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Influence of Grain Size and Additions of Al And Mn on The Magnetic Properties of Non-Oriented Electrical Steels With 3 wt. (%) Si

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The influence of hot-band grain size and additions of aluminum and manganese on the magnetic properties of non-oriented grain (NOG) low-carbon electrical steel with about 3 wt. (%) Si were investigated using optical microscopy and X ray diffraction. The addition of manganese resulted in larger grains after final annealing. Coarse grains in the hot-band and addition of Mn led to a Goss orientation component after final annealing, which resulted in an increase in the magnetic permeability.

Keywords: *electrical steel, crystallographic texture, magnetic properties*

1. Introduction

Electrical steels play an important role in the generation, transmission, distribution and use of electrical power and are one of the most important magnetic materials. These steels are used mainly in electrical engines and transformers, whose efficiency is critically dependent on magnetic permeability and the losses due to eddy currents.

Grain size has a very strong effect on magnetic losses. As the grain size increases, hysteresis losses decrease; however, the anomalous losses increase. Therefore, there is an optimal grain size, between 100 and 150 μm[1]. Another important parameter in these materials is the crystallographic texture, due to a high anisotropy of the magnetic properties caused by the easy magnetization in the <100> direction[2].

Electrical engines use a variable magnetic field, parallel to the sheet surface. For this kind of use, the ideal steel would be the non-oriented grain electrical steel with a texture component {100}<0vw>, that is, grains with planes {100} parallel to the sheet surface and <100> direction uniformly distributed in the sheet plane.

The purpose of this work was to study the combined effect of grain size and additions of Al and Mn on the magnetic properties of fully processed non-oriented grain low-carbon electrical steel with about 3 wt. (%) Si. The steel was processed by hot rolling, coiling simulation, temper rolling, hot-band annealing, cold rolling and final annealing. For each processing stage, microstructural and crystallographic texture analyses were carried out by means of "Leica" model DMRM optical microscope and X ray diffraction, respectively.

2. Materials and Methodology

In this work, three plates of low-carbon steel of about 3 wt. (%) Si with different Al and Mn contents were used, as shown in Table 1.

The starting material was in the form of forged ingots of 40 mm of thickness. The samples were reheated for 20 minutes at 1150 °C and hot rolled, reducing the thickness to 3 mm. This was followed by hot coiling simulation at 700 °C, temper rolling with 10%, hot-band annealing for 3 hours at 800 °C to increase grain size, cold rolling with a total reduction of thickness of 75% and a final annealing for 30 seconds at 1000 °C.

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To better understand the sample symbols in the text, the Table 2 shows the nomenclature of samples indicating the used way of processing.

For texture analysis, the X ray diffraction technique was used, generating ODFs of the hot rolled, hot-band annealed and final annealed samples. It was utilized the Bunge notation for the ODFs.

Magnetic properties were measured using a Brokhauss instrument and the MPG X'Pert application for Windows. Before the measurements, the samples were pickled with HCl 20% and distilled water 80% for 15 minutes and with a solution with HF 5% and H_2O_2 95% for 3 minutes. The magnetic properties were measured in the rolling direction, where the dimensions of the samples were 95 x 30.5 x 0.93 mm. The magnetic properties measured were: magnetic polarization at 5000 A/m with 60 Hz (J_{50}), total magnetic loss ($P_{15/60}$) and relative magnetic permeability ($\mu_{r15/60}$) at induction of 1.5 T with 60 Hz.

3. Results and Discussions

3.1. Microstructural analysis

The hot rolled samples presented similar microstructures, characterized by a partially recrystallized ferritic bulk. This type of microstructure is common for low-carbon steel with a high silicon content (above 2.5 wt. (%) Si), that promotes the ferritic microstructure from the liquid phase, as shown in Figure 1. Haratani et al.[3] found a similar microstructure in hot rolled steel with 2.98 wt. (%) Si.

