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Fiedler

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[54] METHOD OF PRODUCING SILICON-IRON SHEET MATERIAL WITH BORON ADDITION AND PRODUCT

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Related U.S. Application Data

[60] Continuation-in-part of Ser. No. 429,791, Jan. 2, 1974, abandoned, which is a continuation-in-part of Ser. No. 320,669, Jan. 2, 1973, abandoned.

[52] **U.S. Cl.** .... **148/111;** 75/123 B; 75/123 L; 148/31.55; 148/112

[51] **Int. Cl.** **H01f 1/04**

[58] **Field of Search** .... 148/111, 110, 112, 31.55; 75/123 B, 123 L

[56] **References Cited**

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[57] **ABSTRACT**

High-permeability silicon-iron sheet is produced by providing a melt containing about 10 parts per million boron, 45 parts per million nitrogen and about 0.030 per cent of manganese and sulfur, hot rolling from about 2250°F, and finishing with a final cold reduction of 80 per cent.

13 Claims, No Drawings

METHOD OF PRODUCING SILICON-IRON SHEET MATERIAL WITH BORON ADDITION AND PRODUCT

This is a continuation-in-part of my copending patent application Ser. No. 429,791, now abandoned, filed Jan. 2, 1974, which is a continuation-in-part of my patent application Ser. No. 320,669, filed Jan. 2, 1973 (now abandoned), both assigned to the assignee hereof.

The present invention relates generally to the art of making polycrystalline, magnetically soft, rolled silicon-iron products, and is more particularly concerned with a novel method of producing high-permeability, singly oriented silicon-iron sheet including as essential features the use of boron in small but critical amount, nitrogen in the metal in critical ratio to the boron, the presence of manganese and sulfur in a ratio less than 2.1, a cold rolling schedule including an intermediate annealing step and a final heavy cold rolling reduction. This invention additionally concerns a new hot-rolled silicon-iron band product.

CROSS REFERENCES

This invention is related to the invention disclosed and claimed in patent application Ser. No. 431,128, now abandoned, filed Jan. 7, 1974 as a continuation-in-part of patent application Ser. No. 326,852 (now abandoned), filed Jan. 27, 1973, entitled "Method of Producing Oriented Silicon-Iron Sheet Material With Boron Addition" in the name of Herbert E. Grenoble and assigned to the assignee hereof, which pertain to the concept of using small but critical amounts of boron to enable the production of singly-oriented silicon-iron sheet.

The invention disclosed and claimed herein also relates to that disclosed and claimed in patent application Ser. No. 429,800, now abandoned, filed Jan. 2, 1974, as a continuation-in-part of patent application Ser. No. 320,668 (now abandoned), filed Jan. 2, 1973, entitled "Method of Producing Oriented Silicon-Iron Sheet Material With Boron Addition" in my name and assigned to the assignee hereof, which pertain to the novel concept of cold rolling hot-rolled silicon-iron sheet directly to final thickness without an intermediate heat treatment through the use of small but critical amounts of boron and by maintaining the ratio of manganese to sulfur in the metal at less than 1.5.

BACKGROUND OF THE INVENTION

The sheet materials to which the invention is directed are usually referred to in the art as "electrical" silicon steels or, more properly, silicon-irons and are ordinarily composed principally of iron alloyed with about 2.2 to 4.5 per cent silicon and relatively minor amounts of various impurities and very small amounts of carbon. These products are of the "cube-on-edge" type, more than about 70 percent of their crystal structure being oriented in the (110)[001] texture, as described in Miller Indices terms.

Such grain-oriented silicon-iron sheet products are currently made commercially by the sequence of hot rolling, heat treating, cold rolling, heat treating, again cold rolling and then final heat treating to decarburize, desulfurize and recrystallize. Ingots are conventionally hot-worked into a strip or sheet-like configuration less than 0.150 inch in thickness, referred to as "hot rolled band." The hot rolled band is then cold rolled with appropriate intermediate annealing treatment to the finished sheet or strip thickness usually involving at least a 50 per cent reduction in thickness, and given a final or texture-producing annealing treatment.

From time to time, there have been reports in the literature of methods by which unusually high permeability silicon-iron sheet materials can be consistently produced through departures from conventional practice in respect to melt chemistry, rolling schedules and heat-treating conditions. To the best of my knowledge, however, none of these methods has proven to be entirely satisfactory. In some cases the cost is too high, while in others residues of processing additives defy removal efforts and penalize product magnetic properties.

