Oct. 2, 1951 E. A. GAUGLER 2,569,468

METHOD OF PRODUCING GRAIN ORIENTED FERRO-MAGNETIC ALLOYS

Filed June 16, 1948 7 Sheets-Sheet 1

Fig. 1.

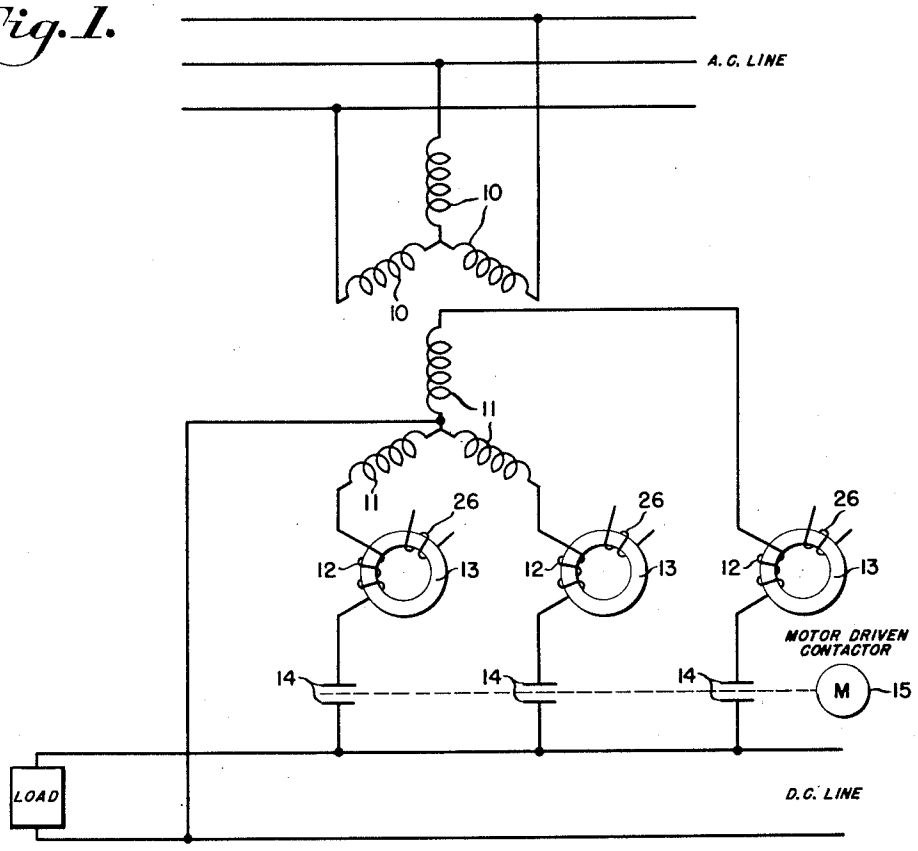
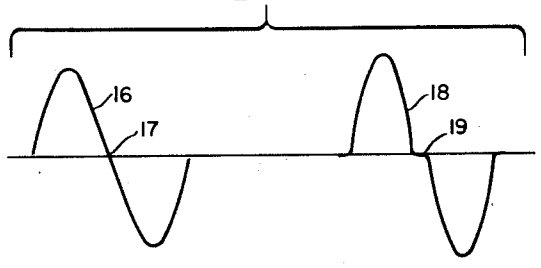


Fig. 2.



Inventor
Edward A. Gaugler

By M. A. Hayes

Attorney

Fig. 3.

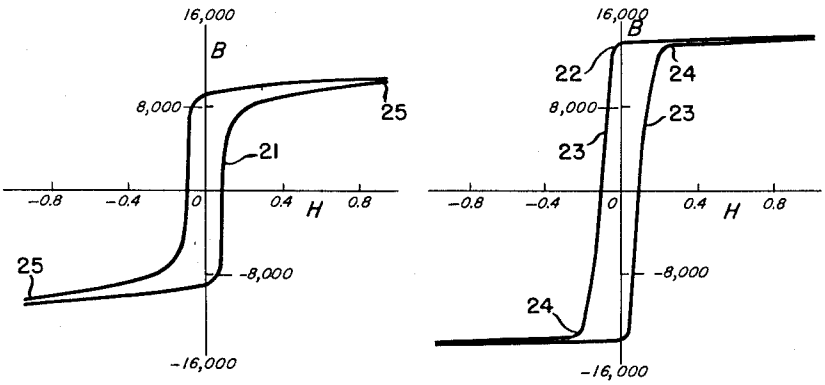
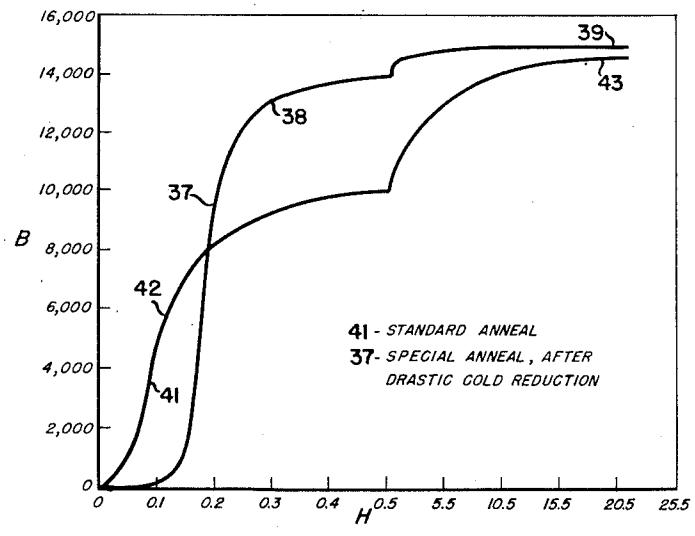


Fig. 5.



Inventor
Edward A. Gaugler

By M. A. Hayes

Attorney

Oct. 2, 1951 E. A. GAUGLER 2,569,468
METHOD OF PRODUCING GRAIN ORIENTED
FERRO-MAGNETIC ALLOYS
Filed June 16, 1948 7 Sheets-Sheet 3

Fig. 4.

