzugsweise nicht mehr als 25%, beträgt.
17. Verfahren nach einem der Ansprüche 2 bis 16, worin der Wert für Co 5% oder mehr beträgt.
18. Verfahren nach einem der vorstehenden Ansprüche, worin die Menge an leichtem Seltenerdmetall oder an leichten Seltenerdmetallen nicht weniger als 50 Atom-% der gesamten Seltenerdmetalle R beträgt.
19. Verfahren nach einem der vorstehenden Ansprüche, worin das Metallpulver so gewählt wird, daß
10 die Summe von Cu, C, P, Ca, Mg, O, Si und S nicht mehr als 5 Atom-% beträgt.
20. Verfahren nach Anspruch 8, worin die Menge der zusätzlichen Elemente M nicht mehr als die nachstehend angegebenen Werte beträgt:

	4,7% Ti,	4,7% Ni,	5,0% Bi,
15	10,5% V,	12,5% Nb,	10,5% Ta,
	8,5% Cr,	9,5% Mo,	8,8% W,
	8,0% Mn,	9,5% Al,	2,5% Sb,
	6,0% Ge,	3,5% Sn,	5,5% Zr,
	und 5,5% Hf,		

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mit der Maßgabe, daß beim Einsatz von zwei oder mehr Elementen M deren Gesamtmenge nicht größer ist als der größte der angegebenen Werte.

21. Verfahren nach einem der vorstehenden Ansprüche 1, 3 bis 5 und 7 bis 20, worin das Metallpulver
25 ein Legierungspulver oder ein Gemisch aus Legierungspulvern mit der entsprechenden Zusammensetzung ist.

22. Verfahren nach einem der Ansprüche 1, 3—5 und 7—20, worin das Metallpulver ein Gemisch aus einer Legierung oder aus Legierungen mit einer Fe-B-R-Basiszusammensetzung und einem Metallpulver mit einer für die entsprechende Endzusammensetzung des Metallpulvers komplementären
30 Zusammensetzung ist.

23. Verfahren nach Anspruch 22, worin das Metallpulver eine Legierung oder Legierungen der die Endzusammensetzung bildenden Elemente enthält.

24. Verfahren nach Anspruch 22, worin das pulverförmige Metall ein Bildungselement oder Bildungselemente der Endzusammensetzung enthält.

- 35 25. Verfahren nach einem der vorstehenden Ansprüche, worin das Sintern bis zu einer Dichte durchgeführt wird, die höher liegt als 95% der theoretisch möglichen Dichte.

Revendications

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1. Procédé de production de matériaux magnétiques permanents du type Fe-B-R, comprenant les étapes consistant à préparer une composition comprenant, en pourcentage atomique, 8 à 30% de R, R étant au moins l'un des éléments faisant partie des terres rares, y compris Y, 2 à 28% de bore (B), le reste étant du fer (Fe), à faire fondre ladite composition, à refroidir l'alliage résultant, à le pulvériser pour
45 préparer une poudre métallique ayant un diamètre moyen de particules de 0,3 à 80 µm, avantageusement de 1 à 40 µm, de préférence de 2 à 20 µm, des diamètres moyens de particules de 3 à 10 µm étant exclus, à compacter ladite poudre métallique et à fritter le corps résultant.

2. Procédé de préparation de matériaux magnétiques permanents du type Fe-B-R, comprenant, en pourcentage atomique, 8 à 30% de R, R étant au moins l'un des éléments faisant partie des terres rares, y
50 compris Y, 2 à 28% de bore (B), le reste étant du fer (Fe), par chauffage d'un mélange d'un oxyde de terre rare et des autres matières métalliques avec un agent réducteur afin de réduire l'oxyde de terre rare, pulvérisation du produit obtenu en une poudre métallique ayant un diamètre moyen de particules de 0,3 à 80 µm, avantageusement de 1 à 40 µm, de préférence de 2 à 20 µm, des diamètres moyens de particules de 3 à 10 µm étant exclus, compactage de ladite poudre métallique et frittage du corps résultant.

- 55 3. Procédé suivant la revendication 1, dans lequel la somme des quantités de Nd et/ou Pr n'est pas inférieure à 50% de la quantité totale des éléments R faisant partie des terres rares.

4. Procédé suivant la revendication 1, dans lequel, dans la poudre métallique, la somme des quantités de Nd et/ou Pr n'est pas inférieure à 50% de la quantité totale des éléments R faisant partie des terres rares et une partie du F est remplacée par du cobalt (Co), de manière que la poudre ne comprenne pas plus de
60 50% de Co.

