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Reid et al.

[11] **3,898,599**

[45] **Aug. 5, 1975**

[54] **TOROIDAL MAGNETIC DEVICE**

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[73] Assignee: **Raytheon Company**, Lexington, Mass.

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[52] **U.S. Cl.** **335/302;** 335/296; 335/306

[51] **Int. Cl.**[2] **H01F 7/02**

[58] **Field of Search** 335/302, 296, 303, 304, 335/306

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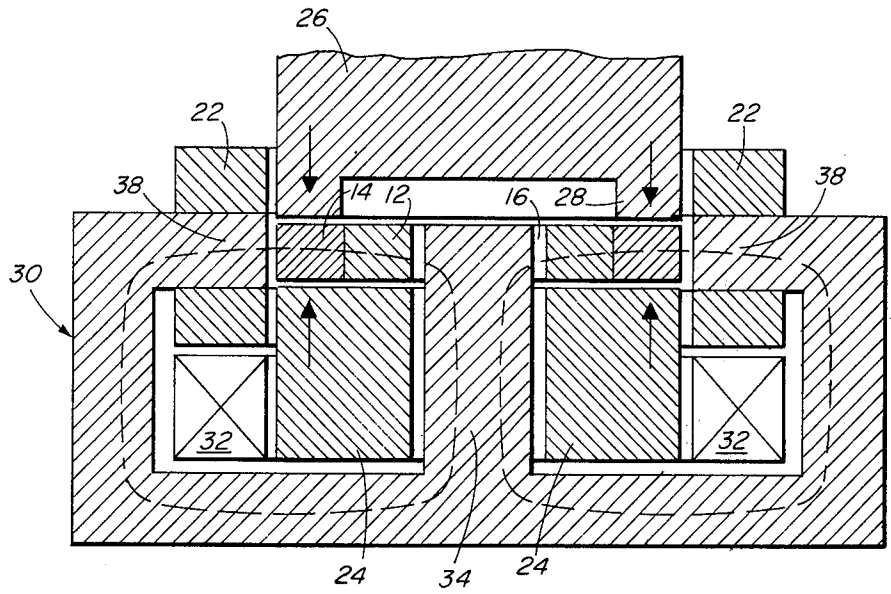
Primary Examiner—Harold Broome

Attorney, Agent, or Firm—John T. Meaney; Harold A. Murphy; Joseph D. Pannone

[57] **ABSTRACT**

A toroidal magnetic device comprising inner and outer concentric rings of compatible magnetic material having interfacing peripheral surfaces diffusion bonded to one another to form a unitary integral structure which is magnetized in the radial direction.

