MECHANICAL WORKING & STEEL PROCESSING XXIII

A PUBLICATION OF THE IRON AND STEEL SOCIETY

MECHANICAL WORKING
AND
STEEL PROCESSING

IRON & STEEL SOCIETY
AIME

DIVISION

410 Commonwealth Drive, Warrendale, Pennsylvania 15086 • Tel. (412) 776-1535 • Telex 866-383

June 24, 1985

Please Reply To: Helen M. Slack

RE: Flat Rolled Products Session I

Mr. Ignacio Ibarrondo
c/o Catalina de Erauso No. 4-80D
20010 - San Sebastian, Spain

Dear Mr. Ibarrondo:

Subject: Paper - "Study on Siderurgical Process for Obtaining the Low Grades of Non-Oriented Silicon Steel Sheets, and Their Applications in Small and Medium Motors"

This will acknowledge your letter of May 27, 1985 requesting that we accept the subject paper for the Fifth International Iron & Steel Congress which will be held in April 1986. Unfortunately, this paper does not fit this conference, but it does fit in very well for our 27th Mechanical Working & Steel Processing Conference which will be held October 27-29, 1985 at Stouffer's Inn on the Square in Cleveland, Ohio, USA.

Your paper has been selected as paper #4 for the above session. An author's kit is enclosed for your convenience in preparing your paper for printing in our Proceedings which is published following the conference. If you have any questions concerning the instructions, please don't hesitate to contact us.

Additional information concerning the MWSP Conference will be sent to you as it becomes available.

Please advise immediately by telex at the above number if it does not meet with your approval to present the paper at the MWSP Conference.

Yours truly,

Helen M. Slack

Helen M. Slack
MWSP Coordinator

hms
Attachments
Air Mail
cc: J. K. Mahaney, Jr. & J. H. Matuska, Technical Program

STUDY ON SIDERURGICAL PROCESSES
FOR OBTAINING LOW GRADES OF NON-ORIENTED
SILICON STEEL SHEETS AND THEIR APPLICATIONS
IN SMALL AND MEDIUM MOTORS

I. Ibarrondo Ph. D.

Applied Physical Department
University of Basque Country
San Sebastián - Spain

ABSTRACT

On the basis of the siderurgical process described here, it is possible to produce a range of non-oriented magnetic sheets, with several silicon levels (0.35-1.20%), in fully and semi-processed qualities. Their adequate characteristics, combined with their low manufacturing cost, make them specially suitable for use in fractional h.p., small and medium sized motors.

1. FOREWORD

It is well known that a high percentage of electrical power, throughout the world, is consumed by electromagnetic equipments. And the growing increase of such energy costs, specially since 1974, gives a special importance to the saving of that energy.

In accordance with it, and with the factors to be considered when choosing magnetic sheet for a motor, which are:

- Costs derived from the grade selected for raw material.
- Processing costs.
- Operating costs.

the need of a steady change in the raw material selecting criteria, is evident. In fact, before the 1974 energy crisis the first of such factors was decisive and the use of carbon mild steel sheet for fractional ($<$ 1 h.p.) and small sized (1-50 h.p.) motors became specially relevant. However, after that date, the bigger importance of the third of such factors is manifest, as well as the need to use higher efficiency electrical motors. This efficiency is obtained selecting the adequate raw material and by the right technological design.

Indeed, we may consider small (1-50 h.p.) and medium sized (50-125 h.p.) motors. Although, on the whole, these motors are no more than 10% of all motors manufactured in U.S.A. in 1977, they do represent -according to F.E. Werner (1)- about 70% of the total energy losses.

Therefore, in this range of small and medium sized motors -as consequence of the energy crisis- exists the biggest potential to save power. As a proof of it, since 1975, higher efficiency motors of this type are produced. It is estimated that in the U.S.A., in 1980, 7% of these motors were already manufactured with this purpose, and this figure is expected to reach 75% in 1990 (2).

The fractional power motors (less than 1 h.p.) also represent a market with optimization possibilities, as their efficiency refers. The reason is that although those motors losses are no more than 10% of the total losses estimated in the U.S.A. in 1977, they have -quantitatively in terms of production- a considerable importance, because they represent about 90% of the total number of motors produced in the U.S.A in 1977 and 60% of those produced in Japan during 1979.

