Magnetic Properties of Silicon Steel Wires

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Abstract. Silicon steel wire fabrication procedures were developed to improve its magnetic properties by increasing grain size and improving the crystallographic texture. Typical texture of steel wire has a fibre <110>//DD (drawing direction), which is not the best for magnetic properties. Three procedures were investigated: increasing the initial grain size prior to final drawing and final annealing, increasing final annealing temperature to achieve grain size above 200microns, and applying slight reduction + final annealing. Those procedures emulate the typical ones applied to NO electrical steels. B_{50} values of 1.64T and hysteresis energy dissipation of 225 J/m^3 were the best values obtained, with grain size of 125microns..

Introduction

There are patents [1,2] claiming the possibility of constructing transformers by using steel wires coiled around a copper conductor. To achieve a good performance, steel wires with the highest possible magnetic properties are necessary. This paper presents results obtained in a preliminary research on that topic, funded by Coelma SA, a Brazilian company owner of one of those patents [2].

The reference value of total magnetic losses to be reached with wires is that of steel sheets used in transformers. Magnetic losses at 1.5T, 60Hz of 1.1 W/kg (for 0,27mm thickness) were considered a suitable goal, as it is not expected to reach the very high permeability of the best grain-oriented sheets. It is convenient to apply the Loss Separation approach, to guide the interpretation of results. That value of total magnetic losses is achieved with classical parasitic losses of 0.3 W/kg (due to small sheet thickness, high electrical resistivity and high electrical insulation between sheets). Typical values of hysteresis losses are around 0.4 W/kg, corresponding to energy dissipation of 50 J/m^3 (obtained with large grain size, extremely sharp texture -- <001>//rolling direction – low non-metallic inclusion content and preferably a certain amount of tensile residual stresses). Excess losses are typically around 0.4 W/kg and depend on electrical resistivity and microstructure in a more complex way.. The challenge is to achieve such a mix of characteristics in wires. Presumably, the most difficult tasks are to produce a sharp <001>//drawing direction (DD) and to minimize residual compressive stresses.

Small values of classic parasitic losses should be easy to achieve, as the classic model predicts for wires a value that is approximately 1/3 of that for sheets, for identical maximum induction, frequency, thickness and electrical resistivity [3].

Large grain size can be achieved by different procedures: normal grain growth, inclusion-controlled abnormal grain growth and recrystallization after small strain, here to be called Strain Induced Boundary Migration – SIBM - recrystallization [4] (or, as some people call, strain induced abnormal grain growth [5,6]. As the inclusion-controlled abnormal grain growth is also dependent on a precisely controlled primary recrystallization texture [7], that route was avoided in this preliminary development. As a result, only normal grain growth and recrystallization after small strain routes were seek.

Literature indicates that the typical steel wire recrystallization texture follows closely the wire deformation texture, having <011>//DD [8], which is unsuitable for the objectives of this project. Bandhari and Cullity [9] described the possibility of changing texture by applying magnetic field, but the resulting texture was not interesting for the objective of this paper It was assumed that the most probable way to obtain a suitable texture was to seek ways to increase the grain size before final drawing, based on a very reproducible behaviour of steel sheet: increasing hot band grain size invariably results in an increase of a texture component with <110>//rolling direction [10].

High electrical resistivity can only be obtained by chemical composition. The highest possible silicon and aluminium content should be used, as long as the enough ductility is preserved. Laboratory cast samples were considered not suitable to minimize inclusion content. Instead, a high quality, commercial, non-oriented silicon steel continuously cast plate should be able to produce the intended high silicon content and low level of non-metallic inclusion formers.

No attempt was made to apply a tensile stress to the wire. Residual compressive stresses are to be avoided by applying a final annealing on the wire coiled in the diameter it should be used in magnetic measurement.

Experimental procedures

The raw material used for wire preparation was a section of a commercial non-oriented silicon steel continuously cast plate produced by Acesita. Its chemical composition is presented in Table 1. As expected, the content of the non-metallic inclusion formers (sulphur, nitrogen and oxygen) is very small. The silicon content is similar to that of the grain-oriented sheets. The presence of a high aluminium content leads to an electrical resistivity that is higher than that of the grain-oriented steels: x,x $\mu\Omega$cm. Its density was found to be 7595 kg/m^3, when measured by the hydrostatic method.