SUMMARY OF THE INVENTION

I have discovered that unusually high permeability silicon-iron sheet material can be consistently produced by a novel process, the economics of which compare favorably with those of present commercial operations. Thus, I have found that these results can be obtained by making new departures from the present general practice which do not require modification of conventional silicon-iron mill production or processing equipment and do not significantly increase either labor or material costs.

In the practice of this invention, a silicon-iron melt containing at least 0.01 per cent manganese and being otherwise of ordinary chemistry can be used, a small but critical amount of boron being added to establish a nitrogen to boron ratio in the metal in the range of one to fifteen parts of nitrogen per part of boron and the ratio of manganese to sulfur being adjusted to less than 2.1. Further, I have found that finished products of substantially improved magnetic properties can be obtained by cold rolling to an intermediate thickness and then heat treating the cold-worked sheet, and thereafter subjecting the silicon-iron sheet to a final heavy cold reduction.

I contemplate in addition the use of selenium in place of part of or all the sulfur required in accordance with this invention. As in the case of sulfur, the selenium requirement of this new process can be met in various ways, my preference being to add the requisite amount to the ladle in elemental form or as ferroselenium.

DETAILED DESCRIPTION OF THE INVENTION

Generally described, my present invention comprises the steps of providing a silicon-iron melt containing 2.2 to 4.5 per cent silicon, manganese and sulfur in amounts in a ratio of manganese to sulfur of less than 2.1, between about three and 35 parts per million boron and between 30 and 60 parts per million nitrogen in the ratio to boron of 1 to 15 parts per part of boron, casting the melt to form an ingot, hot rolling the ingot, then cold rolling the resulting hot-rolled band to intermediate thickness, heat treating the cold-worked sheet, and then subjecting the silicon-iron sheet to a final heavy cold reduction. Thereafter, the cold-rolled sheet is subjected to a final heat treatment to decarburize it and to develop cube-on-edge secondary recrystallization texture in it.

Preferably, the boron content of the metal at the outset of the final heat treatment is from 5 to 25 parts per million, such amount of boron in suitable form being added at the melt stage. It is contemplated, however, that the boron will be in amount from about three to about 35 parts per million as I have found that addition of less than three ppm of boron to silicon-iron melts is not sufficient to consistently produce the new results of this invention, and amounts of boron greater than 35 ppm require the presence of nitrogen in amounts in excess of those normally obtained in conventional melting practice.

The boron content of the metal at the melt stage can differ significantly from that at the hot-rolled band stage, particularly when the melt addition of the boron source is made early or when the ingot is soaked at unusually high temperature or for a prolonged period of time. Boron loss, however, has been found to be negligible when the boron source is added to the ladle and hot rolling is begun as the ingot reaches hot rolling temperature as subsequently described. Thus, it is possible in carrying out this invention process to produce a hot-rolled band and a cold-rolled sheet of final gauge thickness which have apparently the same bulk contents of boron, nitrogen, manganese and sulfur as the melt in the ladle from which they were derived. By the same token, it is possible to produce such band and sheet materials of substantially different chemistry. The important consideration, however, is the composition of the band or sheet, particularly in terms of the foregoing four elements and their critical ratios during the cold rolling and intermediate and final annealing stages of this process.

It will be understood from the foregoing that this invention has both article and method aspects, the new product being a hot-rolled band containing 2.2 to 4.5 per cent silicon, manganese and sulfur in the ratio of manganese to sulfur less than 2.1, between about 3 and 35 parts per million boron, and between 30 and 60 parts per million nitrogen in the ratio to boron of 1 to 15 parts per part of boron.

The boron content of ordinary silicon-iron is negligible, proving on "wet" analysis to be less than one part per million. Accordingly, for practical purposes in this specification and the appended claims, the terms "boron content" and "boron addition" in their various forms have the same essential meaning.

Permeabilities in the rolling direction of typical products of the present invention (11-mil strip materials) are of the order of 1850 to 1920 gauss as measured in a 10-oersted magnetic field. The watt losses of these materials likewise are in a highly favorable range, being of the order of 0.52 to 0.60 watt per pound (wpp) at 15,000 gauss and 0.67 to 0.77 wpp at 17,000 gauss (60 hertz).