Therefore, owing to the growing importance of power saving, constant efforts are made to optimize the efficiency of these motors. This is the aim of the recommendations made by the Japanese Ministry of Industry and Foreign Trade (3) (Moonlight Project), and by the U.S. Dept. of Energy (4), which recommend the use of the lowest silicon grade magnetic steel sheet instead of carbon mild steel sheet in fractional and small sized motors respectively.

Within this context I will define the object of this report: To produce low silicon non-oriented magnetic sheet, with adequate magnetic and mechanical characteristics, for fractional, small and medium sized motors. All of it by the development and implementation of a siderurgical process, adequate for the required characteristics, and involving minimum costs.

2. PHYSICAL AND METALLURGICAL PRINCIPLES

In accordance with this purpose, it is necessary to consider first the relative importance of the several magnetic characteristics for this range of motors, then we can optimize them by means of the study of the several variables which affect these and the consequent adequacy of the siderurgical process.

We may consider first the range of fractional motors ($<$ 1 h.p.). In this case stator copper losses become specially important owing to the high exciting currents required.

These currents are a function of the motor apparent permeability. This permeability, in turn, depends on the relative importance of the material and air gap permeabilities, the whole being conditioned by the motor geometrical design.

These copper losses may be expressed as a function of the apparent permeability, as follows:

$$W_{copper} = K \frac{1}{\mu'^{2}_{apparent}}$$

Where:

$$\mu_{apparent} = f(\mu_{material}, \mu_o, \text{Geom. design})$$

Therefore, in this case, the importance of permeability is evident, owing to its influence on the copper losses.

But, as the motor size increases -small and medium sized motors- the relation between air gap dimension and outside diameter becomes smaller. As a consequence the air gap permeability relative importance also decreases and the material is easier to magnetize. The result is that exciting currents required at the primary are lower, and copper losses -and their relative importance- become smaller.

On the contrary, the area/volume ratio decreases as the motor size increases, therefore heat transfers become more difficult and temperatures rise. As a consequence it is more important to limit total core losses, to a given value.

Therefore, it is necessary to obtain, for this range of fractional, small and medium sized motors, materials combining the following characteristics:

a) Electromagnetic characteristics:
   - Minimum possible total core losses.
   - Maximum attainable permeability.

b) Mechanical characteristics:
   - Adequate to guarantee material punchability.

It is known that, in the case of non-oriented magnetic sheet, the electromagnetic characteristics here indicated, depend mainly on the following variables:

- Silicon percentage.
- Grain size.
- Inner stresses generated during the manufacturing process.
- Impurities in the material.
- Material texture.

These last two variables -impurities in the material and its texture- are at the present the object of work and investigation, to improve non-oriented magnetic sheet electromagnetic characteristics.

If we consider first the impurities in the material, it is known that they generally have a negative effect on magnetic properties.

This negative influence is double:

a) By a direct action on magnetic properties, as a result of the impurities themselves, which:
   - Hinder the Bloch wall motion, by successive pinning of such wall, and increase the viscous friction coefficient.
   - Induce stresses as consequence of distortions produced in the crystal lattice.
   - Cause magnetic dilution effects.

b) By an indirect action, derived from the negative influence of such impurities on grain growing and material texture.

Therefore, in order to remove the negative effect of such impurities, in their direct and indirect form as well, their removal is carried out in the actuality by means of the adequate steel plant treatment. This treatment includes vacuum degassing and desulphurizing, according to modern siderurgical practices indicated by T.W. Smythe (5). This enables lowering oxygen, sulphur and nitrogen contents to less than 30 p.p.m.

As refers the second mentioned variable, i.e. texture developed in the material, siderurgical processes have been developed recently to achieve high permeability by inducing the adequate texture in fully and semi-processed non-oriented magnetic sheets (6) (7) (8).

As I have already mentioned, the elimination of impurities in the material, as well as the development of this kind of textures, are the present improvement trends in the quality of non-oriented high silicon magnetic sheet. However, because of the high cost of these siderurgical processes -and in accordance with the purpose of this work, i.e., to produce a range of steels adequate for fractional, small and medium sized motors- I will not apply these techniques. I will limit myself to the development of a conventional siderurgical process adequate for these materials.

Therefore, I will merely consider -to optimize afterwards the siderurgical process- the influence of the variables: steel silicon content and grain size, on the magnetic characteristics, losses and permeability.

