Journal of Metals, Materials and Minerals. Vol.15 No.2 pp.17-23, 2005.

Influence of Chemistry and Hot Rolling Conditions on High Permeability Non-Grain Oriented Silicon Steel.

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Abstract

This paper discusses the influence of chemical composition, mainly the absence of aluminum, on the final electromagnetic properties in higher permeability material. Furthermore, the effect of the hot rolling practice and the end of austenite transformation temperature range on the hot band microstructure is described. Finally, the electromagnetic properties obtained after the final decarburization and grain growth heat treatment using this technology are reported.

Introduction

One of the most important reasons for the development of high efficiency motors is for the protection of the environmental as well as for energy savings. Considering the environment, this development is necessary in order to decrease emissions, mainly CO. At the same time, improving the magnetic properties of applied materials leads to energy savings.[1] The property requirements of such products have lead to the development of low core loss, high permeability materials. The desired magnetic properties are achieved by appropriate alloying, and control of grain size and texture.[2, 3]

For the production of electromagnetic machines in the electrotechnical industry, cold rolled silicon steels with silicon contents of 0.5 – 3.5 % are most frequently used. They belong to the group of low carbon steels and their major application is for the production of transformers and rotating electric machines where they provide the best possible induction connection between rotor and stator. The main advantage of these sheets is low core loss. Increasing the silicon content generally ensures a decrease in core loss however, it also decreases magnetic saturation and permeability.

To achieve a high magnetizing ability of non-grain oriented (NGO) sheets at a constant level of core loss the utilization of several physical-metallurgical approaches is possible. Each of these approaches can be characterized from the production costs point of view as well as whether additional technological steps are needed to achieve the desired final product properties. One simple way to increase magnetic polarization is to decrease the basic alloying element contents, i.e. silicon and aluminum. This approach however, increases the core loss and decreases both the yield and tensile strengths while increasing the polarization of the final product. Another approach is based on the improvement of the crystallographic texture in the final product by optimization of the production practices prior to the final heat treatment. From the physical-metallurgical point of view, the control of hot band structure and texture is absolutely necessary.

Another frequently exploited way to improve the magnetizing ability of NGO sheets is to use hot band annealing in non-oxidizing atmospheres after pickling. Despite the addition of another processing step and the concomitant increase in production costs, this technology is often used because of the possibility to more closely control the annealing process parameters. The purpose of hot band annealing is to increase the grain size in the hot band and improve the texture in the final product.

The relationship between the hot band microstructure and texture and final product properties is well known. In terms of operational costs, the easiest way to influence the hot band microstructure is through optimization of the hot rolling practice(4-6). One commonly utilized practice is to have coiling temperatures above 700°C. Care must be taken however because high coiling temperatures can deteriorate the surface quality of the hot bands, especially in steels with silicon contents > 1.0 %(7) while also necessitating the need to use lower pickling rates. Use can also be made of the gamma-alpha phase transformation to improve the hot band microstructure. This is the subject of this paper and it is shown to be a very effective way of achieving high polarizations in moderately alloyed NGO fully-processed electrical steels.

Experimental Details

The investigation was carried out using commercially produced steels. The chemical composition of the steel used for this study was characterized by the Si-equivalent, Sieq, calculated through the equation:

$$Sieq = \%Si+2*[\%Al]-0,50*[\%Mn]+2,92*[\%P] \quad (1)$$

This equation was used in conjunction with the appropriate Fe-Si-C phase diagram, shown in Figure 1, to balance the Si, Al, Mn, and P and tune the composition so that the phase transformation temperature could be appropriately positioned in the hot mill. The desired Sieq was about 0.85 – 0.90 and based upon the chemical composition achieved in the steelmaking shop, was typically about 0.88. A significant part of the composition design was based on the absence of aluminum. The main reason for this is to eliminate the AlN effect on grain growth.

