Dec. 10, 1968 J. P. GIMIGLIANO 3,415,696
PROCESS OF PRODUCING SILICON STEEL LAMINATIONS HAVING
A VERY LARGE GRAIN SIZE AFTER
FINAL ANNEAL
Filed Aug. 16, 1965 2 Sheets-Sheet 1

Fig. I

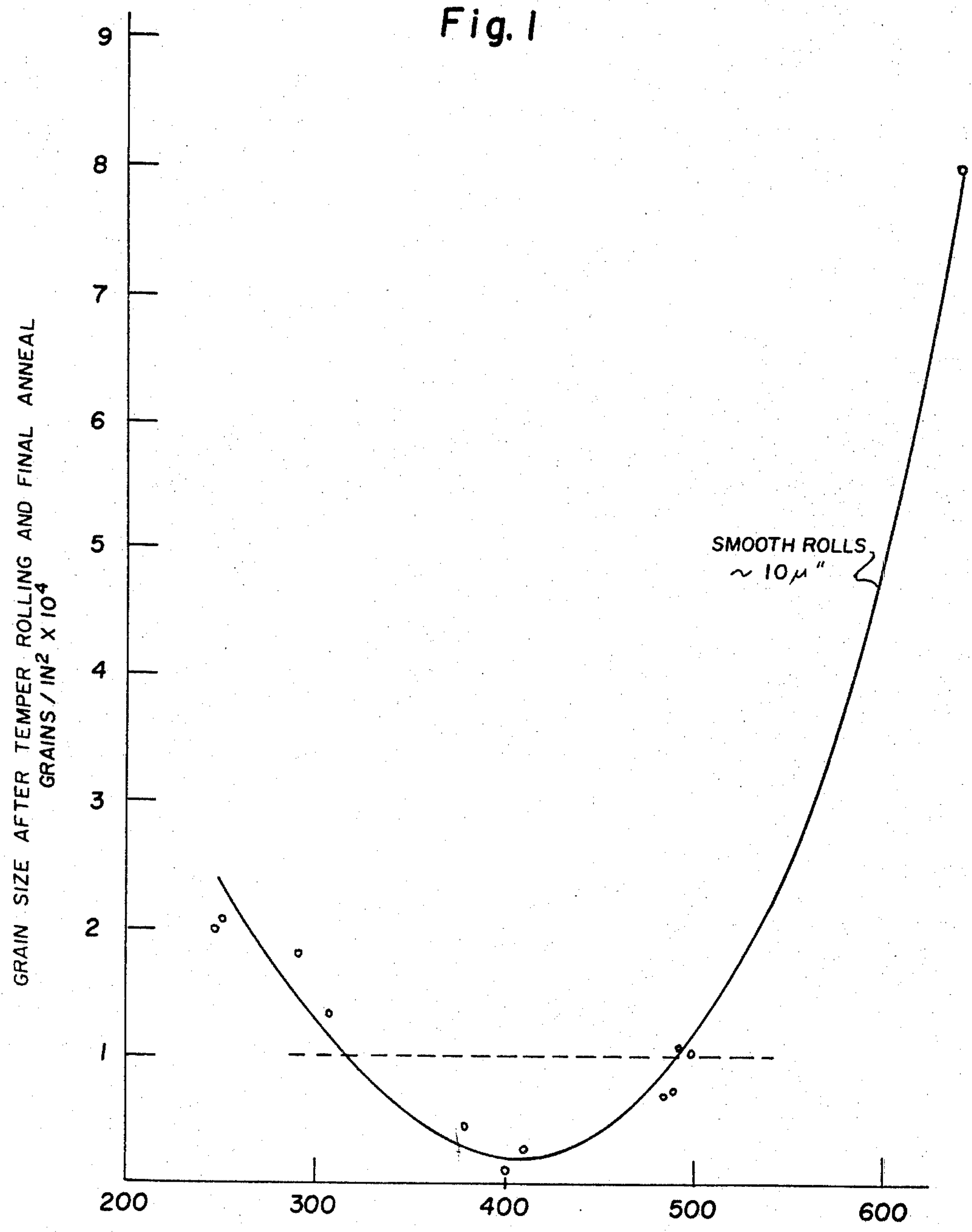

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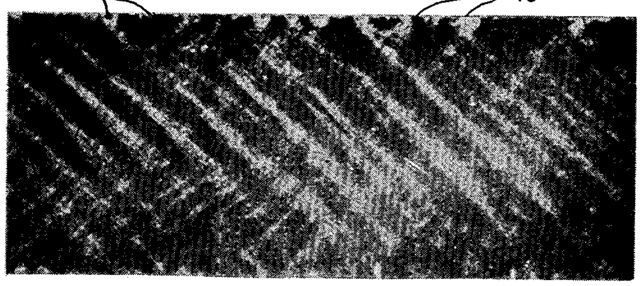
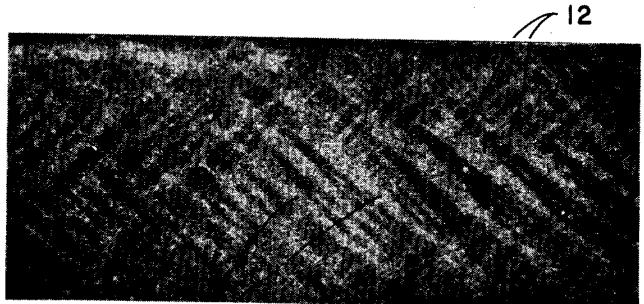
FIG. 2A



STRAIN LINES
SMOOTHNESS
OF TEMPER
ROLLS- 100 μ"

20X

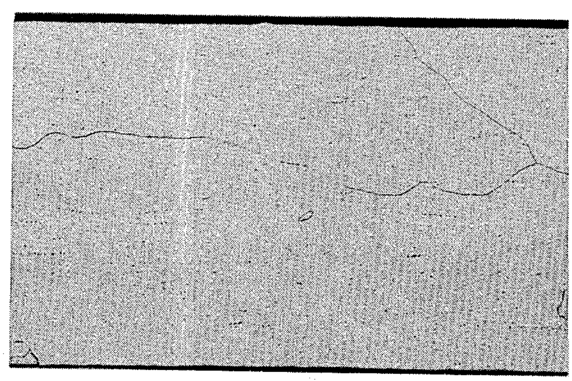
FIG. 2B



STRAIN LINES
SMOOTHNESS
OF TEMPER
ROLLS- 10 μ"

20X

FIG. 3A



GRAIN SIZE
.5 X 10^4 grains/in.^{2}
SMOOTH ROLLS

100X

FIG. 3B

GRAIN SIZE
7 X 10^4 grains/in.^{2}
ROUGH ROLLS

100X

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PROCESS OF PRODUCING SILICON STEEL LAMINATIONS HAVING A VERY LARGE GRAIN SIZE AFTER FINAL ANNEAL

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2 Claims. (Cl. 148—110)

ABSTRACT OF THE DISCLOSURE

Non-oriented silicon-steel laminations of improved low hysteresis loss are produced by using a heat treatment that produces, in strip at final gage except for temper rolling, a grain size of 320–490$\times 10^4$ grains per square inch, and then temper rolling to final gage by using rolls with a smoothness of about 10 microinches surface roughness. The steel is then annealed to develop a grain size of 0.45–1.0$\times 10^4$ grains per square inch. Specific parameters of temperature and time for obtaining the above results are disclosed and claimed.

This invention relates to the production of electrical steels, particularly silicon electrical steels, for use in motor armatures, transformer cores and the like. More particularly, the invention is concerned with a process for developing a large final grain size and resultant lower core and hysteresis losses in silicon electrical sheets.

As is known, the core loss of electrical steels, measured in watts per pound at a specified frequency and gauss rating, is actually the sum of the hysteresis loss and the eddy current loss of the material. Eddy current losses may be decreased by additions of alloying agents such as silicon and aluminum. On the other hand, hysteresis losses are, to a large extent, dependent upon the final grain size of the material; the larger the grain size the lower the hysteresis loss. It has long been recognized that larger final grain sizes and lower overall core losses are enhanced by a critical strain procedure applied to silicon steel of substantially finished gage. This involves subjecting the material to an intermediate decarburizing anneal after cold reduction to gage, followed by temper rolling preceding the final anneal.

An examination of the patented prior art on this subject reveals that the intermediate decarburizing anneal is usually carried out at temperatures in the range of about 1200° F. to 1500° F.; however very little is found in the patented art or literature regarding the grain size achieved in the intermediate anneal, which grain size is a function not only of temperature but also time and the type of annealing furnace employed. Furthermore, while practically nothing is said in the patented art or literature regarding the texture of the rolls used in the final temper rolling procedure, an examination of commercially available grades from various manufacturers in the United States reveals that the smoothness of the rolls is, at best, no better than 20 microinches and oftentimes 100 microinches or rougher.

