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PRODUCTION OF PERMANENT MAGNETS AND ALLOYS THEREFOR

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This invention pertains to improvements in ferrous alloys containing aluminum, nickel and cobalt, and optionally also copper, adapted primarily for use in permanent magnets, to permanent magnets thereof, and to processes for producing the same.

It is known to make permanent magnets of an alloy containing from about 6 to 11% aluminum, 12 to 20% nickel, 16 to 30% cobalt, up to about 7% copper, and the balance substantially iron, so-called "alnico" alloys. It is also known to enhance the magnetic properties of such magnets, particularly the $(BH)_{max}$ values, by rendering the same magnetically anisotropic by heat treatment, i. e. by cooling from above to well below the Curie point while in a magnetic field the lines of force of which follow the direction of subsequent permanent magnetization of the magnets.

However, a serious drawback to the attainment of optimum magnetic properties with magnets of the above alloy analysis, is the susceptibility of the alloy to the formation of a multi-phase, usually a two-phase, microstructure, whereas best permanent magnet properties are secured with a single-phase microstructure.

With reference to this point, the microstructure of an alloy of the above analysis is found to be effected by heat treatment as follows: After homogenizing or normalizing at about 2300 to 2400° F., the alloy will be found to embody a single-phase microstructure. This phase has been identified as having the alpha body centered cubic structure, and is accordingly referred to herein as the "alpha" phase. However, on heating the alloy at about 1500 to 1600° F., the precipitation of a new phase, designated herein as the "beta" phase, occurs, whereby the alloy assumes a two-phase microstructure comprising the solid solution or alpha phase having the beta phase dispersed therein in a fine state of subdivision. This beta phase appears to comprise a precipitate of intermetallic compounds derived from the various alloying constituents. This two-phase microstructure consisting of the alpha and beta phases is also observed in the alloy in the "as-cast" condition. On heating the alloy to a slightly higher temperature of about 1650° F., a single-phase microstructure, consisting only of the alpha phase, is obtained. At higher temperatures, however, of about 1700 to 2250° F., the precipitation of a third phase occurs, referred to herein as the "gamma" phase, which results on cooling from this temperature range, in a two-phase microstructure comprising a mixture, in varying proportions, of the alpha and gamma phases.

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The gamma phase is so designated because there are indications that it consists of gamma iron at the above stated elevated temperature and undergoes transformation to a martensitic-like constituent, as observed under the microscope, on cooling to room temperature.

Both of the two-phase microstructures aforesaid have distinctly inferior magnetic qualities as compared to the single-phase structure resulting from heat treating the alloy at 1650° F. or at 2300 to 2400° F. as aforesaid. This is shown by the test data set forth in Table I below, according to which individual test bars made of an alloy of the above character and having the chemical analysis given in the table, were first soaked respectively at the progressively increasing temperatures given in column 1, were thereupon cooled in a magnetic field to below the Curie point and down to a temperature of about 950 to 1000° F., and thereupon drawn or tempered for five hours at 1100° F. Column 2 shows the relative flux values for the individual specimens resulting from the treatment aforesaid; while column 3 shows the resulting microstructures thereof.

TABLE I

Alloy	Chemical Analysis of Specimen Tested, Percent							
	C	Mn	Si	Al	Ni	Co	Cu	Fe
A	.02	.03	.02	8.7	14.5	24.7	3.3	Bal.

Column 1, Heat Treatment Temp., °F.	Column 2, Resulting Flux Densities on Cooling in Magnetic Field	Column 3, Resulting Microstructure [1]
1,600	75.0	$a+b$
1,650	100.0	a
1,700	92.3	$a+$ 2% g
1,800	51.5	$a+10\%$ g
1,900	44.9	$a+25\%$ g
2,000	29.5	$a+35\%$ g
2,100	38.5	$a+25\%$ g
2,200	65.3	$a+15\%$ g
2,300	100.0	a
2,370	100.0	a

[1] Nomenclature: a, b and g designate the alpha, beta and gamma phases respectively.

It will be seen from the comparative flux values given in the above table that optimum flux values were obtained for the specimens quenched from the normalizing temperature range of about 2300 to 2400° F., or alternatively when quenched from about 1650° F., corresponding to the heat

treatments resulting in the single-phase microstructure as indicated in the table. For heat resulting in the two-phase microstructures, either that embodying the alpha plus beta phases, or that embodying the beta plus gamma phases, the flux values obtainable are materially less than those obtainable for the single-phase microstructure comprising only the alpha phase. It will also be noted that in the two-phase structure containing the gamma phase, the magnetic properties progressively decrease with increase in percentage of the gamma constituent.