7 Claims, 16 Drawing Figures



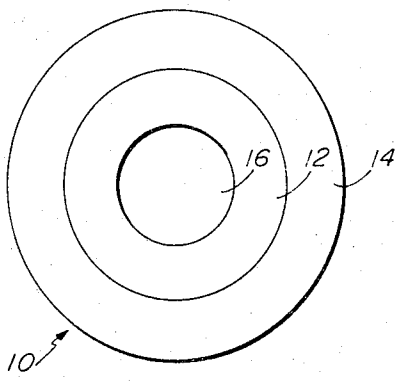


FIG. 1

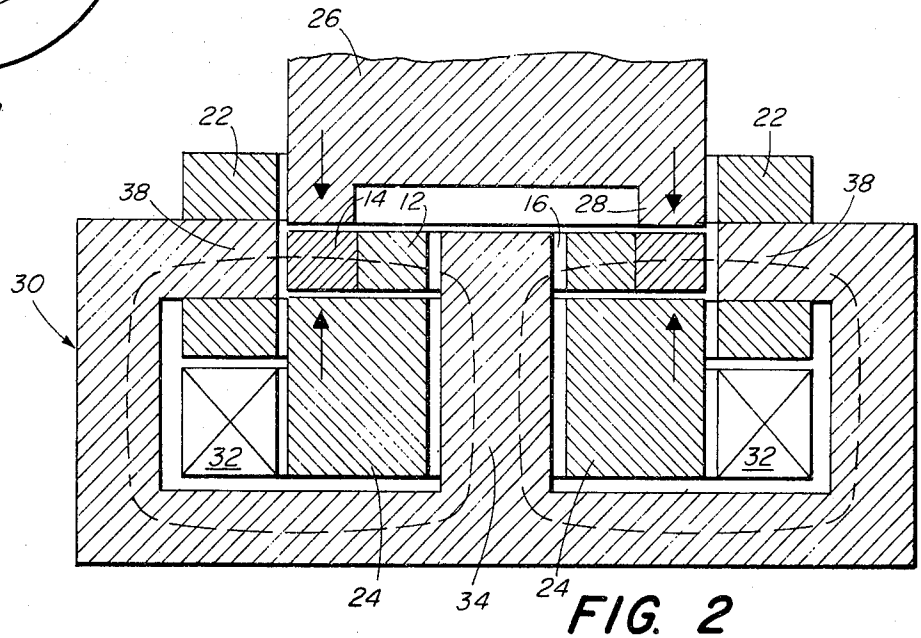


FIG. 2

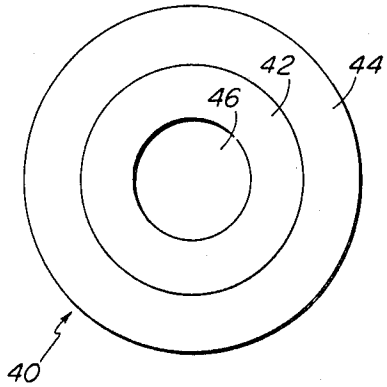
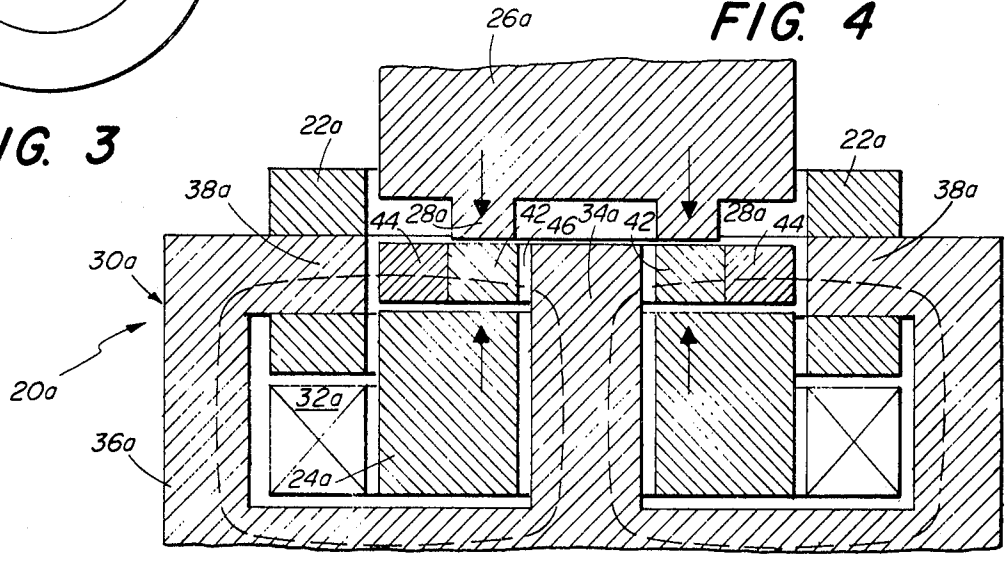


