July 30, 1940. W. CRAFTS 2,209,685

SILICON ELECTRICAL STEEL SHEET

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FIG. 1

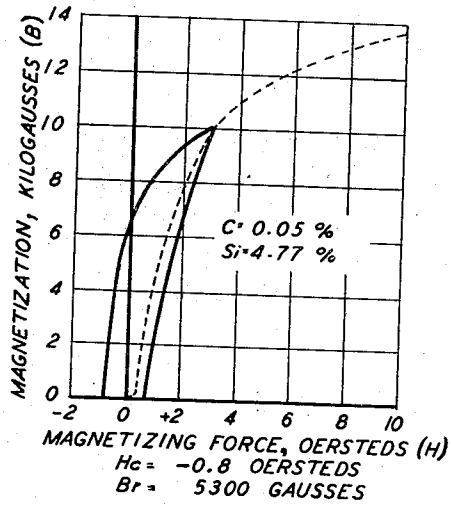


FIG. 2

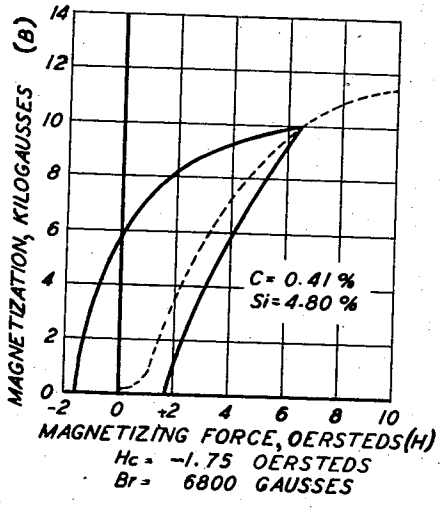
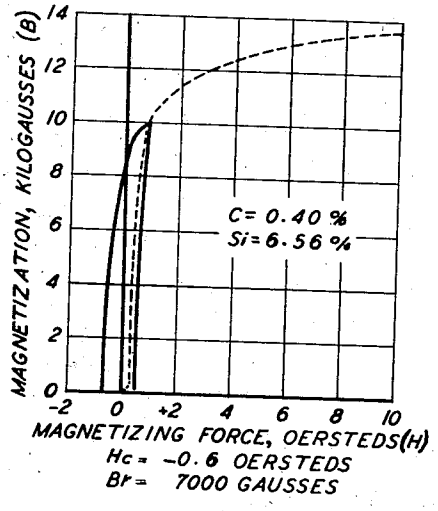


