

ADH/G-11806

HIGH PERFORMANCE HOT-PRESSED MAGNETS

The present invention generally relates to the making of high remanence hot-pressed permanent magnets based primarily on iron, rare earths such as neodymium and/or praseodymium and/or dysprosium, and boron, as specified in the preamble of claim 1. More specifically, this invention concerns the forming of such magnets having magnetic remanences of at least 9 kiloGauss (kG), and most typically about 10 kG, by hot-pressing permanent magnet particles having, in weight percents, a rare earth level of from about 5 percent to 25 percent, most preferably from about 10 percent to about 20 percent, and preferably combined with a boron content of from about 0.5 percent to about 4.5 percent, most preferably from about 0.8 percent to about 4.0 percent, wherein the total amount of the rare earth constituent and boron ranges from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent.

Permanent magnets based on compositions containing iron, neodymium and/or praseodymium, and boron are known and in commercial usage. Such permanent magnets contain as an essential magnetic phase grains of tetragonal crystals in which the proportions of, for example, iron, neodymium and boron are exemplified by the empirical formula $\text{Nd}_2\text{Fe}_{14}\text{B}$. These magnet compositions and methods for making them are described by Croat in US Patent No. 4,802,931 issued February 7, 1989. The grains of the magnetic phase are surrounded by a second phase that is typically rare earth-rich, as an example neodymium-rich, as compared with the essential magnetic phase. It is known that magnets based on such compositions may be prepared by rapidly solidifying, such as by melt-spinning, a melt of the

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composition to produce fine-grained,
magnetically-isotropic platelets of ribbon-like
fragments. Magnets may be formed from these isotropic
particles by practices which are known, such as
5 bonding the particles together with a suitable resin.

Although the magnets formed from these
isotropic ribbons are satisfactory for some
applications, they typically exhibit an energy product
(BHmax) of about 8 to about 10 megaGaussOersteds
10 (MGOe), which is insufficient for many other
applications. To improve the energy product, it is
known to hot-press the isotropic particles to form
magnets having an energy product of about 13 to about
14 MGOe and magnetic remanences of the order of about
15 8 kG.

However, there are applications when it
would be desirable that such hot-pressed magnets
should have higher magnetic remanence values. As an
example, if the hot-pressed magnet is used in an
20 application at or near its maximum magnetic remanence,
it may be desirable to increase its magnetic remanence
so as to increase the working capability of the
magnet.

Conventionally, for hot-pressed magnets of
25 the iron-rare earth metal type, the total rare earth
constituent is greater than about 25 percent, most
typically greater than about 29 percent, by weight.
This is true since compositions containing lower
amounts of the rare earth constituents contain lesser
30 amounts of the intergranular phase, and therefore
require higher pressing temperatures, which are
detrimental to the life of the hot-pressing punches
and add undesirable costs to the pressing process.
Thus, the prior art has generally always taught that
35 hot-pressed permanent magnet compositions of this type

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must contain, as a minimum, at least 25 percent rare earth constituent.

Yet, it would be desirable to provide a means for increasing the magnetic remanence of a hot-pressed magnet, such as to a value of at least 9 kG or 10 kG, whilst simultaneously reducing or minimising the amount of rare earth constituent within the compositions, since the rare earth constituents are typically much more costly as compared to the other constituents. However, the means for accomplishing such an increase in magnetic remanence should not result in increased hot-pressing temperatures.

A method for forming a hot-pressed iron-rare earth boron permanent magnet according to the present invention is characterised by the features specified in the characterising portion of claim 1.

It is therefore an object of this invention to provide an isotropic hot-pressed permanent magnet exhibiting a magnetic remanence of at least 9 kG, preferably about 10 kG.

It is a further object of this invention that such an isotropic hot-pressed magnet should have a composition that has, as its magnetic constituent, the tetragonal crystal phase $RE_2TM_{14}B$ which is based primarily on neodymium and/or praseodymium, iron and boron, and wherein the total amount, in weight percent, of rare earth constituent ranges from about 5 percent to about 25 percent, preferably from about 10 percent to about 20 percent, and is coupled with a boron content of from about 0.5 percent to about 4.5 percent, preferably from about 0.8 percent to about 4.0 percent, such that the combined amount of rare earth and boron within the composition ranges from

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about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent.

Furthermore, it is an object of this invention that such a hot-pressed magnet having a magnetic remanence of at least 9 to 10 kG should be pressed at conventional pressing temperatures.

In accordance with a preferred embodiment of this invention, these and other objects and advantages are accomplished as follows.

According to the present invention, there is provided an isotropic hot-pressed iron-rare earth metal-boron permanent magnet, wherein the hot-pressed permanent magnet exhibits a magnetic remanence of at least 9 kG, and most typically about 10 kG, which is nearly 62% of saturation magnetisation for this material. This is believed to be the highest value reported for an isotropic magnet of this type. The hot-pressed magnet of this invention is produced by pressing a quantity of isotropic iron-rare earth-boron metal particles. The isotropic particles can be formed by known methods, such as by melt-spinning a suitable iron-rare earth-boron metal composition to an overquenched or optimum condition. Isotropic particles formed by melt-spinning are generally ribbon-shaped in configuration and can be readily reduced to a desired particle size.

The preferred composition comprises, on a weight percent basis, from about 5 percent to about 25 percent rare earth, most preferably about 10 percent to about 20 percent rare earth, from about 0.5 percent to about 4.5 percent boron, most preferably from about 0.8 percent to about 4.0 percent boron, with the total combination of rare earth plus boron ranging from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent, and as an

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optional ingredient, from about 2 percent to about 16 percent cobalt, with the balance being essentially iron.

Other elements may also be present in minor amounts of up to about two weight percent, either alone or in combination. These elements include tungsten, chromium, nickel, aluminium, copper, magnesium, manganese, gallium, niobium, vanadium, molybdenum, titanium, tantalum, zirconium, carbon, tin and calcium. Silicon is also typically present in small amounts, as are oxygen and nitrogen.

The isotropic particles are then hot-pressed at conventional temperatures, which is contrary to prior-art teachings wherein the relatively low level of rare earth constituents within the magnet compositions of this invention would require increased hot-pressing temperatures to result in useful magnetic remanences. A particular advantage of this invention is that conventional hot-pressing temperatures may be used, even though relatively low levels of the rare earth constituents are present. It is believed that this is due to the presence of an optimal level of boron coupled with the rare earths, which enables the use of conventional hot-pressing temperatures. The hot-pressed iron-rare earth metal permanent magnets of this invention exhibit an improved magnetic remanence of at least 9 to 10 kG, in contrast to conventional hot-pressed magnets of the prior art containing rare earth levels in excess of about 25 weight percent having a magnetic remanence of about 8 kG.

Accordingly, with the present invention, magnetic remanences of at least 9-kG, and preferably of the order of about 10 kG, may be easily achieved in a hot-pressed magnet, wherein the composition of the magnet includes a relatively low rare earth content.

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coupled with an optimal boron content. Yet the increase in magnetic remanence is achieved in the preferred hot-pressed compositions having the relatively low rare earth content, without the
5 previous requirement for elevated hot-pressing temperatures of those compositions.

In addition, since the rare earth constituent is typically the most expensive component of these types of magnet compositions, a reduction in
10 the amount of rare earth present in the magnet composition corresponds to a reduction in its overall price, which is an additional benefit of the preferred compositions of this invention.

Other objects and advantages of this
15 invention will be better appreciated from the following detailed description.

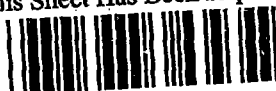
Reference will be made to the accompanying drawings, in which:

Figures 1 to 5 illustrate demagnetisation
20 curves for hot-pressed magnets formed from magnetically isotropic particles of the preferred iron-rare earth-boron compositions of this invention.

The preferred compositions of this invention result in isotropic hot-pressed, fully-dense permanent
25 magnets which exhibit magnetic remanences of at least 9 kG, more typically about 10 kG. The preferred compositions are characterised by a relatively low total rare earth content coupled with boron. Advantageously, the hot-pressed magnets may be formed
30 at conventional hot-pressing temperatures.

Appropriate compositions for the iron-rare earth-metal permanent magnets of this invention include a suitable transition metal component, a suitable rare earth component and boron, as well as
35 possible small additions of cobalt, and are generally

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represented by the empirical formula $RE_2TM_{14}B$. The preferred compositions, as stated previously, consist of, on an atomic percentage basis, about 40 to 90 percent of iron or mixtures of cobalt and iron, with the iron preferably making up at least 60 percent of the non-rare earth metal content; about 3 to about 12 percent of rare earth metal that necessarily includes neodymium and/or praseodymium, with the neodymium and/or praseodymium preferably making up at least 60 percent of the rare earth content; and the rare earth being coupled with about 4 to about 20 percent boron. Preferably, iron makes up at least 40 atomic percent of the total composition.

Specific compositions which have been useful in preparing hot-pressed, fully-dense, isotropic permanent magnets of this type, in corresponding weight percentages, are as follows and contain the hard magnetic phase consisting of $Fe_{14}Nd_2B$ (or the equivalent) tetragonal crystals; from about 5 percent to about 25 percent rare earth, most preferably about 10 percent to about 20 percent rare earth, wherein the majority constituent is neodymium and the remainder is praseodymium and/or dysprosium; from about 0.5 percent to about 4.5 percent boron, most preferably from about 0.8 percent to about 4.0 percent boron, wherein the combined amount of the rare earths and boron ranges from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent, and optionally from about 2 percent to about 16 percent cobalt, with the balance being essentially iron.

As stated previously, other elements may also be present in minor amounts of up to about two weight percent, either alone or in combination. These elements include tungsten, chromium, nickel,

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aluminium, copper, magnesium, manganese, gallium,
niobium, vanadium, molybdenum, titanium, tantalum,
zirconium, carbon, tin and calcium. Silicon is also
typically present in small amounts, as are oxygen and
5 nitrogen.

However, it is to be understood that this
invention is applicable to the larger family of
compositions as described previously in atomic
percentages and which larger family of compositions
10 will be referred to generally as an iron-rare
earth-boron composition.

Generally, permanent magnetic bodies of the
preferred composition are formed by starting with
alloy ingots which are melted by induction heating
15 under a dry, substantially oxygen-free argon, inert or
vacuum atmosphere to form a uniform molten
composition. Preferably, the molten composition is
then rapidly solidified to produce an amorphous
material or a finely crystalline material in which the
20 grain size is less than 400 nanometres at its largest
dimension. It is most preferred that the
rapidly-solidified material should have a grain size
smaller than about 20 nanometres. Such material may
be produced, for example, by conventional
25 melt-spinning operations. Conventionally, the
substantially amorphous or microcrystalline, melt-spun
iron-neodymium-boron ribbons are then milled to a
powder, though the ribbons can be used directly with
the present invention.

30 The iron-neodymium-boron particles, which
are magnetically isotropic at this point, are then
hot-pressed at a sufficient pressure for a sufficient
duration to form a fully-dense material. Typically,
this is achieved by heating the composition to a
35 suitable temperature, such as about 750°C, or

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preferably between about 750°C to about 800°C, in a die, and compacting the composition between upper and lower punches, under a pressure of, for example, about 77.22 MPa to about 92.67 MPa (about 5 to about 6 tons per square inch), so as to form a substantially fully-dense, flat cylindrical plug. Generally, when melt-spun material finer than about 20 nanometres in grain size is heated at such an elevated temperature for a period of a minute or so and then hot-pressed to full density, the resultant body is a permanent magnet. If the particulate material has been held at the hot-pressing temperature for a suitable period of time, it will then have a grain size in the range of about 20 to about 500 nanometres, preferably about 20 to 100 nanometres.

The magnetic properties of hot-pressed isotropic permanent magnets formed in accordance with this invention were determined using conventional Hysteresis Graph Magnetometer (HGM) tests. Test samples were placed so that the axis parallel to the direction of alignment was parallel to the direction of the magnetic field applied by the HGM. The samples were each then magnetised to saturation and then demagnetised.

The second quadrant demagnetisation plots are shown in Figures 1 to 5 [remanence $4\pi M$ in kiloGauss versus coercivity (H) in kiloOersteds] for the preferred isotropic hot-pressed permanent magnets of this invention.

The specific samples tested are described more fully below. For the specific examples below, melt-spinning at a rate of 22 metres/second was followed by crushing of the magnetically-isotropic melt-spun material to form the particulate material which was then shaped into a preform. The preform was

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then hot-pressed at a temperature of about 750°C, and under a pressure of about 77.22 MPa to about 92.67 MPa (5 to about 6 tons per square inch), to form the fully-dense hot-pressed magnets, which are essentially the same conditions used to form conventional hot-pressed permanent magnet bodies having high rare earth contents. It is to be noted that the bounds of this invention are not to be limited by the particular melt-spinning rate and hot-pressing temperatures used for these illustrative examples.