According to the present invention as I prefer to practice it, silicon steels containing about 0.03 per cent of each manganese and sulfur, and about 0.03 per cent of carbon, and usual amounts of incidental impurities are produced in the form of strips or sheets for use in electrical equipment including transformers and motors by providing a melt of the required chemistry and adding to it a source of boron equivalent to 5 to 25 parts per million of boron to establish a nitrogen to boron ratio of one to fifteen parts per part of boron. Ingots cast from the melt are heated preferably to about 2200° to 2300°F and hot rolled in a series of passes until the thickness of the resulting sheets is about 100 mils. After pickling and annealing, the sheets are cold rolled to intermediate thickness of about 60 mils and

reheated and then cold rolled again to final thickness of about 11 mils. Thereafter, the cold-worked sheet is given a decarburizing heat treatment and a recrystallizing ("texturizing") anneal during which boron is largely, if not entirely, eliminated from the sheet or strip product.

In a commercial-scale operation designed to test the capabilities of this new process in a production-type operation, a 70-ton melt was prepared using BOF silicon-iron. Five parts per million of boron in the form of ferroboron were added to the melt in the ladle, which then had the following composition:

Silicon	3.15	percent
Copper	0.24	"
Chromium	0.033	"
Aluminum	0.005	"
Manganese	0.035	"
Sulfur	0.031	"
Carbon	0.030	"
Boron	0.0006	"
Nitrogen	0.0050	"
Iron	Remainder	

Eight ingots were cast from this melt and four of these were heated to 2350° for hot rolling, while the other four were heated to 2250°. Hot rolling was carried out in accordance with standard production practice in a six-strand tandem hot strip mill to provide hot-rolled bands from 90 to 130 mils thick. Samples of the hot-rolled band from the butt and hot top end of each hot-rolled coil were pickled in the conventional acid solution and then heat treated in hydrogen for approximately 3 minutes at 900°C. Some of these sample pieces were cold rolled without tension directly to a thickness of approximately 11 mils, while others were cold rolled without tension to 60 mils thickness and then heat treated in hydrogen for 3 minutes at 900°C before rolling to 11 mils.

Epstein-size strips of all the resulting coldrolled sheet materials were decarburized at 800°C in hydrogen (room temperature dewpoint) by heating for 3 minutes. The strips comprising the Epstein pack were lightly dusted with alumina powder and stacked and then heat treated, being loaded at 800°C and heated at 50°C per hour to 1050°C in nitrogen and then to 1150°C in hydrogen where they were held for two hours. Magnetic properties of the Epstein packs are set forth in Tables I and II.

As shown by the data in Tables I and II, both ends of a coil more consistently develop high permeabilities and low losses if a heat treatment step at 60 mils is included in the cold-rolling schedule. Furthermore, it is apparent from these data that very good magnetic properties are more consistently obtained in these materials when hot rolling is begun at 2250°F than when the temperature of the ingot at the outset of hot rolling is 100°F higher.

TABLE I

Magnetic Properties of Strip Hot-Rolled From 2350°F

Coil	Location	Gage Mils	Losses, mwpp 15.0kB	16.3kB	17.0kB	μ10H
	Direct Cold Rolled					
1	Butt	11.2	598	730	824	1774
1	Hot Top	11.0	605	726	814	1794
4	Butt	11.2	557	665	743	1841
4	Hot Top	11.2	588	708	795	1815
5	Butt	11.3	560	666	744	1842
5	Hot Top	11.2	550	649	708	1873

TABLE I-Continued

Magnetic Properties of Strip Hot-Rolled From 2350°F						
Coil	Location	Gage Mils	Losses, mwpp 15.0kB	16.3kB	17.0kB	μ10H
Two Staged Rolled (60 Mil Intermediate Gage)						
1	Butt	11.2	524	619	677	1903
1	Hot Top	11.2	537	631	689	1898
4	Butt	11.2	534	629	689	1890
4	Hot Top	11.2	551	654	723	1859
5	Butt	11.2	519	617	679	1886
5	Hot Top	11.2	536	629	686	1890

TABLE II

Magnetic Properties of Strip Hot-Rolled From 2250°F						
Coil	Location	Gage Mils	Losses, mwpp 15.0kB	16.3kB	17.0kB	μ10H
Direct Cold Rolled						
6	Butt	11.1	632	790	903	1738
6	Hot Top	11.2	570	675	745	1850
7	Butt	11.3	545	639	706	1896
7	Hot Top	11.3	596	708	784	1830
8	Butt	11.3	534	632	690	1899
8	Hot Top	11.2	594	712	790	1827
Two Staged Rolled (60 Mil Intermediate Gage)						
6	Butt	11.2	516	609	668	1898
6	Hot Top	11.3	549	644	703	1899
7	Butt	11.3	528	621	677	1925
7	Hot Top	11.3	559	658	719	1901
8	Butt	11.3	527	626	683	1900
8	Hot Top	11.2	539	636	693	1892