FIG. 3

FIG. 4



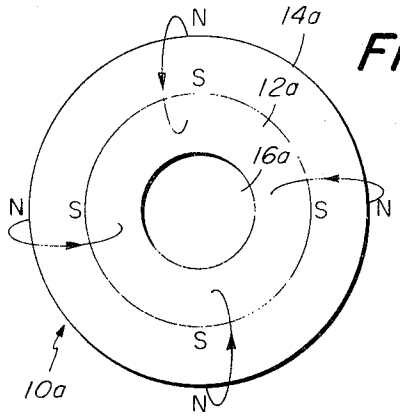


FIG. 7

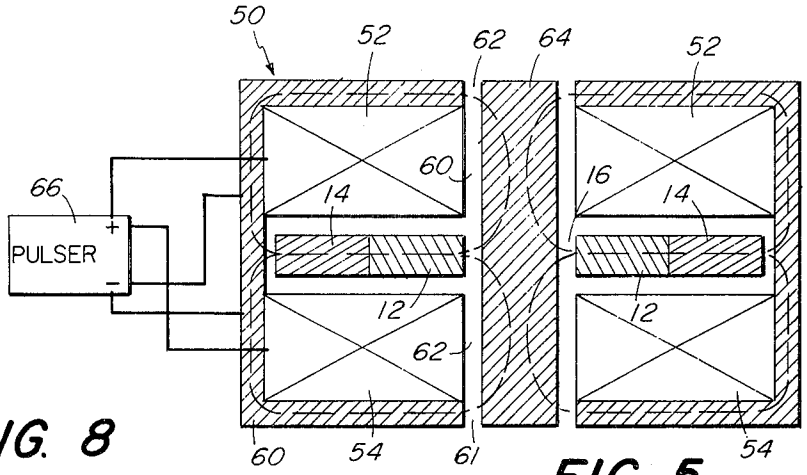


FIG. 5

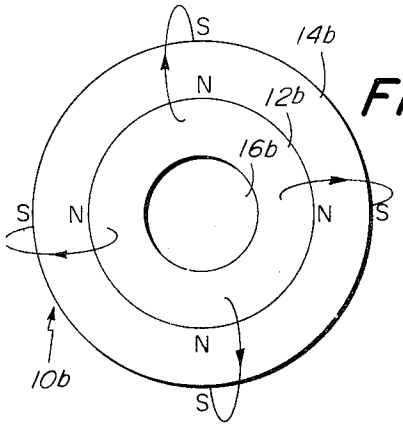


FIG. 8

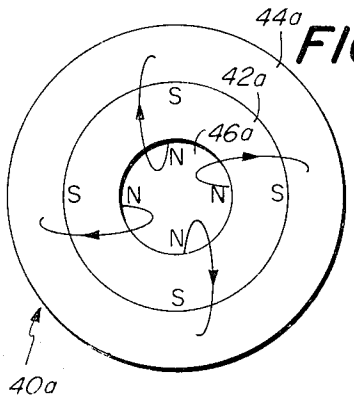


FIG. 9

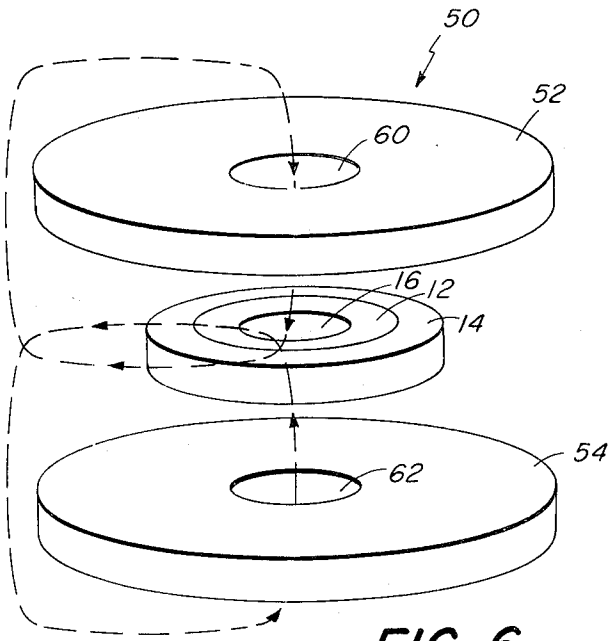


FIG. 6

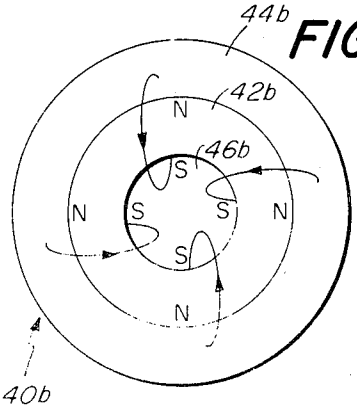


FIG. 10

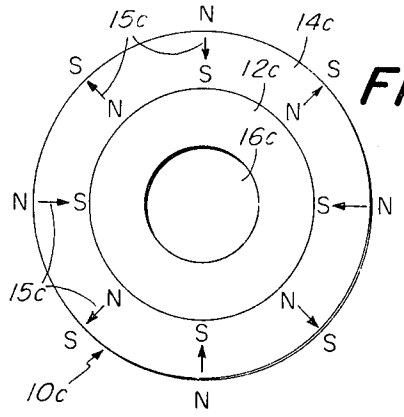


FIG. 13

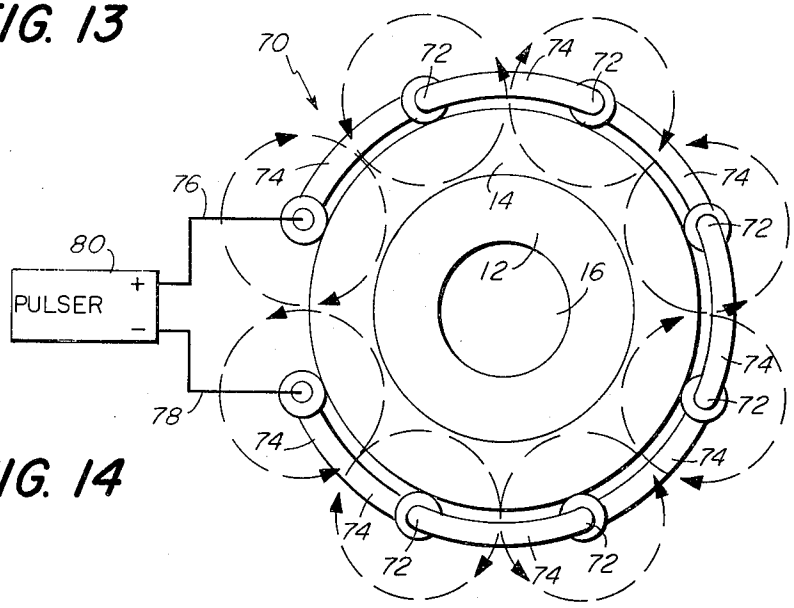


FIG. 11

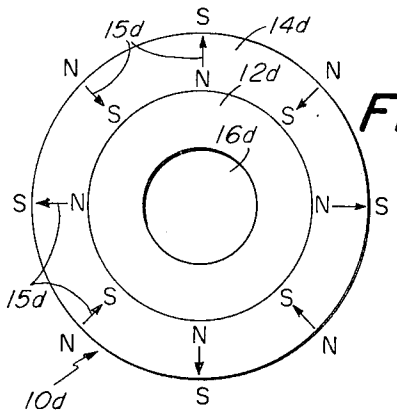


FIG. 14

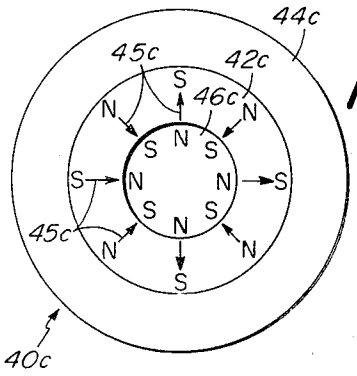


FIG. 15

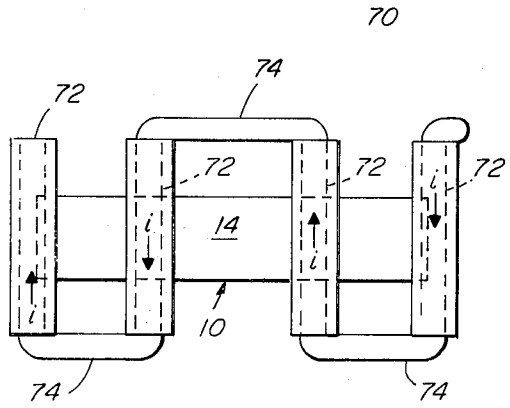


FIG. 12

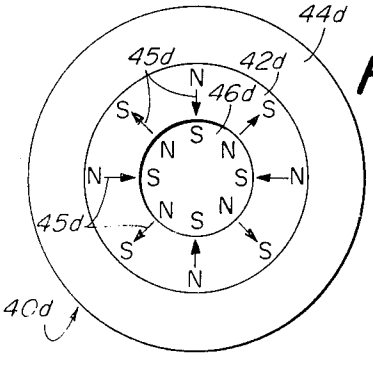


FIG. 16

TOROIDAL MAGNETIC DEVICE

BACKGROUND OF THE INVENTION

This invention relates generally to permanent magnets and is concerned more specifically with a toroidal magnetic device which is magnetized in the radial direction.

Powder metallurgical techniques provide means for manufacturing toroidal permanent magnets very efficiently from sintered powder material. As a result, these toroidal magnets exhibit extremely high energy product and temperature stability. However, the inherent mechanical weakness of the structural material presents serious problems in the handling and finishing of the permanent magnets.

Therefore, it is advantageous and desirable to provide a toroidal permanent magnet made of sintered powder material with a structural support member which cooperates with the permanent magnet to form a very efficient magnetic device.

SUMMARY OF THE INVENTION

Accordingly, this invention provides a toroidal magnetic device comprised of inner and outer concentric rings of compatible magnetic material having interfacing peripheral surfaces diffusion bonded to one another.

One of the rings comprises a support annulus made of paramagnetic material having a relatively low magnetic retentivity and which is conformingly shaped to interfit with the other ring. The other ring comprises a radially polarized permanent magnet which is made from sintered powder material. The powder material is compacted onto a peripheral surface of the support ring while exposed to a particle-orienting magnetic field. After degaussing, the interlocked rings are subjected to the sintering temperature of the powder material whereby the compacted powder material increases in density, and also is diffusion bonded to the adjacent surface of the support ring. The resulting integral structure is placed in a suitable magnetic field for magnetizing the permanent magnet in the radial direction such that the flux lines of the radially polarized field pass through the support ring. Thus, the support ring not only provides structural support but also provides a low reluctance return path for the flux lines emanating from the permanent magnet ring.