Example 1

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and tested. The nominal composition, in weight percent, was about 12.7 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 3.9 percent boron, about 3.5 percent cobalt, about 1.2 percent gallium, and the balance iron. The magnet had a diameter of about 16 millimetres, a height of about 11 millimetres and a weight of about 10 grams.

The second quadrant demagnetisation plot for this magnet is shown in Figure 1 and indicates a magnetic remanence (B_r) of about 10.0 kG and an intrinsic coercivity (H_{ci}) of about 3.4 kiloOersteds (kOe). It was determined that the saturation magnetisation value for this low rare earth composition was about 16 kG; therefore, the magnetic remanence of 10 kG obtained after hot-pressing was greater than 62 percent of the saturation value. It is believed that this value is the highest reported for an isotropic magnet of this type. The properties of the magnet were tested in all three directions and the magnet was determined to be isotropic.

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Example 2

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and had a nominal composition, in weight percent, of about 13.9 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 4 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 2 and indicates a magnetic remanence (B_r) of about 9.6 kG and an intrinsic coercivity (H_{ci}) of about 2.4 kOe.

Example 3

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and had a nominal composition, in weight percent, of about 2.6 percent dysprosium with the total rare earth constituent, including neodymium, being 11.2 percent, about 3.8 percent boron, about 3.5 percent cobalt, about 1.3 percent gallium, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 3 and indicates a magnetic remanence (B_r) of about 10 kG and an intrinsic coercivity (H_{ci}) of about 2.8 kOe.

Example 4

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and tested. The nominal composition, in weight percent, was about 12.6 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 3.8 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 4 and indicates a

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magnetic remanence (B_r) of about 9.9 kG and an intrinsic coercivity (H_{ci}) of about 2.8 kOe.

Example 5

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above having a nominal composition, in weight percent, of about 19 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 1 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 5 and indicates a magnetic remanence (B_r) of about 9.6 kG and an intrinsic coercivity (H_{ci}) of about 4.3 kOe.

From the above, it can be seen that hot-pressed isotropic permanent magnets having improved magnetic remanences of at least 9.0 kG, more typically about 10.0 kG, can be formed using compositions containing relatively low levels of rare earths coupled with a sufficient amount of boron. It was determined that by reducing the amount of neodymium in the preferred Nd-Fe-B alloys, a Fe_3B phase present in the alloy also becomes an equilibrium phase with the $Nd_2Fe_{14}B$ phase. In addition, an α -Fe phase is also present. It is further believed that the magnetic remanences of these preferred alloys are dominated by a soft magnetic Fe_3B phase, whilst magnetic coercivity is controlled by the dispersion of the hard magnetic $Nd_2Fe_{14}B$ phase. Therefore, further improvements in magnetic properties are possible through modifications of intrinsic properties of the individual phases through specific alloying in accordance with the disclosure of this invention.

A particular advantage of this invention is that conventional hot-pressing temperatures may be

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used, even though relatively low levels of the rare earth constituents are present, as opposed to the disclosures in the prior art. It is believed that this is due to the presence of optimal levels of boron
5 coupled with the rare earths. The hot-pressed iron-rare earth-boron permanent magnets of this invention exhibit an improved magnetic remanence of at least 9 to 10 kG, as compared to conventional
10 hot-pressed magnets of the prior art having magnetic remanences of about 8 kG and containing rare earth levels in excess of about 25 weight percent.

In addition, a significant cost saving can be achieved without a discernible loss in magnetic properties with the compositions of this invention
15 since the amount of rare earth constituents, which are the most expensive constituents of these types of permanent magnets, is significantly reduced.

Accordingly, with the disclosure of this invention, magnetic remanences of at least 9 kG, and
20 preferably of the order of about 10 kG, which are believed to be the highest values reported for an isotropic magnet of this type, may be readily achieved in a hot-pressed magnet, wherein the composition of the magnet includes a relatively low rare earth
25 content coupled with an optimal level of boron.

Therefore, whilst this invention has been described in terms of a preferred embodiment thereof, it is apparent that other forms could be adopted by one skilled in the art. For example, the composition
30 of the magnetic particles could be varied within the preferred weight and atomic ranges, with or without other constituents as described above, or different and/or additional processing steps may be employed to produce the isotropic particles used to form the
35 hot-pressed isotropic magnets, as well as other

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variations. Accordingly, the scope of this invention is to be limited only by the scope of the following claims.

- 5 The disclosures in United States patent application no. 148,155, from which this application claims priority, and in the abstract accompanying this application are incorporated herein by reference.

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Claims:

1. A method for forming a hot-pressed iron-rare earth-boron permanent magnet, the method comprising the steps of: providing a quantity of isotropic iron-rare earth-boron metal particles, and hot-pressing said quantity of isotropic iron-rare earth-boron metal particles at a temperature and for a duration sufficient to form a hot-pressed isotropic iron-rare earth-boron metal permanent magnet, characterised in that said quantity of isotropic iron-rare earth-boron metal particles is formed from a composition comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal, and from about 0.5 to about 4.5 percent boron, wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent of the composition, with the balance being principally iron; and the magnet formed has a magnetic remanence of at least 9 kiloGauss.
2. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which the majority of said rare earth constituent is neodymium.
3. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which the composition also includes from about 2 to about 16 percent cobalt.
4. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which said rare earth content of the composition ranges from about 10 to about 20 percent rare earth metal, and said boron content of the composition ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare

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earth metal and said boron in the composition ranges from about 12 to about 22 percent of the composition.

5. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which said isotropic iron-rare earth metal particles have a grain size of not more than 500 nanometres.

6. A method for forming a hot-pressed iron-rare earth-boron permanent magnet, the method comprising the steps of: providing a quantity of isotropic iron-rare earth-boron metal particles having a grain size of not more than 500 nanometres, and hot-pressing said quantity of isotropic iron-rare earth-boron metal particles at a temperature and for a duration sufficient to form a hot-pressed isotropic iron-rare earth-boron metal permanent magnet characterised in that said quantity of isotropic iron-rare earth-boron metal particles is formed from a composition comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal wherein the majority of said rare earth constituent is neodymium, and from about 0.5 to about 4.5 percent boron, and wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent of the composition, with the balance being principally iron; and the magnet formed has the uniform presence of both a hard magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and soft magnetic phases Fe_3B and $\alpha\text{-Fe}$, and a magnetic remanence of at least 9 kiloGauss.

7. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 6, in which the composition also includes from about 2 to about 16 percent cobalt.

8. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to

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claim 6, in which said rare earth content of the composition ranges from about 10 to about 20 percent rare earth metal, and said boron content of the composition ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare earth metal and said boron in the composition ranges from about 12 to about 22 percent of the composition.

9. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 6, in which said hot-pressing step is at a temperature ranging from about 750°C to 800°C.

10. A hot-pressed isotropic iron-rare earth-boron permanent magnet comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal wherein the majority of said rare earth constituent is neodymium, and from about 0.5 to about 4.5 percent boron, and wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent, with the balance being principally iron; which magnet is characterised by the uniform presence of both a hard magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and soft magnetic phases Fe_3B and $\alpha\text{-Fe}$; and which has a magnetic remanence of at least 9 kiloGauss.

11. A hot-pressed isotropic iron-rare earth-boron permanent magnet according to claim 10, in which said magnet further comprises from about 2 to about 16 percent cobalt.

12. A hot-pressed isotropic iron-rare earth-boron permanent magnet according to claim 10, in which said rare earth content ranges from about 10 to about 20 percent rare earth metal, and said boron content ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare earth metal and said boron ranges from about 12 to about 22 percent of the magnet.

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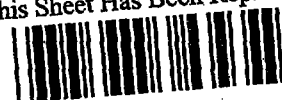


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HIGH PERFORMANCE HOT-PRESSED MAGNETSAbstract

Isotropic hot-pressed iron-rare earth metal permanent magnets are provided wherein the hot-pressed permanent magnets exhibit magnetic remanences of at least 9 kG, and most typically about 10 kG. Preferred compositions include a relatively low rare earth content coupled with an optimal amount of boron. The preferred composition is, on a weight percent basis, from about 5 to about 25 percent rare earth, most preferably about 10 to about 20 percent rare earth, from about 0.5 to about 4.5 percent boron, most preferably from about 0.8 to about 4.0 percent boron, wherein the total combination of the rare earths and boron ranges from about 9 percent to about 26 percent of the composition, most preferably from about 12 percent to about 22 percent, and optionally from about 2 percent to about 16 percent cobalt, with the balance being essentially iron.

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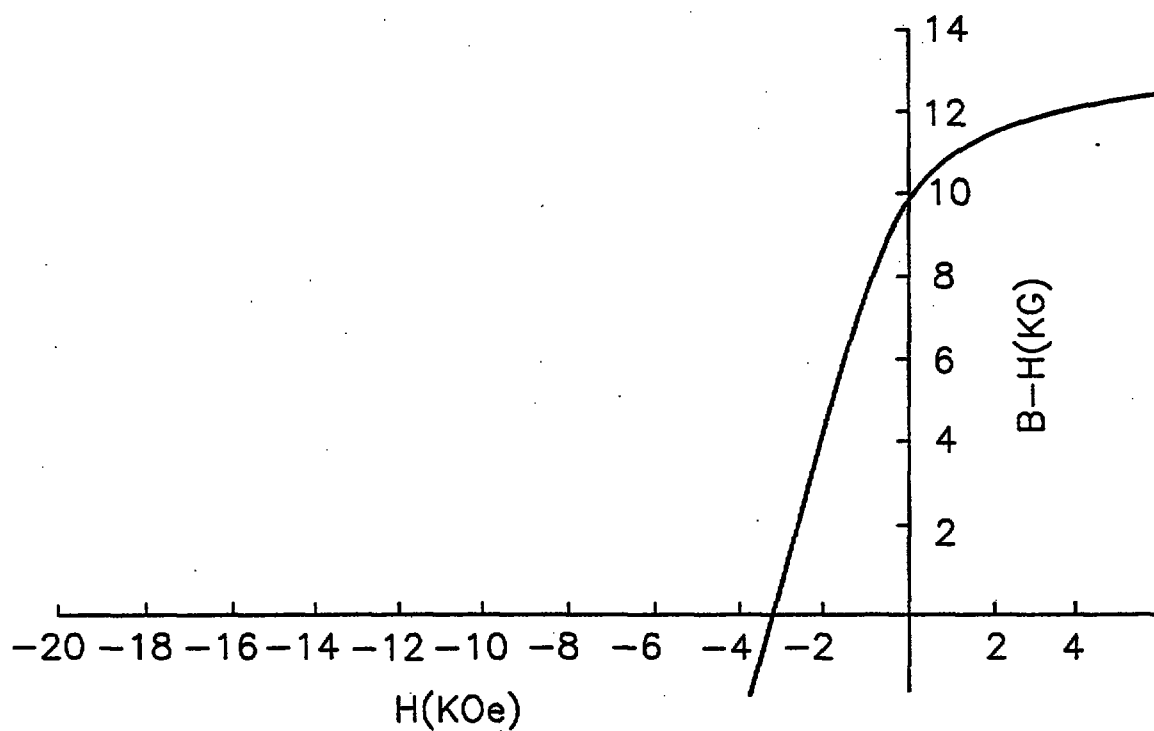


