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PERMANENT MAGNET AND ALLOY THEREFOR

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FIG. 1

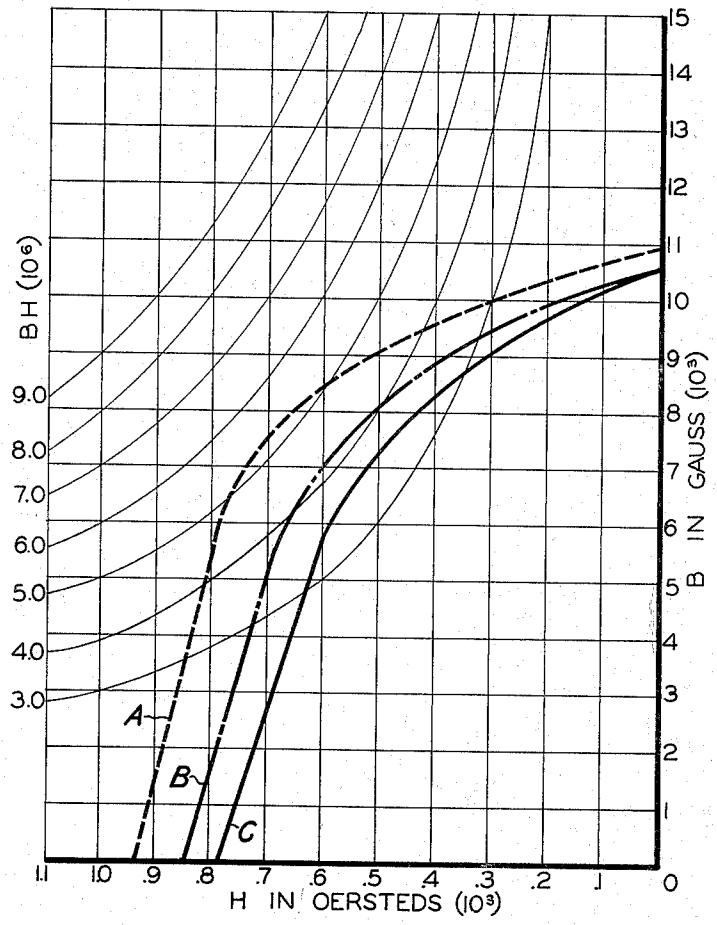
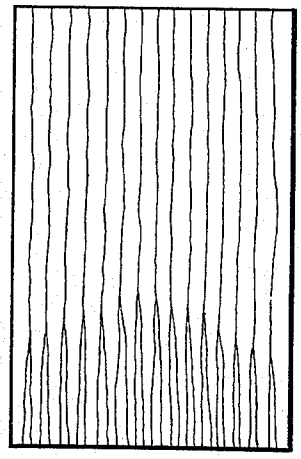


FIG. 2



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PERMANENT MAGNET AND ALLOY THEREFOR

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The present invention relates to permanent magnets and more particularly to magnets of ferrous alloys containing essentially aluminum, nickel, titanium and cobalt having improved mechanical and magnetic properties, and to alloys therefor.

Alloys containing 6.0 to 11.0 percent by weight aluminum, 14.0 to 20.0 percent by weight nickel, 16.0 to 30.0 percent by weight cobalt, 1.0 to 2.0 percent by weight titanium, up to 7.0 percent by weight copper and the remainder principally iron, generally known as Alnico VI–B, have been widely utilized in the production of permanent magnets. Although magnets of this alloy have anisotropic properties, heretofore it has not been considered possible to produce unidirectionally grained magnets having enhanced magnetic properties.

It is an object of the present invention to provide a novel permanent magnet having greatly enhanced coercive strength and maximum energy product.

It is also an object to provide an improved Alnico VI alloy which can be readily cast into a body having the crystals oriented with the (100) plane substantially parallel to the desired direction of magnetization and heat-treated to provide a magnet having greatly enhanced magnetically anisotropic properties.