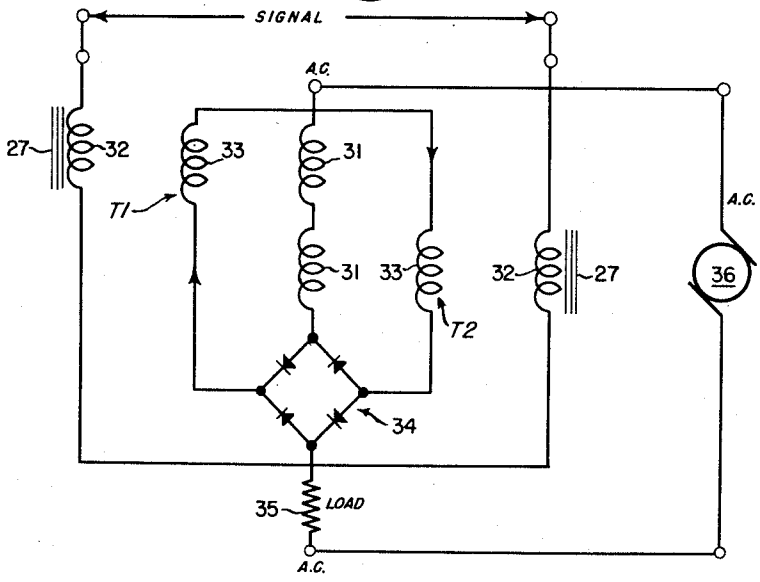
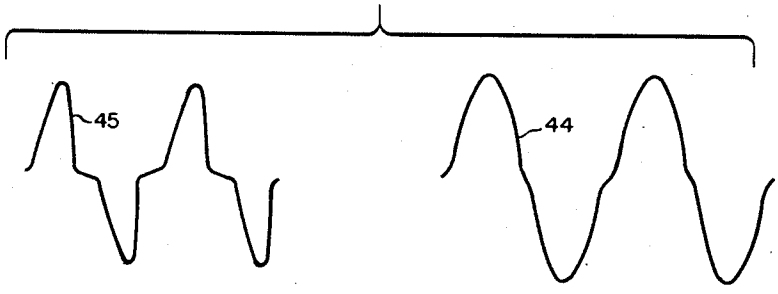


Fig. 6.



Inventor
Edward A. Gaugler
By M. A. Hayes
Attorney

Oct. 2, 1951 E. A. GAUGLER 2,569,468

METHOD OF PRODUCING GRAIN ORIENTED FERRO-MAGNETIC ALLOYS

Filed June 16, 1948 7 Sheets-Sheet 4

Fig. 7.

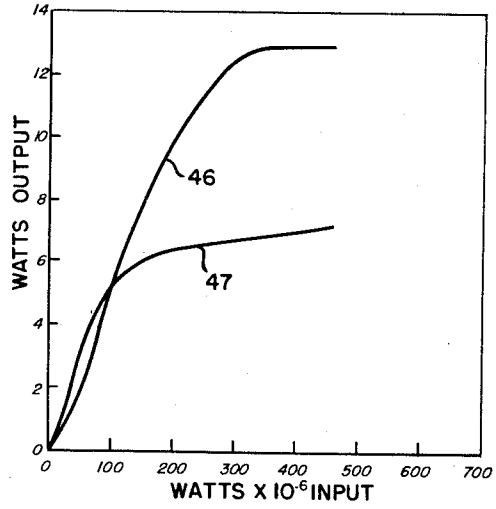


Fig. 8.

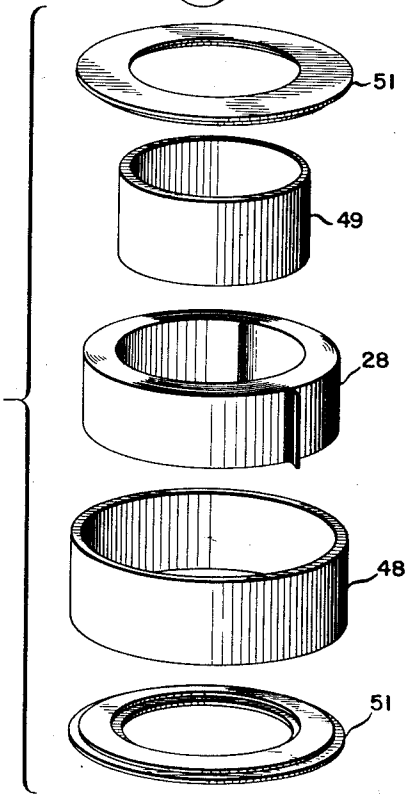
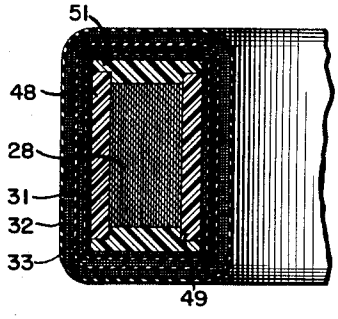


Fig. 9.



Inventor
Edward A. Gaugler

By M. L. Hayes

Attorney

Oct. 2, 1951 E. A. GAUGLER 2,569,468

METHOD OF PRODUCING GRAIN ORIENTED FERRO-MAGNETIC ALLOYS

Filed June 16, 1948 7 Sheets-Sheet 5

Fig. 10.

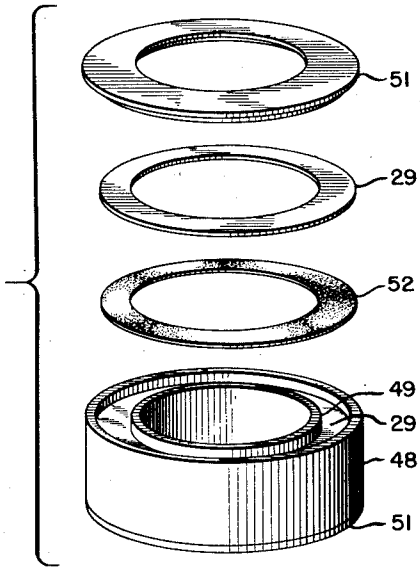


Fig. 11.