In one embodiment of this invention, the toroidal magnetic device is provided with an inner support ring and outer permanent magnet ring.

In an alternative embodiment of this invention, the toroidal magnetic device is provided with an inner permanent magnet ring and an outer support ring.

The permanent magnet ring may be magnetized to have a circumferential magnetic pole adjacent a periphery of the device and a continuous opposite magnetic pole adjacent the support ring.

Alternatively, the permanent magnet ring may be magnetized to provide adjacent a periphery of the device a circular array of alternate north and south magnetic poles, each of which is magnetically associated with a respective opposite magnetic pole radially located therefrom and adjacent the support ring.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of this invention, the following more detailed description makes reference to the accompanying drawings wherein:

FIG. **1** is a plan view of one embodiment of this invention;

FIG. **2** is a fragmentary axial view of an apparatus employed for fabricating the embodiment shown in FIG. **1**;

FIG. **3** is a plan view of another embodiment of this invention;

FIG. **4** is a fragmentary axial view of an apparatus employed for fabricating the embodiment shown in FIG. **3**;

FIG. **5** is an axial view of an apparatus utilized for magnetizing the embodiments shown in FIGS. **1** and **3**;

FIG. **6** is a schematic elevational view of the apparatus shown in FIG. **5**;

FIG. **7** is a plan view of the embodiment shown in FIG. **1** magnetized in a radially inward direction;

FIG. **8** is a plan view of the embodiment shown in FIG. **1** magnetized in a radially outward direction;

FIG. **9** is a plan view of the embodiment shown in FIG. **3** magnetized in a radially inward direction;

FIG. **10** is a plan view of the embodiment shown in FIG. **3** magnetized in a radially outward direction;

FIG. **11** is a plan view of another apparatus utilized for magnetizing the embodiments shown in FIGS. **1** and **3**;