Another object is to provide an alloy and method for making permanent magnets which permits the facile casting of magnet bodies which may be readily heat-treated without an extensive normalizing treatment at high temperatures to produce magnets of high magnetic strength and free from multiphase structure.

Other objects and advantages will be readily apparent from the following detailed specification and appended claims, and from the attached drawing wherein:

FIG. 1 is a graph showing the demagnetization curves of directionally grained magnets and random-grained magnets of the alloy of the present invention and that of conventional Alnico VI–B alloy; and

FIG. 2 is a representation of the grain structure of directionally grained magnets produced from the alloy of the present invention.

It has now been found that the foregoing and related objects can be attained by use of an alloy containing essentially 6.0 to 11.0 percent by weight aluminum, 14.0 to 20.0 percent by weight nickel, 16.0 to 30.0 percent by weight cobalt, up to 7.0 percent by weight copper, 0.5 to 1.5 percent by weight titanium, 0.5 to 1.5 percent by weight columbium, and the remainder substantially entirely iron with the usual impurities such as silicon and carbon. The columbium and titanium are preferably employed in the range of 0.8 to 0.9 and 1.0 to 1.2 percent by weight, respectively, for optimum properties.

To further suppress gamma phase precipitation and reduce brittleness of the castings, sulfur in the amount of 0.075 to 0.15 percent by weight has proven beneficial and is preferably used at about 0.1 percent by weight.

The preferred alloys of the present invention are those ferrous base alloys containing about 8.0 to 8.5 percent aluminum, 14.7 to 15.5 percent nickel, 23.5 to 25.0 percent cobalt, 2.5 to 3.5 percent copper, and columbium and titanium in the amount of 0.7 to 1.5 percent and 1.0 to 1.5 percent, respectively, and most desirably 0.8 to 0.9 and 1.0 to 1.2 percent by weight respectively. For most desirable physical properties, sulfur in the aforedescribed amounts is also added.

Although the alloy of the present invention may be cast according to conventional practice into a random grained structure providing improved magnetic properties, the alloy is preferably superheated to a temperature of about 3300 to 3500° F. and cast in molds preheated to a temperature of about 1200 to 2650° F. and the superheat extracted through a chill plate so as to produce a unidirectionally grained structure having greatly enhanced magnetic properties. Set forth in Table 1 below are the magnetic properties of magnets cast from the alloy according to conventional practice and directionally in accordance with the preferred aspect of the invention.

TABLE 1

Grain Structure	Residual Flux Density, B_r, Gausses	Coercive Force H_c, Oersteds	Maximum Energy Product, Gauss-Oersteds
Random	10,300	830	3.71×10^6
Do	10,650	818	3.81×10^6
Do	10,500	840	3.68×10^6
Do	10,400	810	3.41×10^6
Do	10,200	860	3.55×10^6
Directionalized	10,800	940	5.25×10^6
Do	10,900	915	5.45×10^6
Do	10,700	920	5.40×10^6
Do	10,650	905	5.15×10^6
Do	10,850	950	5.30×10^6

As is evident from the data set forth above, the coercive force and maximum energy product are both greatly enhanced by directionalization of the grain structure. However, it can be seen that even in the random grain structure, the coercive force and maximum energy product are increased over magnets of conventional Alnico VI alloy. FIG. 1 of the attached drawing compares the demagnetization curves of magnets of the present invention both unidirectionally grained (A) and random grained (B) as compared with that of conventional Alnico VI–B magnets (C).

The grain structure of the directionalized castings produced under commercial operating conditions by the present invention is illustrated in FIG. 2 of the drawings. As shown, the casting has about twice as many grains at the chill face as at the opposite face, and the grains are oriented so that the (100) direction is substantially parallel to the longitudinal axis of the casting which is the desired direction of magnetization.

The following is a specific example of alloy of the present invention which has proven highly advantageous for producing superior magnets:

	Percent by weight
Aluminum	8.5
Nickel	15.5
Cobalt	24.3
Copper	3.0
Sulfur	0.1
Titanium	1.1
Columbium	0.8

Remainder iron with minor impurities.