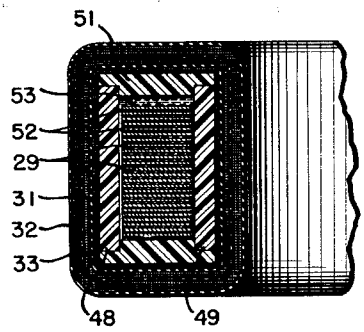
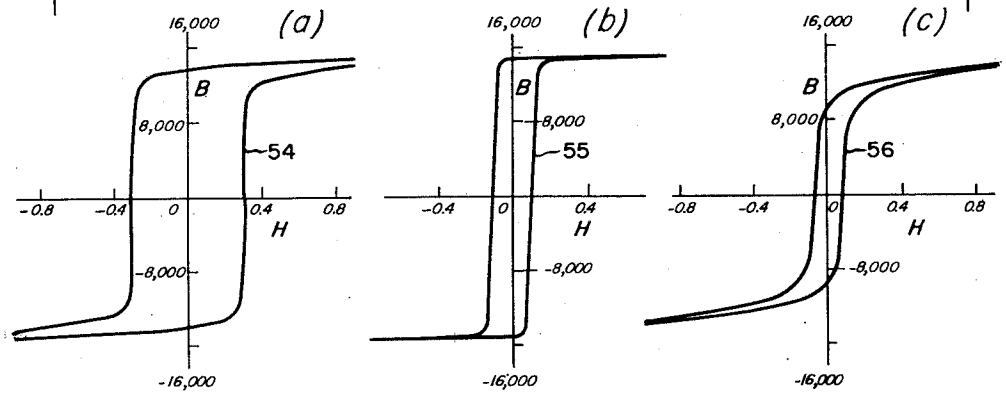


Fig. 12.



Inventor
Edward A. Gaugler

By M. O. Hayes

Attorney

Oct. 2, 1951 E. A. GAUGLER 2,569,468
METHOD OF PRODUCING GRAIN ORIENTED FERRO-MAGNETIC ALLOYS
Filed June 16, 1948 7 Sheets-Sheet 6

Fig. 13.

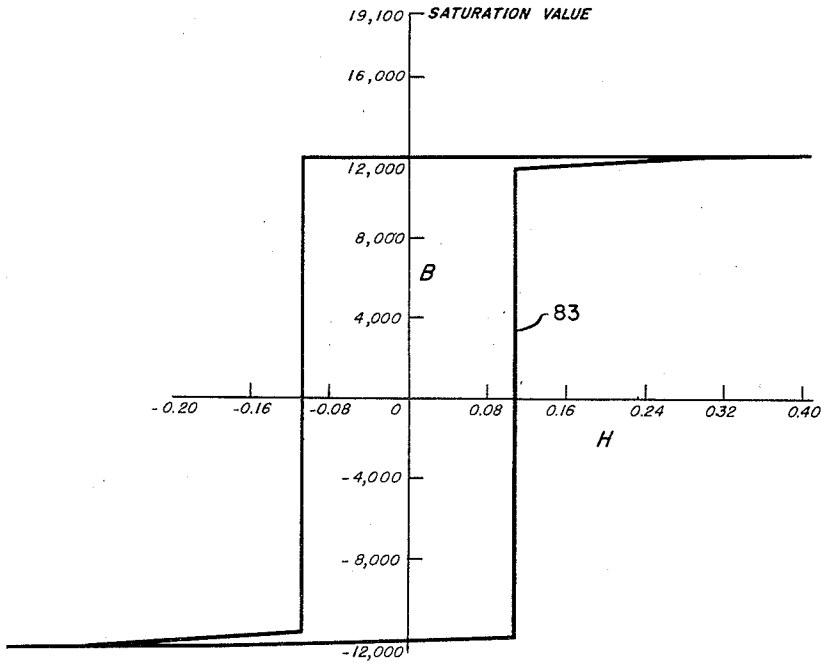
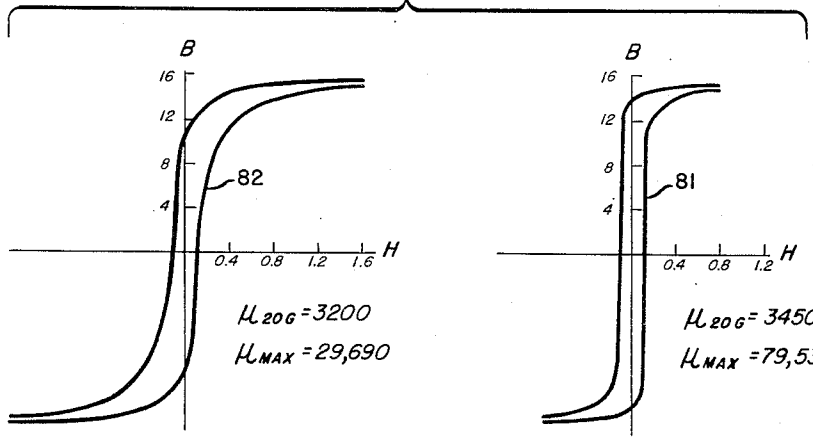


Fig. 14.



Inventor
Edward A. Gaugler

By M. O. Hayes

Attorney

Oct. 2, 1951 E. A. GAUGLER 2,569,468

METHOD OF PRODUCING GRAIN ORIENTED FERRO-MAGNETIC ALLOYS

Filed June 16, 1948 7 Sheets-Sheet 7

Fig. 15.