FIG. 1

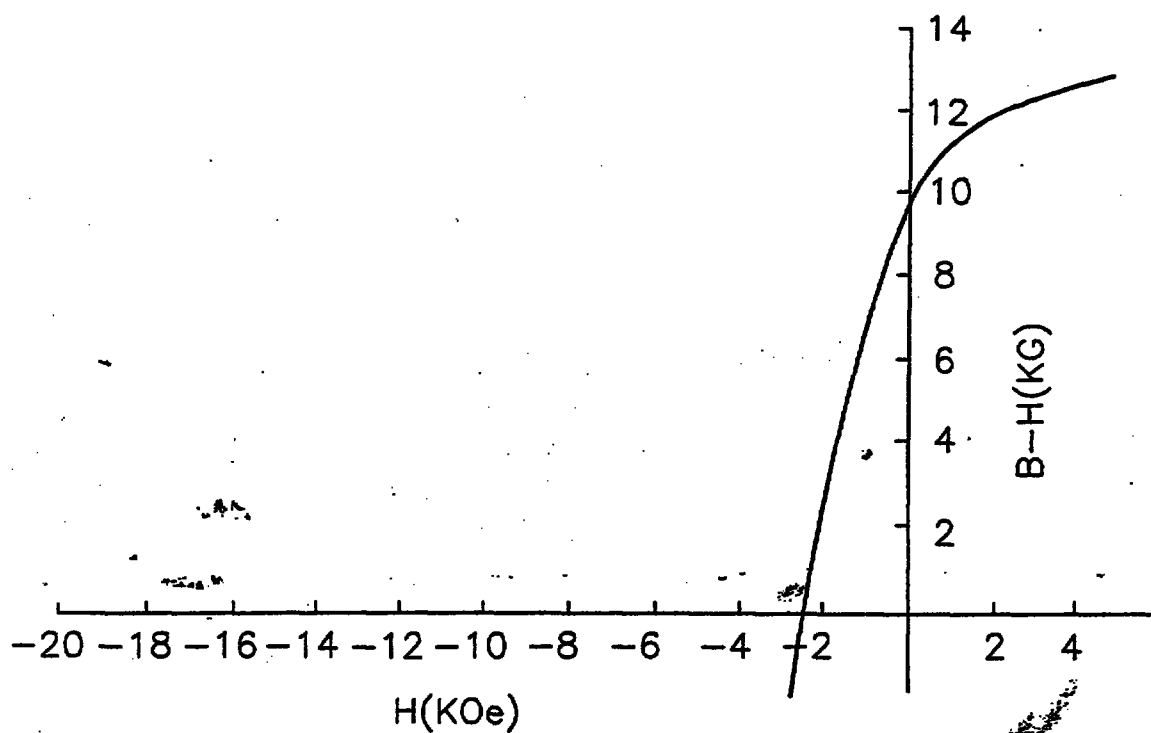


FIG. 2

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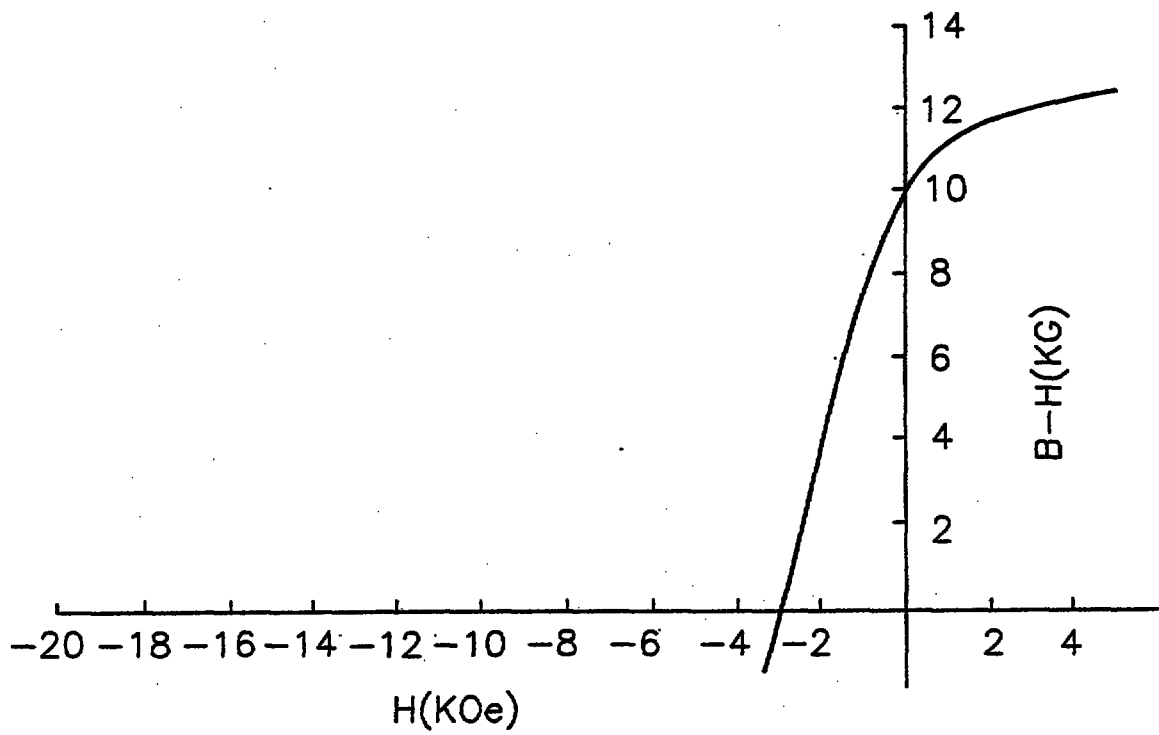


FIG. 3

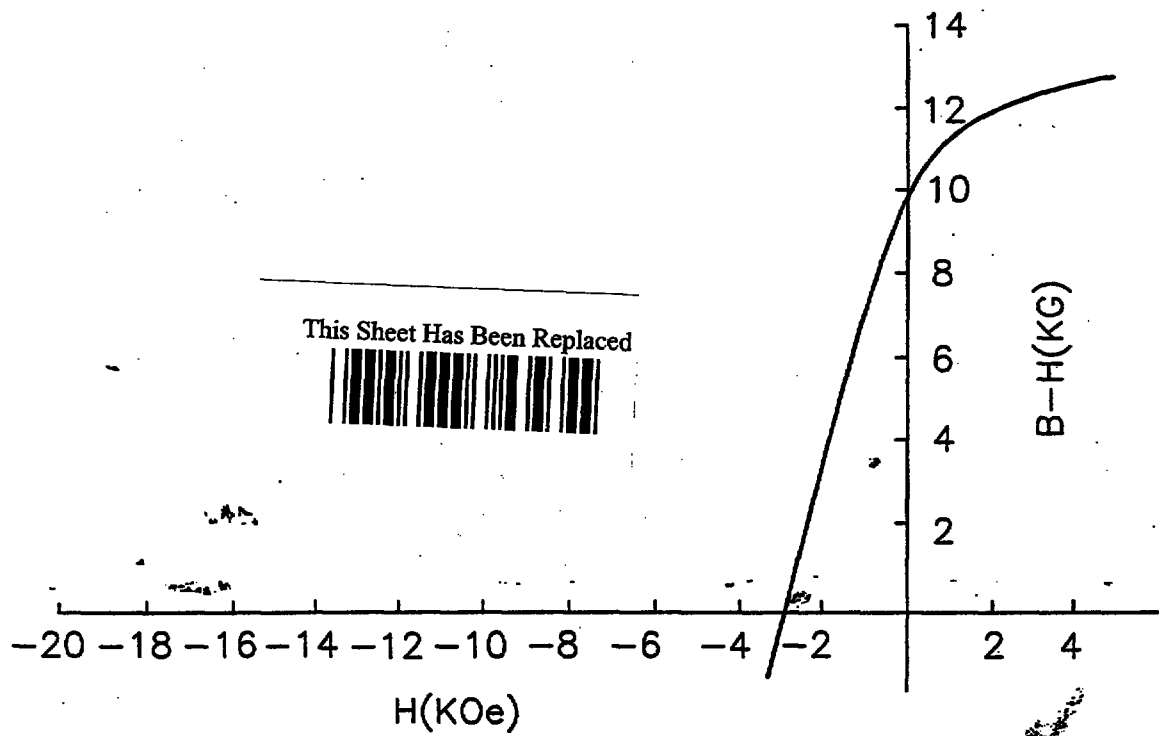


FIG. 4

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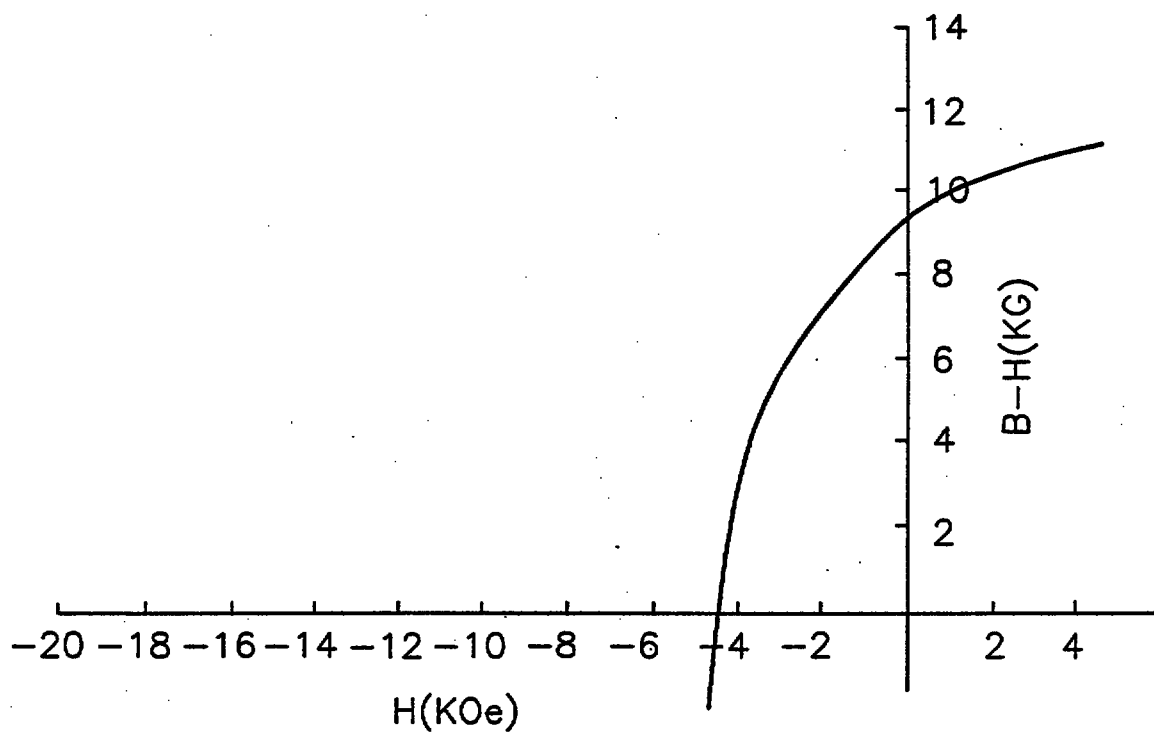


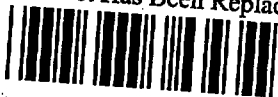
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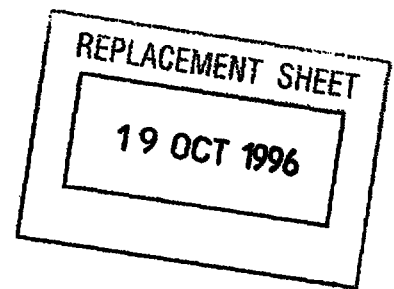
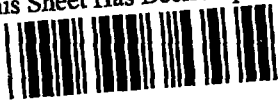
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HIGH PERFORMANCE HOT-PRESSED MAGNETS

The present invention generally relates to the making of high remanence hot-pressed permanent magnets based primarily on iron, rare earths such as neodymium and/or praseodymium and/or dysprosium, and boron, as specified in the preamble of claim 1. More specifically, this invention concerns the forming of such magnets having magnetic remanences of at least 9 kiloGauss (kG), and most typically about 10 kG, by hot-pressing permanent magnet particles having, in weight percents, a rare earth level of from about 5 percent to 25 percent, most preferably from about 10 percent to about 20 percent, and preferably combined with a boron content of from about 0.5 percent to about 4.5 percent, most preferably from about 0.8 percent to about 4.0 percent, wherein the total amount of the rare earth constituent and boron ranges from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent.

Permanent magnets based on compositions containing iron, neodymium and/or praseodymium, and boron are known and in commercial usage. Such permanent magnets contain as an essential magnetic phase grains of tetragonal crystals in which the proportions of, for example, iron, neodymium and boron are exemplified by the empirical formula $\text{Nd}_2\text{Fe}_{14}\text{B}$. These magnet compositions and methods for making them are described by Croat in US Patent No. 4,802,931 issued February 7, 1989. The grains of the magnetic phase are surrounded by a second phase that is typically rare earth-rich, as an example neodymium-rich, as compared with the essential magnetic phase. It is known that magnets based on such compositions may be prepared by rapidly solidifying, such as by melt-spinning, a melt of the

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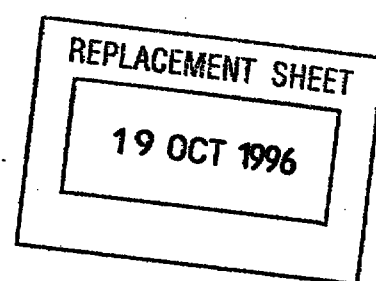


composition to produce fine-grained,
magnetically-isotropic platelets of ribbon-like
fragments. Magnets may be formed from these isotropic
particles by practices which are known, such as
5 bonding the particles together with a suitable resin.

Although the magnets formed from these
isotropic ribbons are satisfactory for some
applications, they typically exhibit an energy product
(BHmax) of about 8 to about 10 megaGaussOersteds
10 (MGOe), which is insufficient for many other
applications. To improve the energy product, it is
known to hot-press the isotropic particles to form
magnets having an energy product of about 13 to about
14 MGOe and magnetic remanences of the order of about
15 8 kG.