By the present invention, random-grained magnets cast in accordance with conventional commercial practice for Alnico VI alloys are produced having a coercive force of at least 780 oersteds and a maximum energy product (BH_{max}) of at least 3.4×10^6 gauss-oersteds in the principal direction. By casting the alloy under the aforedescribed chill-casting conditions, magnets having a substantially unidirectional, columnar grain structure can be produced which have a coercive force of at least 850

oersteds and a maximum energy product (BH_{max}) of at least 5×10^6 gauss-oersteds in the direction of columnar grain growth and generally a coercive force in excess of 900 oersteds, while simultaneously producing an increase in the residual flux density over that of conventional Alnico VI-B magnets.

The alloy of the present invention is particularly advantageous in that it substantially ameliorates the problems attendant to avoiding the production of a multiphase micro-structure in the magnets so as to obtain optimum magnetic properties. More particularly, it has been found that the castings of the present invention do not require normalizing treatment at elevated temperatures above about 2300° F. to eliminate any gamma phase precipitation which may have occurred during casting. Furthermore, the castings of the new alloy may be heat-treated at temperatures and times which enable facile and highly effective production of the magnetized bodies due to eliminating major problems in the development of a multiphase structure during heat-treatment.

In particular, the magnet castings of the new alloy are magnetically stressed by soaking at a temperature of about 1650 to 1700° F. for fifteen to twenty minutes and cooling in a magnetic field parallel to the principal grain direction to a temperature of about 1200° F. in about five to ten minutes. Subsequently, the castings are coercively aged or drawn at a temperature of about 1200 to 1250° F. for two to five hours and then at about 1025 to 1100° F. for ten to twenty-four hours, after which the castings are cooled to room temperature. The conditions for the magnetic stress treatment are quite critical, but the conditions for the coercive aging are relatively broad and free from any significant problems.

The coercive aging precipitates intermetallic compounds in the matrix and enhances the magnet properties which have been developed by freeing of the domains during soaking and alignment thereof during cooling in the magnetic field parallel to the direction of grain growth.

Indicative of the efficacy of the present invention are the following specific examples.

Example 1

An alloy containing 8.5 percent by weight aluminum, 15.5 percent by weight nickel, 24.3 percent by weight cobalt, 3.0 percent by weight copper, 1.1 percent by weight titanium, 0.8 percent columbium, and the remainder principally iron (with impurities consisting mainly of silicon and carbon constituting less than 0.12 percent) was superheated to a temperature of about 3400° F. and cast in refractory molds preheated to a temperature of about 2000° F. and using a chill plate to produce bars ½ inch in diameter and 2 inches in length. Upon inspection of a transverse section, the castings were found to be substantially unidirectionally grained and to have only 80 grains at the chill face diminishing to 40 grains at the opposite face.

The castings were then normalized at about 1670° F. for one-half hour and cooled in a magnetic field parallel to the axis of grain orientation for about ten minutes. The magnet bodies were then subject to coercive aging at a temperature of about 1225° F. for two hours and at about 1030° F. for twenty-four hours followed by cooling to room temperature.

The magnet bodies thus produced were found to have a residual flux density (B_r) of 10,600 gausses, a coercive force (H_c) of 930 oersteds and a maximum energy product (BH_{max}) of 5.2×10^6 gauss-oersteds.

Example 2

The alloy of Example 1 was cast into sand molds using conventional practice without a chill plate to produce castings of similar dimensions.

The magnet bodies thus produced were heat-treated similarly to those of Example 1 with the magnetic field parallel to the preferred magnetic axis. The magnetic properties were determined as follows:

Residual flux density (B_r) ---------gausses--	10,800
Coercive force (H_c) ----------oersteds--	830
Maximum Energy product (BH_{max}) gauss-oersteds--	4.2×10^6

Example 3

An alloy containing 8.6 percent by weight aluminum, 15.25 percent by weight nickel, 23.5 percent by weight cobalt, 2.9 percent by weight copper, 1.3 percent by weight titanium, 0.9 percent by weight columbium, and the remainder principally iron (with impurities consisting mainly of silicon and carbon constituting less than 0.12 percent) was superheated to a temperature of about 3500 F. and cast in refractory molds preheated to a temperature of about 1950° F. and using a chill plate to produce cylinders 0.875 inch in diameter and 3 inches in length. Upon inspection of a transverse section, the castings were found to be substantially unidirectionally grained and to have only about 120 grains at the chill face diminishing to about 80 grains at the opposite face.