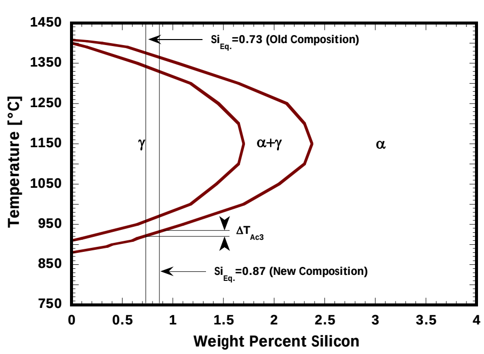

Figure 1. Iron rich corner of the Fe-Si-0.01 weight percent carbon phase diagram.

The steel was produced in an oxygen converter and continuously cast following vacuum degassing. Slabs were reheated to about 1230 – 1270°C, and hot rolled using one of three practices, outlined in Table 1, with consequent coiling temperatures of about 680–720°C. The experimented variables were, (1) finishing temperature, Tf, (2) finish mill entry temperature, T_s, and (3) transfer bar thickness, t_b.

Table 1. Experimental Hot Rolling Processes.

Process	T_f [°C]	t_b [mm]	T_s [°C]
1	880-920	40	1060
2	830-870	40	1060
3a	800-840	40	1060
3b	800-840	40	1000
3c	800-840	30	1060

Following pickling, the coils were cold rolled from the hot band thickness of 2.4 mm to the final thickness of 0.65 mm. The final heat treatment was performed on a continuous decarburizing and annealing "dynamo" line using the same processing parameters for all experimental material. Decarburization was conducted at a temperature of 860°C using a wet H_2 + N_2 atmosphere with a dew point of 30 – 34°C. The resultant magnetic properties were measured via Epstein testing with an exciting current frequency of 50 Hz at a 1.5 T induction after an aging treatment of 225°C for 24 hours. Samples for light microscopy observation were prepared by mechanical grinding, polishing and etching in 2 % Nital. The grain size of the final microstructure was determined according to the STN EN 42 0462 standard.

Crystallographic texture was studied using the X-ray diffraction technique. All the textures were examined by measuring the four incomplete pole figures (110), (200), (112) and (103) in back reflection mode. The orientation distribution function (ODF) was then calculated. For the texture analyses, flat samples of 30 by 30 mm dimension were used. The surface was prepared by grinding and subsequent chemical etching in 7 % HF in H_2O_2 solution in order to remove the residual deformation from the preparation procedure. A Seifert XRD3003 X ray diffraction analyzer equipped with texture goniometer was used to measure the texture with Mo Kα radiation.

For electrical steels, the three directions, (100), (110) and (111), parallel to the normal directions are important. These fibers are analyzed in the ODFs[8-10]. A simplified analysis of electrical sheet textures can be accomplished by a volume fraction analysis of the η, α and γ fibers. These fibers are descrbied as follows:

η - fiber: <100> || ND,
α - fiber: <110> || ND,
γ - fiber: <111> || ND.

The volume fraction of the material where the crystallites are oriented with the <hkl> crystallographic direction parallel to the sample normal direction (ND) is calculated using the orientation distribution function f(g).

Results and Discussion

The flow stress versus temperature curve defines the experimental hot rolling conditions in the hot mill finishing stands as shown in Figure 2. With decreasing temperature in austenite (γ), T_{s1} to T_{s2}, the flow stress increases. When the temperature $Ac_{3\text{-start}}$ is achieved, ferrite (α) starts to form. The flow stress decreases with the increasing α ratio, due to the lower flow stress of α. When the microstructure is completely ferritic, the temperature $Ac_{3\text{-finish}}$ is reached, the flow stress again increases as the deformation temperature is further reduced.