The test results of Table I would appear to indicate that, for purposes of imparting the desired single-phase microstructure to "as-cast" permanent magnets of the above-mentioned alloy, and also for imparting the desired anisotropic magnetic qualities thereto, it would suffice to heat the magnets to a temperature of about 1650° F. followed by cooling substantially below the Curie point in a magnetic field. I have found, however, that in the quantity production of such magnets on a commercial scale, this is decidedly not the case, due for example to such factors as: the tendency of the two-phase microstructure of the "as-cast" magnet to persist on reheating, the strong gamma-phase forming tendencies of carbon unavoidably present in the alloy, and also to variations in individual melts due to melting tolerances, whereby such gamma-phase forming constituents as nickel and cobalt may be present in disproportionate amounts in individual melts, etc.

Due to such considerations, I have found it to be necessary with Alnico alloys of the above mentioned analysis, first to subject the magnets thereof to a normalizing heat treatment within precisely regulated temperature limits, and thereafter to reheat within precisely regulated lower temperature limits prior to cooling in the magnetic field for imparting the above-mentioned single-phase microstructure and anisotropic magnetic qualities to the magnets. Thus, the alloy, after casting into a magnet and subjecting to preliminary processing operations, such as grinding, etc., must be given an initial or normalizing heat treatment, consisting in homogenizing at 2350 to 2400° F. for about fifteen minutes, followed by a rapid cool to room temperature. For imparting the above-mentioned anisotropic properties to the magnet, it must then be reheated above the Curie point (i. e., the temperature at which the alloy transforms from magnetic to non-magnetic), and within the very restricted and critical temperature range of 1610 to 1660° F., for about five to sixty minutes until thoroughly soaked at temperature, this to assure substantial retention of the single-phase microstructure on subsequent cooling. Thereupon, the magnet is cooled in a magnetic field, as aforesaid, until it is sufficiently below the Curie point to secure the full anisotropic effect of the magnetic field, this cooling being ordinarily carried down to a temperature within the range of about 1000 to 1200° F. The magnet is thereupon removed from the magnetic field and air-cooled to room temperature. It is then reheated or drawn at a temperature somewhat above 1100° F. and then cooled below 950° F., for purposes of further improving its magnetic qualities.

The above contrasts with the "normal heat treatment" to which magnets of this character have been subjected in accordance with prior practices. The "normal heat treatment" for the designated Alnico alloys consists in normalizing or homogenizing at the temperatures from 2300° to 2425° F. This is followed by controlled cooling in a magnetic field to substantially below the Curie point, after which the magnet castings are then subjected to a draw operation which consists of reheating to within the temperature range of 950 to 1250° F. for a period of time dependent on the particular temperature or temperatures being employed. The magnets are then cooled to room temperature.

I have found that for reasons above stated, the aforementioned "normal heat treatment" is inadequate in that it does not impart optimum magnetic properties to the magnets when mass-produced on a commercial scale, due to the precipitation of the designated gamma phase on cooling. This undesirable condition has been traced to the heat chemistry wherein unfavorable balance exists between the various alloying elements even though said alloying elements are within the tolerance limits of the manufacturing specification. This precipitation is also found to occur on cooling magnet castings of relatively large section, even when possessing a favorable balance of alloying elements. This is due to the greatly retarded cooling rate imparted to the mass involved.

Now I have further discovered, in accordance with the principal aspect of the present invention, that by the addition of small but substantial amounts of silicon to the alloy having the above-mentioned range of analysis, the desired single-phase microstructure aforesaid may be retained on cooling the alloy from much broader temperature ranges than those aforesaid, and that, in consequence, the heat treatment of magnets made of the aforesaid Alnico alloy incorporating silicon in accordance with my invention, may be greatly simplified. Thus, I find that by adding silicon to the aforesaid alloy in the amount of about 0.15 to 1%, and preferably in the amount of about 0.2 to 0.4%, by weight of the resulting alloy, the initial normalizing heat treatment, consisting in homogenizing at 2350 to 2400° F. and quenching therefrom which I have found to be otherwise required, may be entirely eliminated; and that, furthermore, the heating of the magnet above the Curie point, for imparting the anisotropic properties referred to, may be carried out within a much broader temperature range, viz., 1590 to 1700° F., than the narrow and critical temperature range of 1610 to 1660° F. which I have found to be required with the alloy omitting the silicon content.