The present invention has, as its primary object, the

provision of improvements in the intermediate decarburizing anneal and temper rolling aspects of silicon steel processing to achieve a larger final grain size and resultant lower hysteresis loss than is achieved with prior are methods. In this respect, the invention resides in the discovery that by controlling the grain size achieved in the intermediate decarburizing anneal between upper and lower limits, and by thereafter temper rolling between rolls having a higher degree of smoothness than heretofore employed, the final grain size of the material can be materially increased. Contrary to what might be expected, the final grain size produced in accordance with the teachings of the invention does not necessarily increase as the intermediate grain size increases. Rather, when rolls having a smoothness of at least 20 microinches or smoother are employed in the final temper rolling procedure, the final grain size increases as the intermediate grain size is increased to about 400$\times 10^4$ grains per square inch, but decreases when the intermediate grain size is increased above this value. Thus, when smooth rolls of the type described above are employed, there exists a critical intermediate grain size of about 400$\times 10^4$ grains per square inch which is produced, for example, when the intermediate decarburizing anneal is carried out as an open-coil anneal for six hours at a temperature in the range of about 1380° F. to 1420° F., and preferably 1400° F.

In the specification which follows, the term "smooth rolls" means those having a smoothness better than 20 microinches and preferably 10 microinches or better. That is, the distance between the peaks and valleys which inherently occur on any ground roll is a maximum of 20 microinches. "Rough rolls," on the other hand, means those having a smoothness which is of 20 microinches or worse.

The above and other objects and features of the invention will become apparent from the following detailed description taken in connection with the accompanying drawings, in which:

FIG. 1 comprises a graph illustrating the relationship of grain size achieved in the intermediate anneal to final grain size, using smooth rolls;

FIGS. 2A and 2B are magnified edge views of steel strip rolled by rough and smooth rolls, respectively, showing the appearance of strain lines produced in the strip under the respective rolling conditions; and

FIGS. 3A and 3B are illustrations or photomicrographs showing the final grain size achieved by employing smooth and rough rolls, respectively, in the final temper rolling procedure.

Although not necessarily limited thereto, the invention is particularly adapted for use with silicon steels having the following composition:

Silicon	0.15 to 3%.
Carbon	0.06% max.
Manganese	0.75% max.
Sulphur	0.03% max.
Aluminum	0.60% max.
Iron	Remainder.

After steel of approximately the foregoing composition is melted and cast into ingots, it is slabbed and rolled into hot band having a gage of about 0.075 inch, it being understood that the particular gage may vary without departing from the scope of the invention. As an example, the steel may be heated to about 2300° F. before rolling with a finishing temperature above 1600° F. The hot band is then coiled and permitted to cool in air.

Thereafter, the product is pickled to remove mill scale and cold rolled to reduce its gage to about 0.025 inch. Following cold rolling, the material is open-coil annealed for about six hours at a temperature in the range of 1380° F. to 1420° F., and preferably 1400° F. The time of the anneal will vary depending upon the type of annealing furnace employed and other factors; however it is important that the grain size at the end of the decarburizing anneal be in the range of about 320 to 490×10^4 grains per square inch, and preferably 400×10^4 grains per square inch. As will be seen from the following experimental data, this produces the maximum final grain size after temper rolling and final annealing.

After decarburization with a resultant grain size in the range of 320 to 490×10^4 grains per square inch, the material is temper rolled to reduce its gage by about 1.5%. As was mentioned above, temper rolling must be carried out between rolls having a smoothness of 20 microinches or less in order to achieve the desired large final grain size. In this respect, it has been found that if the intermediate grain size in the range of 320 to 490×10^4 grains per square inch is produced in the intermediate anneal, but that temper rolling is carried out with rolls which are rougher than 20 microinches, the improved results of the present invention are not produced. Thus, the critical grain size produced in the intermediate anneal and the smoothness of the rolls during temper rolling are interdependent.

Finally, following temper rolling, the material may be punched into laminations and annealed in an inert atmosphere such as nitrogen at 1600° F. for two hours.

The effect of the intermediate grain size achieved during the decarburizing anneal on final grain size, assuming that rolls having a smoothness of 20 microinches or less are employed, is shown in the following Table I.