FIG. 3



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FIG. 4

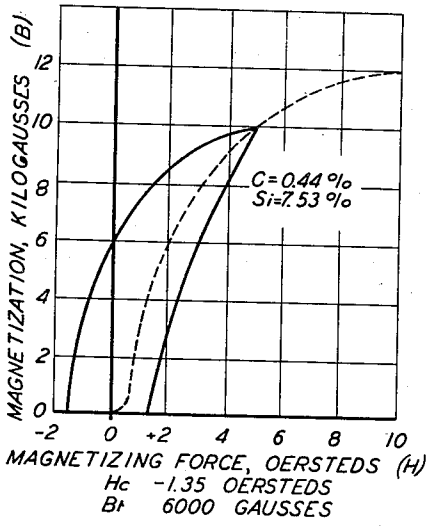


FIG. 6

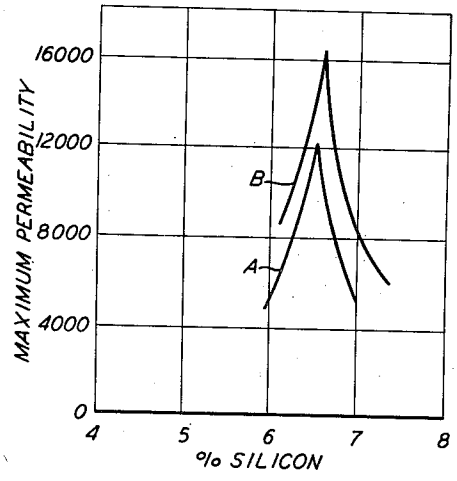


FIG. 5

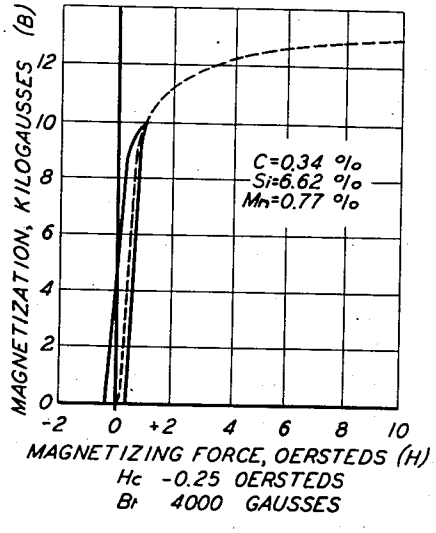
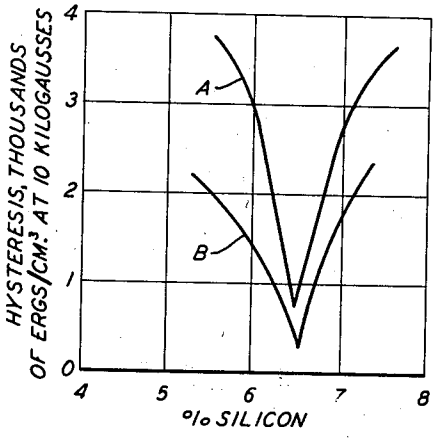


FIG. 7



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SILICON ELECTRICAL STEEL SHEET

Walter Crafts, Niagara Falls, N. Y., assignor to Electro Metallurgical Company, a corporation of West Virginia

Application July 25, 1938, Serial No. 221,171

9 Claims. (Cl. 148—12)

The present invention relates to iron alloys for use as magnetizable parts of electrical machinery, for example: laminated cores for transformers, motors, and dynamos. Iron alloys for this use are frequently called "electrical steels", and for the sake of brevity they will be so designated herein.

The suitability of an electrical steel for a given purpose depends primarily on its magnetic and electrical properties, its physical properties, and its cost in the fully fabricated condition. These factors depend upon the composition, heat treatment and mechanical treatment of the steel in question, and are usually interrelated to a considerable extent. In general, it is desired to secure a material having, under the conditions of use, the highest possible permeability and lowest possible watt loss characteristics consistent with satisfactory fabricating properties, adequate mechanical strength, and appropriate cost in the fabricated form.

The main bulk of electrical steel produced at the present time consists of plain carbon steel and the so-called low, medium, and high silicon steels. Although the magnetic properties of these steels steadily improve as the silicon content is increased, the steels become increasingly brittle and large grained, thereby becoming more difficult to roll and to shear with a smooth edge free from cracks extending into the sheet. The practical upper limit of silicon content has been about 5.5%. With such material it has been of utmost importance to keep the percentages of impurities, especially carbon, extremely small: at low total carbon contents an increase in the carbon content amounting to only a few thousandths of one per cent. appreciably increases hysteresis loss and decreases the maximum permeability of the alloy.

Objects of this invention are to provide electrical steel sheet having a percentage of silicon substantially higher than 5.5%, rolled and sheared with a smooth edge substantially free from cracks extending into the body of the steel; to provide a high silicon electrical steel having a higher maximum permeability, smaller coercive force, lower hysteresis, lower eddy current loss, and lower total watt loss, than the 4.5% to 5.5% silicon steel heretofore used for similar purposes; to provide a high silicon electrical steel having better magnetic properties than other silicon electrical steels containing substantially more, or substantially less, silicon than the steel of the invention; to provide a high silicon electrical steel containing considerably higher percentages of carbon than have been used commercially in the 4.5% to 5.5% silicon electrical steel heretofore used; and to provide means for broadening the range of silicon content that produces optimum magnetic properties in electrical sheet.

There is an optimum silicon content for high silicon electrical steel. This optimum is above 5.5% silicon and at the optimum silicon content the magnetic and electrical properties of the material are better than those of materials, otherwise similar, containing either substantially more or substantially less silicon than the optimum.

The invention is based in part on my discovery that the ductility, grain size, and general mechanical and shearing properties of the steel containing the optimum silicon content may be improved by the addition of substantial amounts of carbon and the use of suitable heat treatment, to such an extent that the steel so treated is, in respect of its mechanical and magnetic properties, at least as suitable for commercial use as the low carbon 4.5% to 5.5% silicon electrical steel sheet heretofore used. Further, I have found that if a proper heat treatment is used, the carbon added to improve the mechanical properties of the steel in question does not destroy the superior magnetic properties of the steel. I have also found that the addition of moderate amounts of certain elements, notably manganese and aluminum, broadens the range of silicon percentages which yield the optimum magnetic properties and improves the ductility of the steel.