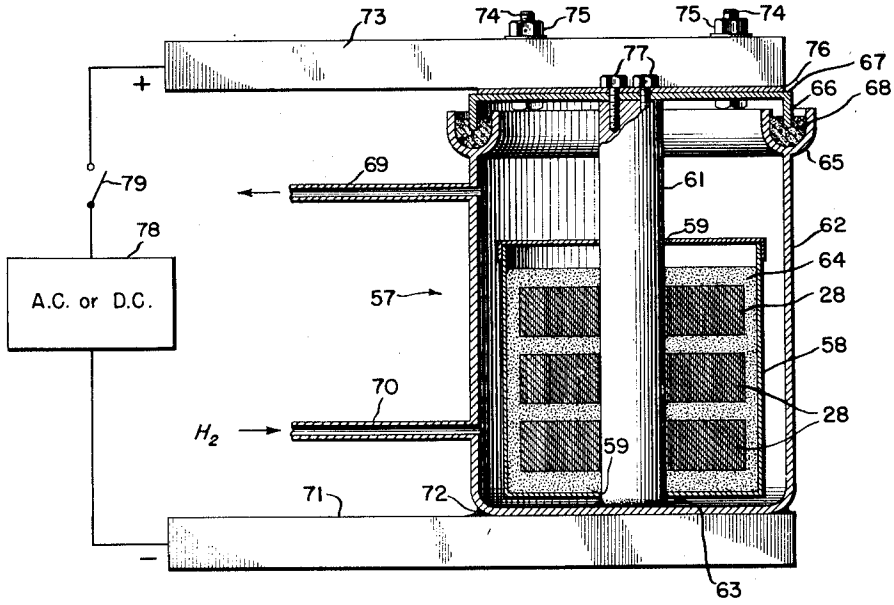
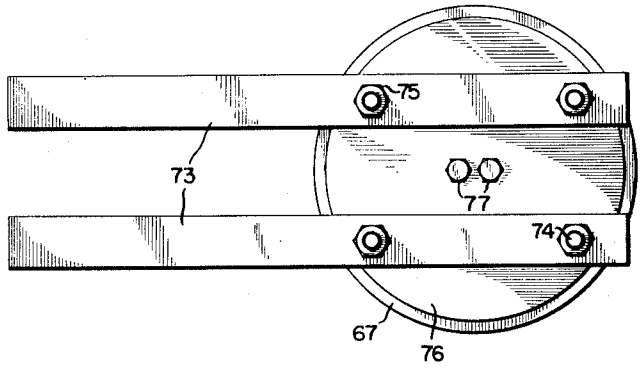


Fig. 16.



Inventor
Edward A. Gaugler
M. O. Hayes

By

Attorney

Patented Oct. 2, 1951

2,569,468

UNITED STATES PATENT OFFICE

2,569,468

METHOD OF PRODUCING GRAIN ORIENTED FERROMAGNETIC ALLOYS

Edward A. Gaugler, Alexandria, Va.

Application June 16, 1948, Serial No. 33,398

4 Claims. (Cl. 148—2)

(Granted under the act of March 3, 1883, as amended April 30, 1928; 370 O. G. 757)

1

This invention relates to magnetic materials and more particularly to new and improved methods of treating ferro-magnetic materials to obtain rectangular hysteresis loops therefrom of improved characteristics.

Ferro-magnetic materials having rectangular hysteresis loops may be used to great advantage, although not exclusively, in contact rectifiers and magnetic amplifiers, superior operating characteristics being obtained from these devices when rectangular hysteresis loop materials are employed in the core structures thereof. Whereas the utility of such core materials is disclosed hereinafter in connection with magnetic amplifiers and contact rectifiers, it will be understood that those skilled in the art may find many more applications for such materials, particularly in the design of saturable magnetic devices and apparatus operating at high flux densities.

In the operation of mechanical rectifiers, difficulties are encountered in obtaining satisfactory commutation which necessarily must take place while the A.-C. current passes through zero value. In an ordinary A.-C. wave, the rate of change of the current is the greatest as the current passes through zero and, as a result, there is no time for commutation without destructive sparking. Substantially sparkless commutation can be obtained, however, by introducing a "step" into the A.-C. wave at the point of zero value thereof, which "step" results in a prolonging of the time of zero current. This is accomplished by the use of saturable reactor coils which are inserted into the rectifier circuit in series with the A.-C. current leads. It has been found that greatly improved results are obtained when the saturable reactor coils employ ferromagnetic cores having rectangular hysteresis loop characteristics. In such case, the commutation takes place at the steep portions of the hysteresis loop, for which reason it is desirable that the vertical portions of the hysteresis loops be as steep as possible, that is to say, the steep portions approach true vertical or true rectangularity, and that they approach the saturation value whereby the commutation interval is extended and the amount of core material required in a specific rectifier may be minimized. Moreover, when the width of the loop is small, the current during commutation is small, although not zero, and may be reduced to zero by the use of an A.-C. biasing current.

When a magnetic material having a rectangular hysteresis loop is employed in a magnetic amplifier having saturable transformers designed

2

to operate at the knee of the magnetization curve, the knee occurs very close to the saturation value whereby the form factor of the load current more nearly approaches that of a sine wave with the result that the amplifier is capable of delivering over twice as much power as when the same amplifier employs commercial or standard core materials. Moreover, the gain of the amplifier when the improved core materials are employed is more constant over the entire operating range of the amplifier and the speed of response thereof to applied signals is greatly increased. From power consideration, it is desirable to operate at high flux density. The higher the density at which the knee occurs, the larger will be the output capacity of a coil with a core of a specific size. Also, in order to increase the amplification the magnetizing force at the knee should be a minimum value. Magnetic core materials having rectangular hysteresis loops of improved characteristics obtainable from the new and improved methods of treatment thereof, hereinafter to be disclosed, fulfill these power and amplification requirements.

Ferro-magnetic materials in the iron-nickel-cobalt series, and having rectangular hysteresis loops, have heretofore been produced in accordance with one method wherein the material is subjected to a high temperature between 500° C. and 1500° C. in a hydrogenous atmosphere for some time, slowly cooled to room temperature, reheated in a magnetic field and preferably in an atmosphere of hydrogen to a temperature near the non-magnetic temperature of the material, maintained under these conditions for some time, after which it is slowly cooled to room temperature while subjected to the magnetic field.