TABLE I

Sample	Decarburizing Temperature, ° F. (6 hours)	Grain Size After Intermediate Anneal, Grains/in.²	Grain Size After Temper Rolling and Final Anneal, Grains/in.²
1	1,250	640×10^4	8×10^4
2	1,300	495×10^4	1.05×10^4
3	1,300	490×10^4	1.09×10^4
4	1,350	490×10^4	$.750\times10^4$
5	1,350	485×10^4	$.740\times10^4$
6	1,400	400×10^4	$.410\times10^4$
7	1,400	410×10^4	$.425\times10^4$
8	1,400	380×10^4	$.430\times10^4$
9	1,450	310×10^4	1.60×10^4
10	1,450	290×10^4	1.80×10^4
11	1,500	245×10^4	2.00×10^4
12	1,500	250×10^4	2.10×10^4

Tests conducted on steel having the following composition: Si, 1.60 to 1.75%; C, .056% max.; Mn, .25% max.; S, .028% max.; P, .010% max.; Al, .18% max.
Smoothness of rolls=10 microinches.

In the foregoing Table I, all samples were hot rolled at a starting temperature of about 2300° F. and a finishing temperature above 1600° F., the resulting hot band being coiled and permitted to cool in air. Following hot rolling, the product was cold rolled to approximately gage. The gage of the strip was reduced about 1.5% during temper rolling, and the product thereafter annealed at 1600° F. for two hours.

Note that as the annealing or decarburizing temperature increases from 1250° F. to 1500° F., the intermediate grain size also increases from about 640×10^4 grains per square inch to 250×10^4 grains per square inch. The grain size after temper rolling and final annealing, however, shows a remarkably different pattern. Thus, between 1250° F. and 1400° F. where the intermediate grain size is 400×10^4 grains per square inch, the final grain size increases from 8×10^4 grains per square inch to about $.420\times10^4$ grains per square inch. Above 1400° F., however, the grain size decreases.

The experimental data of Table I is plotted in FIG. 1 of the drawings as the full-line curve; and it will be noted that there is a critical intermediate grain size approximately between 320 and 490×10^4 grains per square inch where the final grain size is at an optimum. On either side of this optimum range, the grain size decreases as shown by the graph.

In the following Table II, grain size achieved in the intermediate and final anneals with rough rolls (i.e., rolls having a smoothness of above 20 microinches) is tabulated.

TABLE II

Sample	Decarburizing Temperature, ° F.	Grain Size After Intermediate Anneal, Grains/in.²	Grain Size After Temper Rolling and Final Anneal, Grains/in.²
1	1,250	640×10^4	6.15×10^4
2	1,250	570×10^4	8.71×10^4
3	1,300	490×10^4	6.20×10^4
4	1,350	490×10^4	10.70×10^4
5	1,400	400×10^4	6.42×10^4
6	1,450	300×10^4	9.31×10^4
7	1,500	230×10^4	8.55×10^4
8	1,500	135×10^4	5.70×10^4

Test conducted on same type of steel as given in Table I.
Smoothness of rolls=50–100 microinches.

Note that while the grain size increases as the annealing temperature increases in a manner similar to that shown in Table I, the final grain size pattern is entirely different. In almost all cases, the final grain size of Table II where rough rolls were employed is smaller than in the case of smooth rolls. Futhermore, it mill be noted that there does not seem to be any correlation between the intermediate and final grain sizes so as to draw a smooth curve such as that shown in FIG. 1.

One possible explanation for this surprising result can be had by reference to FIGS. 2A and 2B which illustrate the strain lines produced on the edge of temper rolled silicon steels with rough rolls and smooth rolls, respectively, at a reduction of 1.5%. The strain lines are produced in an oxide coating on the edge of the strip, FIGS. 2A and 2B being facsimiles of photomicrographs of the edge at a magnification of 20X. The consistently smaller grain size achieved when smooth rolls are employed is believed to be due to the basic difference in the deformation pattern within the steel with rough rolls and smooth rolls, which leads to different recrystallization characteristics.

It can be seen in FIG. 2A, for example, that the individual peaks on the surface of rough rolls leave discrete strain regions **10** of high deformation, particularly near the surface, which may then be sites for nucleation of new grains during recrystallization. Thus, the rough rolls cause a great many grains to be nucleated at the surface. The use of smooth temper rolls as shown in FIG. 2B results in much fewer strain regions of high deformation near the surface, but many more deformation lines **12** for a given reduction. That is, the deformation is more uniform in FIG. 2B than in FIG. 2A, and this uniformity is a favorable condition for large grain growth.