The microstructure of the samples with high manganese content (composition C in the Table 1) and hot rolled with a reduction of thickness of 90% presented a hardening structure with deformation bands (Figure 2). This characteristic is attributed to a higher Mn content (0.54 wt. (%)), which, according to Cunha[4], provides the stabilization of manganese sulfate (MnS) that, during reheating, probably precipitates in the fine form and dispersed particles.

Material C presented lower hot-band grain size relative to the other materials. This fact can be justified by its hot rolled microstructure that presented greater strain hardening and deformation bands in

Table 1. Chemical composition of sheet samples wt. (%).

Identification	C	Si	Mn	Cr	Ni	Mo	Al	P	S	N
A	0.004	3.25	0.05	0.07	0.04	<0.01	0.51	0.011	0.004	0.0015
B	0.005	3.2	0.04	0.06	0.05	<0.01	**1.06**	0.011	0.0038	0.001
C	0.006	3.18	**0.54**	0.07	0.04	<0.01	0.58	0.012	0.005	0.0014

Table 2. Samples nomenclature.

Nomenclature	Description
HR	Hot Rolling
HB	Hot Band with hardening rolling of 10% and annealing at 800 °C
CR	Cold Rolling of 75%
FA	Final Annealing at 1000 °C after Cold Rolling
W	This letter in the beginning means samples without hardening rolling and hot band annealing
2	Hot Rolling with finishing temperature of 910-940 °C, 5 passes, total reduction of thickness of 87.5%
4	Hot Rolling with finishing temperature of 740 °C, 6 passes, total reduction of thickness of 90%
RD	Rolling Direction
ND	Normal Direction

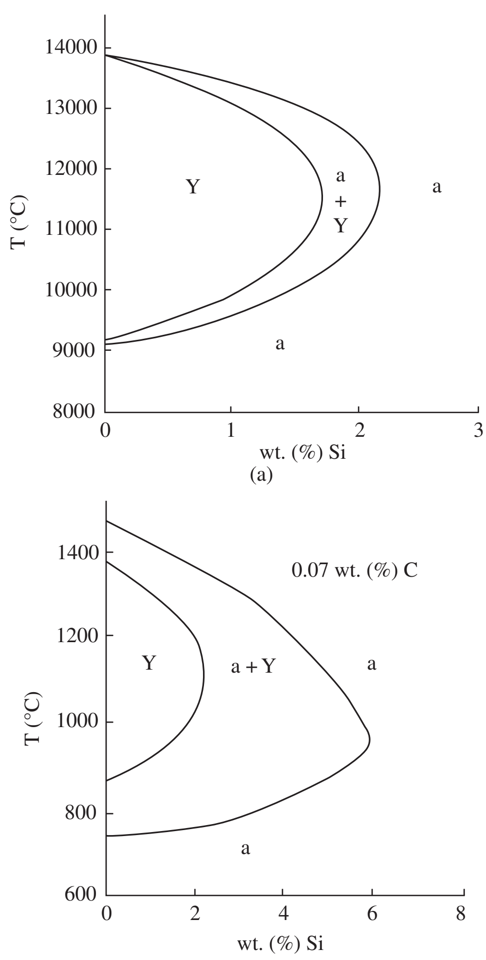


Figure 1. Fe-Si diagram, a) rich region in Fe; b) the effect of the 0.07 wt. (%) C addition in this diagram region[3].