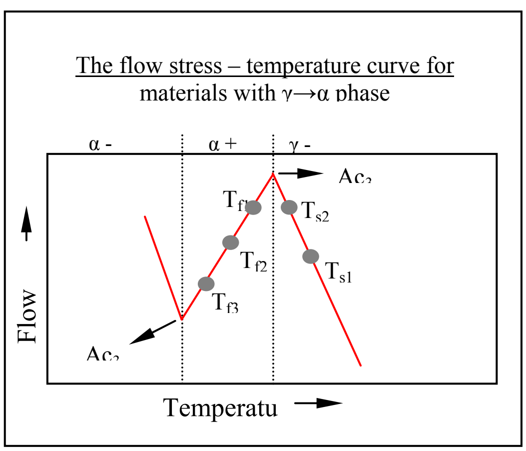

Figure 2. Flow stress versus temperature curve for Si_{eq}=0,88 in relation to the hot rolling conditions.

The three experimental hot rolling campaigns are shown in Figure 2. For each case, the finish rolling begins with the material in γ. The three campaigns end however in the two-phase γ + α area but with different γ : α ratios.

Process 1 - Tf1 = 880 – 920˚C

The hot rolling deformation in the last stands of the finishing mill started in the γ region. The temperature before finishing was T_{s1} = 1060˚C while the finishing temperature was maintained at T_{f1} = 880 – 920˚C. Figures 3, 4 show fine-grained hot band microstructures with a different grain size at the surface and in the center within the sample thickness.

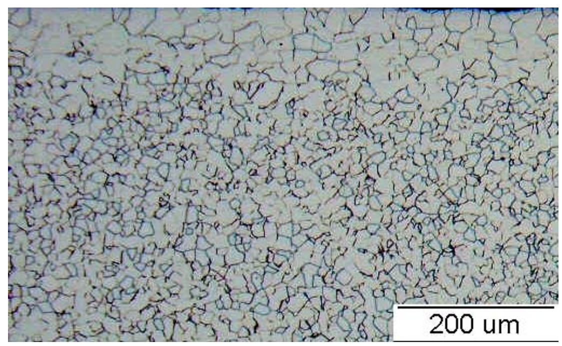

Figure 3. Hot band microstructure – surface, T_{f1} = 880 – 920˚C.

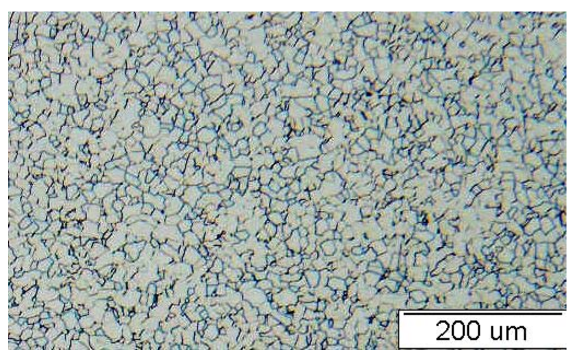

Figure 4. Hot band microstructure – center, T_{f1} = 880 – 920°C.

The small grain size microstructure in the center of the strip resulted from residual austenite transformation to ferrite after the hot rolling process. The final dynamo line heat treatment was performed according to the aforementioned parameters. Figure 5 documents the final heterogeneous microstructure characterized by a major presence of small grains resulting from the residual austenite transformation. Magnetic properties were measured after the final heat treatment and showed the material to have low induction and high core loss as summarized in Table 2.

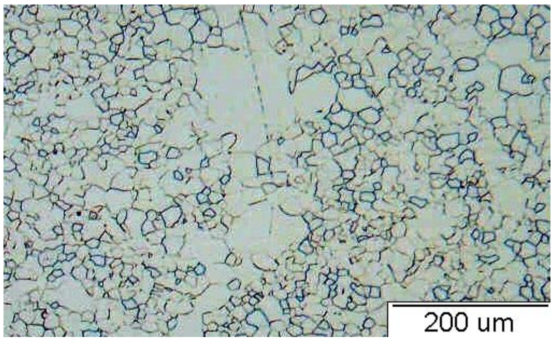

Figure 5. Final microstructure – center, T_{f1} = 880 – 920°C.

Table 2. Summary of Magnetic Properties.