This invention has been further explored in a series of 15 experiments designed to test the composition and processing parameters, particularly the boron content, the manganese and sulfur content and ratio, and the extent of thickness reduction during the final or second cold-rolling phase of a two-stage cold-rolling process. In carrying out these experiments, each of the heats was melted in an air induction furnace in an argon atmosphere using electrolytic iron of 98 per cent ferrosilicon to provide a melt of the following composition:

Silicon	3.1	percent
Carbon	0.025	"
Copper	0.1	"
Chromium	0.03	"
Nitrogen	0.0045	"
Iron	Remainder	

Preparation of these and subsequent heats resulted in nitrogen contents from 30 to 60 parts per million with above-indicated average content.

The manganese and sulfur analyses and the boron added in each instance are set out in Table III together with the rolling and heat-treating conditions and the results of permeability and watt loss measurements made on each individual finished product.

Slices 1.75 inch thick were cut from 50-pound ingots cast from each melt of this series and heated either to 1175°C or 1200°C for hot rolling, as noted in Table III. The ingot portions were hot rolled to 90 mils thickness in six passes without reheating. Each resulting hot-rolled band was pickled and then cold rolled to intermediate thickness either of 60 mils or of 28 mils, then heat treated for three minutes at 900° in hydrogen and finally cold rolled to 11-mil thickness. (Nominal 11-mil strip ranged in these runs from 11.0 to 11.3 mils in thickness.)

Epstein strips of each of these cold-rolled sheet products were decarburized by subjecting them for 3 minutes to a temperature of 800°c in hydrogen at room temperature dewpoint. Then, for the final anneal, watt loss strips (3 cm × 30.5 cm) were lightly dusted with alumina powder and stacked. Packs of 11-mil strips were loaded at 800°C, heated at 50° per hour to 1050°C in nitrogen and then to 1150°C in hydrogen, where they were held for 2 hours.

TABLE III

Magnetic Properties of Epstein Packs of 11-Mil Thick Strips Processed With An Intermediate Heat Treatment

					Heat Treated at 60 Mils			Heat Treated at 28 Mils		
	ppm B	Losses, mwpp, 60 Hertz			Losses, mwpp, 60 Hertz					
Run	Added	% Mn	% S	Mn/S	15.0kB	17.0kB	μ10H	15.0kB	17.0kB	μ10H
1	5	.030	.011	2.7	1002	---	1475	800	—	1588
2	15	.030	.009	3.3	777	---	1604	645	—	1702
3	0	.034	.017	2.0	878	—	1543	631	902	1721
4	5	.033	.016	2.1	627	—	1727	561	763	1832*
5	15	.034	.017	2.0	534	704	1870	537	724	1844
6	0	.033	.025	1.3	1069	..	1444	601	849	1779
7	5	.036	.025	1.4	548	709	1883	548	741	1848
8	10	.034	.023	1.5	543	717	1886	555	740	1855
9	20	.034	.023	1.5	537	685	1905	551	723	1860
10	30	.031	.023	1.35	548	702	1888	585	776	1850
11	40	.031	.022	1.4	622	910	1700	575	830	1756
12	0	.032	.033	1.0	1054	—	1478	591	841	1772
13	5	.032	.036	0.9	555	697	1916*	560	725	1868*
14	10	.033	.033	1.0	555	711	1901	575	761	1833
15	10	.031	.039	0.8	567	730	1886	—	—	—

*Hot rolled from 1175°C; all others hot rolled from 1200°C.

As indicated by the data reported in Table III, the magnetic properties of the products were substantially improved by the addition of boron when the ratio of manganese to sulfur in the silicon-iron was less than 2.1. Further, high permeabilities were obtained through the addition of five to 30 parts per million of boron, but the addition of 40 parts per million of boron resulted in incomplete secondary recrystallization and consequent substantially diminished permeability. Finally, permeability was improved by heavier final cold reductions, which is surprising in view of general experience in conventional practice to the contrary.