Table 1. Steel plate chemical composition

Si [%]	Al [%]	Mn	C [ppm]	S [ppm]	N [ppm]	O [ppm]
3,26	0,96		34	9	18	18

A 2kg bar was milled from the plate and hot rolled down to a 12 mm diameter bar. The bar was heated to 200° C and cold rolled to a diameter of 5 mm. Surface defects were detected, but it should not interfere with the following operations. After annealing at 760° C for 1h, the rod was submitted to drawing down to 1.6mm, reaching hardness of 212HV. A new annealing at 800° C for 1h, under a 90%N2 + 10%H2 atmosphere brought the hardness down to 189HV, grain size of 32 μm.

To increase the grain size before the final cold rolling, the wire was submitted to a small strain (10% area reduction, taking the diameter down to 1.51mm) followed by a new annealing at 800°C for 1h. The grain size reached 73 μm.

A new drawing operation took the wire to 0.76mm diameter. Annealing at 800°C for 1h led to a grain size of 43 μm. To follow the two different routes of grain enlargement, part of the wire was annealed again to produce normal grain growth -- annealing at 900° C for 1h – leading to a grain size of 124 μm (*sample A*). A second set, designed to increase grain size by primary recrystallization, was drawn to 0.74mm (a 5% area reduction) and annealed at 800° C for 1h, producing a final grain size of 112μm (*sample B*).

Difractograms and texture measurements were performed in sections whose normal was parallel to the drawing direction. (110) pole figures were obtained in a Shimadzu instrument, equipped with a texture goniometer. Intensity values are not comparable, as the sample area was not constant in all measurements.

For the magnetic measurements, samples with approximately 5g were coiled with a diameter around 80mm before been submitted to the two final annealings, described above. Primary and secondary copper coil with 300 turns were applied to each sample. Magnetic Loss at 1.5T was measured at 60Hz and quasi static condition. Total Loss was divided in its 3 components, hysteresis (using quasi static measurement), classical eddy current losses (calculated as indicated by Bozorth) and excess losses (by difference).

According to Bozorth [3], classical parasitic losses for cylinders should be calculated by the equation 1, where Φ for stands for wire diameter, B for maximum induction, f for frequency, ρ for resistivity and d for density. The main difference between the equation for sheets and for rods is the numerical factor 6, substituted for 16.