Process	J_{5000} [T]	$P_{1.5}$ [W.kg^{-1}]	Grain Size [μm]
1	1,705	7,482	15,8
2	1,750	6,599	23,0
3a	1,760	6,551	21,0
3b	1,769	7,397	15,6
3c	1,771	6,315	23,2

Process 2 - Tf2 = 830 – 870˚C

After hot rolling with a finishing temperature range of T_{f1} = 880 – 920˚C, a heterogeneous fine grain microstructure was observed. In order to improve magnetic properties and achieve a better microstructure, the finishing temperature was decreased to the range T_{f2} = 830 – 870°C. The resulting hot band microstructure displayed a more homogeneous and larger grain size at the surface area of the strip, as seen in Figure 6, but the center still exhibited a heterogeneous fine grain structure of ferritic grains transformed from residual austenite, as in Figure 7.

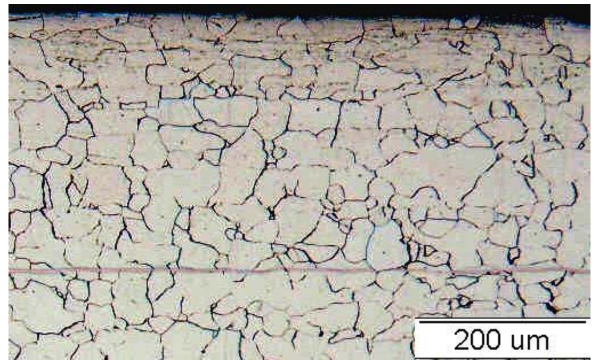

Figure 6. Hot band microstructure – surface, T_{f2} = 830 – 870˚C.

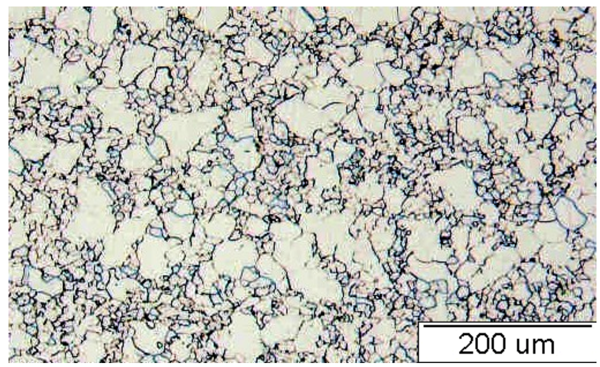

Figure 7. Hot band microstructure – center, T_{f2} = 830 – 870˚C.

The post-dynamo-line annealed microstructure in material finished in the T_{f2} = 830 – 870˚C temperature range, however, still contained smaller ferritic grains from residual austenite. The material did possess a more homogeneous microstructure, Figure 8, and had better magnetic properties after the final heat treatment in comparison to the steel processed at the finishing temperature T_{f1} = 880 – 920˚C. The magnetic properties for this process are also in Table 2.

Process 3 - Tf3 = 800 – 840˚C.

Since, the desired magnetic polarization J5000 of 1.74 T was not achieved, yet a lower finishing temperature T_{f3} was explored. Initially, an equal amount of deformation and the same temperature prior to finishing were applied, as in hot rolling campaigns 1 and 2. The hot band microstructure at the surface and in the center of the strip was different, with a noticeably lower ratio of

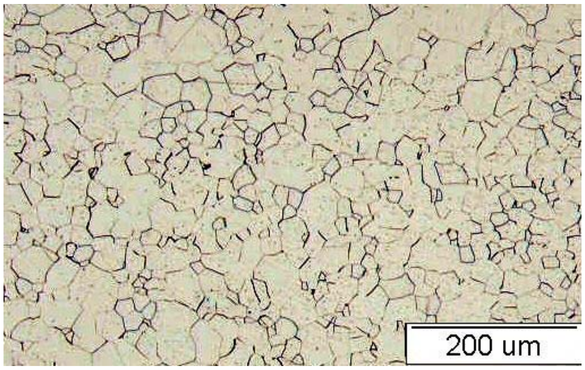

Figure 8. Final microstructure – center, T_{f2} = 830 – 870°C.

small ferrite grains as documented in Figures 9 and 10. The microstructure after the final dynamo line heat treatment from this material is shown in the Figure 11. The microstructure is characterized by a minimum fraction of small ferrite grains transformed from the residual austenite after the finishing.

