Oct. 27, 1942. R. M. BOZORTH ET AL 2,300,336

MAGNETIC ALLOY OF IRON AND ALUMINUM

Filed Aug. 7, 1940 2 Sheets-Sheet 1

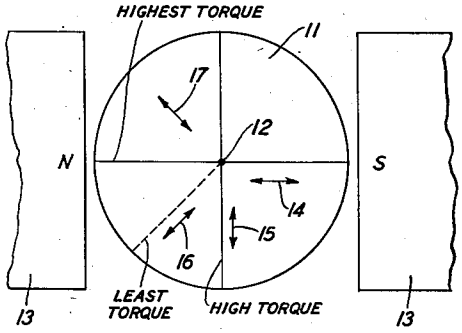


FIG. 1

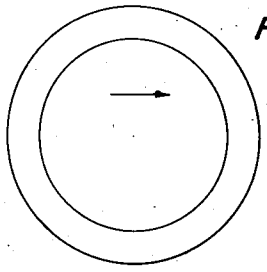


FIG. 2

FIG. 4

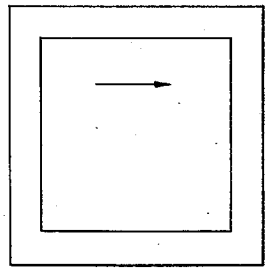


FIG. 3

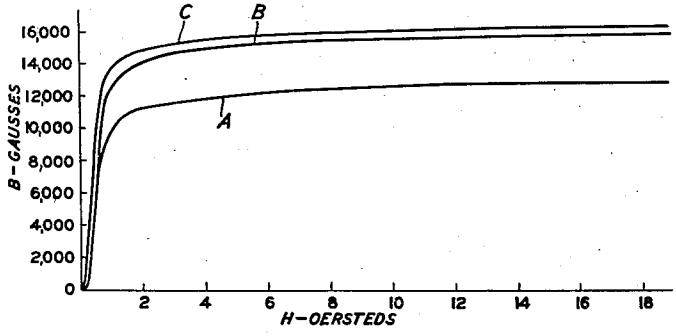


FIG. 5

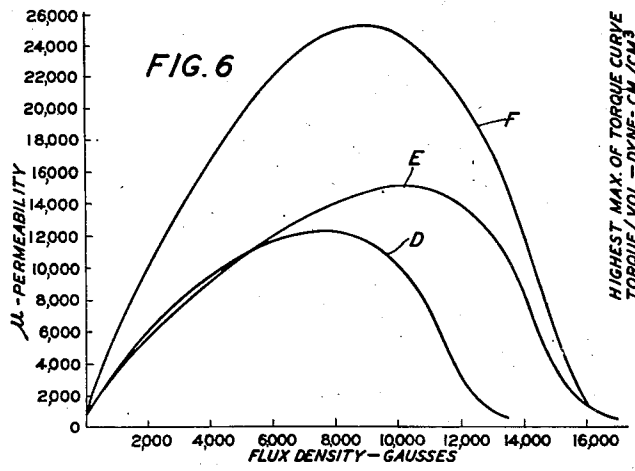
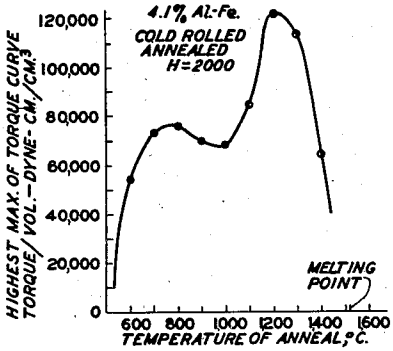


FIG. 6

FIG. 10



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MAGNETIC ALLOY OF IRON AND ALUMINUM