- Silicon content influence.

In the case of these steels, the addition of different silicon contents produces the following known effects:

- Higher resistivity and lower magnetocrystalline anisotropy constant. The consequence of this is a reduction of eddy current losses and slightly lower hysteresis losses.
- Better mechanical characteristics, specially as punchability is concerned.
- Decreasing, for high induction, of the permeability values. This is due to the magnetic moment reduction per unit of volume, caused by silicon atoms magnetic dilution effect (9).

Therefore, it is necessary -specially for small and medium sized motors- to adjust silicon concentrations. The objective is to reach a balance between the advantages obtained: reduction of losses and improvement of mechanical characteristics, and its main disadvantage: reduction of permeability.

- Grain size influence.

As refers this variable, it can be said that, the remaining factors being constant:

. Hysteresis losses are inversely proportional to grain size.

$$W_h = K\ (1/D)$$

. Eddy current losses are approximately proportional to grain size.

$$W_f = K'\ (D)$$

The reason of this is the higher magnetizing energy, required by Bloch wall motion to overcome crystalline distortion inherent to grain joints. This implies that, in principle, it is better to have the lowest possible number of grain joints, in order to obtain minimum energy losses.

However, experimental tests show that, from a given grain size, the reverse takes place and losses increase. This may be due to eddy currents generated by Bloch wall motion, as suggested by R.H. Pry and C.P. Bean (10).

As an immediate consequence, it is interesting to fit the several stages of the siderurgical process to obtain the following: Optimum grain size and subsequent minimum total losses as well as adequate permeability. And all this depending on the material end use.

It is known that, in the case of our steels, the final grain size depends mainly on the following:

- Impurities in the material.
- Decarburizing grade attained in the first annealing.
- Cold reduction given to the material before the final annealing.
- Type of final annealing, as well as temperature and its soaking time.

We consider now the above items.

As refers the first one, impurities in the steel are decisive in grain growing. But I have already mentioned that I would not deal with them. The reason is the high cost to eliminate impurities in the steel plant, which is not in accordance with the type of material we want to produce.

Therefore, to obtain the required grain size increase in these steels, I will develop a siderurgical process including a decarburizing stage in open-coil followed by a critical reduction previous to the final annealing. This way, the parameters of the last three items become optimizing variables.

As refers these parameters, D.J. Knight and P.J. Adzema (11) carried out previous research on decarburized mild steel sheets for electrical applications. They reported that optimum magnetic characteristics were obtained for the bigger grain sizes and the lowest possible carbon contents. This corresponded to reductions, before the final annealing, between 4 and 10%, and the temperature of this last annealing was 760° C. These results agree with similar work carried out by the author (12) who reported 10% critical reductions before the final annealing at 780° C +/- 10° C.

More recently N.G. Bochkov and G.V. Parfenov (13) have worked on non-decarburized low silicon sheets obtained by a conventional process, and also M.A. Anan'evsky et al (14) on the same material processed by continuous casting. They report that optimum losses were obtained by reductions, before the final annealing, comprised between 3 and 8%. Then, such annealing consisted of 3-5 soaking hours at 850° C.

In both cases, the use of reduction ratios of less than 3-5% caused a band structure, where the coarse grain appeared at the periphery, and the core had a fine grain structure. On the contrary, reduction ratios higher than 5% caused a uniform structure, but with smaller grain size.

In our case, considering the low silicon content, specially in the range corresponding to fractional h.p. motors (0.35-0.58%) -and with the double aim of having a uniform metallographic structure, together with the right mechanical characteristics- we shall use reduction ratios between 8 and 12%.

3. SIDERURGICAL PROCESS

Figure 1, (A) and (B) shows diagrams of the siderurgical processes used to produce the non-oriented magnetic sheet object of this work. The first diagram corresponds to the fully-processed grade, exclusively obtained in the high silicon range (0.83-1.20%) to get the right mechanical characteristics. The second one corresponds to the semi-processed grade.

We will describe now, on the basis of the theoretical principles of the above paragraphs, the several steps that make up these siderurgical processes.

- STEEL PLANT PROCESS

The steel plant process to obtain these magnetic sheet grades is carried out in a conventional way, in B.O.F. converters. The reason is that the improvement of magnetic properties due to the use of other techniques -such as synthetic slag- does not compensate the overcost of using them (15). However, in our case the bath deoxidizing step deserves special attention. After that, and according to the required magnetic sheet grade, chemical composition adjustments are made by corresponding ferrosilicon additions.