The permanent magnet alloy in accordance with my invention has the following broad and preferred ranges of analysis:

Carbon—as low as possible, i. e. 0 to 0.1% max., and preferably under 0.05% max.
Manganese—0 to 1%
Nickel—10 to 20%
Cobalt—16 to 30%
Aluminum—6 to 11%
Copper—0 to 7% and preferably 0 to 3.5%
Silicon—0.15 to 1%, and preferably 0.2 to 0.4%
Remainder—substantially iron.

I find that in addition to the advantages above stated resulting from the use in permanent magnets of my improved alloy containing silicon, permanent magnets thereof have materially better average and optimum magnetic properties than similar magnets made of the alloy excluding silicon. Thus, in the commercial or quantity production of permanent magnets made of my alloy, I find that the $(BH)_{max}$ values there-

of range consistently above 4.5 million and up to 5.5 million or higher, as compared to corresponding values ranging from about 4 to 5 million obtained in the quantity production of similar magnets made of the alloy omitting silicon. Stated somewhat differently, by employing the alloy of my invention in the quantity production of permanent magnets, a minimum $(BH)_{max}$ of 4.5 million is assured, whereas this value is frequently as low as 4.0 million for magnets made of the alloy omitting silicon.

In Table II below, I give the results of comparative tests typifying the improvements in magnetic properties of permanent magnets resulting from silicon additions, in accordance with my invention, to the aforesaid previously known alloy omitting silicon. In accordance with these tests, heats were made of alloys having the chemical analyses set forth in Table II as alloys A to C respectively, these alloys analyzing substantially the same except for silicon which was present therein in the percentages of 0.02, 0.26 and 0.61 respectively, as indicated. For the magnetic tests, ½-inch square bars of each analysis were made up and ground to $\frac{7}{16}$ inch square, cut to 2-inch lengths and squared on the ends to 1.875 inch in length. These were normalized in a gas-fired rotary furnace at 1650° F. for fifteen to twenty minutes, and thereupon cooled to 1100° F. in 4.5 minutes, while in a magnetic field. The specimens were then drawn by heating to 1125° F. for five minutes and furnace-cooled to 950° F. in sixty minutes, and checked for magnetic properties in the permeameter with the results as given in Table II.

TABLE II

Alloy	Chemical Analysis of Specimens Tested, Percent							
	C	Mn	Si	Al	Ni	Co	Cu	Bal.
A	.020	.03	.02	8.7	14.5	24.7	3.3	Fe
B	.015	.02	.26	8.7	13.5	23.9	3.1	Fe
C	.015	.02	.61	8.4	13.4	23.7	3.1	Fe

	Results of Magnetic Tests		
	Alloy A .02% Si	Alloy B .26% Si	Alloy C .61% Si
Hc	510	572	502
Br	12,650	12,860	13,180
Hd		495	430
Bd		10,000	10,800
$(BH)_{max}$	4.22	4.95	4.65

It will thus be seen that the addition of silicon within the limits above stated has greatly increased the $(BH)_{max}$ value without sacrifice in other magnetic qualities, the increase amounting to about 20% for the .26% silicon addition.

Table III below gives the results of comparative tests on alloys A to C respectively of Table II, to show the effects of silicon additions in restricting the formation of a two-phase microstructure, on cooling the alloys to progressively lower temperatures from the normalizing temperature before quenching; while Table IV below shows, for the same alloys, the effects of silicon additions in restricting the formation of a two-phase microstructure, on heating the alloy from room temperature to progressively increasing temperatures.

TABLE III

[Nomenclature: α—alpha phase, γ—gamma phase.]

Heat Treatment, °F.	Alloy A .02% Si	Alloy B .26% Si	Alloy C .61% Si
2400°—15′ cooled to:			
2400°—Water Quench	α	α	α.
2300°—10′ Water Quench	α	α	α.
2250°—10′ Water Quench	α+5% γ	α	α.
2200°—10′ Water Quench	α+35% γ	α	α.
2150°—10′ Water Quench	α+35% γ	α	α.
2100°—10′ Water Quench	α+35% γ	α	α.
2050°—10′ Water Quench	α+35% γ	α+trace γ	α.
2000°—10′ Water Quench	α+35% γ	α+5% γ	α+trace γ.
1950°—10′ Water Quench	α+35% γ	α+25% γ	α+trace γ.

TABLE IV

[Nomenclature: α—alpha phase, γ—gamma phase.]