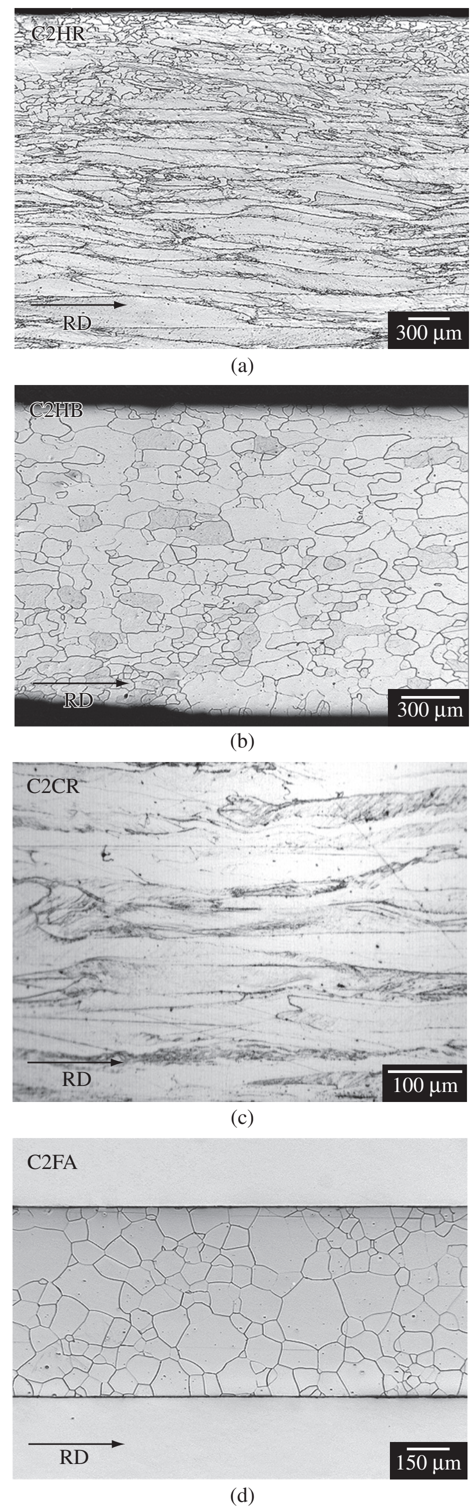


Figure 2. Micrographs of C2 sample: a) hot rolled, b) hot-banded after temper rolling and annealing at 800 °C, c) cold rolled with reduction of thickness of 75%, and d) final annealing at 1000 °C.

the bulk or, in other words, greater stored energy. Therefore, during hot-band annealing, there will be greater nucleation in the beginning of the recrystallization, resulting in smaller grain size. All the samples presented a totally recrystallized microstructure after the final annealing. The grain size varied as a function of the chemical composition with the "C" sample presenting the largest grain size. Therefore, addition of manganese was more efficient for the grain growth in the last processing stage.

3.2. Crystallographic texture analysis

The following main orientations and fibers were found for each processing stage in the crystallographic texture analysis:

- Hot rolled: most of the samples presented the {331}[116] texture component that is due to deformation bands formed near the sheet surface (Figure 3).
- Hot-band annealed: presence of the {001}<110> (rotated cube) component in almost all the samples, due to the SIBM mechanism. The presence of the Goss orientation peak in the sample C2HB was probably due to deformation bands in the hot rolled microstructure (Figure 4);
- Final annealing: all the samples that were submitted to the hot-band grain growth treatment showed a peak in the Goss orientation or close to it due to the presence of coarse grains before cold rolling, which gave rise to deformation bands. These bands are preferential places for the nucleation of grains with Goss orientation during recrystallization (Figure 5). Samples B2FA and WA4FA presented heterogeneities in the grain size where there were regions with coarse grains and others with fine grains (Figure 6). Coarse grains must be related to a high intensity {001}[110] (rotated cube) component, probably due to a (100)[011] component of the deformation texture.

The additions of Al and Mn gave rise to a <001> fiber //ND which is in agreement with the theory of oriented growth. In all the samples submitted to final annealing, it was observed the presence of the {332}<113> component, near to {111}<112>, that is common in the primary recrystallization texture of silicon steel with the BCC structure, possibly originated from the {112}<110> component of the cold rolling texture.

Type "C" material presented the largest final grain size (87.4 μm) and the highest intensity of the {332}<113> component, when compared with all the samples. This result showed that grain growth favored the strengthening of the {111}<112> orientation along the fiber <111>//ND.