Table I shows the chemical composition limits for these grades.

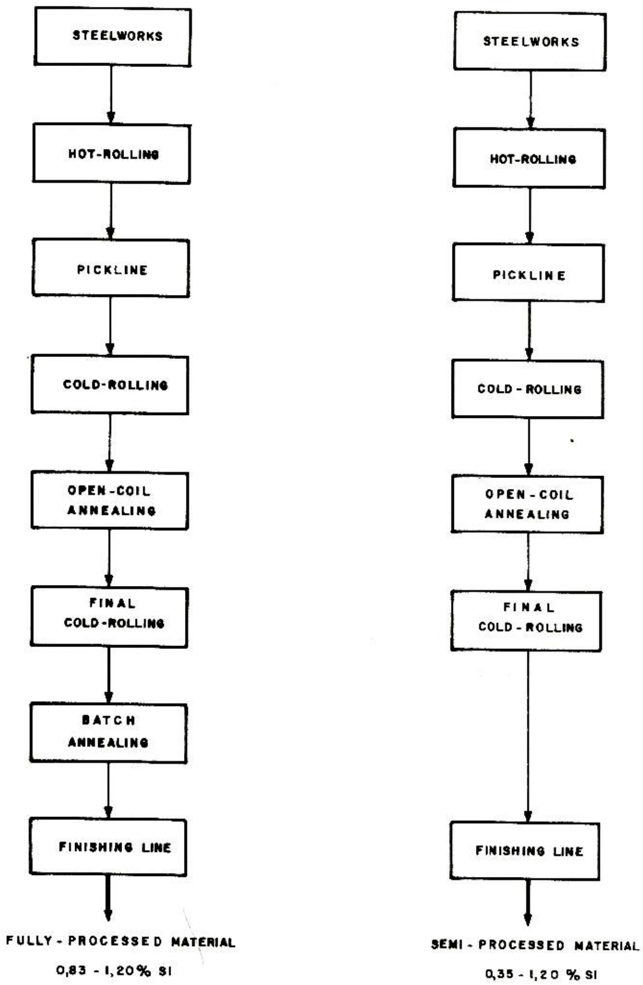


Fig. 1 - Siderurgical process diagram used in making non-oriented magnetic steel sheets, fully and semi-processed qualities.

- HOT AND COLD ROLLING

In the hot rolling step -depending on the silicon content- were used process temperatures between the following limits:

Rough rolling temperature : 950-870° C
Finish rolling temperature : 860-790° C
Coiling temperature : > 720° C

This provides hot rolled material with thicknesses between 2.55 and 2.70 mm.

The cold reduction process is carried out in a single step including reduction rates of about 80%, obtained by means of adequate high saponification emulsion index.

- DECARBURIZING ANNEALING

This step comprises a decarburizing annealing to reduce carbon content to less than 0.005%.

For this annealing I shall use the open coil system. The reason is that it is possible to make here a decarburizing annealing under temperature A_1, and -owing to our steel chemical composition- the grain columnar structure, that would be caused by continuous annealing at higher temperature (16) (17), does not appear. Besides, in our case, the production of this type of furnace is not so high as the one corresponding to high silicon contents.

Figure 2 shows a sketch of the decarburizing cycle to produce these materials, according to values measured by the author.

A more complete survey of the equipments, as well as of the theoretical principles and factors affecting the decarburizing processes kinetics -specially as refers the annealing atmosphere- may be seen in previous studies by the author (18) (19) (20).

A special mention has to be made -owing to the final use of these materials- to prevent as far as possible, any oxidation of the material. The reason is, according to recent works by G.P. Huffman (21) and A.L. Geiger (22), an oxide sublayer generated near the gas-metal interface, during the decarburizing process, that deteriorates magnetic properties, taking into account the additional difficulty in commutation by the Bloch wall movement.