Heat Treatment, °F.	Alloy A .02% Si	Alloy B .26% Si	Alloy C .61% Si
1700°—30′ Air Cool	α+1% γ	α	α.
1750°—30′ Air Cool	α+1% γ	α+1% γ	α.
1800°—30′ Air Cool	α+10% γ	α+1% γ	α+1% γ.
1850°—30′ Air Cool	α+10% γ	α+10% γ	α+1% γ.
1900°—30′ Air Cool	α+10% γ	α+30% γ	α+1% γ.
1950°—30′ Air Cool	α+30% γ	α+25% γ	α+5% γ.
1700°—60′ Air Cool	α+35% γ	α	α.

It will be observed from Tables III and IV that the effect of silicon is greatly to restrict the formation of the two-phase microstructure, both as regards cooling from the normalizing temperature and as regards heating from room to elevated temperature. Thus, as shown by Table III, where silicon is present in the alloy in the amounts stated, the single phase microstructure is obtained on normalizing or homogenizing over the relatively wide temperature range of 2100° to 2425° F. Tests of a similar nature have established that where silicon is present in the amounts stated, the single phase microstructure is also obtainable by the single step of heating the "as-cast" magnet within the relatively broad lower temperature range of about 1590° to 1700° F.

It is by reason of these effects that I am enabled in the quantity production of silicon containing permanent magnets in accordance with my invention to obtain the desired single phase microstructure, either by the single step normalizing or homogenizing the "as-cast" magnet over the relatively broad temperature range of 2100° to 2425° F., or alternatively, by the single step of heat treating the "as-cast" magnet within the lower temperature range of 1590° to 1700° F. The first procedure above-mentioned, viz., normalizing or homogenizing to 2100° to 2425° F., constitutes a modification of the "normal heat treatment" above described, and one which results in a satisfactory magnet. My preferred heat treatment, however, is that last mentioned, namely, the complete omission of the normalizing treatment previously required, and the substitution therefor of the single step of heat treating within the temperature range of about 1590° to 1700° F.

Thus the production and preferred heat treatment of the magnets, in accordance with my invention, are as follows: The magnet is cast and subjected to the usual preliminary processing operations, such as grinding, etc. It is then heat treated by heating above the Curie point, and held above this point for about five to sixty minutes until thoroughly soaked at temperature. Ordinarily, this heating is carried out at about 1590° to 1700° F. The magnet is then transferred to a magnetic field of about 600 to 3000 gauss and

air-cooled sufficiently below the Curie point to secure the full anisotropic effect of the magnetic field, this cooling being ordinarily carried down to a temperature within the range of about 1000 to 1200° F. The magnet is then removed from the magnetic field, and air-cooled to room temperature. It is thereupon reheated above 1100° F. and cooled therefrom at about 25° to 50° per hour, either slowly or in successive steps, down to a temperature of about 950° F., and thereupon air-cooled to room temperature. A magnet made of the silicon-containing alloy of my invention, and heat treated as aforesaid, will have a $(BH)_{max}$ ranging consistently above 4.5 million and up to 5.5 million or more.

In order further to demonstrate the effectiveness of silicon additions to Alnico alloys of the type aforementioned, permeameter values are given in Table V below, of two magnets possessing the relatively large sectional dimensions and the chemical analysis given in said table. The permeameter values were obtained on sections cut from magnets having minimum slip coil values. The magnet castings were heat treated at 1635° F. for 50 to 60 minutes, and were then cooled in a magnetic field to temperature of 1000° to 1100° F. in 9 to 11 minutes, and then removed from the magnetic field and cooled to room temperature. They were then drawn by reheating to a temperature somewhat above 1100° F. followed by cooling to about 950° F., with results as given in said Table V as follows:

TABLE V

Alloy	Chemical Analysis of Magnets Tested, Percent						
	C	Si	Mn	Ni	Cu	Al	Co
D	.018	.34	.01	14.15	3.40	8.61	23.58

Permeameter test results

Size of Magnet	Hc	Br	$(BH)_{max} \times 10^6$
3.4" x 3.4" x 1"	645	12,500	5.02
3.4" x 3.4" x 2"	650	12,200	4.81

In an alloy of the above type without silicon and of corresponding sectional dimensions, optimum magnetic properties cannot be realized on heat treating from the aforesaid restricted low temperature range of 1610° to 1660° F., due to the segregation present in the "as-cast" condition which is imparted by the precipitation of the so-called gamma phase during the cooling after solidification. Neither can optimum properties be realized on cooling from above the gamma region within the aforesaid restricted temperature range of 2200° to 2425° F. and in a magnetic field, as reprecipitation of the gamma phase occurs. It is further not possible to cool the magnet casting rapidly from a temperature of 2200° to 2425° F. and to below the gamma region with the purpose of preventing its reprecipitation and to be followed by heat treating in a magnetic field from within the range of 1610° to 1660° F. This is due to the excessive cracking which thereby occurs.