The invention is embodied in punched or otherwise sheared electrical steel sheet comprising as essential constituents, aside from the iron, 5.5% to 7% silicon and 0.2% to 0.9% carbon, and in suitable processes for its production and heat treatment. The preferred range of silicon is between 6% and 7%, and the carbon content is preferably below 0.5%. Optional constituents which favorably modify the mechanical or magnetic characteristics, or both, of the steel are the austenite-forming metals of the group manganese, nickel, copper, cobalt, and silver in amounts between 0.3% and 2% each, although the preferred range of silver is 0.05% to 0.15%; the deoxidizing elements of the group aluminum, calcium, zirconium, beryllium, and boron, in amounts not exceeding about 1% each; the carbide forming elements of the group chromium, molybdenum, tungsten, titanium, columbium, and

tantalum in small amounts not exceeding a total of about 0.25%, although chromium may be as high as 1%; and small amounts of one or more elements of the group arsenic, phosphorus, tin, and antimony. The preferred compositions fall within the limits specified in Table A.

Table A

	Per cent.
Silicon	6.3 to 6.7
Carbon	0.3 to 0.4
Manganese	0.6 to 0.9
Copper	0 to 0.75
Aluminum	0 to 1.5
Iron	The remainder

By the use of suitable heat treatment, as described more fully hereinafter, the steel of the invention may be forged and rolled to the 29 gage (0.014 inch thickness) sheet ordinarily used for electrical apparatus, and even to thinner sheet if desired; this sheet may be cold punched or otherwise sheared readily with a good edge; and the resulting electrical sheet may be given excellent magnetic properties.

The improvement in magnetic and other electrical characteristics provided by the invention is indicated by the data appearing in Table B. These data show the relative improvement rather than the best properties attainable under commercial conditions.

Table B

No.	Composition (remainder Fe)			D. C. measurements			Losses at 60 cycles	
	Percent C	Percent Mn	Percent Si	Hysteresis	Maximum permeability	Resistance*	Hysteresis, watts/lb.	Eddy current, watts/lb.
1	0.03	0.07	4.54	2,269	4,600	54.7	0.449	0.216
2	0.03	Low	6.39	1,298	12,400	70.8		
3	0.03	Low	6.61	1,554	9,500	74.0		
4	0.06	Low	7.45	2,268	5,100	77.3		
5	0.41	Low	4.80	5,715	2,300	49.3		
6	0.36	0.12	6.37	1,044	15,600	72.7	0.397	0.108
7	0.42	Low	6.66	1,988	6,550	75.2		
8	0.44	Low	7.53	3,568	2,950	80.8		
9	0.27	0.75	6.25	1,222	11,000	74.5		
10	0.35	0.76	6.42	1,071	13,800	75.0	0.369	0.126
11	0.34	0.77	6.62	994	16,000	76.1	0.347	0.103
12	0.42	0.79	6.74	1,502	10,200	77.5		

*Microhms per cubic centimeter.

All samples, except No. 5, on which direct current measurements were made, were annealed at 900° C. in hydrogen for 6 hours and cooled in the furnace; sample 5 was annealed at 820° C. in hydrogen for 6 hours and furnace cooled. The samples on which alternating current measurements were made, except for sample No. 1, were annealed at 1050° C. in hydrogen for 6 hours, slowly cooled to 900° C. and there held for 6 hours, slowly cooled to 875° C. and there held for 6 hours, and furnace cooled; sample No. 1 was annealed at 900° C. in hydrogen for 10 hours and furnace cooled.

The data appearing under the headings "Hysteresis" and "Maximum permeability," in Table B, were obtained by the use of a Fahy Simplex permeameter and magnetic test specimens with the dimensions 0.5 inch by 0.5 inch by 10 inches. The accuracy of the permeameter and of the test procedure was insured by checking several of the experimental results with comparison tests made by the U. S. Bureau of Standards. The values of hysteresis represent the areas of hysteresis loops at a maximum induction of 10 kilogausses, and are expressed in ergs per cubic centimeter at 10 kilogausses.

The data under the general heading "Direct current measurements" indicate, first, that the magnetic properties of low carbon silicon steels reach an optimum in the neighborhood of 6.5% silicon. Second, raising the carbon to 0.35% or 0.45% does not greatly change the optimum silicon percentage, does deleteriously affect the magnetic properties of steels having substantially less or more silicon than the optimum, but does not deleteriously affect, and may even improve, the magnetic properties of steel containing about 6.5% silicon. Third, the addition of manganese, 0.75% to 0.8% for instance, broadens the range of silicon percentages within which substantially optimum magnetic properties can be attained in the high carbon steels.