TABLE I

CHEMICAL COMPOSITION OF THE MAGNETIC SHEET DEVELOPED IN THIS WORK

ELEMENT	%	MAX. % ACCEPTED
C	0.03-0.09	0.12
Mn	0.25-0.30	0.45
Si	0.35-1.20	-
Al	0.001-0.003	0.005
P	0.012-0.020	0.030
S	0.010-0.020	0.030
Cu	0.002-0.006	0.020
Ni	0.010-0.015	0.015
Cr	0.004-0.006	0.015
Mo	-	0.015
As	-	0.010
Sb	-	0.010

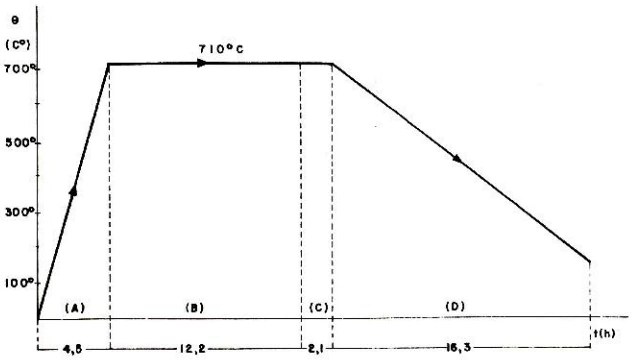
- FINAL ANNEALING

In the case of our materials, this final annealing, including a grain growing step, may be provided by the customers or carried out in tight coil, as final step of the siderurgical process.

In this last case, the process is carried out according to the following steps:

. Heating and soaking stages.

Both stages are closely related, as their correct combination is necessary to reach the right temperature and its uniform distribution in the whole load. These two things are specially important for magnetic materials.



(A) : HEATING STEP : Gas flow 35,5 $m^3/h.$, H.N.X.
Steam injection : 620°C

(B) : SOAKING STEP : Gas flow 65 $m^3/h.$, H.N.X D.P.: 28°
Steam interruption in % CO ≃ 0,5 %

(C) : DRYING STEP : Gas flow 35,5 $m^3/h.$, H.N.X.

(D) : COOLING STEP : Gas flow 35,5 $m^3/h.$, H.N.X.

Fig. 2 - Diagram of the decarburizing cycle in the open-coil annealing process. Weight of coils ≃ 20 Tm.

Therefore, I shall begin the soaking stage when the thermocouple indicates a temperature in the material between 800° and 830° C, depending on the silicon grade that is processed. This temperature is maintained, to have an homogeneous load, during a time period between 10 and 16 hours, depending on several factors among which: weight and number of coils on the base and geometrical dimensions of these coils.

. Cooling stage.

This process stage is particularly important owing to the negative effect exerted by the material residual inner tensions on magnetic properties, hysteresis losses and permeability. Therefore, cooling from soaking temperature must in no case take place at a rate higher than 25° C/hour. In this sense the advantage of batch furnace cooling is evident, against the one taking place in a continuous furnace, where it is more difficult to diversify and control such cooling rates.

4. TEST CARRIED OUT AND RESULTS OBTAINED

Starting with experimental heat (50 tons each), processed according to the above mentioned siderurgical methods, we obtained samples corresponding to the several silicon levels in their fully and semi-processed qualities. As refers the latter ones, such samples were taken from the material after the critical reduction, then submitted to a controlled final annealing in a laboratory furnace and tested after this.

As refers physical and chemical tests, they were carried out in a similar way to what has been reported in previous works of the author (23). Losses and permeability tests were made according to A.S.T.M A.343-69.

Tables II and III show the final average results of all these tests.

From these results, corresponding to tests made for both qualities and in all silicon levels, we deduce immediately what follows: Owing to the low mechanical characteristics obtained in the low silicon range (0.10-0.58%), with the fully processed quality, these materials cannot be processed at industrial level, and it is necessary to use higher silicon contents.

As for the magnetic characteristics, losses and permeability, it is possible to set -as comparison- the equivalence between the qualities so obtained with reference to the values required for the several silicon levels according to A.S.T.M A.677-77, A.683-77 and DIN 46.400 (1^{st} and 2^{nd} part) specifications. It is worth mentioning that in the case of permeability, the values obtained here are much higher than the ones mentioned in the specifications, which makes them specially adequate for their end use.

As refers the metallographic structure, and according to the observed samples, it is possible to state that such structure is an equiaxial one, and with a grain size between 2 and 3 in the A.S.T.M scale.