FIG. **12** is a schematic elevational view of the apparatus shown in FIG. **11**;

FIG. **13** is a plan view of the embodiment shown in FIG. **1** magnetized as a multi-polar magnetic device;

FIG. **14** is a plan view of the embodiment shown in FIG. **13** but having the magnetic poles slightly rotated;

FIG. **15** is a plan view of the embodiment shown in FIG. **3** magnetized as a multi-polar magnetic device; and

FIG. **16** is a plan view of the embodiment shown in FIG. **15** but having the magnetic poles slightly rotated.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring more particularly to the drawings wherein like characters of reference designate like parts throughout the several views, there is shown in FIG. **1** a toroidal magnetic device **10** including inner and outer concentric rings, **12** and **14**, respectively, which encircle a central aperture **16**.

The outer ring **14** comprises a radially polarized permanent magnet made of sintered powder material, such as samarium cobalt, for example. Alternatively, the rare earth component of the compound may comprise one or more members of the group including lanthanum, cerium, samarium, praseodium, ytrrium, and cerium rich mischmetal. When combined with cobalt, the members of the group form intermetallic compounds having hexagonal crystalline structures with single easy axes of magnetization. The resulting magnetic material exhibits high values of coercive force, magnetic saturation, and Curie temperature which provide a permanent magnet having extremely high energy product and temperature stability.

The inner ring **12** comprises a support annulus made of a soft magnetic material having relatively low coercive force such as cobalt, for example, which is com-

patible with the samarium cobalt material of permanent magnet ring **14**. The conforming configuration of support ring **12** interfits with the permanent magnet ring **14** such that the outer peripheral surface of support ring **12** interfaces with the inner peripheral surface of permanent magnet ring **14**. As a result, the magnetic permeable material of support ring **12** provides a low reluctance path for the flux of radially polarized magnet **14** thereby enhancing the efficiency of magnetic device **10**. Since the material of support ring **12** is compatible with the material of magnet ring **14**, the possibility of deleterious reactions occurring between the interfacing materials is minimized. Also, by having the material of support ring **12** compatible with the material of magnet ring **14**, the coefficients of thermal expansion of the respective rings **12** and **14** are very close to one another, thus reducing the possibility of thermal stresses causing rupturing or cracking of the magnetic material, as during sintering and subsequent cooling for example.

The magnetic device **10** may be fabricated very efficiently by means of a high speed die pressing and magnetization technique to be described. A mixture comprising one-third by weight samarium and two-thirds by weight cobalt is placed in a crucible and exposed to a suitable temperature, such as 1350° C, for example, for melting the constituent elements in a protective atmosphere of inert gas, such as helium, for example. After cooling, the resulting samarium cobalt compound is pulverized, by conventional means, to yield a fine powder having particles approximately twelve microns in size, for example. As shown in FIG. **2**, a predetermined quantity of the samarium cobalt powder is circularly disposed adjacent the outer periphery of a preformed cobalt ring **12**. The ring **12** is disposed in a fixture (not shown) which is positioned in a cylindrical die **22** of a suitable press **20**, such as Model HPM-100 made by Bussman Simetag of Munich, Germany, for example.

The press **20** may include a lower ram **24** which is encircled by a coil **32** of a particle-orienting electromagnet **30**. Extending axially through the lower ram **24** and through the support ring **12** is a centrally located pole piece **34** of the electromagnet **30**. The pole piece **34** is magnetically coupled to a cylindrical metal wall **36** having a flanged rim **38** which constitutes the other pole piece of the electromagnet **30**. The samarium cobalt powder is supported in alignment with a cylindrical punch **26** of an upper ram **28** which is reciprocally movable toward and away from the lower ram **24** within the die **22**.

In operation, the coil **32** of electromagnet **30** is energized to establish between the central pole piece **34** and the surrounding pole piece **38**, a radially extending field of magnetic flux. As a result, the fine particles of samarium cobalt are radially oriented and aligned with adjacent particles of the powder material. Then the upper punch **28** and the lower rams **24** cooperate to compact the samarium cobalt powder onto the outer periphery of support ring **12** in the form of a densely packed ring **14** of radially oriented particles. Consequently, when the pressure exerted by the press **20** is released, the fine particles of compacted samarium cobalt material remain radially oriented, even during a subsequent degaussing operation. Thus, the support ring **12** and the compacted material of ring **14** are formed into a unitary toroidal device **10** having interfacing peripheral surfaces.

Subsequently, the coil **32** of electromagnet **30** may be energized in the reverse direction to establish a degaussing magnetic field which removes any residual magnetism from the samarium cobalt material of ring **14**. The assembled device **10** is removed from press **20** and placed in a conventional sintering furnace (not shown) such as Heavy Duty Model Omega **1** made by Lindbergh, Inc., of Watertown, Wisconsin, for example. In the furnace, the device **10** is subjected to a suitable sintering temperature, such as 1120° C, for example, whereby the radially aligned particles of samarium cobalt become more densely packed and fusion bonded to one another. Furthermore, it has been found that, during the sintering operation, the samarium cobalt material of ring **14** also is diffusion bonded to the cobalt material of support ring **12** thereby forming an integral structure.