Filed Aug. 7, 1940 2 Sheets-Sheet 2

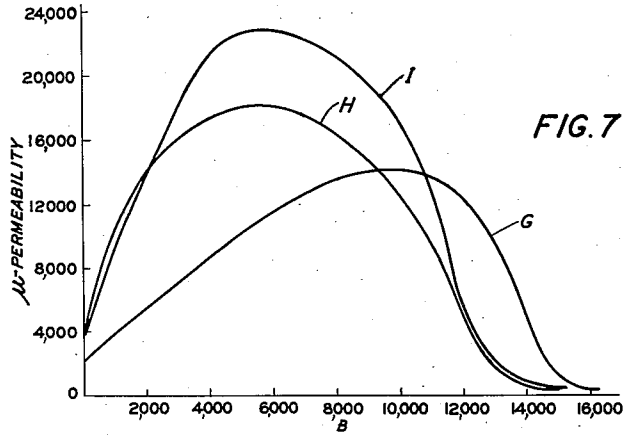

FIG. 7

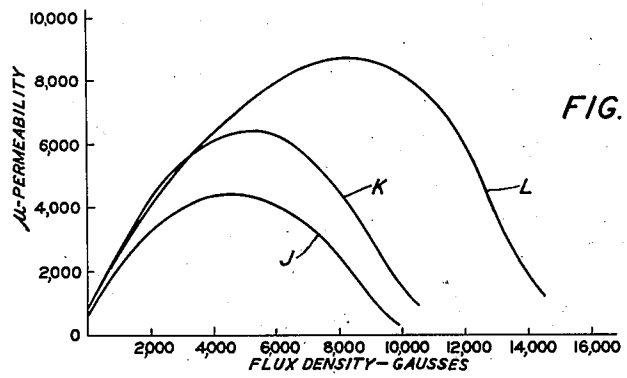

FIG. 8

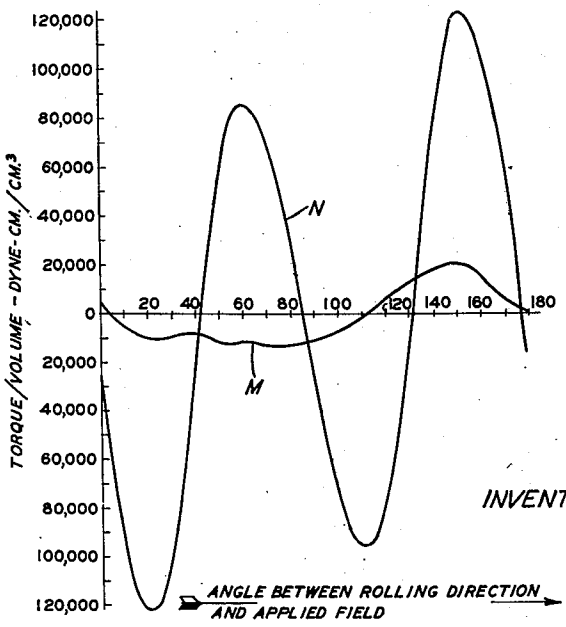

FIG. 9

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MAGNETIC ALLOY OF IRON AND ALUMINUM

Richard M. Bozorth, Short Hills, and Howell J. Williams, Chatham, N. J., assignors to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application August 7, 1940, Serial No. 351,684

2 Claims. (Cl. 148—12)

This invention or discovery relates to magnetic materials consisting of iron alloyed with around 2 to 10 per cent of aluminum and caused to have high permeability, low coercive force and low hysteresis force.

A feature of the discovery is that alloys having the composition stated may be caused to have their magnetic properties improved by cold rolling prior to their final heat treatment; a subsidiary feature is that the magnetic properties may be modified or further improved by extended heat treatment in the presence of hydrogen.

A feature of the invention consists of an iron-aluminum alloy having around 2 to 10 per cent aluminum and the balance essentially iron caused to have improved magnetic properties by cold rolling.

Another feature is the method of treatment of such iron-aluminum alloys by which they are caused to have the improved properties.

A further feature comprises iron alloyed with around 2 to 10 per cent aluminum having directional or anisotropic magnetic properties.

The discovery will be further illustrated in connection with the accompanying drawings wherein:

Figs. 1 to 4, inclusive, disclose test specimens used in measuring the magnetic properties of alloys according to the present invention and demonstrating their directional characteristics, that is:

Fig. 1 discloses a specimen in the form of a disc diagrammatically shown as being employed to measure the torque exhibited on the disc when placed in a magnetic field parallel to the plane of the disc;

Fig. 2 discloses a ring-shaped specimen cut from a rolled sheet of material;

Fig. 3 discloses a piece of test material in the form of a hollow square cut from a rolled sheet, the direction of rolling being indicated by the arrow;

Fig. 4 discloses a rolled or swaged rod with the direction of rolling or elongation being shown by the arrow;

Fig. 5 shows magnetization curves plotted on a quantitative scale;

Fig. 6 shows permeability curves of such specimens plotted on a quantitative scale;

Fig. 7 shows permeability curves plotted on a quantitative scale designed to show the effect of long heat treatment in hydrogen;

Fig. 8 shows permeability curves designed to show the improvement resulting from cold rolling of the material as compared to hot rolling; and

Fig. 9 shows curves of torque per unit of volume of material for different angular positions obtained by testing disc-shaped test specimens in a torque magnetometer in the manner diagrammatically indicated in Fig. 1.