However, there are applications when it
would be desirable that such hot-pressed magnets
should have higher magnetic remanence values. As an
example, if the hot-pressed magnet is used in an
20 application at or near its maximum magnetic remanence,
it may be desirable to increase its magnetic remanence
so as to increase the working capability of the
magnet.

Conventionally, for hot-pressed magnets of
25 the iron-rare earth metal type, the total rare earth
constituent is greater than about 25 percent, most
typically greater than about 29 percent, by weight.
This is true since compositions containing lower
amounts of the rare earth constituents contain lesser
30 amounts of the intergranular phase, and therefore
require higher pressing temperatures, which are
detrimental to the life of the hot-pressing punches
and add undesirable costs to the pressing process.
Thus, the prior art has generally always taught that
35 hot-pressed permanent magnet compositions of this type



must contain, as a minimum, at least 25 percent rare earth constituent.

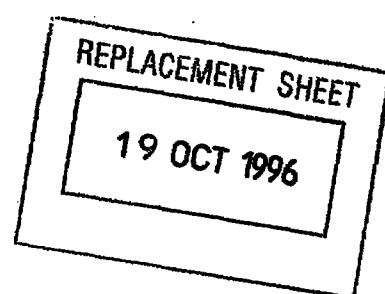
Yet, it would be desirable to provide a means for increasing the magnetic remanence of a
5 hot-pressed magnet, such as to a value of at least 9 kG or 10 kG, whilst simultaneously reducing or minimising the amount of rare earth constituent within the compositions, since the rare earth constituents are typically much more costly as compared to the
10 other constituents. However, the means for accomplishing such an increase in magnetic remanence should not result in increased hot-pressing temperatures.

A method for forming a hot-pressed iron-rare
15 earth boron permanent magnet according to the present invention is characterised by the features specified in the characterising portion of claim 1.

It is therefore an object of this invention to provide an isotropic hot-pressed permanent magnet
20 exhibiting a magnetic remanence of at least 9 kG, preferably about 10 kG.

It is a further object of this invention that such an isotropic hot-pressed magnet should have a composition that has, as its magnetic constituent,
25 the tetragonal crystal phase $RE_2TM_{14}B$ which is based primarily on neodymium and/or praseodymium, iron and boron, and wherein the total amount, in weight percent, of rare earth constituent ranges from about 5 percent to about 25 percent, preferably from about 10
30 percent to about 20 percent, and is coupled with a boron content of from about 0.5 percent to about 4.5 percent, preferably from about 0.8 percent to about 4.0 percent, such that the combined amount of rare earth and boron within the composition ranges from

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about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent.

Furthermore, it is an object of this invention that such a hot-pressed magnet having a magnetic remanence of at least 9 to 10 kG should be pressed at conventional pressing temperatures.

In accordance with a preferred embodiment of this invention, these and other objects and advantages are accomplished as follows.

According to the present invention, there is provided an isotropic hot-pressed iron-rare earth metal-boron permanent magnet, wherein the hot-pressed permanent magnet exhibits a magnetic remanence of at least 9 kG, and most typically about 10 kG, which is nearly 62% of saturation magnetisation for this material. This is believed to be the highest value reported for an isotropic magnet of this type. The hot-pressed magnet of this invention is produced by pressing a quantity of isotropic iron-rare earth-boron metal particles. The isotropic particles can be formed by known methods, such as by melt-spinning a suitable iron-rare earth-boron metal composition to an overquenched or optimum condition. Isotropic particles formed by melt-spinning are generally ribbon-shaped in configuration and can be readily reduced to a desired particle size.

The preferred composition comprises, on a weight percent basis, from about 5 percent to about 25 percent rare earth, most preferably about 10 percent to about 20 percent rare earth, from about 0.5 percent to about 4.5 percent boron, most preferably from about 0.8 percent to about 4.0 percent boron, with the total combination of rare earth plus boron ranging from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent, and as an

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optional ingredient, from about 2 percent to about 16 percent cobalt, with the balance being essentially iron.

Other elements may also be present in minor amounts of up to about two weight percent, either alone or in combination. These elements include tungsten, chromium, nickel, aluminium, copper, magnesium, manganese, gallium, niobium, vanadium, molybdenum, titanium, tantalum, zirconium, carbon, tin and calcium. Silicon is also typically present in small amounts, as are oxygen and nitrogen.

The isotropic particles are then hot-pressed at conventional temperatures, which is contrary to prior-art teachings wherein the relatively low level of rare earth constituents within the magnet compositions of this invention would require increased hot-pressing temperatures to result in useful magnetic remanences. A particular advantage of this invention is that conventional hot-pressing temperatures may be used, even though relatively low levels of the rare earth constituents are present. It is believed that this is due to the presence of an optimal level of boron coupled with the rare earths, which enables the use of conventional hot-pressing temperatures. The hot-pressed iron-rare earth metal permanent magnets of this invention exhibit an improved magnetic remanence of at least 9 to 10 kG, in contrast to conventional hot-pressed magnets of the prior art containing rare earth levels in excess of about 25 weight percent having a magnetic remanence of about 8 kG.

Accordingly, with the present invention, magnetic remanences of at least 9 kG, and preferably of the order of about 10 kG, may be easily achieved in a hot-pressed magnet, wherein the composition of the magnet includes a relatively low rare earth content

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coupled with an optimal boron content. Yet the increase in magnetic remanence is achieved in the preferred hot-pressed compositions having the relatively low rare earth content, without the
5 previous requirement for elevated hot-pressing temperatures of those compositions.

In addition, since the rare earth constituent is typically the most expensive component of these types of magnet compositions, a reduction in
10 the amount of rare earth present in the magnet composition corresponds to a reduction in its overall price, which is an additional benefit of the preferred compositions of this invention.

Other objects and advantages of this
15 invention will be better appreciated from the following detailed description.

Reference will be made to the accompanying drawings, in which:

Figures 1 to 5 illustrate demagnetisation
20 curves for hot-pressed magnets formed from magnetically isotropic particles of the preferred iron-rare earth-boron compositions of this invention.

The preferred compositions of this invention result in isotropic hot-pressed, fully-dense permanent
25 magnets which exhibit magnetic remanences of at least 9 kG, more typically about 10 kG. The preferred compositions are characterised by a relatively low total rare earth content coupled with boron. Advantageously, the hot-pressed magnets may be formed
30 at conventional hot-pressing temperatures.

Appropriate compositions for the iron-rare earth metal permanent magnets of this invention include a suitable transition metal component, a suitable rare earth component and boron, as well as
35 possible small additions of cobalt, and are generally

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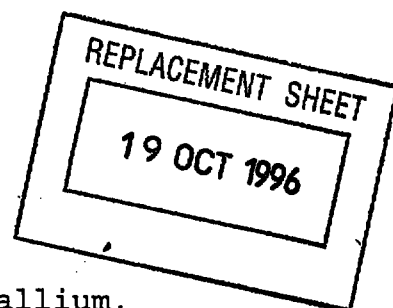
represented by the empirical formula $RE_2TM_{14}B$. The preferred compositions, as stated previously, consist of, on an atomic percentage basis, about 40 to 90 percent of iron or mixtures of cobalt and iron, with
5 the iron preferably making up at least 60 percent of the non-rare earth metal content; about 3 to about 12 percent of rare earth metal that necessarily includes neodymium and/or praseodymium, with the neodymium and/or praseodymium preferably making up at least 60
10 percent of the rare earth content; and the rare earth being coupled with about 4 to about 20 percent boron. Preferably, iron makes up at least 40 atomic percent of the total composition.

Specific compositions which have been useful
15 in preparing hot-pressed, fully-dense, isotropic permanent magnets of this type, in corresponding weight percentages, are as follows and contain the hard magnetic phase consisting of $Fe_{14}Nd_2B$ (or the equivalent) tetragonal crystals; from about 5 percent
20 to about 25 percent rare earth, most preferably about 10 percent to about 20 percent rare earth, wherein the majority constituent is neodymium and the remainder is praseodymium and/or dysprosium; from about 0.5 percent to about 4.5 percent boron, most preferably from about
25 0.8 percent to about 4.0 percent boron, wherein the combined amount of the rare earths and boron ranges from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent, and optionally from about 2 percent to about 16
30 percent cobalt, with the balance being essentially iron.

As stated previously, other elements may also be present in minor amounts of up to about two weight percent, either alone or in combination. These
35 elements include tungsten, chromium, nickel,

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aluminium, copper, magnesium, manganese, gallium,
niobium, vanadium, molybdenum, titanium, tantalum,
zirconium, carbon, tin and calcium. Silicon is also
typically present in small amounts, as are oxygen and
5 nitrogen.

However, it is to be understood that this
invention is applicable to the larger family of
compositions as described previously in atomic
percentages and which larger family of compositions
10 will be referred to generally as an iron-rare
earth-boron composition.

Generally, permanent magnetic bodies of the
preferred composition are formed by starting with
alloy ingots which are melted by induction heating
15 under a dry, substantially oxygen-free argon, inert or
vacuum atmosphere to form a uniform molten
composition. Preferably, the molten composition is
then rapidly solidified to produce an amorphous
material or a finely crystalline material in which the
20 grain size is less than 400 nanometres at its largest
dimension. It is most preferred that the
rapidly-solidified material should have a grain size
smaller than about 20 nanometres. Such material may
be produced, for example, by conventional
25 melt-spinning operations. Conventionally, the
substantially amorphous or microcrystalline, melt-spun
iron-neodymium-boron ribbons are then milled to a
powder, though the ribbons can be used directly with
the present invention.

30 The iron-neodymium-boron particles, which
are magnetically isotropic at this point, are then
hot-pressed at a sufficient pressure for a sufficient
duration to form a fully-dense material. Typically,
this is achieved by heating the composition to a
35 suitable temperature, such as about 750°C, or

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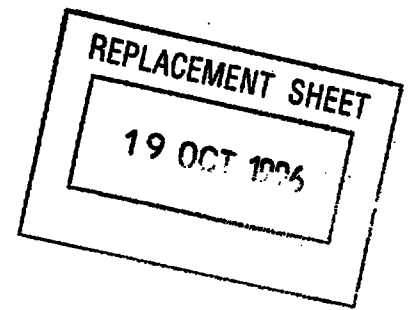
preferably between about 750°C to about 800°C, in a die, and compacting the composition between upper and lower punches, under a pressure of, for example, about 77.22 MPa to about 92.67 MPa (about 5 to about 6 tons per square inch), so as to form a substantially fully-dense, flat cylindrical plug. Generally, when melt-spun material finer than about 20 nanometres in grain size is heated at such an elevated temperature for a period of a minute or so and then hot-pressed to full density, the resultant body is a permanent magnet. If the particulate material has been held at the hot-pressing temperature for a suitable period of time, it will then have a grain size in the range of about 20 to about 500 nanometres, preferably about 20 to 100 nanometres.

The magnetic properties of hot-pressed isotropic permanent magnets formed in accordance with this invention were determined using conventional Hysteresis Graph Magnetometer (HGM) tests. Test samples were placed so that the axis parallel to the direction of alignment was parallel to the direction of the magnetic field applied by the HGM. The samples were each then magnetised to saturation and then demagnetised.

The second quadrant demagnetisation plots are shown in Figures 1 to 5 [remanence $4\pi M$ in kiloGauss versus coercivity (H) in kiloOersteds] for the preferred isotropic hot-pressed permanent magnets of this invention.

The specific samples tested are described more fully below. For the specific examples below, melt-spinning at a rate of 22 metres/second was followed by crushing of the magnetically-isotropic melt-spun material to form the particulate material which was then shaped into a preform. The preform was

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then hot-pressed at a temperature of about 750°C, and under a pressure of about 77.22 MPa to about 92.67 MPa (5 to about 6 tons per square inch), to form the fully-dense hot-pressed magnets, which are essentially the same conditions used to form conventional hot-pressed permanent magnet bodies having high rare earth contents. It is to be noted that the bounds of this invention are not to be limited by the particular melt-spinning rate and hot-pressing temperatures used for these illustrative examples.

Example 1

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and tested. The nominal composition, in weight percent, was about 12.7 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 3.9 percent boron, about 3.5 percent cobalt, about 1.2 percent gallium, and the balance iron. The magnet had a diameter of about 16 millimetres, a height of about 11 millimetres and a weight of about 10 grams.

The second quadrant demagnetisation plot for this magnet is shown in Figure 1 and indicates a magnetic remanence (B_r) of about 10.0 kG and an intrinsic coercivity (H_{ci}) of about 3.4 kiloOersteds (kOe). It was determined that the saturation magnetisation value for this low rare earth composition was about 16 kG; therefore, the magnetic remanence of 10 kG obtained after hot-pressing was greater than 62 percent of the saturation value. It is believed that this value is the highest reported for an isotropic magnet of this type. The properties of the magnet were tested in all three directions and the magnet was determined to be isotropic.