There is shown in FIG. **3** an alternative embodiment comprising a magnetic device **40** having inner and outer concentric rings, **42** and **44**, respectively, which encircle a central aperture **46**. The inner ring **42** comprises a radially polarized, permanent magnet made of sintered powder material, such as samarium cobalt, for example. The outer ring **44** comprises a support annulus made of soft magnetic material having relatively low coercive force such as cobalt, for example, and which is compatible with the material of magnet ring **42**. Thus, the magnet device **40** is structurally similar to the magnetic device **10** except the permanent magnet rings and the support rings of the respective devices **10** and **40** are transposed with respect to one another.

The magnetic device **40** also may be fabricated by means of the high speed die-pressing technique described in relation to the magnetic device **10**. However, as shown in FIG. **4**, the press **20***a* utilized for fabricating the magnetic device **40** differs from the press **20** shown in FIG. **2** by the location of the upper punch **26***a* carried on the upper ram **28***a*. The punch **26***a* is aligned with the powdered material of the inner concentric ring **42** rather than with the outer concentric ring **14** as shown in FIG. **2**. Otherwise, the preparation of the samarium cobalt powder and the compacting thereof onto the inner peripheral surface of support ring **44** is substantially the same as previously described for the fabrication of magnetic device **10**. Consequently, the densely packed ring **42** forms with the support ring **44** a unitary device which is subjected to a sintering temperature environment, as described in connection with the magnetic device **10**. Accordingly, during the sintering operation, the radially oriented particles of the magnet ring **42** become even more densely packed and fusion bonded to one another. Also, during the sintering operation, the samarium cobalt material of the inner ring **42** is diffusion bonded to the cobalt material of outer ring **44** to form an integral structure.

After sintering and cooling, the respective devices **10** and **40** may be magnetized in the radial direction by means of suitable magnetizing apparatus, such as Impulse Magnetizer Model 8100 made by Raytheon Manufacturing Company of Lexington, Massachusetts, for example. As shown in FIGS. **5** and **6**, the magnetizing apparatus may comprise a magnetizer **50** having a pair of bucking pancake coils **52** and **54** respectively, disposed in spaced parallel relationship within a magnetically permeable casing **60**. The coils **52** and **54** are provided with respective central apertures **56** and **58** which are axially aligned with a pair of opposed open-

ings **61** and **62**, respectively, in the casing **60**. A magnetic device, such as **10**, for example, may be interposed between the respective coils **52** and **54** such that the central aperture **16** of device **10** is axially aligned with the central apertures **56** and **58** of the coils **52** and **54**, respectively. A magnetically permeable core **64** then may be inserted axially through the mutually aligned apertures **56**, **16** and **58**, respectively, and through the aligned openings **61** and **62** of casing **60**.

The coils **52** and **54**, respectively, may be connected electrically to polarized terminals of a pulser **66** in a reverse manner with respect to one another. Thus, the coils **52** and **54** may be energized to establish respective toroidal magnetic fields having, within the core **64**, oppositely directed flux lines which radially enhance one another in the plane of the magnetic device **10**. As a result, the radially oriented and densely packed particles of ring **14** are permanently magnetized in the radial direction relative to the device **10**. Consequently, the magnet ring **14** is provided with a circumferential magnetic pole adjacent the outer periphery of device **10** and a continuous opposite magnetic pole adjacent the support ring **12**.

Accordingly, as shown in FIG. **7**, there may be produced a magnetic device **10***a* including a permanently magnetized outer ring **14***a* having a circumferential north magnetic pole adjacent the outer periphery of device **10***a* and a continuous south magnetic pole adjacent the inner support ring **12***a*, the poles being coupled to one another externally of the device **10***a* by a toroidal-shaped magnetic field. By convention, the magnetic field lines of magnet ring **14***a* are directed radially inward of the device from the circumferential north pole toward the continuous south pole. However, the magnetic field lines enter the south pole by way of the low reluctance path provided by the support ring **12***a*. Thus, there is provided a magnetic device **10***a* having magnetic field lines which do not extend substantially inward of the central aperture **16***a* and which provide a uniform salient magnetic field adjacent the outer periphery of the device. Consequently, the magnetic device **10***a* is especially adapted to function efficiently as a journal member of a magnetically suspended friction-free bearing for example.

As shown in FIG. **8**, a magnetic device **10***b* may be produced by reversing the respective electrical connections of the coils **52** and **54** at the polarizer **66**, after magnetizing a device such as **10***a*, for example. The device **10***b* includes a permanently magnetized outer ring **14***b* having a circumferential south magnetic pole adjacent the outer periphery of device **10***b*, and a continuous north magnetic pole adjacent the inner support ring **12***b*. Consequently, the magnetic field lines emanating from the north pole of magnet ring **14***b* pass through the magnetically permeable material of support ring **12**b and are directed radially outward of the device **10***b*. The magnetic field lines extend beyond the outer periphery of the device before entering the circumferential south pole of magnet ring **14***b*. Thus, the device **14***b* is similar to the device **10***a* shown in FIG. **7** and functions as efficiently when used in place thereof.