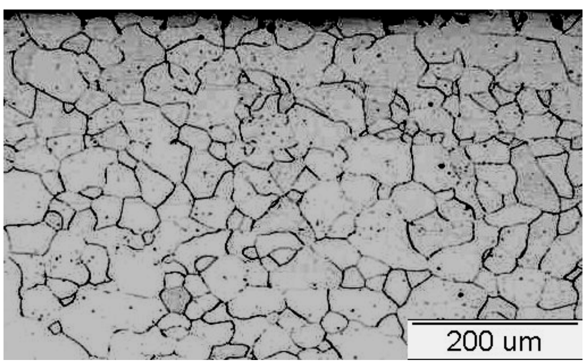

Figure 9. Hot band microstructure – surface, T_{f3} = 800 – 840°C.

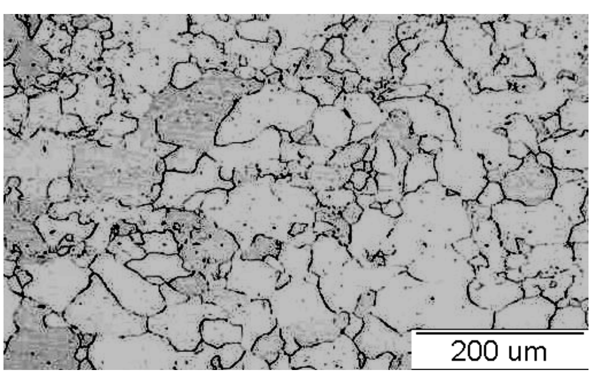

Figure 10. Hot band microstructure – center, T_{f3} = 800 – 840°C.

The effect of the austenite deformation amount, based upon the final electromagnetic properties, was evaluated according to the finish mill entry temperature T_{s2} = 1000°C. In order to verify the effect of total deformation amount on final magnetic properties, the thickness of the bar was decreased from t_{b1} = 40 mm to t_{b2} = 30 mm. Table 2 presents the final magnetic properties of the materials produced by the three different technological options – a, b, c.

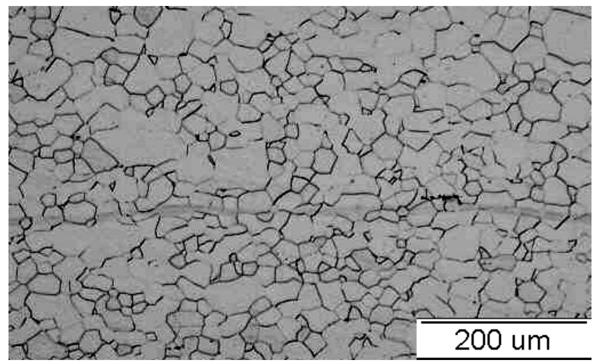

Figure 11. Final microstructure, T_{f3} = 800 – 840°C.

Texture analysis

It is known that rotated cube components in the texture give better magnetic polarization. It is very difficult to achieve an ideal magnetic texture in the operational process because of other requirements on the product, such as strength, elongation, etc. Additionally, conventional flat processing of steel including NGO Si-steel which includes hot rolling, cold rolling, and annealing typically produces non-ideal textures, such as γ fiber types, for magnetic properties. Textures with high volume fractions of (111) oriented grains are not acceptable for NGO Si steels because of the deterioration in magnetic polarization

In the analysis of magnetic steel textures, a better way to quantify the texture is by comparing the volume fractions of the planes (100) and (111). The higher the ratio (100) / (111), the better the magnetic properties achieved. Therefore, it is more beneficial to increase the volume fraction of the cube planes (100) in a material or decrease the volume fraction of the (111) planes in the plane of the sheet.