Fig. 10 shows the torque per unit volume for one angular position of material after cold rolling and then heat treating at various temperatures.

Alloys consisting principally of iron with up to 10 per cent content of aluminum as magnetic materials are known; they are also known to be of high resistivity; the present discovery consists in the fact that such alloys may be made to have directional magnetic properties by rolling or swaging and more particularly, by cold rolling or cold swaging; also in the discovery that the magnetic properties thus produced are higher than heretofore obtained; and furthermore, in the discovery that these magnetic properties may be usefully modified and improved by further annealing the material; this may be done conveniently in hydrogen.

The upper limit of aluminum content for the purposes of this invention is set at around 10 per cent; this limit is established at around this value by the limitations of rolling technique which may vary somewhat with the skill of the operator and the percentages of small amounts of various impurities.

In Fig. 5 the magnetizing curve A is made from measurements taken upon a specimen consisting of iron with 3.5 per cent of aluminum prepared by hot rolling a sheet at 1000° C., which rolling was continued while the sheet was reduced from one inch to about 0.35 inch followed by a further reduction in the cold state from 0.35 inch down to 0.109 inch. Curve A relates to a ring-shaped specimen such as Fig. 2 taken from such a sheet and curve B represents a specimen in the form of a hollow square, such as Fig. 3, taken from the same sheet. Curve C relates to a rod 0.25 inch in diameter in the form of Fig. 4 produced by hot swaging a sample of the same material from a 1 inch diameter to 0.50 inch and then cold swaging from 0.50 inch to 0.25 inch. All these specimens were then heated at 1000° C. in hydrogen and cooled slowly.

By examination of Fig. 2 one observes that if the specimen is tested as a ring-shaped specimen, and assuming also that permeability is greater in some directions in the plane of the sheet than in other directions in the plane of the

sheet due to the effective rolling process, the effective permeability of the specimen measured in the ring will be the rough average of the permeability in all directions. However, if the effect of the rolling has been such as to cause the permeability to be increased in the direction of rolling and also increased in a direction transverse to the rolling, the measurement of the permeability of a sample such as that of Fig. 3 will give an increased permeability. Curve B of Fig. 5 relates to such a sample and a considerable increase of permeability is noted. If, however, the increase in permeability is greater in the direction of rolling than is the increase in permeability transverse to the direction of rolling, then a plot of measurements upon a specimen in the form of a rod, such as Fig. 4, would be expected to show a still higher permeability. Curve C relates to such a rod and a slightly higher permeability is indicated.

Curves D and E of Fig. 6 are curves of permeability plotted against flux density in gausses for the same ring and hollow square specimens consisting of iron containing 3.5 per cent aluminum. It is noted that the curve D for the ring specimen shows a lower permeability at the higher values of flux density than does the curve E for the specimen in the shape of a hollow square. Curve F is plotted to show the permeability with variations in flux density of a rod of a diameter 0.25 inch hot swaged down from 1 inch to 0.50 inch and then swaged from 0.50 inch to 0.25 inch while cold and thereafter pot annealed for one hour at 1050° C. in hydrogen. Not all such specimens have shown a maximum permeability rising to the high value indicated; this curve is for one of the best specimens. Some have been lower and in another instance the maximum permeability was 18,800 which is about the average of maximum permeability expected.

The hysteresis loss of the specimen containing 3.5 per cent aluminum and pot annealed at 1050° C. for one hour and measured in the direction of rolling has been found to be 800 ergs per cubic centimeter per cycle at a maximum induction of 10,000 gauss. (W_h=800 ergs/cc./cycle at B= 10,000 gauss.) The hysteresis loss of another specimen containing 4 per cent aluminum and heat treated for 17 hours in hydrogen at 1330° C. was found to be 330 ergs/cm./cycle at B_m= 10,000.