$$P = \frac{(\pi\Phi Bf)^2}{16\rho d} \quad (1)$$

Results and discussion

Figure 1 describes the evolution of some texture components at certain processing stages. Cold rolled and annealed 4.2mm wire shows a strong <110>//DD but some <100> and <211>//DD are also present. At the 1.6mm diameter stage, SIBM recrystallization increased grain size to 73µm. Subsequent drawing to 0.76mm increased <110>, while <100> and <211> almost disappears. Annealing brings back <211>, with little <100> change. So, contrary to what was expected, increasing previous grain size did not develop a <100>//DD component. Further grain growth (sample A) did not change the texture, while the SIBM recrystallization (sample B) had a profound texture change, when <211> is now the dominating component.
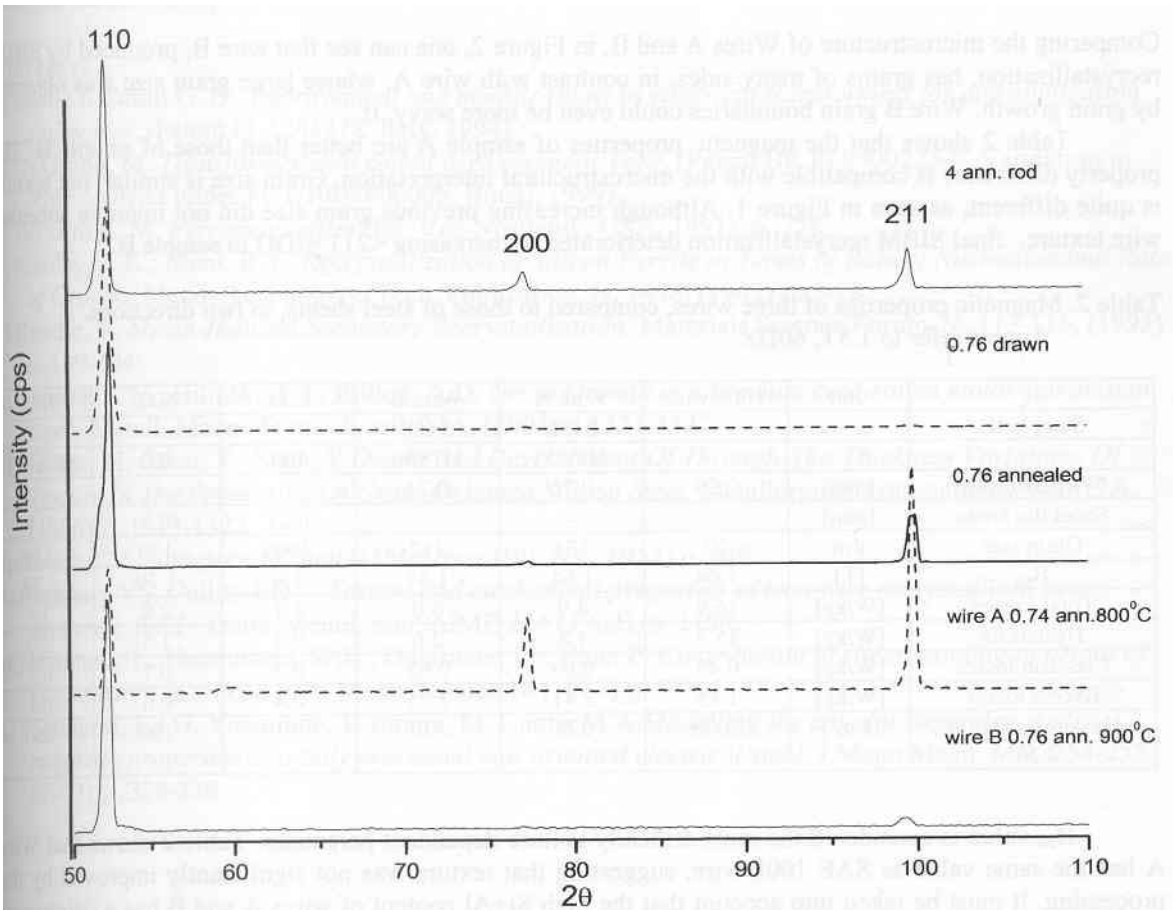

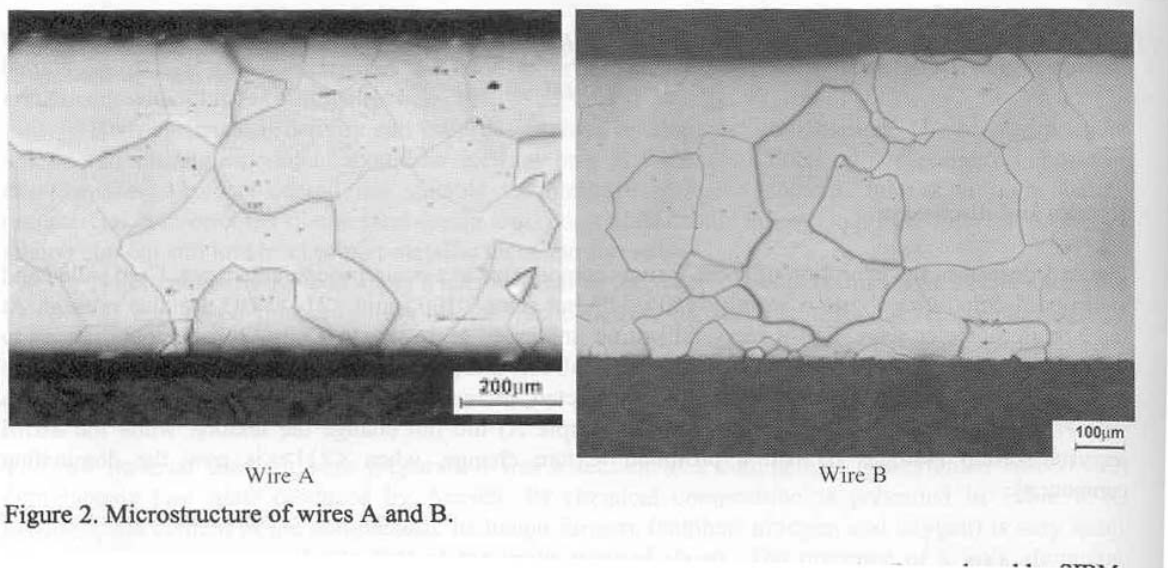igure 1. Co K alpha radiation diffractograms of wires in different processing stages.