This method of treatment, which is disclosed in U. S. Patent to R. M. Bozarth et al., 2,002,689, May 28, 1935, has not been found to be entirely satisfactory in service for the reason that it will not produce rectangular hysteresis loops in certain ferro-magnetic materials such, for example, as 50% Ni-Fe alloy or silicon steel wherein the impurities present in commercial or standard grades of these materials prevent the crystals from assuming a preferred direction of magnetic orientation in response to the influence of the magnetic field. From the standpoint of obtaining increased efficiency of operation of electrical apparatus, it is desirable that ferro-magnetic materials such, for example, as 50% Ni-Fe having a specific resistance of approximately 45 microohm centimeters and capable of being reduced

to a tape thickness as low as .0012 inch without loss of optimum magnetic characteristics be employed. From the standpoint of armament and defense of the country, it is desirable that non-strategic materials such, for example, as silicon steel be produced in such a manner as to obtain rectangular hysteresis loop characteristics therefrom.

According to another prior art method it has been found that a 50% Ni-Fe alloy can be produced with resulting rectangular hysteresis loops by subjecting the material to severe cold rolling providing a thickness reduction in the order of 99% to a final thickness below .002 inch followed by final special annealing in which the material is heated rapidly to a predetermined temperature in the order of 1000° to 1150° C., held at this temperature for approximately two hours and thereafter cooled rapidly. This method has not been found to be entirely satisfactory in service for the reason that the rapid cooling introduces strains into the material which adversely affects the magnetic properties thereof and for the additional reason that the same magnetic properties cannot be duplicated in similar specimens to which the same heat treatment has been applied.

A feature of the present invention resides in the combination treatment of ferro-magnetic materials wherein the material is subjected to severe cold reduction sufficient to produce grain-orientation resulting in optimum magnetic properties of the material followed by special annealing in a magnetic field to produce rectangular hysteresis loops having optimum characteristics. This method of treatment is particularly well suited for use with ferro-magnetic materials which by reason of their inherent impurities will not respond to magnetic treatment without first having been given a preferred magnetic grain-orientation as a result of drastic cold reduction. Thus, in the application of the combination treatment of the present invention it has been found possible to obtain rectangular hysteresis loop characteristics from 50% Ni-Fe alloys and commercial grades of silicon steel which have first been subjected to drastic cold reduction to produce grain-orientation. The methods of orienting crystals of a magnetic material which results in the material exhibiting preferred directions of magnetization by subjecting the material to severe cold rolling are well known in the art and are taught, for example, by the U. S. Patent to N. P. Goss, 1,965,559, July 3, 1934.

According to the preferred method of treatment of the present invention the ferro-magnetic material from which it is desired to obtain rectangular hysteresis loop characteristics is first treated to obtain preferred orientation of the material as in the aforementioned prior art method wherein severe cold reduction of the material is followed by special annealing comprising rapid heating of the material to a predetermined temperature above the magnetic transformation point, holding this temperature for a fixed predetermined period of time, and rapidly cooling the material. The material is then given a second anneal above the magnetic transformation point and in an atmosphere of pure hydrogen, the material is held in this condition for a predetermined period of time followed by slow cooling in a strong magnetic field, the field being applied in the same direction in the material as the magnetic field in which the material is to be used.

According to an alternate method of treatment of the present invention, the grain-oriented ferro-magnetic material is rapidly heated in a magnetic annealing pot to a predetermined high temperature above the magnetic transformation point and in an atmosphere of pure hydrogen, the material is held under these conditions for a definite period of time sufficient to bring the material up to this temperature, the material is cooled in the hydrogenous atmosphere to a second predetermined temperature at or below the magnetic transformation point, and thereafter is slowly cooled in a strong magnetic field which is applied in the same direction as the magnetic field in which the material is to be used.

An object of the present invention is to produce new and improved ferro-magnetic materials having rectangular hysteresis loops.

Another object is to produce ferro-magnetic materials having rectangular hysteresis loops of improved characteristics.

Another object is to produce rectangular hysteresis loop characteristics in ferro-magnetic materials having high specific resistance, high saturation, and capable of reduction to small thicknesses whereby highly efficient operation of electrical apparatus employing such materials may be obtained.

A further object is to produce rectangular hysteresis loop characteristics in ferro-magnetic materials by a combination process of grain-orientation obtained through severe cold reduction and special annealing in a magnetic field.

A further object resides in the provision of new and improved ferro-magnetic materials having increased magnetic permeabilities, particularly at high flux densities, and in the provision of a method of treatment thereof whereby such characteristics may be obtained therefrom.

An additional object is to provide a magnetic annealing treatment for grain-oriented ferro-magnetic materials whereby rectangular hysteresis loops of improved characteristics may be obtained therefrom and readily duplicated in different specimens of the material which have been processed under substantially identical conditions.

Other objects and many of the attendant advantages of this invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

Fig. 1 is a diagrammatic view of a contact rectifier from which superior operating characteristics may be obtained when ferro-magnetic materials having rectangular hysteresis loop characteristics are employed in the saturable reactor coils of the rectifier;

Fig. 2 shows a pair of current waves illustrating the form or shape of the current wave of the current applied to the rectifier contacts for the case in which saturable reactors are in the circuit and for the case in which the reactors alternatively are not in the circuit, the step in the current wave appearing in the first named case;

Fig. 3 shows a pair of hysteresis loops for two cores of the same material, one of the cores having been treated by standard methods and the other core having been specially processed to give a rectangular hysteresis loop in accordance with the aforementioned prior art process for 50% Ni-Fe;

Fig. 4 is a diagrammatic view of a magnetic amplifier from which superior operating characteristics may be obtained in the use of ferro-magnetic core materials which have been processed in accordance with the method of treatment of the present invention to obtain rectangular hysteresis loops of improved characteristics;

Fig. 5 shows the magnetization curve of two 50% nickel-iron alloy cores of substantially the same composition, one of which has been given a special treatment to produce a rectangular hysteresis loop while the other has been given a standard heat treatment;