In the same Table B, the data under the heading "Losses at 60 cycles" were obtained by standard core loss tests, using alternating current and standard Epstein strip samples (0.014 inch thick) prepared as specified by the American Society for Testing Materials. The hysteresis and eddy current losses were separated by the well-known two-frequency method, using 60 cycle and 30 cycle currents, respectively. These data indicate that the total core losses at 60 cycles and 10 kiloguasses are about 25% lower in the high carbon 6.4% silicon material than in the low carbon 4.5% silicon steel.

The relatively low eddy current losses characteristic of the high-carbon, high silicon steel are probably the result of the high specific resistance of the material.

The physical characteristics of the steel of the invention are indicated by the data in Table C. These data were obtained by hot rolling silicon steel to sheet 0.014 inch thick, heat treating the sheet to toughen it, cold shearing the sheet into samples one-half inch by two inches, bending the samples, transverse to their longer axes, about a three-sixteenths inch diameter round pin with a bending radius of three-fourths of an inch, until incipient cracking began at the bends, and measuring the angle of bend required to start a crack and the angle of permanent set. Although this method of test would be expected to give, at best, only a rough approximation of relative ductilities, I have found from actual shearing tests that the relative ductilities in Table C are in the same order as the relative suitability of the steels for shearing.

Table C

Composition (remainder iron)			Steel as-rolled		Steel annealed*	
Percent C	Percent Mn	Percent Si	Permanent set, degrees	Total bend, degrees	Permanent set, degrees	Total bend, degrees
0.05	Low	4.77	180	180	46	80
0.03	Low	5.53	20	54	10	35
0.03	Low	6.37	0	19	0	17
0.06	Low	7.45	0	5	0	12
0.41	Low	4.80	123	176	180	180
0.38	Low	5.82	53	87	162	180
0.42	Low	6.66	2	28	7	34
0.44	Low	7.53	0	12	0	15
0.27	0.75	6.25	14	35	75	104
0.35	0.75	6.40	28	51	110	133
0.44	0.78	6.23	36	61	50	87

*As described herein below.

As indicated by the data in this Table C, the ductility and toughness of low carbon steel decrease rapidly as the silicon is raised above 5%, and become negligible above 6% silicon. Annealing these low carbon steels serves only to decrease the ductility still further, because of the coarsening of the grain size brought about by such heat treatment. The addition of carbon not only raises the ductility and toughness of the steel in the as-rolled state, but also makes the steel amenable to a toughening anneal. In the absence of manganese, the addition of about 0.35% carbon and the use of a toughening anneal renders a 6.5% silicon steel about as tough and ductile as a low carbon 5.5% silicon steel. The further addition of about 0.75% manganese raises still further the ductility and toughness of the high silicon steel.

A clearer understanding of the improvements in the magnetic properties of silicon steels brought about by the present invention may be attained by referring to the accompanying drawings, in which

Figures 1 to 5, inclusive, are the normal magnetization curves (dotted lines), and the normal hysteresis half-loops (solid lines) plotted at a maximum magnetization of ten kilogausses, of five silicon electrical steels;

Figure 6 is a graph indicating the effect of various silicon contents, and of manganese, upon the maximum permeability of medium carbon steel; and

Figure 7 is a graph indicating the effect of various silicon contents, and of manganese, upon the normal hysteresis of medium carbon steel at ten thousand gausses. All of the figures, 1 through 7, are based on experimental data obtained through the use of a Fahy simplex permeameter. In Figures 1 through 5, the magnetizing force is expressed in "Oersteds."

Referring specifically to Figures 1, 2, and 3, it will be observed that the low carbon 4.5% silicon steel of Figure 1 has a high permeability at magnetizations up to about 10 kilogausses, a low residual magnetization (Br), a small coercive force (Hc), and low hysteresis. Increasing the carbon, as in Figure 2, produces relatively a very great decrease in permeability and increases in residual magnetization, coercive force, and hysteresis. When, however, both the carbon and the silicon are increased, and a suitable heat treatment is employed, magnetic properties similar to those indicated in Figure 3 are obtained.

If the silicon content is too great, even the high carbon material has relatively poor magnetic properties, as shown in Figure 4.