Four additional experiments were run as a series to test the two-stage cold reduction process against the single stage or direct cold reduction method. Permeability and watt loss measurements made on finished 11-mil silicon-iron strip materials resulted in the data set out in Table IV, which also indicates in each instance the rolling procedure and lists the amounts of boron added and the manganese and sulfur content of each individual melt of this series.

In each of these four experimental runs, the procedure from providing the melt at the outset through cold rolling was as described above in reference to the series of 12 runs, except that direct cold rolling involved reduction from 90 to 11 mils thickness without intermediate heat treatment of the silicon-iron sheet material.

As shown by the data reported in Table IV, heat treatment at an intermediate thickness generally improves the magnetic properties of the final product, as contrasted to cold rolling direct to final gauge from the hot rolled band.

TABLE IV

Comparison of Properties Obtained By Direct Cold Rolling to 11 Mils With Heat Treatment at Intermediate Gage of 60 Mils

Run	Rolling Procedure	ppm B Added	% Mn	% S	15.0kB	17.0kB	μ10H
16*	Direct	5	0.032	0.036	568	758	1849
17*	60 mil IG				555	697	1916
18	Direct	10	0.041	0.039	574	745	1855
19	60 mil IG				530	673	1908

Hot rolled from 1175°C, others hot rolled from 1200°C

In addition, in view of the foregoing experimental results, it will be understood that the final cold reduction carried out in the two-stage cold-rolling operation of this invention is preferably of the order of at least 60 per cent and most desirably upwards of 70 or 80 per cent. Acceptable or satisfactory results may, however, be obtained at reductions of the order of 50 per cent and even less, other factors influencing the development of secondary recrystallization texture and good magnetic properties being the same and within the critical limits defined above.

In laboratory experiments illustrating the utility of selenium in this process, four heats were melted in an air induction furnace under an argon cover using electrolytic iron and 98 per cent ferrosilicon. Five parts per million of boron were added to each heat and 0.025 per cent of selenium was added to two heats (B and C) and 0.045 per cent selenium was added to another (heat D). The chemical analyses of these heats were as follows:

TABLE V

	% Mn	% S	% Se	% Si	% Cr	% Cu	% C
A	0.036	0.007	0	3.1	0.03	0.1	0.025
B	0.033	0.005	0.019	3.1	0.03	0.1	0.025
C	0.029	0.003	0.024	3.1	0.03	0.1	0.025
D	0.029	0.003	0.037	3.1	0.03	0.1	0.025

Slices 1.75 inches thick from the resulting 50-pound ingots were heated to 1200°C and rolled without reheating in six passes to a thickness of 90 to 100 mils. After pickling, samples of the hot rolled band were heated in hydrogen for 3 minutes, cold rolled to 60 mils, heated again for 3 minutes at 900°C in hydrogen and cold rolled to the final thickness of 11 mils. Epstein strips were decarburized by heating for 3 minutes at 800°C in wet hydrogen, after which they were separated with alumina powder and given the final anneal. The final anneal consisted of heating at 50°C per hour from 800°C to 1050°C in nitrogen, then in hydrogen to 1175°C and holding 3 hours. The magnetic properties of Epstein packs of these materials were measured with the following results:

TABLE VI

	Gage	mwpp 15kB	16.3kB	17kB	μ10H
A	11.3	910	—	—	1522
B	10.8	510	594	646	1912
C	10.9	552	641	696	1902
D	10.9	567	668	734	1879

In one instance in the course of carrying out this experiment, 0.020 per cent of selenium was added to the melt which had the following analyzed composition:

% Mn	% S	% Se	% Si	% Cu	% Cr	% C
0.031	0.004	0.015	3.1	0.1	0.03	0.03

As in the other heats of this series, five parts per million of boron were added to the molten metal and processing for one sample (X) was as described above, while in the case of a second sample (Y), the intermediate heat treatment was carried out at 1000°C instead of 900°C. The measured magnetic characteristics of these final products were:

	Gage (mils)	mwpp 15kB	17kB	μ10H
X	10.9	621	908	1710
Y	10.8	547	702	1904

It is apparent that selenium is more effective than sulfur when compared on an atomic weight basis, at least 0.026 atomic per cent sulfur being required with 0.030 per cent manganese but only 0.017 atomic per cent of selenium being necessary.

As used herein and in the appended claims, the term "ingot" means and refers to a body made by solidifying by any casting method a molten steel made by any suitable steelmaking method, and this includes a slab-like ingot obtained by a continuous casting method.