The texture analysis was performed on two types of material, a standard (S) and a high permeability (HP) grade of the same composition with a Sieq of 0.88. Table 3 compares the magnetic properties of these two grades.

Table 3. Magnetic properties.

Sample	J_{5000} [T]	$P_{1.5}$ [W/kg]
S – standard	1,721	7,630
HP – high permeability	1,778	6,475

The (200) pole figure measure on the HP samples is shown in Figure 12. It has characteristic of the Goss texture {110}<001> and as such will have a low fraction of (111) oriented crystal planes in the plane of the sheet. By comparison, the (200) pole figure for the S sample, shown in Figure 13, has a much different texture, one with a much higher fraction of (111) oriented grains in the plane of the sheet. ODF's were calculated for each sample and the η and γ fibers were extracted for a more detailed analysis. Volume fractions of the (001) and (111) were calculated along their respective η and γ fibers which are shown in Figures 14 and 15. The volume fractions of the important low index crystal planes for the S and the HP samples are presented in Table 4. The HP sample possesses a higher volume fraction of the more magnetically favorable (100) and (110) oriented grains and substantially less of the magnetically poor (111) oriented grains than the S sample. This results in a noticeably higher (100) / (111) ratio than the standard S material sample. This is explained by the much lower volume fraction of (111) planes along the γ- fiber as shown in Figure 15.

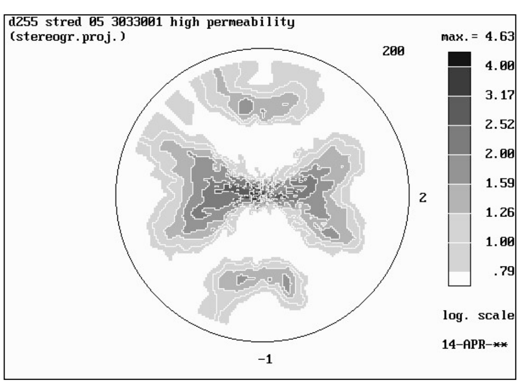

Figure 12. Pole figure of the plane (200) – HP sample.

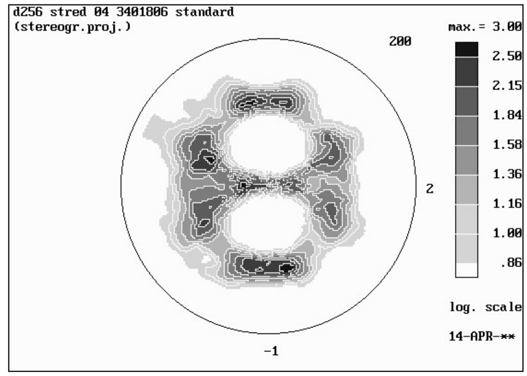

Figure 13. Pole figure of the plane (200) – S sample.

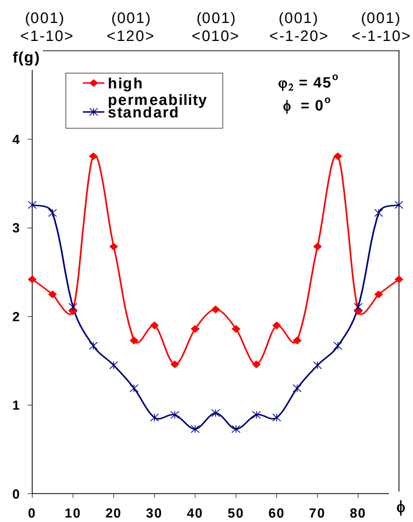

Figure 14. Volume fraction of the (001) planes along the η - fiber.