The addition of manganese to a steel containing suitable percentages of silicon and carbon has a favorable effect upon the magnetic properties. This effect is illustrated in Figure 5.

Referring specifically to Figures 6 and 7, the curves labelled A represent the behavior of high carbon (0.4% C.) silicon steels containing little or no manganese, and the curves labelled B represent the characteristics of high carbon (0.4% C.) silicon steels containing about 0.75% manganese. It will be observed that the highest maximum permeability is obtained at substantially the same silicon percentage as the lowest hysteresis. It will further be observed that the general effects of manganese on the magnetic properties are to broaden the range of optimum silicon percentages, especially at the lower silicon percentages, and to improve the magnetic properties attainable at the optimum silicon percentages. That is, in the B curves, the hysteresis and permeability do not change as rapidly with changes in silicon content on each side of the maximum, as they do in the A curves. Manganese also seems to shift the optimum silicon percentage (the cusps of the curves) to a slightly higher percentage.

In considering cusp type curves such as those of Figures 6 and 7, it should not be forgotten that, in actual practice, it is not possible to attain the properties indicated by the extreme tip of the cusp, primarily because of miscosegregation in the steel; but such ideal properties can be approached fairly closely, as indicated by a comparison of Table B with Figures 6 and 7.

The effects of nickel, silver, cobalt, and copper additions to the high carbon high silicon steel are to increase the toughness and the electrical resistivity of the steel. The carbide-forming elements, such as chromium, titanium, molybdenum, tungsten, vanadium, columbium, and tantalum, have little effect on the range of optimum silicon percentages, but have a beneficial effect on the toughness of the steel.

Deoxidizing elements, such as calcium, aluminum, zirconium, beryllium, and boron, tend to improve the hot working characteristics and uniformity of the steel of the invention, although in percentages above 1% or 2% they reduce somewhat the ductility and saturation induction. These elements broaden somewhat the range of optimum silicon percentages and shift the range slightly in the direction of lower silicon: Aluminum is particularly effective in this respect, and if 4% aluminum is added, the hysteresis value does not rise prohibitively with silicon as low as about 4.5%.

The high carbon, high silicon steel of the invention may be forged and rolled without difficulty at about 1150° C. to 900° C., and the finishing temperature of thin sheet may be somewhat below 500° C. There is some advantage to be gained by finishing the rolling operation, even in thin sheet, at about 700° C. or somewhat higher. It is also advisable to avoid excessive decarburization caused by unduly prolonged holding in the air at high temperatures.

After rolling into sheet, the steel may be annealed and then toughened for shearing by rapidly cooling it to room temperature from an elevated temperature. For the annealing treatment, satisfactory results have been attained by holding the sheet at temperatures between 650° C. and 1050° C. for a time ranging from 48 hours at the lower temperatures to about one minute at the higher temperatures. and the best results

can be obtained by holding the sheet at 700° C. to 900° C. for one-half hour to twenty hours. The toughening treatment may be effected by simple cooling in air from the annealing treatment or by reheating for a short time, say 5 to 15 minutes, and then air cooling. A more rapid quench than air cooling may be employed if desired. The toughening treatment produces a fine grained structure.

Shearing and punching may be done while the sheet is cold or heated to a temperature not over several hundred degrees centigrade. After shearing, it is advisable to subject the sheet to another heat treatment to develop the optimum magnetic properties. This latter heat treatment consists in heating the steel at a temperature within or above the critical range (about 1000° C. to 1200° C.) and then cooling it to a temperature (700° C. to 900° C.) below the critical range. The cooling rate should be sufficiently slow to insure that substantially all of the carbon exists as discrete particles so distributed as to have no seriously deleterious effect on the magnetic properties of the sheet. A typical procedure is to heat the steel at 1050° C. for six hours, cool it slowly to 900° C., and furnace cool it to a black heat, whereupon substantially all of the carbon will be found to be in the form of graphite particles. It is preferred that this heat treatment, and also the previously described toughening anneal, be effected in an inert or reducing atmosphere, such as hydrogen or a hydrogen-nitrogen mixture.

This application is in part a continuation of my application Serial No. 94,727, filed August 7, 1936.