Whenever in this specification and in the appended claims reference is made to amounts, ratios, percentages or proportions, the weight basis is meant and intended unless otherwise expressly stated.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. The method of producing grain-oriented silicon-iron sheet which comprises the steps of providing a silicon-iron melt containing 2.2 to 4.5 per cent silicon, manganese and sulfur in amounts in a ratio of manganese to sulfur less than 2.1, between about three and about 35 parts per million boron, and between 30 and 60 parts per million nitrogen in the ratio to boron of one to fifteen parts per part of boron, casting the melt to form an ingot, hot rolling the ingot, then cold rolling to intermediate thickness, then heat treating the resulting cold-worked sheet, then cold rolling and reducing the sheet to final thickness, and finally subjecting the cold-rolled sheet to heat treatment to decarburize it and to develop (110)[001] secondary recrystallization texture in it.

2. The method of claim 1 in which the hot rolling step is begun with the ingot at temperature in the range from 2100°F to 2400°F.

3. The method of claim 1 in which the hot rolling step is begun with the ingot at temperature between 2200°F and 2300°F.

4. The method of claim 1 in which the sheet is reduced in thickness to about 60 mils in the first cold-rolling operation, and in which the second cold rolling operation results in about 80 per cent reduction in thickness of the sheet.

5. The method of claim 1 in which the final cold-rolling step results in reduction of thickness of the silicon-iron sheet of about 60 per cent.

6. The method of claim 1 in which the amount of manganese is from about 0.01 to 0.10 per cent and the amount of sulfur is from about 0.005 to 0.05 per cent.

7. The method of claim 1 in which the melt contains about 50 parts per million nitrogen, about five parts per million boron are added to the melt, and in which the manganese content of the melt is about 0.035 per cent and the sulfur content of the melt is about 0.030 per cent, and the ingot is at 2250°F at the outset of hot rolling, and the sheet thickness is reduced to 60 mils in the first cold rolling stage and the sheet is then normalized in hydrogen for 3 minutes at 900°C and thereafter cold rolled to final thickness of about 11 mils.

8. The method of claim 1 in which the manganese content of the silicon-iron melt is at least 0.01 per cent.

9. The method of producing grain-oriented silicon-iron sheet which comprises the steps of providing a silicon-iron melt containing 2.2 to 4.5 per cent silicon, additionally containing sulfur or selenium or sulfur and selenium in amount from 0.005 to 0.05 per cent, and additionally containing from 0.01 to 0.10 per cent manganese in an amount in the ratio to sulfur or selenium or sulfur plus selenium of less than 2.1, and containing between 30 and 60 parts per million nitrogen, and finally containing incidental impurities and the balance consisting of iron, adding from about three to about 35 parts per million of boron to the melt and thereby establishing a nitrogen to boron ratio to the melt of 1 to 15 parts of nitrogen per part of boron, casting the melt to form an ingot, hot rolling the ingot, then cold rolling to intermediate thickness, then heat treating the resulting cold-worked sheet, then cold rolling and reducing the sheet to final thickness, and finally subjecting the cold-rolled sheet to heat treatment to decarburize it and to develop (110)[001] secondary recrystallization texture in it.

10. The method of claim 9 in which the metal melt contains about 0.019 per cent selenium, about 0.004 per cent sulfur and about 0.033 per cent manganese.

11. The method of claim 9 in which the metal melt contains from 0.015 to 0.037 per cent selenium, about 0.004 per cent sulfur and about 0.03 per cent manganese.

12. The method of producing grain-oriented silicon-iron sheet which comprises the steps of providing a hot-rolled band containing 2.2 to 4.5 per cent silicon, between three 35 parts per million boron, between 30 and 60 parts per million nitrogen in the ratio of 1 to 15 parts per part of boron, and amounts of manganese and sulfur in the ratio of manganese to sulfur less than 2.1, cold rolling the hot-rolled band to intermediate thickness, then heating the resulting cold-worked sheet, then cold rolling and reducing the sheet to final gauge thickness, and finally subjecting the cold-rolled sheet to heat treatment to develop (110)[001] secondary recrystallization texture in it.

13. A silicon-iron hot-rolled band containing 2.2 to 4.5 per cent silicon, manganese and sulfur in amounts in a ratio of manganese to sulfur less than 2.1, between about three and 35 parts per million boron, and between 30 and 60 parts per million nitrogen in the ratio to boron of 1 to 15 parts per part of boron.

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