About this, from the several tests made by the author on the materials considered, and the remaining factors being constant, we deduce what follows: The value of total losses decreases steadily as the grain size increases, then it increases again from a grain size of about 170 μm (A.S.T.M ≃ 2). The values mentioned in this respect vary from 100 μm (A.S.T.M ≃ 4-3) reported by H. Shimanaka (24) to 180-240 μm (A.S.T.M ≃ 2-0) as indicated by T.W. Smythe (25) for non-oriented magnetic sheets with silicon contents of 1.8 and 3% respectively.

Finally, with the double objective of an economic optimization of the manufacture of our fully-processed quality in the high silicon level (0.83-1.20%), and of improving at the same time the punchability of the material so obtained, we modified the siderurgical process used to produce these materials (Fig. 1). Such modification was the increase of phosphorus content to levels between 0.08 and 0.12%, eliminating simultaneously the critical reduction stage and combining in a single duplex annealing the steps corresponding to decarburizing annealing and final annealing. For this it was necessary to self-sustain the second coil loaded in the open-coil plant.

TABLE II

MAGNETIC AND MECHANICAL CHARACTERISTICS CORRESPONDING TO FULLY PROCESSED MATERIAL

% Si	ρ $\mu\Omega/cm^3$	e mm.	W_{50} 10,000	Watts/Kgr 15,000	μ 50 Hz P 15000 Gauss/Oe	MECHANICAL CHARACTERISTICS R Kgr/mm^2	E Kgr/mm^2	A % Iso 80x20
ZERO	14.6	0.50	3.10	6.95	2,920	Mild steel sheet, decarburized by open-coil.		
0.10	15.8	0.50	2.71	6.35	2,810	31-32	18-20	33-35
		0.63	3.14	7.07	2,860			
0.35	18.4	0.50	2.61	.6.12	2,290	33-34	21-22	32-33
		0.63	2.95	6.75	2,500			
0.58	20.8	0.50	2.41	5.85	2,110	34-36	22-23	30-31
		0.63	2.74	6.52	2,250			
0.83	23.5	0.50	2.21	5.48	2,040	35-37	22-24	29-30
		0.63	2.59	6.05	2,160			
1.00	25.4	0.50	2.15	5.00	2,020	37-39	23-24	29-30
		0.63	2.43	5.60	2,090			
1.20	27.6	0.50	2.03	4.35	1,950	38-40	24-24.5	28-29
		0.63	2.28	4.93	2,070			

TABLE III

MAGNETIC CHARACTERISTICS CORRESPONDING TO SEMI-PROCESSED MATERIAL

% Si	ρ $\mu\Omega/cm^3$	e mm.	W_{50} 10,000	Watts/Kgr 15,000	μ 50 Hz P15000 Gauss/Oe
ZERO	14.6	0.50	2.78	6.41	3,350
0.10	15.8	0.50	2.40	5.67	3,170
		0.63	2.66	6.54	3,310
0.35	18.4	0.50	2.35	5.58	2,670
		0.63	2.59	6.35	2,850
0.58	20.8	0.50	2.15	5.33	2,380
		0.63	2.41	6.04	2,590
0.83	23.5	0.50	1.97	5.03	2,260
		0.63	2.27	5.62	2,470
1.00	25.4	0.50	1.94	4.56	2,210
		0.63	2.14	5.21	2,370
1.20	27.6	0.50	1.83	3.98	2,180
		0.63	2.02	4.59	2,260

Mechanical characteristics are not specified, as they vary depending on critical reduction, according to customer specifications.

Fig. 3 shows a diagram of the process, together with the cycle used and the results obtained according to several experimental castings.