The castings were then heat-treated similarly to those in Example 1.

The magnets had a residual flux density (B_r) of 10,300 gausses, a coercive force (H_c) of 950 oersteds and a maximum energy product (BH_{max}) of 5.6×10^6 gauss-oersteds.

Example 4

The alloy of Example 1 was cast into sand molds using conventional practice without a chill plate to produce castings of similar dimensions.

The magnet bodies thus produced were heat-treated similarly to those of Example 1 with the magnetic field parallel to the preferred magnetic axis. The magnetic properties were determined as follows:

Residual flux density (B_r) ----------gausses--	10,400
Coercive force (H_c) ----------oersteds--	810
Maximum energy product (BH_{max}) ----------gauss-oersteds--	3.95×10^6

As can be seen from the foregoing specific examples and detailed specification, the magnets of the present invention have superior magnetic properties to those of conventional Alnico VI–B alloys. In accordance with the preferred aspect of the invention, the alloy is cast in preheated molds using a chill plate to produce a unidirectionally grained columnar grain structure having greatly enhanced magnetic properties. Additionally, the new alloy does not require as precise control over temperatures and times to produce the desired alpha-phase microstructure.

We claim:

1. An alloy adapted to produce permanent magnets having a single-phase unidirectionally grained microstructure consisting essentially of about 6.0 to 11.0 percent by weight aluminum, 14.0 to 20.0 percent by weight nickel, 16.0 to 30.0 percent by weight cobalt, up to 7.0 percent by weight copper, 0.5 to 1.5 percent by weight titanium, 0.5 to 1.5 percent by weight columbium, and the remainder being substantially all iron with minor impurities.

2. The alloy of claim 1 additionally containing 0.075 to 0.15 percent by weight sulfur.

3. An alloy adapted to produce permanent magnets having a single-phase unidirectionally grained microstructure consisting essentially of about 8.0 to 8.8 percent by weight aluminum, 13.7 to 15.5 percent by weight nickel, 23.5 to 25.0 percent by weight cobalt, up to 7.0 percent by weight copper, 0.5 to 1.5 percent by weight titanium, 0.5 to 1.5 percent by weight columbium, and the remainder being substantially all iron with minor impurities.

4. The alloy of claim 3 wherein said copper constitutes about 2.5 to 3.5 percent by weight.

5. The alloy of claim 3 wherein said titanium and columbium constitute about 1.0 to 1.2 percent by weight and 0.8 to 0.9 percent by weight, respectively.

6. The alloy of claim 3 additionally containing 0.075 to 0.10 percent by weight sulfur.

7. An alloy adapted to produce permanent magnets having a single-phase unidirectionally grained microstructure, consisting essentially of 8.5 percent by weight aluminum, 15.5 percent by weight nickel, 24.3 percent by weight cobalt, 3.0 percent by weight copper, 1.1 percent by weight titanium, 0.8 percent by weight columbium, 0.1 percent by weight sulfur and the remainder iron with minor impurities.

8. A magnet having a single-phase microstructure formed from an alloy consisting essentially of about 6.0 to 11.0 per cent by weight aluminum, 14.0 to 20.0 percent by weight nickel, 16.0 to 30.0 percent by weight cobalt, up to 7.0 percent by weight copper, 0.5 to 1.5 percent by weight titanium, 0.5 to 1.5 per cent by weight columbium, and the remainder being substantially all iron with minor impurities.