5. Procédé suivant l'une quelconque des revendications précédentes, dans lequel la poudre métallique comprend facultativement au moins l'un des éléments supplémentaires M en une quantité non supérieure aux valeurs, en pourcentage atomique, mentionnées ci-dessous sous réserve que, lorsque deux ou plus de deux éléments M sont ajoutés, leur quantité totale soit non supérieure à la plus forte valeur parmi les
65 valeurs mentionnées des éléments réellement ajoutés:





4,5% Ti,	8,0% Ni,	5,0% Bi,
9,5% V,	12,5% Nb,	10,5% Ta,
8,5% Cr,	9,5% Mo,	9,5% W,
8,0% Mn,	9,5% Al,	2,5% Sb,
7,0% Ge,	3,5% Sn,	5,5% Zr,
et 5,5% Hf.		

6. Procédé suivant la revendication 1, dans lequel le refroidissement est effectué de manière à parvenir à un état pratiquement cristallin.

7. Procédé suivant l'une des revendications précédentes, dans lequel le compactage est effectué dans un champ magnétique.

8. Procédé suivant l'une quelconque des revendications 1 à 6, dans lequel la poudre métallique comprend, en pourcentage atomique, 10 à 25%, avantageusement 12 à 20%, de préférence 12 à 16% de R et 3 à 23%, avantageusement 5 à 18%, de préférence 6 à 18% de B, et le compactage est effectué sans application du champ magnétique.

9. Procédé suivant l'une des revendications précédentes, dans lequel le frittage est effectué à une température de 900 à 1200°C.

10. Procédé suivant la revendication 9, dans lequel le frittage est effectué à une température de 1000 à 1180°C.

11. Procédé suivant l'une des revendications précédentes, dans lequel le frittage est effectué sous une atmosphère non oxydante ou réductrice.

12. Procédé suivant l'une des revendications précédentes, dans lequel le frittage est effectué sous pression réduite.

13. Procédé suivant la revendication 12, dans lequel la pression est égale ou inférieure à 1,33 Pa (10^{-2} torr).

14. Procédé suivant l'une des revendications précédentes, dans lequel R est présent en une quantité de 12 à 24% et B est présent en une quantité de 3 à 27%.

15. Procédé suivant la revendication 14, dans lequel R est présent en une quantité de 12 à 20% et B est présente en une quantité de 4 à 24%.

16. Procédé suivant l'une des revendications 2 à 15, dans lequel Co est présent en une quantité non supérieure à 35%, de préférence non supérieure à 25%.

17. Procédé suivant l'une des revendications 2 à 16, dans lequel Co est présent en une quantité égale ou supérieure à 5%.

18. Procédé suivant l'une des revendications précédentes, dans lequel la quantité du ou des éléments légers faisant partie des terres rares est non inférieure à 50% de la quantité totale des éléments R faisant partie des terres rares.

19. Procédé suivant l'une des revendications précédentes, dans lequel la poudre métallique est choisie de sorte que la somme des quantités de Cu, C, P, Ca, Mg, O, Si et S soit non supérieure à 5%, en pourcentage atomique.

20. Procédé suivant la revendication 8, dans lequel les éléments supplémentaires M sont présents en des quantités non supérieures aux valeurs mentionnées ci-dessous:

4,7% Ti,	4,7% Ni,	5,0% Bi,
10,5% V,	12,5% Nb,	10,5% Ta,
8,5% Cr,	9,5% Mo,	8,8% W,
8,0% Mn,	9,5% Al,	2,5% Sb,
6,0% Ge,	3,5% Sn,	5,5% Zr,
et 5,5% Hf,		

sous réserve que, lorsque deux ou plus de deux éléments M sont ajoutés, la quantité totale de ces éléments soit non supérieure à la plus forte valeur parmi lesdites valeurs mentionnées.

21. Procédé suivant l'une quelconque des revendications 1, 3 à 5 et 7 à 20 précédentes, dans lequel la poudre métallique est une poudre d'alliage ou un mélange de poudres d'alliages dont la composition correspond aux proportions respectives.

22. Procédé suivant l'une des revendications 3—5 et 7—20, dans lequel la poudre métallique est un mélange d'un ou plusieurs alliages ayant une composition de base Fe-B-R et d'une poudre métallique ayant une composition complémentaire, permettant d'atteindre la composition finale, en les proportions respectives, de ladite poudre métallique.

23. Procédé suivant la revendication 22, dans lequel la poudre métallique comprend un ou plusieurs alliages des éléments constitutifs de la composition finale.

24. Procédé suivant la revendication 22, dans lequel le métal pulvérulent comprend un ou plusieurs éléments constitutifs de la composition finale.

25. Procédé suivant l'une des revendications précédentes, dans lequel le frittage est effectué à une densité supérieure à 95% de la densité théoriquement possible.