The magnetizer **50** also may be employed for magnetizing as described, the magnetic device **40** shown in FIG. **3**, whereby the radially oriented and densely packed particles of magnet ring **42** will be permanently magnetized in the radial direction relative to the device **40**. Consequently, the inner magnet ring **42** will be provided with a circumferential magnetic pole adjacent the inner periphery of device **40**, and a continuous opposite magnetic pole adjacent the outer support ring **44**.

Thus, as shown in FIG. **9**, there may be produced a magnetic device **40***a* including a permanently magnetized inner ring **42***a* having a circumferential north pole adjacent the inner periphery of device **40***a* and a continuous south pole adjacent the outer support ring **44***a*. Therefore, the magnetic field lines of magnet ring **42***a* extend radially inward of the central aperture **46***a* and then are directed radially outward toward the support ring **42***a*. The support ring **44***a* provides a low reluctance path for the magnetic flux to enter the adjacent south pole of magnet ring **42***a*. Accordingly, there is provided a magnetic device **40***a* having magnetic field lines which extend radially inward of the central aperture **46***a* and do not extend substantially beyond the outer periphery of device **40***a*. Consequently, the magnetic device **40***a* is especially adapted to function efficiently as the sleeve member of a magnetically suspended friction-free bearing, for example, which has a circular array of rotor pole pieces disposed adjacent the inner periphery of the stator.

As shown in FIG. **10**, a magnetic device **40***b* may be produced by reversing the respective electrical connections of the coils **52** and **54** at the pulser **66**, after magnetizing a device such as **40***a*, for example. The device **40***b* includes a permanently magnetized inner ring **42***b* having a circumferential south magnetic pole adjacent to inner periphery of device **40***b*, and a continuous north magnetic pole adjacent the outer support ring **44***b*. Consequently, the magnetic lines emanating from the continuous north pole of magnet ring **42***b* pass through the magnetically permeable material of support ring **44***b* and are directed radially inward of the device. The magnetic field lines extend into the central aperture **46***b* before entering the circumferential south pole of magnet ring **42***b*. Thus, the magnetic device **40** is similar to the device **40***a* and functions as efficiently when used in place thereof.

Alternatively, as shown in FIGS. **11** and **12**, the magnetizing apparatus may comprise a magnetizer **70** having a circular array of spaced conductors **72** which are perpendicularly disposed with respect to a magnetic device, such as **10**, for example, and positioned adjacent the outer periphery of the device. The conductors **72** are connected in series with adjacent conductors **72** of the array by respective interconnecting conductors **74**. Terminal leads **76** and **78**, respectively, of the circular array are electrically connected to respective polarized terminals of a pulser **80**. Thus, an energizing current *i* flowing from the positive terminal of the pulser **80** passes sequentially through each of the conductors **72** before returning to the negative terminal of the pulser **80**. Consequently, there is established around the conductors **72** respective cylindrical magnetic fields which permanently magnetize the adjacent, densely packed particles of magnet ring **14** in the radial direction relative to the device **10**.

However, the current *i* passing in one direction through a particular conductor **72** of the array passes in the opposite direction through the adjacent conductors **72** on either side thereof. Accordingly, the magnetic field established around the particular conductor **72** has field lines which curve in the opposite angular direction with respect to the magnetic field lines estab-

lished around the adjacent conductors **72** of the array. Consequently, the magnetic field lines around the particular conductor **72** enhance the field lines around the adjacent conductors **72** on either side thereof to produce respective radially inwardly and outwardly directed magnetic intensity forces. As a result, the magnet ring **14** of device **10** is provided with alternating north and south poles having radially inward and outward directed field lines, respectively.

In this manner, as shown in FIG. **13**, there may be produced a magnetic device **10***c* having an inner support ring **12***c* and an outer permanent magnet ring **14***c*. Adjacent the outer periphery of device **10***c*, the magnet ring **14***c* is provided with a circular array of alternate north and south poles, each of which is magnetically associated with a respective opposite magnetic pole radially located therefrom and adjacent the support ring **12***c*. Thus, the inner periphery of magnet ring **14***c* is provided with a similar circular array of south and north poles. Consequently adjacent arcuate portions of the magnet ring **14***c* are magnetized in opposing radial directions, as shown by the magnetization vectors **15***c*. Accordingly, adjacent the inner periphery of ring **14***c*, the magnetic field lines enter the magnetically permeable material of support ring **12***c* and, adjacent the outer periphery of ring **14***c*, the magnet field lines extend outwardly beyond the outer periphery of device **10***c*. As a result, there is provided a magnetic device **10***c* having magnetic field lines which do not extend substantially into the central aperture **16***c*, and which provide oppositely directed, salient magnetic fields adjacent the outer periphery of device **10***c*. A magnetic device of this type is especially adapted to function efficiently as an armature in a polyphase generator, for example.

As shown in FIG. **14**, a magnetic device **10***d* may be produced by reversing the respective terminal leads **76** and **78** at the pulser **80** after magnetizing a device such as **10***c* for example. The device **10***d* is similar to the device **10***c* shown in FIG. **13** and operates as efficiently when used in place of the device **10***c*.