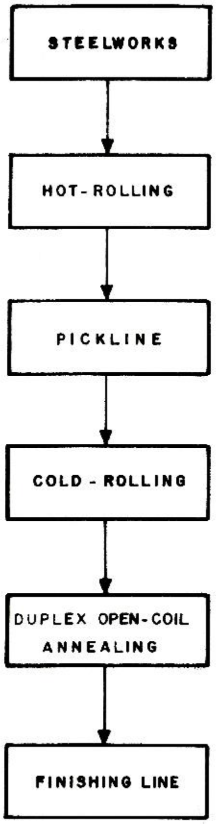
5. CONCLUSIONS

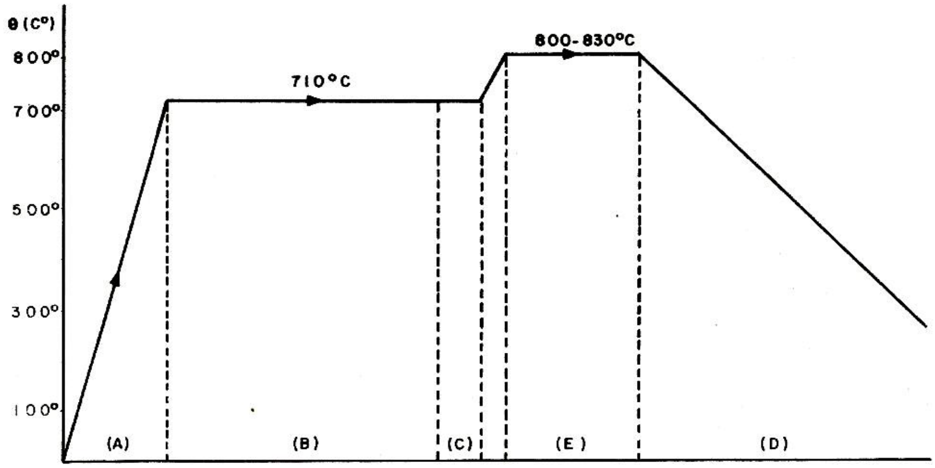
On the basis of the siderurgical process described here, and according to the results obtained, it is possible to produce a range of steels very adequate for fractional h.p., small and medium sized motors.

The low silicon range (0.35-0.58%), in its semi-processed quality is the most suitable for fractional h.p. and small sized motors, replacing carbon mild steel sheet, owing to its right combination of core losses and permeability.

As for the high silicon range, in its fully and semi-processed qualities, it is also a very suitable material for the manufacture of small and medium sized motors. The reason is that it combines adequate losses with permeability values higher than the ones required in the mentioned specifications.

From the operating point of view, the siderurgical process described here does not require special facilities to produce this type of steels. All equipments are conventional, except the open coil system, whose use, by the way, is not limited exclusively to the manufacture of this kind of steel. All this enables us to minimize the manufacturing process costs.





STEP (A) (B) (C) (D) : The same as shown in Fig. N°2

STEP (E) : Gas flow 35,5 m^3/h . Soaking time 6h

e (m m.)	% Si	% P	ρ $\mu\Omega/cm^3$	$W_{50}^{15.000}$ Watt / Kgr	$\mu_{50}^{15.000}$ Gauss/Oe	R Kgr/mm^2
0,5	0,87	0,08 0,12	26	5,90	1920	39-41
0,5	1,19	0,08 0,12	34	5,20	1860	42-43

Fig. 3 - Modification to the siderurgical process in the fully-processed quality.
High silicon level 0.83-1.20%.

Owing to all this -in accordance with the proposed objective- it is possible to produce a non-oriented magnetic sheet that combines, with its low manufacturing cost, a reduction of the motor operating costs. This reduction is obtained by an increase of the motor performance, and its market expectations improve as time goes on.

BIBLIOGRAPHIC REFERENCES

1. F.E. Werner - "Electrical Steels: 1970-1990" ENERGY EFFICIENT ELECTRICAL STEELS - PROCEEDINGS OF A SYMPOSIUM AT THE T.S.M.-A.I.M.E. FALL MEETING OF THE METALLURGICAL SOCIETY OF A.I.M.E. - PITTSBURGH, PENNSYLVANIA, OCTOBER 5-9, 1980, pp. (1-33), pp. 9.

2. Ref. Nº 1, pp. 17.

3. H. Shimanaka et al - "Recent Development of Non-Oriented Electrical Steel Sheets" - J. MAGN. MAGN. MATER. MAR. 1982, 26, (1-3), pp. 57-64, pp. 59-61.

4. U.S. Department of Energy - "Energy Efficient and Electric Motors" - CHAPTER IV: TECHNICAL AND ECONOMIC EVALUATION APRIL, 1978, pp. 57-85.

5. T.W. Smythe - "Electrical Steels Produced by Vacuum Degassing and Continuous Casting"- B.H.P. TECH. BULL. NOV. 1981, 25, (2), pp. 25-30.

6. I. Goto et al - "Development of a Non-Oriented Electrical Steel R.M-8 with High Magnetic Induction and Low Core Loss" - PROC. CONF. ON SOFT MAGNETIC MATERIALS, 3th CONFERENCE SEPT. 14-16, 1977, BRATISLAVA, CZECHOSLOVAKIA.