Figure 2. Microstructure of wires A and B.

Comparing the microstructures of wires A and B, in Figure 2, one can see that wire B, produced by SIBM recrystallization, has grains of many sides, in contrast with wire A, whose large grain size was obtained by grain growth.

Table 2 shows that the magnetic properties of sample A are better than those of sample B. The property difference is compatible with the microstructural interpretation. Grain size is similar, but texture is quite different, as seen in Figure 1. Although increasing previous grain size did not improve annealed wire texture, final SIBM recrystallization deteriorated it, increasing <211>//DD in sample B.

Table 2. magnetic properties of two wires, compared to those a steel sheet, in two directions. .
Losses refer to 1.5T, 60Hz

	unit	1008 wire	Wire A	Wire B	G.O.	N.O.	N.O.
Sample ID			5151	5150			
			HT900	HT800	RD	RD	55°
Wire diameter	[mm]	0.29	0.76	0.74		-	-
Sheet thickness	[mm]	-	-	-	0,27	0,5	0,5
Grain size	μm	10	124	112	3000	130	130
B_{50}	[T]	1.64	1.64	1.47		1.70	1.58
Total Losses	[W/kg]	16.9	4.9	6.0	1.1	2.8	3.4
Hysteresis	[W/kg]	15.3	1.8	2.6	0.4	1.5	2.0
Classical losses	[W/kg]	0.45	0.69	0.65	0.3	0.7	0.7
Excess losses	[W/kg]	1.15	2.41	2.75	0.4	0.6	0.7
Hysteresis area at 1.5T	[J/m^3]	2000	225	330	50	190	250

B50 value is considered the most critically texture dependent parameter. Table 2 shows that wire A has the same value as SAE 1008 wire, suggesting that texture was not significantly improved by processing. It must be taken into account that the high Si+Al contents of wires A and B has a deleterious impact on B50: saturation magnetization is reduced from 2.1 to 1.9T, supposedly having a similar effect on B50. It deserves mentioning that the value obtained in Wire A is between the values for a sheet of a similar steel, as that property is strongly anisotropic [11]. It is somewhat surprising that wire B value is so much smaller than N.O. steel measured at 55o from Rolling direction, where <111>, the worst direction for magnetization, predominates.

Table 2 also shows that Total Losses obtained in the silicon steel wires are much higher than those of a grain-oriented steel and also higher than a non-oriented electrical steel sheet of similar composition, measured in two different directions [11].   Losses separation shows that hysteresis loss and of B_{50} value of wire A is between those of the N.O. steel in its best and worst directions, while wire B is worse in both properties. This means that the hysteresis loss of the two wires can be understood in terms of their texture. Nevertheless, the total losses of the two wires are much larger than the corresponding sheets. The main source of difference is the excess losses.

Excess losses are more than 3 times larger than its sheet counterpart. This might be due to wire diameter. SAE 1008 wire presents a much smaller value, but its grain size is much smaller too.

Conclusions

Total losses of a high silicon 0.76mm wire are much larger (4.9W/kg) than the values for a 0.27mm grain oriented sheet (1.1W/kg) and also larger than those of a 0.5mm sheet of similar composition (2.8W/kg). The main reason for the higher losses is the larger excess losses, while the hysteresis loss of the wire is similar to that of the non-oriented steel.

Acknowledgements

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