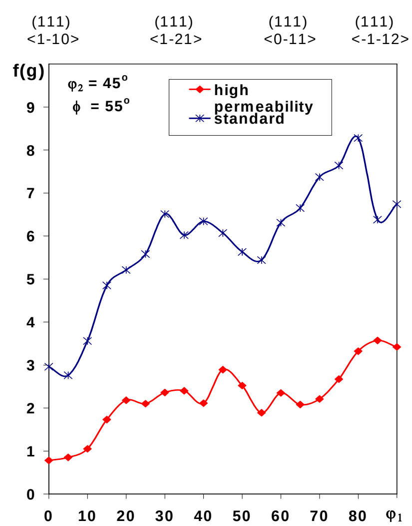

Figure 15. Volume fraction of the (111) planes along the γ - fiber.

Table 4. Volume fraction of Important Crystallographic Planes.

Sample	(100)	(110)	(111)	(100)/(111)
HP	1,61	0,64	1,61	1,00
S	1,19	0,24	4,17	0,28

Conclusions

1. When the finishing portion of the hot rolling process was conducted in the two-phase $\alpha + \gamma$ region in the Tf1 finishing temperature range of 880 to 920˚C, the major phase fraction was austenite. This hot rolling condition resulted in a surface to center-thickness microstructure variation. This hot strip microstructure produced a heterogeneous final microstructure with a low J_{5000} magnetic polarization of 1.705 T.

2. When the finishing temperature ranged from 830 to 870˚C, a lower volume fraction of austenite was obtained. This produced a more homogeneous hot band microstructure at the surface but it was still heterogeneous in the center of the strip. For this condition, the J5000 magnetic polarization increased to 1.750 T.

3. When the hot rolling process was conducted with a finishing temperature in the range of 800 to 840˚C, a minimum phase fraction of γ was obtained. The final J_{5000} magnetic polarization for his case was 1.76 T.

4. Decreasing the amount of deformation and the temperature before finish hot rolling demonstrated additional possibilities of how to improve the J_{5000} magnetic polarization so that values higher than 1.770 T can be achieved.

5. Texture analysis showed that the high permeability material has reached the appropriate final texture by a decrease in the γ fiber portion, i.e. via a reduction in the volume fraction of (111) oriented grains in the plane of the sheet.

References

(1) Takashima, M. Morito, N. Honda, A. Ch. Maeda. 1991 : Nonoriented electrical steel sheet with low iron loss for high-efficiency motor cores. *Transactions on Magnetics*. 35, (1) January.

(2) Nakayama, T. Takahashi, M. 1995. Effect of vanadium on magnetic properties of semi-processed non-oriented electrical steel sheets. *J. Mater. Sci*. 30.

(3) Nakayama, T. Honjou, N. 2000. Effect of zirconium on magnetic properties of nonoriented semi-processed electrical steel sheets. J. *Mater. Engine. Performance*. 9 (October).

(4) Yashiki, H. Okamoto, A. 1987. Effect of Hot-Band Grain Size on Magnetic Properties of Non-Oriented Electrical Steels. *IEEE Trans. Magne*. Vol. mag.-23, (5) September

(5) Hughes, I. 1971. The Effect of Finishing Temperature on the Texture and Structure of Hot Rolled 1 pct Si Steel. *Metall. Trans*. 2 (April)

(6) Mager, S. Wieting, J. 1994. Influence of the hot rolling conditions on texture formation in Fe-Si sheets. *J. Magn. Magn. Mater*. 133.

(7) Nishimoto,A. Hosoya, Y. Tomita, K. Urabe, T. Jitsukawa, M. 1992. Method of Making Non-oriented Electrical Steel Sheets having Excellent Magnetic Properties. *U. S. Patent No. 5,116,436.*(May) : 26.

(8) Bunge, H J. 1982. *Texture Analysis in Materials Science*. Butterworths,

(9) Kocks, U. F. Tome, V. N. Wenk, H. R. 1998. *Texture and Anisotropy*. Cambridge University Press.

(10) Kallend, J. S. Kocks, U. K. Rollet, A. D. Wenk, H. R. 1991. *Mater. Sci. Eng.* A132 : 1-11.