Fig. 6 shows the current wave forms for each of the cores whose magnetization curves are illustrated in Fig. 5;

Fig. 7 shows curves which illustrate the relationship between the watts output and the watts input of the magnetic amplifier of Fig. 4 for the two cases in which the cores whose magnetization curves are illustrated in Fig. 5 are alternatively employed in the magnetic amplifier;

Fig. 8 is an exploded view of a core assembly of suitable design for full utilization of the improved magnetic characteristics of a core which has been been processed in accordance with the present invention to obtain rectangular hysteresis loop characteristics;

Fig. 9 is a fragmentary sectional view of a coil assembly including the core assembly of Fig. 8;

Fig. 10 is a view similar to Fig. 8 and illustrates a core in which the core is made up of washer-type laminations;

Fig. 11 is a view similar to Fig. 9 and illustrates a coil and core assembly including the core assembly of Fig. 10;

Fig. 12 shows a group of hysteresis curves illustrating the optimum temperature for obtaining a rectangular hysteresis loop from a 50% Ni-Fe alloy which has been treated in accordance with the aforementioned prior art method;

Fig. 13 shows the hysteresis loop obtained from high purity 5.0% Si-Fe steel which has been cooled in a magnetic field;

Fig. 14 shows a pair of hysteresis loops obtained from a pair of grain-oriented silicon steel cores, one of which has been annealed and slowly cooled without an applied field, and the other of which has been slowly cooled after annealing in a magnetic field applied parallel to the direction of preferred orientation in accordance with the method of the present invention;

Fig. 15 is a sectional view of a magnetic annealing pot suitable for practicing the method of treatment of the present invention; and

Fig. 16 is a plan view of the cover for the pot of Fig. 15.

Referring now to the drawings for a more complete understanding of the invention and more particularly to Fig. 1 thereof there is shown thereon a basic circuit for a three phase contact rectifier including a Y-connected three phase transformer whose primary windings **10** are connected to the three phase A. C. line and whose secondary windings **11** are connected respectively to the coils **12** of three identical saturable core reactors each having a core **13** composed of ferro-magnetic material having rectangular hysteresis loops. The other ends of coils **12** are connected respectively to three sets of contacts **14** which are mechanically coupled to the motor **15** which is constructed and arranged in a manner well known in the art to interrupt the contacts **14** in predetermined sequence according to the frequency of the three phase line as the motor is driven at a predetermined speed, thereby to supply a continuous D.-C. current to the load.

When the saturable reactors are not in the circuit, the current supplied by each of secondary windings **12** to contacts **14** individual thereto has the form or shape of curve **16** of Fig. 2. The commutation, however, must take place while the current passes through zero value as at point **17** in the curve. The rate of change of the current is the greatest at this point and, as a result, there is no time for commutation, without destructive sparking.

When the saturable reactors are connected into the rectifier circuit, as shown, the current to contacts **14** has the shape or form of curve **18** of Fig. 2 in which case a "step" **19** is introduced into the wave form of the current which prolongs the time of zero current so that substantially sparkless commutation is obtained. It has been found that this effect has been greatly enhanced in the use of saturable reactor coils which employ ferro-magnetic cores having rectangular hysteresis loops. When such cores are employed, it has been found possible to produce commercially, mechanical rectifiers having capacities up to 10,000 amperes and 400 volts D.-C. with an overall efficiency in the order of 97–98%.

Hysteresis loop **21** of Fig. 3 was obtained from a core which had been treated by a standard or conventional method, and hysteresis loop **22** was obtained from a core which had been given a special treatment to produce the rectangular form of the loop. Commutation takes place at the steep portions **23** of loop **22**, for which reason it is desirable that these portions approach parallelism with respect to the B axis in closely spaced relation with respect thereto and that they closely approach the saturation value substantially as at point **24** in curve **22**. It will be noted that the saturation point **25** in loop **21** is removed a considerable distance along the H axis from the vertical portions of loop **21**. When the width of the loop along the H axis is small, the current during commutation will remain small. The current will not be zero, however, and in order to reduce the current to zero, an A.-C. biasing current is supplied through the auxiliary windings **26** of Fig. 2 which, for this purpose, may be connected in any convenient manner to any suitable A.-C. bias source.

A magnetic amplifier circuit of a type employing regeneration is shown in Fig. 4 and comprises a pair of saturable transformers designated T1 and T2. Each of these transformers is a type in which the ferro-magnetic core **27** thereof is toroidal or closed in form, being either a ribbon wound core such as core **28** of Figs. 8 and 9, or in certain cases, being formed of a stack of washer-shaped laminations **29** such as are disclosed in Figs. 10 and 11.

Each core **27** has an output or load winding **31**, a signal or input winding **32**, and a feedback winding **33** wound thereabout. A full wave rectifier generally designated **34** is connected in series with feedback windings **33** and interposed between the load **35** and output windings **31** to cause a D. C. current proportional to the load current to flow from the A. C. source **36** through feedback windings **33** in the proper direction therethrough to produce regeneration of the unbalance which occurs in the shapes of the hysteresis loops of the transformer cores when a D.-C. signal is applied to the opposedly connected signal windings **32**. The use of the rec-

tified load current through the feedback windings for purposes of regeneration requires a suitable D.-C. bias, not shown, to minimize the load current at zero signal.

Transformers T1 and T2 are designed to operate at the knee of the magnetization curve of cores 27 which are composed of magnetic material having rectangular hysteresis loops. Thus, in the absence of the signal, the core material is operated in the rectangular region of the hysteresis loop. When the signal is applied, the shapes of the hysteresis loops of the cores are changed and the magnetizing and load currents are greatly increased without any change in peak flux density. This decreases the time of response of the amplifier to the signal, renders the wave form of the output current substantially sinusoidal and free of distortion, and provides greater efficiency for the reason that the core material may be operated at maximum flux density. The higher the density at which the knee of the saturation curve occurs, the larger is the output power capacity of a coil with a core of a given size. Also, in order to increase the amplification, the magnetizing force at the knee should be a minimum.