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Example 2

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and had a nominal composition, in weight percent, of about 13.9 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 4 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 2 and indicates a magnetic remanence (B_r) of about 9.6 kG and an intrinsic coercivity (H_{ci}) of about 2.4 kOe.

Example 3

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and had a nominal composition, in weight percent, of about 2.6 percent dysprosium with the total rare earth constituent, including neodymium, being 11.2 percent, about 3.8 percent boron, about 3.5 percent cobalt, about 1.3 percent gallium, and the balance iron.

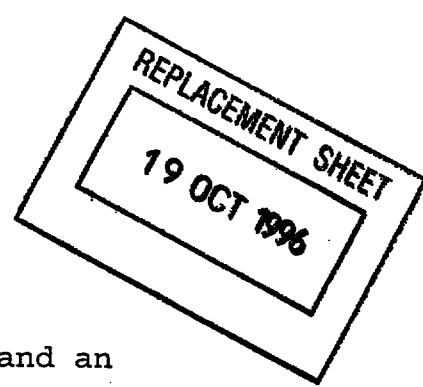
The second quadrant demagnetisation plot for this magnet is shown in Figure 3 and indicates a magnetic remanence (B_r) of about 10 kG and an intrinsic coercivity (H_{ci}) of about 2.8 kOe.

Example 4

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and tested. The nominal composition, in weight percent, was about 12.6 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 3.8 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 4 and indicates a

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magnetic remanence (B_r) of about 9.9 kG and an intrinsic coercivity (H_{ci}) of about 2.8 kOe.

Example 5

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above having a nominal composition, in weight percent, of about 19 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 1 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 5 and indicates a magnetic remanence (B_r) of about 9.6 kG and an intrinsic coercivity (H_{ci}) of about 4.3 kOe.

From the above, it can be seen that hot-pressed isotropic permanent magnets having improved magnetic remanences of at least 9.0 kG, more typically about 10.0 kG, can be formed using compositions containing relatively low levels of rare earths coupled with a sufficient amount of boron. It was determined that by reducing the amount of neodymium in the preferred Nd-Fe-B alloys, a Fe_3B phase present in the alloy also becomes an equilibrium phase with the $Nd_2Fe_{14}B$ phase. In addition, an α -Fe phase is also present. It is further believed that the magnetic remanences of these preferred alloys are dominated by a soft magnetic Fe_3B phase, whilst magnetic coercivity is controlled by the dispersion of the hard magnetic $Nd_2Fe_{14}B$ phase. Therefore, further improvements in magnetic properties are possible through modifications of intrinsic properties of the individual phases through specific alloying in accordance with the disclosure of this invention.

A particular advantage of this invention is that conventional hot-pressing temperatures may be

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used, even though relatively low levels of the rare earth constituents are present, as opposed to the disclosures in the prior art. It is believed that this is due to the presence of optimal levels of boron
5 coupled with the rare earths. The hot-pressed iron-rare earth-boron permanent magnets of this invention exhibit an improved magnetic remanence of at least 9 to 10 kG, as compared to conventional
10 hot-pressed magnets of the prior art having magnetic remanences of about 8 kG and containing rare earth levels in excess of about 25 weight percent.

In addition, a significant cost saving can be achieved without a discernible loss in magnetic properties with the compositions of this invention
15 since the amount of rare earth constituents, which are the most expensive constituents of these types of permanent magnets, is significantly reduced.

Accordingly, with the disclosure of this invention, magnetic remanences of at least 9 kG, and
20 preferably of the order of about 10 kG, which are believed to be the highest values reported for an isotropic magnet of this type, may be readily achieved in a hot-pressed magnet, wherein the composition of the magnet includes a relatively low rare earth
25 content coupled with an optimal level of boron.

Therefore, whilst this invention has been described in terms of a preferred embodiment thereof, it is apparent that other forms could be adopted by one skilled in the art. For example, the composition
30 of the magnetic particles could be varied within the preferred weight and atomic ranges, with or without other constituents as described above, or different and/or additional processing steps may be employed to produce the isotropic particles used to form the
35 hot-pressed isotropic magnets, as well as other

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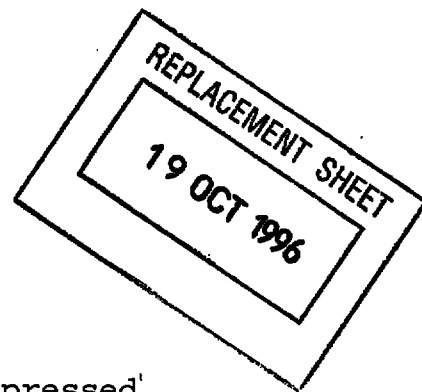
variations. Accordingly, the scope of this invention is to be limited only by the scope of the following claims.

5 The disclosures in United States patent application no. 148,155, from which this application claims priority, and in the abstract accompanying this application are incorporated herein by reference.

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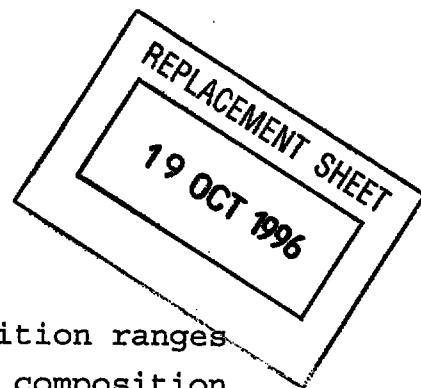
Claims:

1. A method for forming a hot-pressed iron-rare earth-boron permanent magnet, the method comprising the steps of: providing a quantity of isotropic iron-rare earth-boron metal particles, and hot-pressing said quantity of isotropic iron-rare earth-boron metal particles at a temperature and for a duration sufficient to form a hot-pressed isotropic iron-rare earth-boron metal permanent magnet, characterised in that said quantity of isotropic iron-rare earth-boron metal particles is formed from a composition comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal, and from about 0.5 to about 4.5 percent boron, wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent of the composition, with the balance being principally iron; and the magnet formed has a magnetic remanence of at least 9 kiloGauss.
2. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which the majority of said rare earth constituent is neodymium.
3. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which the composition also includes from about 2 to about 16 percent cobalt.
4. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which said rare earth content of the composition ranges from about 10 to about 20 percent rare earth metal, and said boron content of the composition ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare

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earth metal and said boron in the composition ranges from about 12 to about 22 percent of the composition.

5. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which said isotropic iron-rare earth metal particles have a grain size of not more than 500 nanometres.

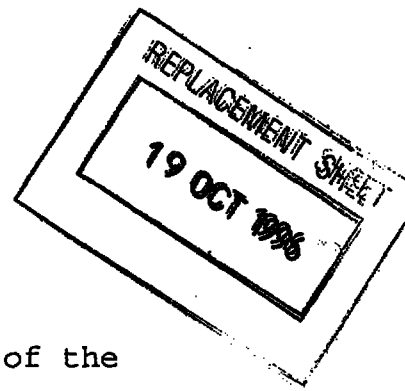
6. A method for forming a hot-pressed iron-rare earth-boron permanent magnet, the method comprising the steps of: providing a quantity of isotropic iron-rare earth-boron metal particles having a grain size of not more than 500 nanometres, and hot-pressing said quantity of isotropic iron-rare earth-boron metal particles at a temperature and for a duration sufficient to form a hot-pressed isotropic iron-rare earth-boron metal permanent magnet characterised in that said quantity of isotropic iron-rare earth-boron metal particles is formed from a composition comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal wherein the majority of said rare earth constituent is neodymium, and from about 0.5 to about 4.5 percent boron, and wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent of the composition, with the balance being principally iron; and the magnet formed has the uniform presence of both a hard magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and soft magnetic phases Fe_3B and $\alpha\text{-Fe}$, and a magnetic remanence of at least 9 kiloGauss.

7. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 6, in which the composition also includes from about 2 to about 16 percent cobalt.

8. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to

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claim 6, in which said rare earth content of the composition ranges from about 10 to about 20 percent rare earth metal, and said boron content of the composition ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare earth metal and said boron in the composition ranges from about 12 to about 22 percent of the composition.

9. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 6, in which said hot-pressing step is at a temperature ranging from about 750°C to 800°C.

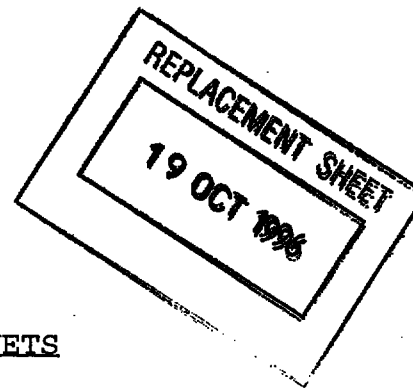
10. A hot-pressed isotropic iron-rare earth-boron permanent magnet comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal wherein the majority of said rare earth constituent is neodymium, and from about 0.5 to about 4.5 percent boron, and wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent, with the balance being principally iron; which magnet is characterised by the uniform presence of both a hard magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and soft magnetic phases Fe_3B and $\alpha\text{-Fe}$; and which has a magnetic remanence of at least 9 kiloGauss.

11. A hot-pressed isotropic iron-rare earth-boron permanent magnet according to claim 10, in which said magnet further comprises from about 2 to about 16 percent cobalt.

12. A hot-pressed isotropic iron-rare earth-boron permanent magnet according to claim 10, in which said rare earth content ranges from about 10 to about 20 percent rare earth metal, and said boron content ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare earth metal and said boron ranges from about 12 to about 22 percent of the magnet.

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HIGH PERFORMANCE HOT-PRESSED MAGNETS

Abstract

Isotropic hot-pressed iron-rare earth metal permanent magnets are provided wherein the hot-pressed permanent magnets exhibit magnetic remanences of at least 9 kG, and most typically about 10 kG. Preferred
5 compositions include a relatively low rare earth content coupled with an optimal amount of boron. The preferred composition is, on a weight percent basis, from about 5 to about 25 percent rare earth, most preferably about 10 to about 20 percent rare earth,
10 from about 0.5 to about 4.5 percent boron, most preferably from about 0.8 to about 4.0 percent boron, wherein the total combination of the rare earths and boron ranges from about 9 percent to about 26 percent of the composition, most preferably from about 12
15 percent to about 22 percent, and optionally from about 2 percent to about 16 percent cobalt, with the balance being essentially iron.

FIGURE 1

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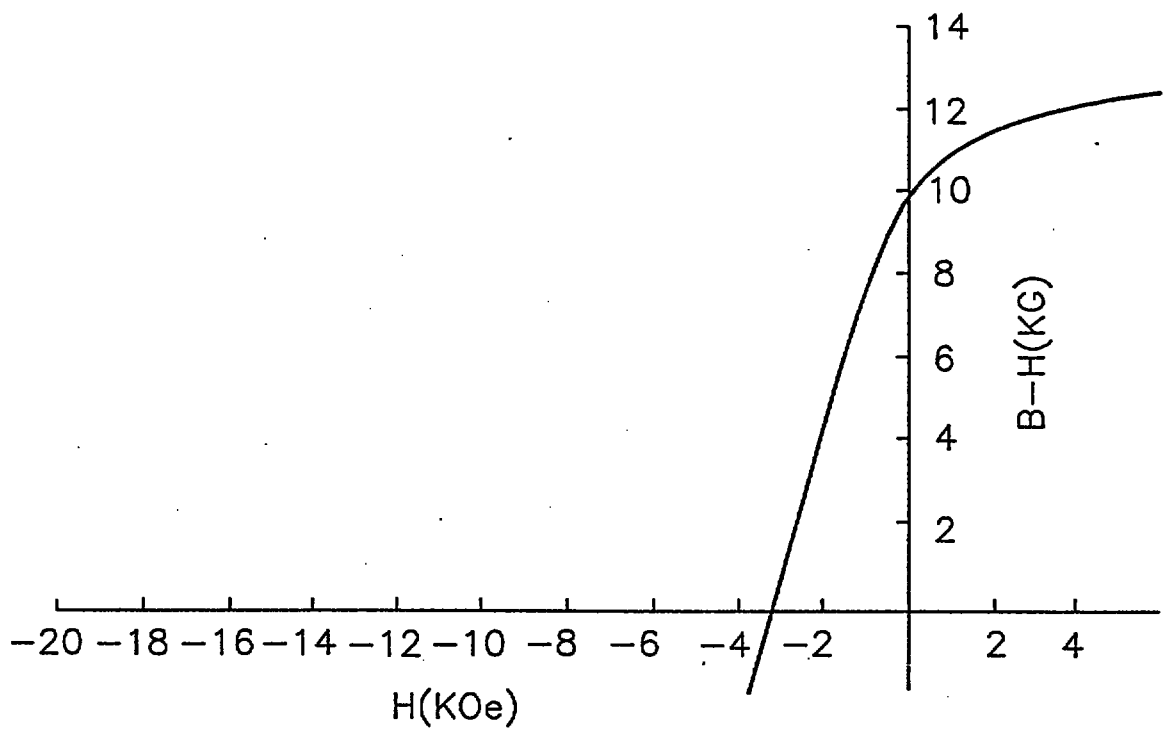