The curves of Fig. 7 are curves of permeability plotted against flux density of a hollow square sample of material, such as is shown in Fig. 3. All the curves relate to the same material. Curve G was plotted from measurements taken after cold rolling the material and heating it in hydrogen for one hour at 1000° C. The coercive force of the material at this stage was 0.52. Curve H was plotted from measurements taken upon the same specimen after it had been given an additional heat treatment in hydrogen at 1330° C. for seventeen hours. The coercive force of the material at this time was 0.11. Curve I was plotted from measurements taken from the same material after it had been given an additional heating at 1450° C., for twenty hours in hydrogen. The coercive force at this stage was 0.08.

It is noted, according to curves G, H and I, that heat treatment in hydrogen at a high temperature for a long time increases the maximum permeability but lowers the permeability at high flux densities. From this it is concluded that the special orientation or orientations of the crystals of the material which cause the high permeability at high flux densities is wholly or considerably modified by heating above 1300° C., in hydrogen for many hours.

Fig. 8 shows curves relating to a composition containing iron with 4 per cent aluminum; in each case a specimen, as the last step of its preparation, was heat treated for five hours at 880° C., in hydrogen and thereafter slowly cooled. In the case of curve J the material was hot rolled at 900° C., during which time it was reduced in thickness from 0.13 inch to 0.013 inch. In the case of curve K the material was hot rolled at 450° C., while reduced in thickness from 0.13 inch to 0.011 inch. In the case of curve L the material was cold rolled during reduction in thickness from 0.13 inch to 0.013 inch. The considerable improvement resulting from cold rolling is clearly indicated. The samples were in the form of a hollow square.

Refer now to Fig. 1. Let numeral 11 represent a disc cut from a sheet of rolled material. An axis of suspension 12 is indicated for the free suspension of the disc and magnetic poles 13 of equal strength but opposite polarity are presented to the edges of the disc on opposite sides of its center. If the material has a high permeability in the direction 14, and a high but possibly somewhat different permeability in the direction 15 and a lower permeability in the directions 16 and 17, and if one should measure the torque while he held the specimen in position to be measured, we should expect that the torque would be zero for the position indicated and would have two maximums in a positive direction and two minimums (maximums in a negative direction) for 180 degrees of revolution. Such is found to be the case with a material consisting of iron with 4 per cent aluminum which has been hot rolled at 1000° C., down to 0.109 inch in thickness and thereafter cold rolled down to 0.028 inch in thickness; and thereafter heated in hydrogen for one hour at 1200° C. Curve N of Fig. 9 is plotted from data relating to such torque measurements. For comparison purposes curve M is plotted from a material otherwise the same except that the last stage of reduction in thickness was by hot rolling at 900° C. Curve N proves that the material has directional magnetic properties and that these reach a maximum in two directions approximately at right angles to each other.

Torque curves similar to N are found to have different amplitudes depending on the temperature at which the material is heated after the final reduction by cold rolling. Curve O of Fig. 10 is a graph of the highest points in the torque curve for annealing temperatures ranging from 600° C., to 1400° C. This curve indicates that substantial directional properties are obtained by heating in this range of temperatures.

The exact limitation of temperature considered as the line of demarkation between cold rolling and hot rolling is a matter of opinion. It may be roughly considered as around 400° C., to 500° C., below which point the improved results begin to be distinctly manifested.

Heat treating or annealing in hydrogen is not essential; pot annealing in a closed sealed pot which limits access of air has been found to be quite satisfactory.

A long felt need has existed for a magnetic material for relays which gives the tractive force of iron and the speed of response of high permeability alloys of 45 per cent nickel and the

balance iron. Alloys composed and treated according to the present invention and used with the field in their direction of maximum permeability have been found to achieve this long desired combination of high tractive force and high speed of response.

"Cold rolling" is a specific term intended to have a broad significance of forcibly elongating or changing the form chiefly along one axis by application of mechanical force.

What is claimed is:

1. Method of improving the magnetic properties at high flux densities and in one general direction of alloy containing 2 to 10 per cent aluminum, balance essentially iron, which comprises rolling the alloy down to a lesser fraction of its thickness or cross-section with the direction of rolling being in the direction in which a magnetic field is to traverse the material in use and thereafter treating it at a temperature above 600° C., for a considerable time.

2. A magnetic alloy consisting essentially of iron with 2 to 10 per cent aluminum caused to have anisotropic grain structure and high anisotropic permeability along one coordinate axis of the material at high flux densities by forcible elongation while cold followed by heating to a temperature at or above 600° C. and below 1425° C.

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