In a 50% Ni-Fe material having a rectangular hysteresis loop, and whose magnetization curve 37 is shown in Fig. 5, the knee 38 of the curve, with respect to the B axis, occurs close to saturation at point 39 in the curve. In a core material of the same composition but which has been given a standard or conventional heat treatment, the magnetization curve 41 thereof has the knee 42 of the curve displaced considerably along the B axis from the saturation point 43 of the curve. In Fig. 6, it will be seen that the current wave form 44 of the core having the rectangular hysteresis loop has greatly improved sinusoidal characteristics as compared with the current wave 45 of the core which has been given the standard heat treatment. In Fig. 7, the power outputs of these cores are compared, curve 46 being that of the material having the rectangular hysteresis loop and curve 47 being that of the other material. It will be noted that at 300 x 10^{-6} watts input, for example, the output of curve 46 is approximately double that of curve 47. It will be further noted that the gain over the entire range of curve 46 is more constant than that of curve 47.

In order to effectively utilize the improved characteristics obtainable from magnetic cores having rectangular hysteresis loops in transformers T1 and T2, it is essential that air gaps in the magnetic circuit thereof be minimized in order not to shear over the hysteresis loop. This can be obtained from core designs of uncut wound cores or tapes 28, Fig. 8, or to ungapped punchings 29, Fig. 10. Although the fundamental excitation frequency may be low, the transit time during reversal of saturation may be exceedingly short and consequently the specific resistance of the material should be high and the material thickness a minimum in order to minimize eddy current losses. In a specific design of the mechanical rectifier operating at 50 cycles, for example, the transit time was approximately one millisecond, tape thickness .0012–.002 inch, and the specific resistance 45 micro-ohm centimeters.

Other precautions must be taken in order to obtain a sharp knee in the magnetization curve. For example, the magnetizing force must be uniform over the entire cross section of the core, which thus requires a relatively narrow annular

width. After final heat treatment care must be taken to prevent introduction of mechanical strains into the core material. To this end, the cores 28 or 29, as the case may be, are mounted in plastic troughs 48 and 49 with plastic covers 51 to support the windings.

In the case of the washer-shaped punchings 29, adjacent pairs of the washers preferably are separated by insulation washers 52 and the stack of punchings and washers permitted to move several thousandths of an inch both radially and axially within the container therefor so as to permit a suitable semi-fluid or fluid 53 to seep thereinto, all in the manner and for the purpose of avoiding strains to the magnetic material as set forth in the co-pending application of G. W. Elmen and E. A. Gaugler for Magnetic Amplifier, Serial No. 600,629, filed June 20, 1945.

Although the methods of the present invention of treating ferro-magnetic materials to obtain rectangular hysteresis loop characteristics therefrom contemplate as the first step thereof any of the well known processes of drastic cold reduction resulting in crystal and grain-orientation of the material which provides optimum magnetic characteristics, the steps of the aforementioned prior art treatment for 50% Ni-Fe alloys are given as a satisfactory example of such treatment.

Special precautions are taken to reduce impurities in the 50% Ni-Fe alloy, both in regard to those introduced by the raw materials and by the melting operations. Further purification is obtained by melting and casting in vacua and subsequently annealing at high temperatures in pure dry hydrogen. By these precautions, the oxygen and carbon content of the alloy is reduced below .01%. The ingots are hot rolled down to .24 inch thick, and are reduced to final size of .0012 to .002 inch thick by cold rolling without further annealing below 0.10 inch. This amounts to a 98 to 99% reduction. The sheets are slit into the desired width of tape at .014 inch.

The final tape is insulated and wound into spiral cores by conventional or standard methods. These cores are mounted in an annealing pot having provision for introducing hydrogen thereinto and the pot is inserted into a superheated furnace at temperatures between 1000° and 1150° C. The cores are held under these conditions for two hours, and thereafter cooled rapidly by withdrawing the pot from the furnace. The optimum temperature for each heat is determined magnetically by using small test samples. Fig. 12 shows hysteresis loops 54, 55 and 56 of three samples of this material heated respectively at temperatures of 975° C., 1100° C., and 1175° C., the temperature of 1100° C. providing optimum rectangular hysteresis characteristics for these samples.

When the foregoing process is departed from to the extent of cooling the cores slowly from the furnace temperature, the rectangular hysteresis characteristics are not obtained. The rapid cooling, however, introduces strains in the magnetic material and difficulty is encountered in duplicating results on two pieces of material processed under substantially identical conditions.

These difficulties are obviated according to the preferred method of the present invention by giving the 50% Ni-Fe alloy a second anneal in an atmosphere of pure hydrogen above the magnetic transformation point at approximately 500° C., holding for a period of time sufficient to bring the cores up to this temperature, say 15

minutes, and thereafter cooling slowly in a strong magnetic field of approximately 87 oersted, the field being applied in the same direction as the magnetic field in which the material is to be used. The rate of cooling should be at an optimum rate which may be determined experimentally. The rate of cooling for a particular 50% Ni-Fe alloy in the order of 18 hours from 500° C. down to 100° C. was found to be satisfactory.

For the aforementioned second anneal, the cores 28 are mounted in an annealing pot generally designated 57 and comprising an inner housing or casing 58 composed of any suitable refractory metallic material which may also serve as a magnetic shield to isolate the earth's magnetic field. Casing 58 has end openings 59 whereby the casing may be concentrically mounted with respect to the cylindrical conductor 61 which, in turn, is concentrically mounted within the cylindrical pot 62 which is formed of a suitable refractory metallic material such, for example, as Nichrome, conductor 61 being welded to the bottom of the pot as at 63.

The cores are suspended or supported in spaced relation within casing 58 by a suitable medium such, for example, as aluminum oxide 64. The rim of pot 62 is formed as a trough 65 to receive the depending rim portion 66 of cover 67 in spaced relation therewithin whereby a gas-tight seal may be formed between the cover 67 and pot 62 as by inserting a suitable refractory cement 68 within the trough 65. Hydrogen is admitted into pot 62 by way of suitable ports 69 and 70 formed therein.