FIGS. 3A and 3B illustrate the grain size achieved with smooth temper rolls and rough temper rolls, respectively. In the samples shown in FIGS. 3A and 3B, both were annealed at 1400° F. for six hours in order to produce an intermediate grain size of about 400×10^4 grains per square inch. However, after temper rolling with smooth rolls, the resulting final grain size of FIG. 3A is on the order of about $.5\times10^4$ grains per square inch while those shown in FIG. 3B with the use of rough rolls have a grain size of about 7×10^4 grains per square inch.

A comparison of hysteresis losses achieved by following the teachings of the invention, as contrasted with conventional practice, is illustrated in the following Table III.

TABLE III

Sample No.	Chemistry, Percent					Surface Roughness, μ inches	Final Grain Size Grains/ in.^{2} x 10^4	Hysteresis Loss, w./lb., B–15 kg., 60 c.p.s.	Eddy Current Loss
	C	Si	Mn	S	Al				
1	0.006	1.13	0.25	0.017	0.58	40–48	4.0	1.21	1.35
2	0.015	2.74	0.37	0.016	0.28	25–32	1.5	1.75	1.01
3	0.012	1.96	0.35	0.014	0.28	20–30	6.0	1.25	1.05
4	0.012	2.82	0.20	0.017	0.29	20–28	4.0	1.17	0.86
5	0.020	1.93	0.25	0.020	0.34	35–42	2.0	1.20	1.01
6	0.020	1.58	0.35	0.025	0.30	55–65	1.5	2.75	1.33
7	0.020	1.92	0.23	0.020	0.37	45–55	5.0	1.22	0.97
8	0.013	1.08	0.30	0.014	0.60	20–30	50	1.86	1.03
9	0.003	1.76	0.22	0.021	.003	10	1.18	0.97	1.26
10	0.005	1.78	0.22	0.019	.003	10	0.96	0.96	1.20
11	0.003	1.64	0.24	0.025	.002	10	1.07	0.98	1.34
12	0.006	1.64	0.24	0.024	.002	10	0.96	0.93	1.35
13	0.005	1.64	0.24	0.024	.002	10	0.56	0.89	1.37
14	0.003	1.64	0.24	0.024	.002	10	0.50	0.84	1.39
15	0.004	1.64	0.24	0.024	.002	10	0.45	0.80	1.39

Gage of all samples is 0.025″.

In the table, the first eight samples were derived from four different manufacturers in the United States. Note that the surface roughness of the Samples 1 through 8 is at least 20 microinches, indicating the use of "rough" temper rolls in accordance with the definition given above. This produces a final grain size no less than 1.5×10^4 grains per square inch. The hysteresis loss ranges between 1.17 watts per pound for Sample 4 to 2.75 watts per pound for Sample 6 at 15 kilogausses and 60 cycles.

The samples processed in accordance with the present invention are numbered 9 through 15, in which case the surface roughness is consistently about 10. In this case, the final grain size is materially increased and the hysteresis loss decreased, being no greater than .98 watt per pound. In certain cases, the eddy current loss is actually increased, but this is a function of composition (i.e., Si and Al) rather than grain size, as was explained above. Thus, it can be concluded that by employing smooth rolls in combination with a critical intermediate grain size of $320–490 \times 10^4$ grains per square inch produces optimum hysteresis loss characteristics.

Although the invention has been shown in connection with certain specific examples, it will be readily apparent to those skilled in the art that various changes may be made to suit requirements without departing from the spirit and scope of the invention.

I claim as my invention:

1. A process for making laminations of non-oriented silicon steel consisting essentially of 0.15 to 3% silicon, 0.06% maximum carbon, 0.75% maximum manganese, 0.03% maximum sulphur, 0.60% maximum aluminum, and the remainder iron, that comprises the steps, in the order named, of:

hot rolling the steel to band gage;

pickling the hot band;

cold reducing the steel to a thickness that exceeds that of the final product by about 1.5%;

annealing and decarburizing the steel under conditions of time at temperature such as to yield a grain size of about $320–490 \times 10^4$ grains per square inch;

temper rolling to effect a thickness reduction of about 1.5% and reach final gage, said temper rolling being done between rolls each having a surface roughness of at most 20 microinches; and then

annealing for about two hours at about 1600° F. to develop a grain size of about $0.45–1.0 \times 10^4$ grains per square inch and electrical properties including a hysteresis loss, for material 0.025 inch thick, of about 0.80–0.97 watt per pound at 15 kilogausses and 60 cycles per second.

2. A process as defined in claim **1**, characterized in that said annealing and decarburizing step is conducted by open coil annealing at a temperature of about 1380–1420° F. for about 6 hours.

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