By way of demonstrating the improvements resulting from the invention in the quantity production of permanent magnets on a commercial scale, 300-pound induction heats of the above alloy were made, directed to similar analyses except for silicon, with respect to which, however, the aim was to produce heats having silicon contents of 0.1, 0.2 and 0.3% respectively. The

analyses actually obtained are as given for alloys E, F and G in Table VI below. These heats were then cast into magnets of similar dimensions, which were given the heat treatment aforesaid, including soaking at 1650° F. followed by cooling in a magnetic field below the Curie point to about 1000 to 1200° F., and subsequently drawn by reheating above 1100° followed by cooling below 950° F. The resulting magnets were then tested in the permeameter for $(BH)_{max}$ values with results as shown in Table VI, as follows:

TABLE VI

Alloy	Chemical Analyses of Magnets Tested, Percent							
	C	Si	Mn	Ni	Cu	Al	Co	Fe
E	.022	.13	.02	13.65	3.20	8.36	24.00	Bal.
F	.031	.23	.02	13.80	3.24	8.41	23.86	Bal.
G	.015	.32	.02	13.75	3.20	8.49	24.14	Bal.

Results of permeameter tests expressed in cumulative percentage of magnets tested having indicated $(BH)_{max}$ values

$(BH)_{max}$ 10^6	Alloy E .13% Si	Alloy F .23% Si	Alloy G .32% Si
Under 4.00	6.25	0	0
Under 4.25		0	0
Under 4.50	12.50	.95	0
Under 4.75		1.90	4.25
Under 5.00	56.00	6.66	19.75
Under 5.25	89.70	62.76	70.15
Under 5.50	100.00	100.00	100.00
Total Number of Magnets Tested	48	159	94

It will be seen from the above tabulations that for the lowest silicon content of .13%, the cumulative percentage of magnets tested having $(BH)_{max}$ values below any given value between 4.0 and 5.5 million is considerably higher than are the corresponding percentages for the magnets having hgher silicon contents within the range of analysis of my invention. This is of importance in the rejection of magnets for low $(BH)_{max}$ values in quantity production. Thus, for example, if the lower acceptable commercial limit for $(BH)_{max}$ is set at 4.5 million, the above table shows that the rejections in the case of the 0.13% silicon analysis would be 12.50%, as compared to rejection of only about 1% for the .23% silicon analysis and 0% for the .32% silicon analysis.

A direct comparison is given in the following Table VII of magnets obtained from two 300 pound production heats, in one case consisting of an alloy without silicon, and the other with silicon. The alloys are designated as H and I respectively. Alloy H was heat treated from above the gamma region; cooled rapidly to below said region and then subjected to a magnetic treatment from 1650° F. Alloy I was heat treated directly from 1650° F. into a magnetic field. Both were followed by a draw treatment which consisted of heating to somewhat above 1100° F. and cooling to about 950° F. The energy product distribution is expressed in cumulative percentages.

TABLE VII

Alloy	Chemical Analyses of Magnets Tested, Percent						
	C	Si	Ni	Cu	Al	Co	Fe
H	.032	.02	13.90	3.36	8.58	23.72	Bal.
I	.020	.28	13.90	3.22	8.44	23.72	Bal.

TABLE VII—*Continued*

Results of $(BH)_{max}$ tests expressed in cumulative percentage of magnets tested

$(BH)_{max}\times10^6$	Alloy H .02% Si	Alloy I .28% Si
Under 4.75	45.2	2.0
Under 5.00	75.2	5.9
Under 5.25	98.3	49.1
Under 5.50	100 0	96.1
Under 5.75	100.0	100.0
	Total number of Magnets Tested	
	177	51

Complete permeameter tests

Alloy	Hc	Br	$(BH)_{max}\times10^6$
H	675	12,450	4.87
I	679	12,700	5.43

From the foregoing table it is obvious that improved magnetic properties are obtained with the silicon alloy which are over and above those obtained when heat treating an alloy without silicon by the best known practice.