9. The magnet of claim 8 wherein said alloy contains 0.075 to 0.15 percent by weight sulfur.

10. A magnet having a single-phase microstructure formed from an alloy consisting essentially of about 8.0 to 8.8 percent by weight aluminum, 14.7 to 15.5 percent by weight nickel, 23.5 to 25.0 percent by weight cobalt, up to 7.0 percent by weight copper, 0.5 to 1.5 per cent by weight titanium, 0.5 to 1.5 percent by weight columbium and the remainder being substantially all iron with minor impurities, said magnet having a coercive force of at least 780 oersteds.

11. The magnet of claim 10 wherein said alloy contains 0.075 to 0.15 percent by weight sulfur.

12. A magnet having a single-phase unidirectional columnar grain structure formed from a ferrous base alloy consisting essentially of about 6.0 to 11.0 percent by weight aluminum, 14.0 to 20.0 percent by weight nickel, 16.0 to 30.0 percent by weight cobalt, up to 7.0 percent by weight copper, 0.5 to 1.5 percent by weight titanium, 0.5 to 1.5 percent by weight columbium, and the remainder being substantially all iron with minor impurities, said magnet having a coercive force of at least 850 oersteds and a maximum energy product (BH_{max}) of at least 5.0×10^6 gauss-oersteds.

13. The magnet of claim 12 wherein said copper constitutes about 2.5 to 3.5 percent by weight of said alloy.

14. The magnet of claim 12 wherein said titanium and columbium constitute 1.0 to 1.2 percent by weight and 0.8 to 0.9 percent by weight, respectively, of said alloy.

15. The magnet of claim 12 wherein said alloy contains 0.075 to 0.15 percent by weight sulfur.

16. A magnet having a single-phase unidirectional columnar grain structure formed from an alloy consisting essentially of about 8.5 percent by weight aluminum, 15.5 percent by weight nickel, 24.3 percent by weight cobalt, 3.0 percent by weight copper, 1.1 percent by weight titanium, 0.8 percent by weight columbium, and the remainder being substantially all iron with minor impurities, said magnets having a coercive force of at least 850 oersteds and a maximum energy product (BH_{max}) of at least 5.0×10^6 gauss-oersteds.

17. The method of making single-phase, unidirectionally columnar grained magnets comprising: introducing into one end of mold chambers opening at the other end on a chill plate a ferrous alloy consisting essentially of about 6.0 to 11.0 percent by weight aluminum, 14.0 to 20.0 percent by weight nickel, 16.0 to 30.0 percent by weight cobalt, up to 7.0 percent by weight copper, 0.5 to 1.5 percent by weight titanium, 0.5 to 1.5 percent by weight columbium, and the remainder being substantially all iron with minor impurities and chilling said ferrous alloy substantially entirely through said chill plate to form magnet bodies of the desired configuration with unidirectionally columnar grains; magnetically stressing said magnet bodies by soaking at a temperature of about 1650 to 1700° F. for about fifteen to twenty minutes and cooling in a magnetic field parallel to the principal grain direction to a temperature of about 1200° F. in a period of about five to ten minutes; coercive aging said magnet bodies at a temperature of about 1200 to 1250° F. for two to five hours and thereafter at a temperature of about 1025 to 1100° F. for ten to twenty-four hours to precipitate intermetallic compounds in the matrix; and cooling to room temperature.

18. The method in accordance with claim 17 wherein said cooper constitutes about 2.5 to 3.5 percent by weight of said alloy.

19. The method in accordance with claim 17 wherein said ferrous-base alloy consists essentially of about 8.0 to 8.5 percent by weight aluminum, 14.7 to 15.5 percent by weight nickel, 23.5 to 25.0 percent by weight cobalt, up to 7.0 percent by weight copper, 0.5 to 1.5 percent by weight titanium, 0.5 to 1.5 percent by weight columbium, and the remainder being substantially all iron with minor impurities.

20. The method in accordance with claim 17 wherein said ferrous-base alloy contains about 8.0 to 8.8 percent by weight aluminum, 14.7 to 15.5 percent by weight nickel, 23.5 to 25.0 percent by weight cobalt, up to 7.0 percent by weight copper, 1.0 to 1.5 percent by weight titanium, 0.7 to 1.5 percent by weight columbium, and the remainder being substantially all iron with minor impurities.

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