The magnetizer **70** also may be employed, as described, for magnetizing the magnetic device **40** shown in FIG. **3**. Thus, as shown in FIG. **15**, there may be produced a magnetic device **40***c* having an inner permanent magnet ring **42***c* and an outer support ring **44***c* encircling a central aperture **46***c*. Adjacent the inner periphery of device **40***c*, the magnet ring **42***c* is provided with a circular array of alternate north and south magnetic poles, each of which is magnetically associated with a respective opposite magnetic pole radially located therefrom and adjacent the support ring **44***c*. Thus, the outer periphery of magnet ring **42***c* is provided with a similar circular array of south and north poles. Consequently, adjacent arcuate portions of the magnet ring **42***c* are magnetized in opposing radial directions, as shown by the magnetization vectors **45***c*. Accordingly, adjacent the outer periphery of ring **42***c*, the magnetic field lines enter the magnetically permeable material of support ring **44***c*, and adjacent the inner periphery of ring **42***c*, the magnetic field lines extend inwardly of the central aperture **46***c*. As a result, there is provided a magnetic device **40***c* having magnetic field lines which do not extend substantially beyond the outer periphery of the device, and which provide oppositely directed, salient magnetic fields adjacent the inner periphery of device **40***c*. A magnetic device of the described type is especially adapted to function efficiently as a stator in a polyphase motor, for example.

As shown in FIG. **16**, a magnetic device **40***d* may be produced by reversing the respective terminal lead **76** and **78** at the pulser **80**, after magnetizing a device such as **40***c*, for example. The device **40***d* is similar to the device **40***c* previously described and operates as efficiently when used in place of device **40***c*.

Thus, there has been disclosed herein a toroidal magnetic device comprising inner and outer concentric rings encircling a central aperture and having interfacing peripheral surfaces diffusion bonded to one another. One of the rings constitutes a sintered powder permanent magnet having radially oriented and densely packed particles magnetized in the radial direction relative to the magnetic device. The other ring constitutes a support annulus made of magnetically permeable material which is compatible with the sintered powder material of the permanent magnet ring and which provides a low reluctance path for the magnetic field lines of the magnet ring. The permanent magnet ring may be magnetized to have a circumferential magnetic pole adjacent a periphery of the magnetic device and a continuous opposite magnetic pole adjacent the support ring. Alternatively, the permanent magnet ring may be magnetized to have adjacent a periphery of the magnetic device a circular array of alternate north and south magnetic poles, each of which is magnetically associated with an opposite magnetic pole radially located therefrom and adjacent the support ring.

From the foregoing, it will be apparent that all of the objectives of this invention have been achieved by the structures shown and described herein. It also will be apparent, however, that various changes may be made by those skilled in the art without departing from the spirit of the invention as expressed in the appended claims. It is to be understood, therefore, all matter shown and described herein is to be interpreted as illustrative and not in a limiting sense.

We claim:

1. A toroidal magnetic device comprising inner and outer concentric rings having interfaced peripheral portions diffusion bonded to one another, one of the rings being a radially polarized permanent magnet made of compacted powder material and the other ring being a support annulus made of soft magnetic material having relatively low magnetic retentivity.

2. A toroidal magnetic device comprising inner and outer concentric rings having interfaced peripheral portions diffusion bonded to one another, one of the rings being a support annulus made of soft magnetic material and the other ring being a compacted powder permanent magnet having a circumferential magnetic pole adjacent one periphery of the device and a continuous opposite magnetic pole adjacent the support annulus.

3. A toroidal magnetic device as set forth in claim **2** wherein the inner ring comprises the support annulus and the outer ring comprises the permanent magnet having a circumferential magnetic pole adjacent the outer periphery of the device and a continuous opposite magnetic pole adjacent the support annulus.

4. A toroidal magnetic device as set forth in claim **2** wherein the outer ring comprises the support annulus and the inner ring comprises the permanent magnet having a circumferential magnetic pole adjacent the inner periphery of the device and a continuous opposite magnetic pole adjacent the support annulus.

5. A toroidal magnetic device comprising inner and outer concentric rings having interfaced peripheral portions diffusion bonded to one another, one of the rings being a support annulus made of soft magnetic material and the other ring being a compacted powder permanent magnet having adjacent one periphery of the device a circular array of alternate north and south poles, each of which is magnetically associated with a respective opposite magnetic pole radially located therefrom and adjacent the support annulus.

6. A toroidal magnetic device as set forth in claim 5 wherein the inner ring comprises the support annulus and the outer ring comprises the permanent magnet having adjacent the outer periphery of the device a circular array of alternate north and south magnetic poles and adjacent the support annulus a similar circular array of south and noth magnetic poles.

7. A toroidal magnetic device as set forth in claim 5 wherein the outer ring comprises the support annulus and the inner ring comprises the permanent magnet having adjacent the inner periphery of the device a circular array of alternate north and south magnetic poles and adjacent the support annulus a similar circular array of alternate south and north magnetic poles.

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