FIG.1

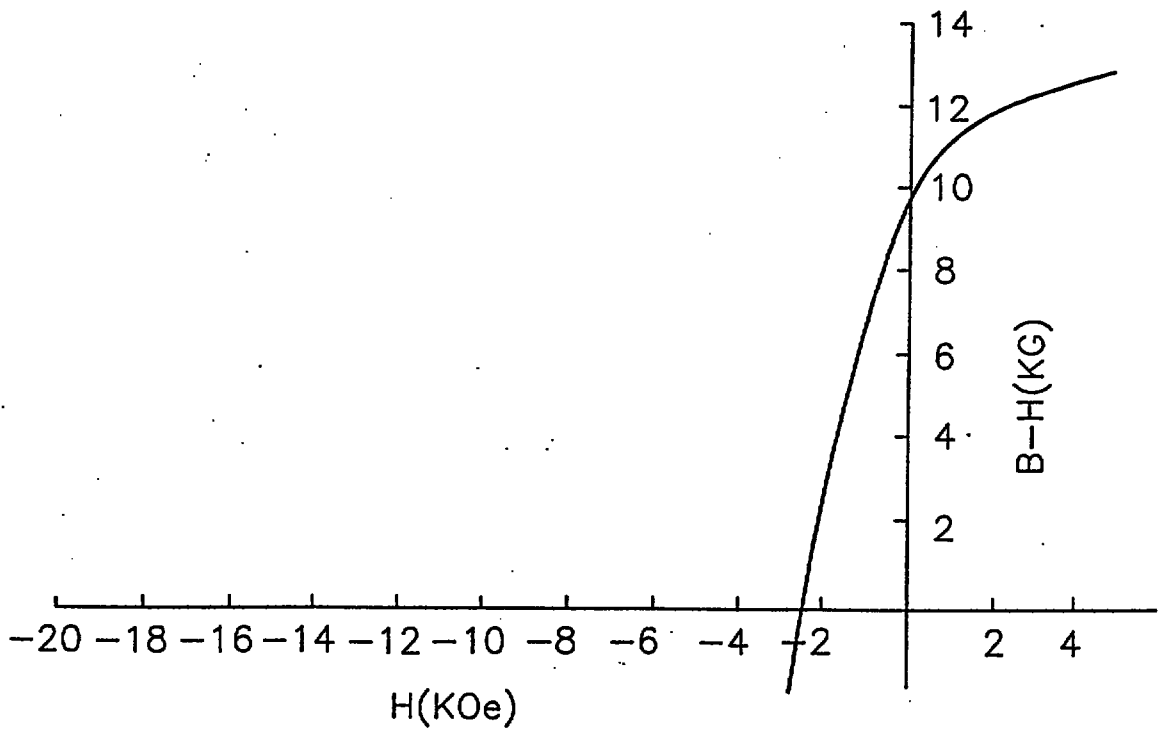


FIG.2

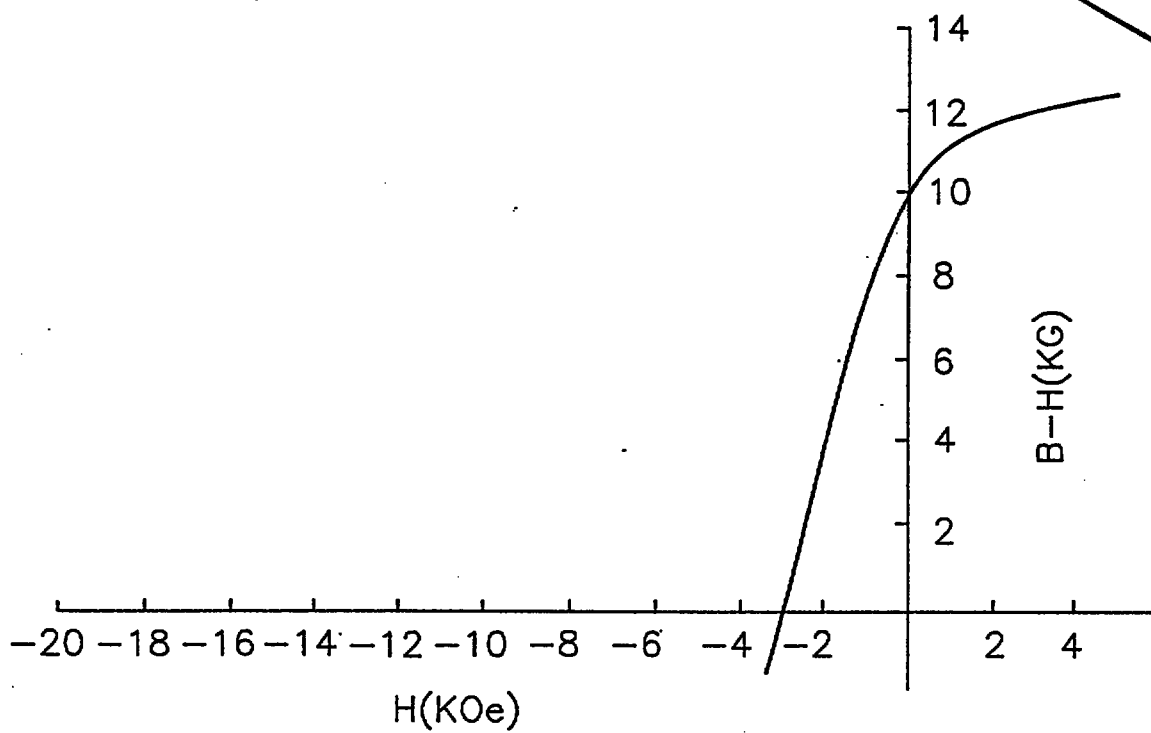
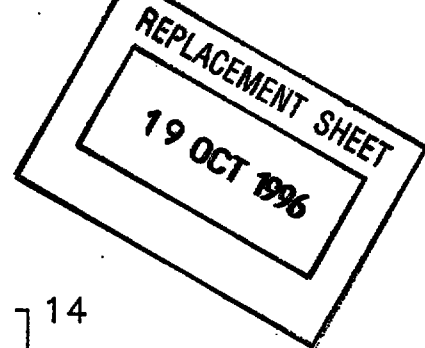


FIG.3

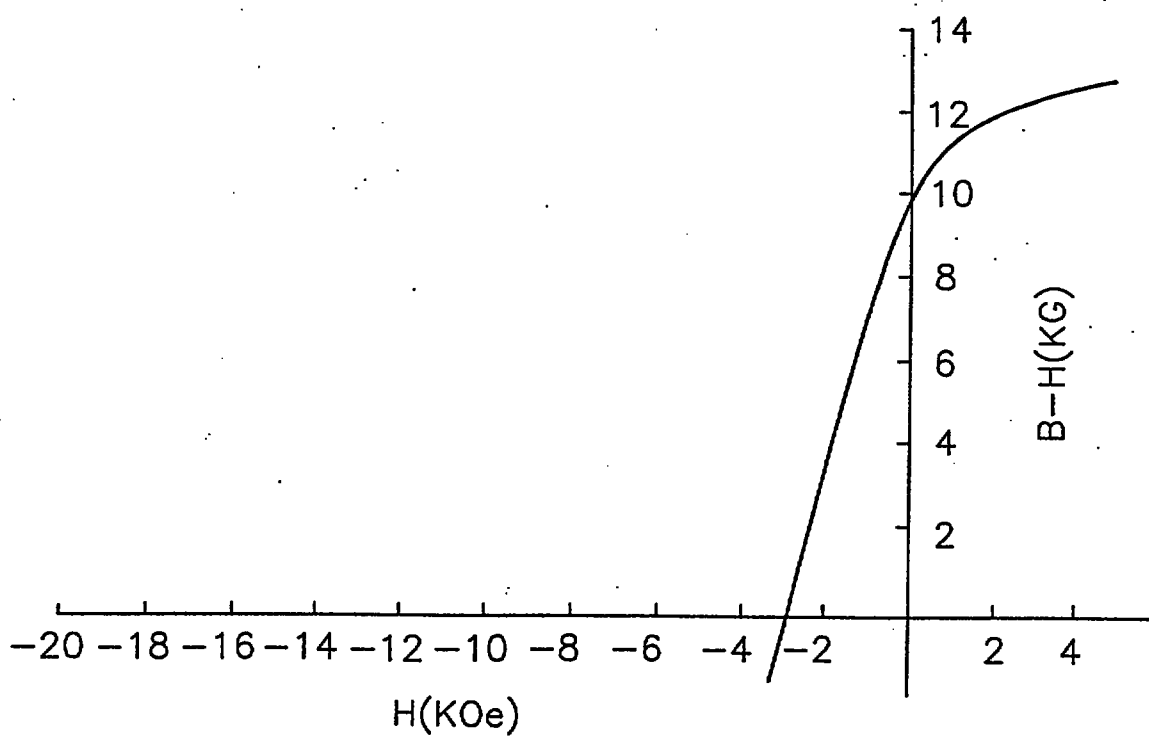


FIG.4

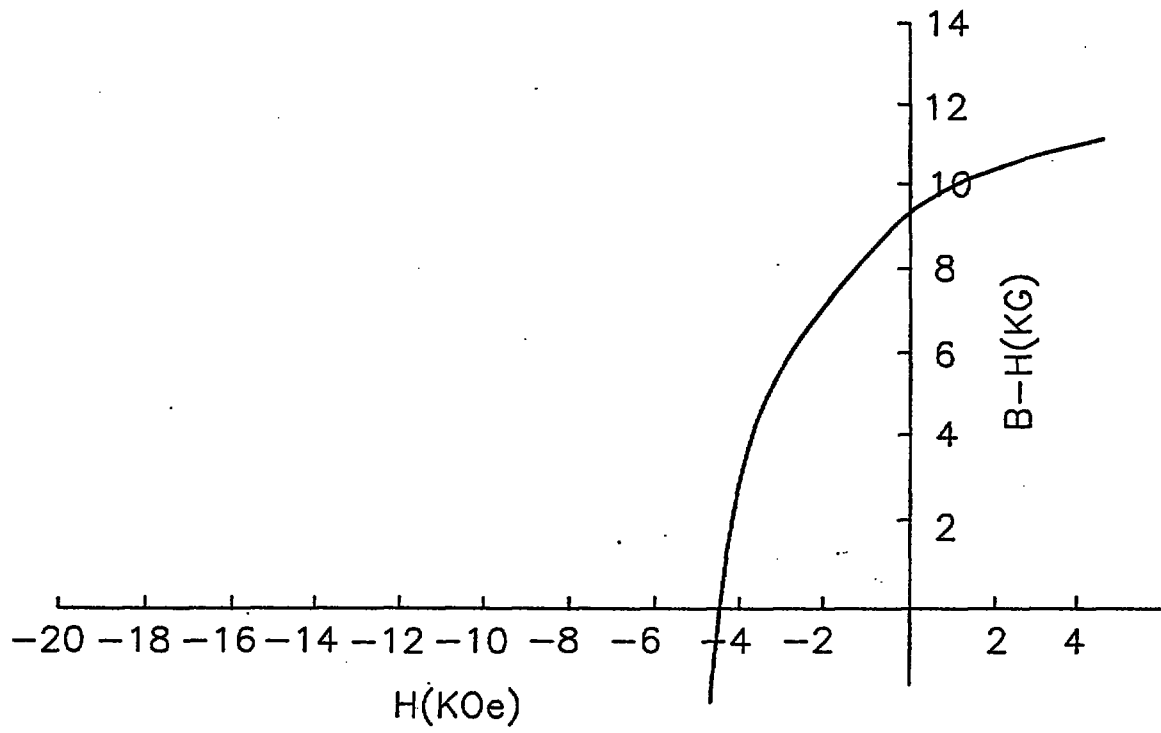
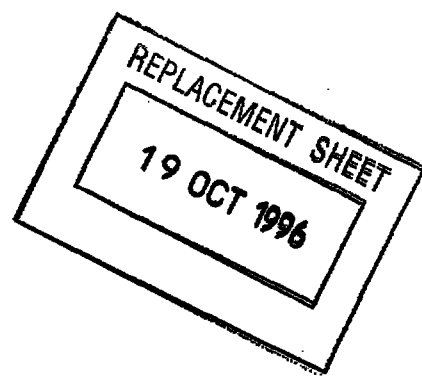


FIG.5

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HIGH PERFORMANCE HOT-PRESSED MAGNETS

The present invention generally relates to the making of high remanence hot-pressed permanent magnets based primarily on iron, rare earths such as neodymium and/or praseodymium and/or dysprosium, and boron, as specified in the preamble of claim 1. More specifically, this invention concerns the forming of such magnets having magnetic remanences of at least 9 kiloGauss (kG), and most typically about 10 kG, by hot-pressing permanent magnet particles having, in weight percents, a rare earth level of from about 5 percent to 25 percent, most preferably from about 10 percent to about 20 percent, and preferably combined with a boron content of from about 0.5 percent to about 4.0 percent, most preferably from about 0.8 percent to about 4.0 percent, wherein the total amount of the rare earth constituent and boron ranges from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent.