An electrode 71 is secured to the bottom of pot 62 by welding as at 72, and a pair of electrodes 73 are secured to cover 67 by means of bolts 74 and locking nuts 75 therefor, a copper plate 76 being inserted between the cover and electrodes 73 to provide efficient electrical contact therebetween. The cover and plate 76 are bolted to conductor rod 61 by bolts 77, thereby to complete the electrical circuit including the electrical power source 78 which may be either A. C. or D. C. By reason of this circuit arrangement, a circular field is applied to the tape wound cores 28 when a current is caused to flow through conductor 61, the concentricity of the conductor and cores insuring the application of a circular field thereto. The electrodes and conductor 61 may be formed of copper or stainless steel depending on the temperatures and atmospheres encountered.

As an alternate method of the present invention, cores 28 may be treated to obtain similar characteristics by charging the annealing pot of Fig. 15, having the cores mounted therein, as shown, into the furnace superheated to 1000 to 1150° C. with the hydrogen admitted into the pot, holding at this temperature for two hours, followed by cooling to approximately 500° C. in the case of 50% Ni-Fe alloys, and thereafter closing switch 79 when the alloy reaches a temperature of approximately 300° F. to apply the magnetic field followed by slow cooling in the magnetic field.

A 3% Si-Fe grain-oriented steel was treated by the foregoing process of the present invention to produce the rectangular hysteresis loop 81 of Fig. 14, the material having been cooled from approximately 850° C. in a magnetic field of 1.0 oersted applied parallel to the direction of rolling, i. e., in the circular direction of the field applied by the magnetic annealing pot of Fig. 15. Hysteresis loop 82 was obtained from the same material upon slow cooling without the applied magnetic field. Characteristics similar to those of curve 81 may be obtained from silicon steels having the usual silicon content ranging from 0.5 to 5%.

The hysteresis loop 83 of Fig. 13 was obtained from very pure 5% Si-Fe steel in accordance with a prior art method wherein the material was cooled in a magnetic field of .3 oersted.

It will be understood that in general permeability can be increased substantially in the use of the foregoing methods of the present invention as indicated in Fig. 14 even though rectangular hysteresis loop characteristics may or may not be obtained. This is particularly true near high flux densities although increased permeability is also achieved at lower flux densities. For example, if material having curve 56 of Fig. 12 is magnetically annealed as set forth hereinbefore, not only will the maximum permeability be increased but also the initial permeability. This is not so in the case of the core material having curve 55 in which case the initial permeability is reduced by magnetic annealing and a rectangular loop is obtained.

In the foregoing and in the claims appended hereto, where the material is said to be cooled, in the absence of a specific terminal temperature, it is assumed that the terminal or final temperature is room temperature.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. The method of improving the magnetic characteristics of a 50% Ni-Fe alloy comprising the steps of melting the alloy, casting the molten alloy into ingot form in partial vacuum until the oxygen and carbon content thereof is less than 0.01%, annealing the ingot in pure dry hydrogen, hot rolling the ingot into a sheet having a thickness of 0.24 inch, cold rolling the sheet to a thickness of between 0.0012 and 0.002 inch to produce a crystal orientation having a direction of optimum magnetic susceptibility, slitting the cold rolled sheet into tape material, winding the tape material into a spiral core, heating the core in hydrogen to a temperature within the range of 1000° to 1150° C., maintaining the temperature constant for approximately two hours, rapidly cooling the core by removing the heat from the core and allowing the core to cool to room temperature, heating the core in a pure hydrogen atmosphere to 500° C., slowly cooling the core to 100° C. during a time interval of 18 hours, and applying a strong magnetic field of approximately 87 oersteds to the core during said slow cooling and in said direction of magnetic susceptibility.

2. A method of producing grain-oriented ferromagnetic alloys having superior magnetic and electrical characteristics comprising the steps of grain-orienting a grain-orientable alloy by a severe cold reduction providing a thickness reduction of about 99% so as to align the grains thereof in a preferred direction of magnetization, and annealing said grain-oriented alloy in a mag-

netic field applied to the alloy in said preferred direction of magnetization.

3. The method of producing grain-oriented ferro-magnetic alloys having superior magnetic characteristics comprising the steps of grain-orienting a grain-orientable alloy by a severe cold reduction providing a thickness reduction of about 99% to produce a direction of preferred alignment of the grains thereof, heating the alloy in hydrogen to a temperature above the magnetic transformation point of the alloy, maintaining the temperature constant for a predetermined time interval, rapidly cooling the alloy by removing the heat from the alloy and allowing the alloy to cool to room temperature, reheating the alloy in hydrogen to the vicinity of the magnetic transformation point, slowly cooling the alloy to room temperature during a predetermined time period, and simultaneously with the slow cooling applying a strong magnetic field to the alloy in the direction of preferred alignment of the oriented grains of the alloy.

4. The method of improving the magnetic characteristics of a 50% Ni-Fe alloy comprising the steps of grain orienting the alloy by a severe cold reduction providing a thickness reduction of about 99% so that the grains of the alloy in each of a plurality of predetermined planes thereof assume an alignment to produce a preferred direction of magnetization, heating the alloy in hydrogen to a temperature within the range of 1000° to 1150° C., maintaining the temperature constant for approximately two hours, rapidly cooling the alloy by removing the heat therefrom and allowing the alloy to cool to room temperature, heating the alloy in a pure hydrogen atmosphere to 500° C., slowly cooling the alloy to 100° C. during a time interval of 18 hours, and applying a strong magnetic field of approximately 87 oersteds to the alloy during the slow cooling and in the preferred direction of magnetization.

EDWARD A. GAUGLER.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
1,807,021	Yensen	May 26, 1931
2,002,689	Bozarth et al.	May 28, 1935
2,002,696	Kelsall	May 28, 1935
2,158,065	Cole et al.	May 16, 1939