7. H. Shimanaka et al - "Non-Oriented Si-Steel Useful for Energy Efficient Electrical Apparatus" - PROCEEDINGS OF A SYMPOSIUM AT THE T.S.M.-A.T.M.E. FALL MEETING OF THE METALLURGICAL SOCIETY OF A.I.M.E., PITTSBURGH, PENNSYLVANIA, OCTOBER 5-9, 1980, pp. 193-204

8. H. Shimanaka et al - "A New Non-Oriented Si-Steel with Texture of {100}<o v w>" - J. MAGN. MAGN. MATER. 19 (1980), pp. 63-64.

9. P. Brissoneau - "Non-Oriented Si-Fe Sheets"- J. MAGN. MAGN. MATER. APR. 1980, 19 (1-3), pp. 52-59, pp. 54.

10. R.H. Pry and C.P. Bean - "Calculation of the Energy Loss in Magnetic Sheets Materials Using a Domain Model" - J. APPL. PHYS. VOL. 29, 1958, pp. 532-533.

11. D.J. Knight and P.J. Adzema - "Some Processing Factors Affecting the Magnetic Properties of Low - Carbon Steel" - TRANS A.S.M. VOL. 54, 1961, pp. 355-361.

12. I. Ibarrondo - "Estudio de la Descarburación de chapa de calidad comercial laminada en frío para la obtención de nuevas calidades de chapa magnética" - REVISTA DE METALURGIA C.E.N.I.M. VOL. 19 (1983) Nº 6, pp. 343-348.

13. N.G. Bochkov, G.V. Parfenov - "Effect of Temper-Rolling Schedules and of Recrystallization and Final Annealing on the Magnetic Properties of Dynamo Steel" - STEEL IN THE U.S.S.R. VOL. 5 Nº 3, MAR. 1975, pp. 166-168

14. M.A. Anan'evsky, N.G. Bochkov, G.V. Parfenov - "Formation of Structure and Texture in Unalloyed Electrical Steel" - STEEL IN THE U.S.S.R., JULY 1972, 2, (7), pp. 567-568

15. S.G. Afanas'ev et al - "Production of Oxygen-Converter Non-Oriented Cold Rolled Steel" - STAL IN ENGLISH Nº 3 MAR. 1969, pp. 259-262.

16. K.M. Gorman - "Formation of Columnar Grains by Decarburization" - INTER-OFFICE CORRESPONDENCE OF BETHLEHEM STEEL, 19 JANUARY 1981.

17. P.J. Adzema and D.J. Knight - "Columnar Grain Growth in Low Carbon Steel" - TRANS. OF THE A.S.M., VOL. 56, 1963, pp. 576-582.

18. I. Ibarrondo - "Contribuciones a la Optimización del Procedimiento Open-Coil" - TESIS DOCTORAL, ESCUELA SUPERIOR DE INGENIEROS INDUSTRIALES DE BILBAO (UNIVERSIDAD DEL PAIS VASCO), MAYO 1980.

19. I. Ibarrondo - "Contribuciones a la Optimización del Procedimiento Open-Coil" - V ASAMBLEA GENERAL DEL CENTRO NACIONAL DE INVESTIGACIONES METALURGICAS. (CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS). TOMO II (T-74), OCTUBRE 1981. MADRID.

20. I. Ibarrondo - "Contribuciones a la Optimización del Procedimiento Open-Coil" - DYNA Nº 11, NOV. 1982, pp. 25-29.

21. G.P. Huffman and E.B. Stanley - "Effect of Solute Oxidation on the Magnetic Properties of Non-Oriented Electrical Sheet Steel" - J. APPL. PHYS. MARCH 1979, 50, (3-11), pp. 2363-2365.

22. A.L. Geiger - "Effect of Internal Oxidation and Nitridation on the Magnetic Properties of Non-Oriented Electrical Steels" - J. APPL. PHYS. MARCH 1979, 50, (3-11), pp. 2366-2368.

23. Ref. Nº 14, pp. 346.

24. Ref. Nº 3, pp. 60.

25. T.W. Smythe - "Annealing of Electrical Steels" - MET. AUST. DEC. 1975 - JAN. 1976, 7, (11), pp. 280-282.