Permanent magnets based on compositions containing iron, neodymium and/or praseodymium, and boron are known and in commercial usage. Such permanent magnets contain as an essential magnetic phase grains of tetragonal crystals in which the proportions of, for example, iron, neodymium and boron are exemplified by the empirical formula $\text{Nd}_2\text{Fe}_{14}\text{B}$. These magnet compositions and methods for making them are described by Croat in US Patent No. 4,802,931 issued February 7, 1989. The grains of the magnetic phase are surrounded by a second phase that is typically rare earth-rich, as an example neodymium-rich, as compared with the essential magnetic phase. It is known that magnets based on such compositions may be prepared by rapidly solidifying, such as by melt-spinning, a melt of the

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23 AUG 1999

composition to produce fine-grained, magnetically-isotropic platelets of ribbon-like fragments. Magnets may be formed from these isotropic particles by practices which are known, such as bonding the particles together with a suitable resin.

Although the magnets formed from these isotropic ribbons are satisfactory for some applications, they typically exhibit an energy product (BH_{max}) of about 8 to about 10 megaGaussOersteds (MGOe), which is insufficient for many other applications. To improve the energy product, it is known to hot-press the isotropic particles to form magnets having an energy product of about 13 to about 14 MGOe and magnetic remanences of the order of about 8 kG.

However, there are applications when it would be desirable that such hot-pressed magnets should have higher magnetic remanence values. As an example, if the hot-pressed magnet is used in an application at or near its maximum magnetic remanence, it may be desirable to increase its magnetic remanence so as to increase the working capability of the magnet.

Conventionally, for hot-pressed magnets of the iron-rare earth metal type, the total rare earth constituent is greater than about 25 percent, most typically greater than about 29 percent, by weight. This is true since compositions containing lower amounts of the rare earth constituents contain lesser amounts of the intergranular phase, and therefore require higher pressing temperatures, which are detrimental to the life of the hot-pressing punches and add undesirable costs to the pressing process. Thus, the prior art has generally always taught that hot-pressed permanent magnet compositions of this type

23 AUG 1999

must contain, as a minimum, at least 25 percent rare earth constituent.

Yet, it would be desirable to provide a means for increasing the magnetic remanence of a hot-pressed magnet, such as to a value of at least 9kG or 10 kG, whilst simultaneously reducing or minimising the amount of rare earth constituent within the compositions, since the rare earth constituents are typically much more costly as compared to the other constituents. However, the means for accomplishing such an increase in magnetic remanence should not result in increased hot-pressing temperatures.

An article by Zhou, Li and Morrish in *Hyperfine Interactions*, vol. 72, no 1-3, 15 March 1992, Basel CH, pages 111-121 investigates the effects of boron concentration and annealing time on the magnetic properties of rapidly quenched $\text{Nd}_2\text{Fe}_{14}\text{B}$ after crystallization.

A method for forming a hot-pressed iron-rare earth boron permanent magnet according to the present invention is characterised portion of claim 1.

It is therefore, an object of this invention to provide an isotropic hot-pressed permanent magnet exhibiting a magnetic remanence of at least 9 kG, preferably about 10 kG.

It is a further object of this invention that such an isotropic hot-pressed magnet should have a composition that has, as its magnetic constituent, the tetragonal crystal phase $\text{RE}_2\text{TM}_{14}\text{B}$ which is based primarily on neodymium and/or praseodymium, iron and boron, and wherein the total amount,

23 AUG 1999

- 4 -

in weight percent, or rare earth constituent ranges from about 5 percent to about 25 percent, preferably from about 10 percent to about 20 percent, and is coupled with a boron quantity of from about 0.5 percent to about 4.0 percent, such that the combined amount of rare earth and boron within the composition ranges from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent.

Furthermore, it is an object of this invention that such a hot-pressed magnet having a magnetic remanence of at least 9 to 10 kG should be pressed at conventional pressing temperatures.

In accordance with a preferred embodiment of this invention, these and other objects and advantages are accomplished as follows.

According to one aspect of the present invention, there is provided a hot-pressed isotropic iron-rare earth-boron permanent magnet comprising, on a weight percent basis from about 5 to about 25 percent rare earth metal wherein the majority of said rare earth constituent is neodymium, and from about 0.5 to about 4.0 percent boron, and wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent, with the balance being principally iron; which magnet is characterised by the uniform presence of both a hard magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and soft magnetic phases Fe_3B and $\alpha\text{-Fe}$; and which has a magnetic remanence of at least 9 kiloGauss and intrinsic coercivity of at least 2 kiloOersted.

23 AUG 1999

The isotropic hot-pressed iron-rare earth boron permanent magnet, exhibits a magnetic remanence of at least 9 kG, and most typically about 10 kG, which is nearly 62% of saturation magnetisation for this material. This is believed to be the highest value reported for an isotropic magnet of this type. The hot-pressed magnet of this invention is produced by pressing a quantity of isotropic iron-rare earth-boron metal particles. The isotropic particles can be formed by known methods, such as by melt-spinning a suitable iron-rare earth-boron metal composition to an overquenched or optimum condition. Isotropic particles formed by melt-spinning are generally ribbon-shaped in configuration and can be readily reduced to a desired particle size.

The composition comprises, on a weight percent basis, from about 5 percent to about 25 percent rare earth, more preferably about 10 percent to about 20 percent rare earth, from about 0.5 percent to about 4.0 percent boron, most preferably from about 0.8 percent to about 4.0 percent boron, with the total combination of rare earth plus boron, ranging from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent, and as an

REPLACEMENT SHEET

23 AUG 1999

- 6 -

REPLACEMENT SHEET

optional ingredient, from about 2 percent to about 16 percent cobalt, with the balance being essentially iron.

Other elements may also be present in minor amounts of up to about two weight percent, either alone or in combination. These elements include tungsten, chromium, nickel, aluminium, copper, magnesium, manganese, gallium, niobium, vanadium, molybdenum, titanium, tantalum, zirconium, carbon, tin and calcium. Silicon is also typically present in small amounts, as are oxygen and nitrogen.

The isotropic particles are then hot-pressed at conventional temperatures, which is contrary to prior-art teachings wherein the relatively low level of rare earth constituents within the magnet compositions of this invention would require increased hot-pressing temperatures to result in useful magnetic remanences. A particular advantage of this invention is that conventional hot-pressing temperatures may be used, even though relatively low levels of the rare earth constituents are present. It is believed that this is due to the presence of an optimal level of boron coupled with the rare earths, which enables the use of conventional hot-pressing temperatures. The hot-pressed iron-rare earth metal permanent magnets of this invention exhibit an improved magnetic remanence of at least 9 to 10 kG, in contrast to conventional hot-pressed magnets of the prior art containing rare earth levels in excess of about 25 weight percent having a magnetic remanence of about 8 kG.

Accordingly, with the present invention, magnetic remanences of at least 9 kG, and preferably of the order of about 10 kG, may be easily achieved in a hot-pressed magnet, wherein the composition of the magnet includes a relatively low rare earth content

23 AUG 1999

- 7 -

coupled with an optical boron content. Yet the increase in magnetic remanence is achieved in the preferred hot-pressed compositions having the relatively low rare earth content, without the previous requirement for elevated hot-pressing temperatures of those compositions.

In addition, since the rare earth constituent is typically the most expensive component of these types of magnet compositions, a reduction in the amount of rare earth present in the magnet composition corresponds to a reduction in its overall price, which is an additional benefit of the preferred compositions of this invention.

According to a second aspect of the present invention, there is provided a method for forming a hot-pressed iron-rare earth-boron permanent magnet, the method comprising the steps of: providing a quantity of isotropic iron-rare earth-boron metal particles, and hot-pressing said quantity of isotropic iron-rare earth-boron metal particles at a temperature and for a duration sufficient to form a hot-pressed isotropic iron-rare earth-boron metal permanent magnet, characterised in that said quantity of isotropic iron-rare earth-boron metal particles is formed from a composition comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal, and from about 0.5 to about 4.0 percent boron, wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent of the composition, with the balance being principally iron; and the magnet formed has a magnetic remanence of at least 9 kiloGauss and intrinsic coercivity

23 AUG 1999

of at least 2 kiloOrested.

According to a third aspect of the present invention, there is provided a method for forming a hot-pressed iron-rare earth-boron permanent magnet, the method of comprising the steps of: providing a quantity of isotropic iron-rare earth-boron metal particles having a grain size of not more than 500 nanometres, and hot-pressing said quantity of isotropic iron-rare earth-boron metal particles at a temperature and for a duration sufficient to form a hot-pressed isotropic iron-rare earth-boron metal permanent magnet characterised in that said quantity of isotropic iron-rare earth-boron metal particles is formed from a composition comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal wherein the majority of said rare earth constituent is neodymium, and from about 0.5 to about 4.0 percent boron, and wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent of the composition, with the balance being principally iron; and the magnet formed has the uniform presence of both a hard magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and soft magnetic phases Fe_3B phase and $\alpha\text{-Fe}$, and a magnetic remanence of at least 9 kiloGauss and intrinsic coercivity or at least 2 kiloOrested.

Other objects and advantages of this invention will be better appreciated from the following detailed description.

Reference will be made to the accompanying drawings, in which:

Figures 1 to 5 illustrate demagnetisation curves for

23 AUG 1999

hot-pressed magnets formed from magnetically isotropic particles of the preferred iron-rare earth-boron compositions of this invention.

The preferred compositions of this invention results in isotropic hot-pressed, fully-dense permanent magnets which exhibit magnetic remanences of at least 9kG, more typically about 10kG. The preferred compositions are characterised by a relatively low total rare earth content coupled with boron. Advantageously, the hot-pressed magnets may be formed at conventional hot-pressing temperatures.

Appropriate compositions for the iron-rare earth metal permanent magnets of this invention include a suitable transition metal component, a suitable rare earth component and boron, as well as possible small additions of cobalt, and are generally

23 AUG 1999

represented by the empirical formula $RE_2TM_{14}B$. The preferred compositions, as stated previously, consist of, on an atomic percentage basis, about 40 to 90 percent of iron or mixtures of cobalt and iron, with the iron preferably making up at least 60 percent of the non-rare earth metal content; about 3 to about 12 percent of rare earth metal that necessarily includes neodymium and/or praseodymium, with the neodymium and/or praseodymium preferably making up at least 60 percent of the rare earth content; and the rare earth being coupled with about 4 to about 20 percent boron. Preferably, iron makes up at least 40 atomic percent of the total composition.

Specific compositions which have been useful in preparing hot-pressed, fully-dense, isotropic permanent magnets of this type, in corresponding weight percentages, are as follows and contain the hard magnetic phase consisting of $Fe_{14}Nd_2B$ (or the equivalent) tetragonal crystals; from about 5 percent to about 25 percent rare earth, most preferably about 10 percent to about 20 percent rare earth, wherein the majority constituent is neodymium and the remainder is praseodymium and/or dysprosium; from about 0.5 percent to about 4.0 percent boron, most preferably from about 0.8 percent to about 4.0 percent boron, wherein the combined amount of the rare earths and boron ranges from about 9 percent to about 26 percent, most preferably from about 12 percent to about 22 percent, and optionally from about 2 percent to about 16 percent cobalt, with the balance being essentially iron.

As stated previously, other elements may also be present in minor amounts of up to about two weight percent, either alone or in combination. These elements include tungsten, chromium, nickel,

23 AUG 1999

- 11 -

aluminium, copper, magnesium, manganese, gallium, niobium, vanadium, molybdenum, titanium, tantalum, zirconium, carbon, tin and calcium. Silicon is also typically present in small amounts, as are oxygen and nitrogen.

However, it is to be understood that this invention is applicable to the larger family of compositions as described previously in atomic percentages and which larger family of compositions will be referred to generally as an iron-rare earth-boron composition.