I claim:

1. A ferrous alloy adapted for use in permanent magnets containing: about 10 to 20% nickel, about 16 to 30% cobalt, about 6 to 11% aluminum, up to about 7% copper, up to about 1% manganese, up to about 0.1% carbon, from about 0.15 to 1% silicon, and the balance substantially all iron, said silicon being present in amount such as to impart to said alloy a substantially single phase microstructure on heating at about 1600° to 1700° F. and cooling therefrom.

2. A permanent magnet made of a ferrous alloy containing: about 10 to 20% nickel, about 16 to 30% cobalt, about 6 to 11% aluminum, up to about 7% copper, up to about 1% manganese, up to about 0.1% carbon, from about 0.15 to 1% silicon, and the balance substantially all iron, said magnet having a substantially single-phase microstructure.

3. A permanent magnet made of a ferrous alloy containing: about 10 to 20% nickel, about 16 to 30% cobalt, about 6 to 11% aluminum, up to about 7% copper, up to about 1% manganese, up to about 0.1% carbon, from about 0.15 to 1% silicon, and the balance substantially all iron, said magnet having a substantially single-phase microstructure, being magnetically anisotropic and having a $(BH)_{max}$ value in the principal direction of at least 4.5 million.

4. In the manufacture of permanent magnets, the process which comprises: casting into the shape of a permanent magnet a ferrous alloy containing about 10 to 20% nickel, about 16 to 30% cobalt, about 6 to 11% aluminum, up to about 7% copper, up to about 1% manganese, up to about 0.1% carbon, from about 0.15 to 1% silicon, and the balance substantially iron; thereafter heating the so-cast magnet to a temperature within the range of about 1590 to 1700° F. and allowing said magnet to cool from said temperature while in a magnetic field to a temperature sufficiently below the Curie point to impart anisotropic properties to said magnet.

5. In the manufacture of permanent magnets, the process which comprises: casting into the shape of a permanent magnet a ferrous alloy containing about 10 to 20% nickel, about 16 to 30% cobalt, about 6 to 11% aluminum, up to about 3% copper, up to about 0.1% carbon, from about 0.2 to 0.4% silicon, up to about 1% manganese, and the balance substantially iron; thereafter heating the so-cast magnet to a temperature within the range of about 1590 to 1700° F. and allowing said magnet to cool from said temperature while in a magnetic field to a temperature sufficiently below the Curie point to impart anisotropic properties to said magnet.

6. In the production of permanent magnets, the process which comprises: casting into the form of a magnet a molten ferrous alloy containing about 10 to 20% nickel, about 16 to 30% cobalt, about 6 to 11% aluminum, up to about 3% copper, up to about 0.1% carbon, from about 0.2 to 0.4% silicon, up to about 1% manganese, and the balance substantially iron; allowing the so-cast magnet to cool substantially to room temperature; thereupon heating the magnet to a temperature within the range of about 1590 to 1700° F. until thoroughly soaked at said temperature; applying to the so-heated magnet a magnetic field, said field being applied in the direction of permanent magnetization of said magnet; allowing the magnet to cool in said field to a temperature sufficiently below the Curie point to render said magnet magnetically anisotropic; and thereupon heating said magnet above 1100° F. and allowing it to cool below 950° F.

7. The method of heat treating a permanent magnet containing about 10 to 20% nickel, about 16 to 30% cobalt, about 6 to 11% aluminum, up to about 7% copper, up to about 1% manganese, up to about 0.1% carbon, and the balance principally iron, said method comprising: heating said magnet to temperature of about 2350 to 2400° F. and thereupon cooling substantially to room temperature, thereupon reheating the magnet to temperature of about 1610 to 1660° F. until thoroughly soaked at temperature, and cooling in a magnetic field to a temperature sufficiently below the Curie point to impart anisotropic properties thereto.

8. A ferrous alloy adapted for use in permanent magnets, containing: about 10 to 20% nickel, from more than 20% to about 30% cobalt, about 6 to 11% aluminum, up to about 7% copper, up to about 1% manganese, up to about 0.1% carbon, from about 0.15 to 1% silicon, and the balance substantially all iron, said silicon being present in amount such as to impart a substantially single phase microstructure to said alloy upon heating at about 1600° to 1700° F. and cooling therefrom.

9. A permanent magnet made of a ferrous alloy containing: about 10 to 20% nickel, from more than 20% to about 30% cobalt, about 6 to 11% aluminum, up to about 7% copper, up to about 1% manganese, up to about 0.1% carbon, from about 0.15 to 1% silicon, and the balance substantially all iron, said magnet having a substantially single phase microstructure, being magnetically anisotropic and having a $(BH)_{max}$ value in the principal direction of at least 4.5 million.

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