I claim:

1. Punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet, suitable for use as magnetic core material in alternating current electrical devices, and having substantially the composition: 6% to 7% silicon, 0.2% to 0.9% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper, cobalt, and silver, and the remainder iron; practically all of the carbon being in the form of discrete particles so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

2. Punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet, suitable for use as magnetic core material in alternating current electrical devices, and having substantially the composition: 6% to 7% silicon, 0.2% to 0.5% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper, cobalt and silver, and the remainder iron; practically all of the carbon being in the form of discrete particles so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

3. Punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet, suitable for use as magnetic core material in alternating current electrical devices, and having substantially the composition: 6.3% to 6.7% silicon, 0.3% to 0.4% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper, cobalt, and silver, and the remainder iron; practically all of the carbon being in the form of discrete particles of graphite so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

4. Punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet, suitable for use as magnetic core material in alternating current electrical devices, and having substantially the composition: 5.5% to 7% silicon, 0.2% to 0.9% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper, cobalt, and silver, and the remainder iron; which sheet has been toughened by being heated at a temperature between 650° C. and 1050° C. rapidly cooled to produce a fine-grained structure; then punched or otherwise sheared; and thereafter heat treated, to improve its magnetic properties, by cooling it from a temperature between 1000° C. and 1200° C. at a rate sufficiently slow to insure that substantially all of the carbon is in the form of discrete particles so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

5. Punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet, suitable for use as magnetic core material in alternating current electrical devices, and having substantially the composition: 6% to 7% silicon, 0.2% to 0.5% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper, cobalt, and silver, and the remainder iron; which sheet has been toughened by being heated at a temperature between 650° C. and 1050° C. and rapidly cooled to produce a fine-grained structure; then punched or otherwise sheared; and thereafter heat treated to improve its magnetic properties, by cooling it from a temperature between 1000° C. and 1200° C. at a rate sufficiently slow to insure that substantially all of the carbon is in the form of discrete particles so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

6. Punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet, suitable for use as magnetic core material in alternating current electrical devices, and having substantially the composition: 6.3% to 6.7% silicon, 0.3% to 0.4% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper, cobalt, and silver, and the remainder iron; which sheet has been toughened by being heated at a temperature between 700° C. and 900° C. and rapidly cooled to produce a fine-grained structure; then punched or otherwise sheared; and thereafter heat treated, to improve its magnetic properties, by cooling it from a temperature between 1000° C. and 1200° C. at a rate sufficiently slow to insure that substantially all of the carbon is in the form of discrete particles of graphite so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

7. Method of producing a punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet and suitable for use as magnetic core material in alternating current electrical devices, which method comprises hot rolling to sheet form a steel containing 5.5% to 7% silicon, 0.2% to 0.9% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper,

cobalt and silver, remainder substantially all iron; imparting good shearing properties to such rolled sheet by heating it at a temperature between 650° C. and 1050° C. and rapidly cooling it to produce a fine-grained structure; then punching or otherwise shearing the toughened sheet; reheating the sheared sheet to a temperature between 1000° C. and 1200° C., and cooling it at a rate sufficiently slow to insure that substantially all of the carbon is in the form of discrete particles so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

8. Method of producing a punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet and suitable for use as magnetic core material in alternating current electrical devices, which method comprises hot rolling to sheet form a steel containing 6% to 7% silicon, 0.2% to 0.5% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper, cobalt, and silver, remainder substantially all iron; imparting good shearing properties to such rolled sheet by heating it at a temperature between 700° C. and 900° C. and rapidly cooling it to produce a fine-grained structure; then punching or otherwise shearing the toughened sheet; reheating the sheared sheet to a temperature between 1000° C. and 1200° C., and cooling it at a rate sufficiently slow to insure that substantially all of the carbon is in the form of discrete particles so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

9. Method of producing a punched or otherwise sheared electrical steel sheet having smooth edges substantially free from cracks extending into the body of the sheet and suitable for use as magnetic core material in alternating current electrical devices, which method comprises hot rolling to sheet form a steel containing 6.3% to 6.7% silicon, 0.3% to 0.4% carbon, 0.3% to 2% of at least one austenite-forming material of the group consisting of manganese, nickel, copper, cobalt, and silver, remainder substantially all iron; imparting good shearing properties to such rolled sheet by heating it at a temperature between 700° C. and 900° C. and rapidly cooling it to produce a fine-grained structure; then punching or otherwise shearing the toughened sheet; reheating the sheared sheet to a temperature between 1000° C. and 1200° C., and cooling it at a rate sufficiently slow to insure that substantially all of the carbon is in the form of discrete particles of graphite so distributed as not to have any seriously detrimental effect on the magnetic properties of the sheet.

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