Generally, permanent magnetic bodies of the preferred composition are formed by starting with alloy ingots which are melted by induction heating under a dry, substantially oxygen-free argon, inert or vacuum atmosphere to form a uniform molten composition. Preferably, the molten composition is then rapidly solidified to produce an amorphous material or a finely crystalline material in which the grain size is less than 400 nanometres at its largest dimension. It is most preferred that the rapidly-solidified material should have a grain size smaller than about 20 nanometres. Such material may be produced, for example, by conventional melt-spinning operations. Conventionally, the substantially amorphous or microcrystalline, melt-spun iron-neodymium-boron ribbons are then milled to a powder, though the ribbons can be used directly with the present invention.

The iron-neodymium-boron particles, which are magnetically isotropic at this point, are then hot-pressed at a sufficient pressure for a sufficient duration to form a fully-dense material. Typically, this is achieved by heating the composition to a suitable temperature, such as about 750°C, or

23 AUG 1999

- 12 -

preferably between about 750°C to about 800°C, in a die, and compacting the composition between upper and lower punches, under a pressure of, for example, about 77.22 MPa to about 92.67 MPa (about 5 to about 6 tons per square inch), so as to form a substantially fully-dense, flat cylindrical plug. Generally, when melt-spun material finer than about 20 nanometres in grain size is heated at such an elevated temperature for a period of a minute or so and then hot-pressed to full density, the resultant body is a permanent magnet. If the particulate material has been held at the hot-pressing temperature for a suitable period of time, it will then have a grain size in the range of about 20 to about 500 nanometres, preferably about 20 to 100 nanometres.

The magnetic properties of hot-pressed isotropic permanent magnets formed in accordance with this invention were determined using conventional Hysteresis Graph Magnetometer (HGM) tests. Test samples were placed so that the axis parallel to the direction of alignment was parallel to the direction of the magnetic field applied by the HGM. The samples were each then magnetised to saturation and then demagnetised.

The second quadrant demagnetisation plots are shown in Figures 1 to 5 [remanence $4\pi M$ in kiloGauss versus coercivity (H) in kiloOersteds] for the preferred isotropic hot-pressed permanent magnets of this invention.

The specific samples tested are described more fully below. For the specific examples below, melt-spinning at a rate of 22 metres/second was followed by crushing of the magnetically-isotropic melt-spun material to form the particulate material which was then shaped into a preform. The preform was

23 AUG 1999

- 13 -

then hot-pressed at a temperature of about 750°C, and under a pressure of about 77.22 MPa to about 92.67 MPa (5 to about 6 tons per square inch), to form the fully-dense hot-pressed magnets, which are essentially the same conditions used to form conventional hot-pressed permanent magnet bodies having high rare earth contents. It is to be noted that the bounds of this invention are not to be limited by the particular melt-spinning rate and hot-pressing temperatures used for these illustrative examples.

Example 1

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and tested. The nominal composition, in weight percent, was about 12.7 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 3.9 percent boron, about 3.5 percent cobalt, about 1.2 percent gallium, and the balance iron. The magnet had a diameter of about 16 millimetres, a height of about 11 millimetres and a weight of about 10 grams.

The second quadrant demagnetisation plot for this magnet is shown in Figure 1 and indicates a magnetic remanence (B_r) of about 10.0 kG and an intrinsic coercivity (H_{ci}) of about 3.4 kiloOersteds (kOe). It was determined that the saturation magnetisation value for this low rare earth composition was about 16 kG; therefore, the magnetic remanence of 10 kG obtained after hot-pressing was greater than 62 percent of the saturation value. It is believed that this value is the highest reported for an isotropic magnet of this type. The properties of the magnet were tested in all three directions and the magnet was determined to be isotropic.

23 AUG 1999

Example 2

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and had a nominal composition, in weight percent, of about 13.9 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 4 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 2 and indicates a magnetic remanence (B_r) of about 9.6 kG and an intrinsic coercivity (H_{ci}) of about 2.4 kOe.

Example 3

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and had a nominal composition, in weight percent, of about 2.6 percent dysprosium with the total rare earth constituent, including neodymium, being 11.2 percent, about 3.8 percent boron, about 3.5 percent cobalt, about 1.3 percent gallium, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 3 and indicates a magnetic remanence (B_r) of about 10 kG and an intrinsic coercivity (H_{ci}) of about 2.8 kOe.

Example 4

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above and tested. The nominal composition, in weight percent, was about 12.6 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 3.8 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 4 and indicates a

23 AUG 1999

magnetic remanence (B_r) of about 9.9 kG and an intrinsic coercivity (H_{ci}) of about 2.8 kOe.

Example 5

A fully-dense, hot-pressed isotropic permanent magnet was formed as described above having a nominal composition, in weight percent, of about 19 percent total rare earth (at least 95 percent of this constituent being neodymium and the remainder being essentially praseodymium), about 1 percent boron, and the balance iron.

The second quadrant demagnetisation plot for this magnet is shown in Figure 5 and indicates a magnetic remanence (B_r) of about 9.6 kG and an intrinsic coercivity (H_{ci}) of about 4.3 kOe.

From the above, it can be seen that hot-pressed isotropic permanent magnets having improved magnetic remanences of at least 9.0 kG, more typically about 10.0 kG, can be formed using compositions containing relatively low levels of rare earths coupled with a sufficient amount of boron. It was determined that by reducing the amount of neodymium in the preferred Nd-Fe-B alloys, a Fe_3B phase present in the alloy also becomes an equilibrium phase with the $Nd_2Fe_{14}B$ phase. In addition, an α -Fe phase is also present. It is further believed that the magnetic remanences of these preferred alloys are dominated by a soft magnetic Fe_3B phase, whilst magnetic coercivity is controlled by the dispersion of the hard magnetic $Nd_2Fe_{14}B$ phase. Therefore, further improvements in magnetic properties are possible through modifications of intrinsic properties of the individual phases through specific alloying in accordance with the disclosure of this invention.

A particular advantage of this invention is that conventional hot-pressing temperatures may be

23 AUG 1999

used, even though relatively low levels of the rare earth constituents are present, as opposed to the disclosures in the prior art. It is believed that this is due to the presence of optimal levels of boron coupled with the rare earths. The hot-pressed iron-rare earth-boron permanent magnets of this invention exhibit an improved magnetic remanence of at least 9 to 10 kG, as compared to conventional hot-pressed magnets of the prior art having magnetic remanences of about 8 kG and containing rare earth levels in excess of about 25 weight percent.

In addition, a significant cost saving can be achieved without a discernible loss in magnetic properties with the compositions of this invention since the amount of rare earth constituents, which are the most expensive constituents of these types of permanent magnets, is significantly reduced.

Accordingly, with the disclosure of this invention, magnetic remanences of at least 9 kG, and preferably of the order of about 10 kG, which are believed to be the highest values reported for an isotropic magnet of this type, may be readily achieved in a hot-pressed magnet, wherein the composition of the magnet includes a relatively low rare earth content coupled with an optimal level of boron.

Therefore, whilst this invention has been described in terms of a preferred embodiment thereof, it is apparent that other forms could be adopted by one skilled in the art. For example, the composition of the magnetic particles could be varied within the preferred weight and atomic ranges, with or without other constituents as described above, or different and/or additional processing steps may be employed to produce the isotropic particles used to form the hot-pressed isotropic magnets, as well as other

REPLACEMENT SHEET

23 AUG 1999

- 17 -

REPLACEMENT SHEET

variations. Accordingly, the scope of this invention is to be limited only by the scope of the following claims.

The disclosures in United States patent application no. 148,155, from which this application claims priority, and in the abstract accompanying this application are incorporated herein by reference.

23 AUG 1999

CLAIMS

1. A method for forming a hot-pressed iron-rare earth-boron permanent magnet, the method comprising the steps of: providing a quantity of isotropic iron-rare earth-boron metal particles, and hot-pressing said quantity of isotropic iron-rare earth-boron metal particles at a temperature and for a duration sufficient to form a hot-pressed isotropic iron-rare earth-boron metal permanent magnet, characterised in that said quantity of isotropic iron-rare earth-boron metal particles is formed from a composition comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal, and from about 0.5 to about 4.0 percent boron, wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent of the composition, with the balance being principally iron; and the magnet formed has a magnetic remanence of at least 9 kiloGauss and intrinsic coercivity of at least 2 kiloOersted.

2 A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which the majority of said rare earth constituent is neodymium.

3. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which the composition also includes from about 2 to about 16 percent cobalt.





REPLACEMENT SHEET

23 AUG 1999

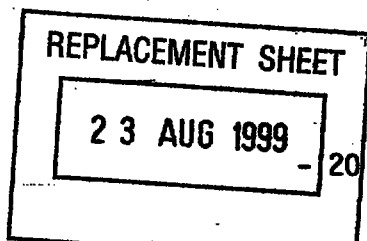
- 19 -

REPLACEMENT SHEET

4. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which said rare earth content of the composition ranges from about 10 to about 20 percent rare earth metal, and said boron content of the composition ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare earth metal and said boron in the composition ranges from about 12 to about 22 percent of the composition.

5. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 1, in which the said isotropic iron-rare earth metal particles have a grain size of not more than 500 nanometres.

6 A method for forming a hot-pressed iron-rare earth-boron permanent magnet, the method of comprising the steps of: providing a quantity of isotropic iron-rare earth-boron metal particles having a grain size of not more than 500 nanometres, and hot-pressing said quantity of isotropic iron-rare earth-boron metal particles at a temperature and for a duration sufficient to form a hot-pressed isotropic iron-rare earth-boron metal permanent magnet characterised in that said quantity of isotropic iron-rare earth-boron metal particles is formed from a composition comprising, on a weight percent basis, from about 5 to about 25 percent rare earth metal wherein the majority of said rare earth constituent is neodymium, and from about 0.5 to about 4.0 percent boron, and wherein the total of said rare earth



REPLACEMENT SHEET

metal and said boron ranges from about 9 to about 26 percent of the composition, with the balance being principally iron; and the magnet formed has the uniform presence of both a hard magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and soft magnetic phases Fe_3B phase and $\alpha\text{-Fe}$, and a magnetic remanence of at least 9 kiloGauss and intrinsic coercivity or at least 2 kiloOrested.

7. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 6, in which the composition also includes from about 2 to about 16 percent cobalt.

8. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 6, in which said rare earth content of the composition ranges from about 10 to about 20 percent rare earth metal, and said boron content of the composition ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare earth metal and said boron in the composition ranges from about 12 to about 22 percent of the composition.

9. A method for forming a hot-pressed iron-rare earth-boron permanent magnet according to claim 6, in which said hot-pressing step is at least a temperature ranging from 750° to 800°C .



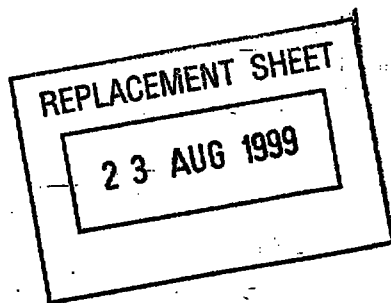
23 AUG 1999

10. A hot-pressed isotropic iron-rare earth-boron permanent magnet comprising, on a weight percent basis from about 5 to about 25 percent rare earth metal wherein the majority of said rare earth constituent is neodymium, and from about 0.5 to about 4.0 percent boron, and wherein the total of said rare earth metal and said boron ranges from about 9 to about 26 percent, with the balance being principally iron; which magnet is characterised by the uniform presence of both a hard magnetic $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and soft magnetic phases Fe_3B and $\alpha\text{-Fe}$; and which has a magnetic remanence of at least 9kiloGauss and intrinsic coercivity of at least 2kiloOrested.

11. A hot-pressed isotropic iron-rare earth-boron permanent magnet according to claim 10, in which said magnet further comprises from about 2 to about 16 percent cobalt.

12. A hot-pressed isotropic iron-rare earth-boron permanent magnet according to claim 10, in which said rare earth content ranges from about 10 to about 20 percent rare earth metal, and said boron content ranges from about 0.8 to about 4.0 percent boron, and in which said total content of said rare earth metal and said boron ranges from about 12 to about 22 percent of the magnet.



HIGH PERFORMANCE HOT-PRESSED MAGNETSAbstract

Isotropic hot-pressed iron-rare earth metal permanent magnets are provided wherein the hot-pressed permanent magnets exhibit magnetic remanences of at least 9 kG, and most typically about 10 kG. Preferred compositions include a relatively low rare earth content coupled with an optimal amount of boron. The preferred composition is, on a weight percent basis, from about 5 to about 25 percent rare earth, most preferably about 10 to about 20 percent rare earth, from about 0.5 to about 4.5 percent boron, most preferably from about 0.8 to about 4.0 percent boron, wherein the total combination of the rare earths and boron ranges from about 9 percent to about 26 percent of the composition, most preferably from about 12 percent to about 22 percent, and optionally from about 2 percent to about 16 percent cobalt, with the balance being essentially iron.

FIGURE 1