Analysis of the magnetic properties (Table 3), of some samples, showed that the sample C4FA presented the highest magnetic polarization (1.72 T) which was explained by the presence of a Goss texture component with 5.7x random; {001}<150> (near to cube) with 4.4x and {110}<114> (near to Goss) with 4.4x. B2FA sample had the smallest value of magnetic polarization (1.69 T) due to its weak texture that presented Goss orientation with low intensity. Therefore, addition of manganese, probably, contributed to the development of a more appropriate texture for the magnetic properties. It is convenient to highlight that this magnetic polarization difference is significant since the measurement precision is thousandths of militesla.

The results of relative magnetic permeability $\mu_{r15/60}$ (Table 3) were consistent with the measured texture, since the C4FA sample presented the highest value and B4FA the smallest. These results suggest that the final reduction of thickness of 90%, in the hot rolling, produced the lower magnetic permeability for the material B. Therefore, addition of Mn favored the intensification of this property and that addition of Al was deleterious.

In the case of magnetic losses, two variables were important, the final grain size and the chemical composition. The empirical equation

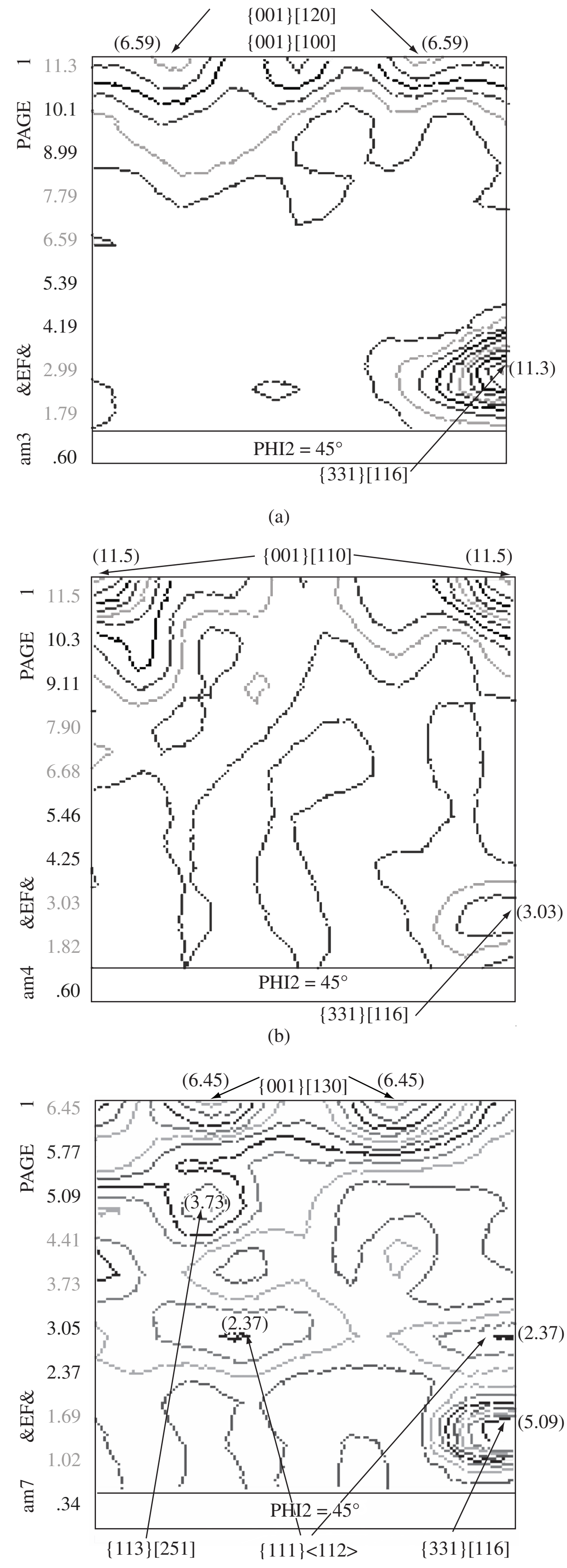


Figure 3. ODFs, section $\varphi_2 = 45°$, for a) A4HR, b) B2HR and c) C2HR samples, as hot rolled. The maximum intensities and J index are 11.45, 12.22, 6.82 and 3.18, 2.50, 2.31, respectively.

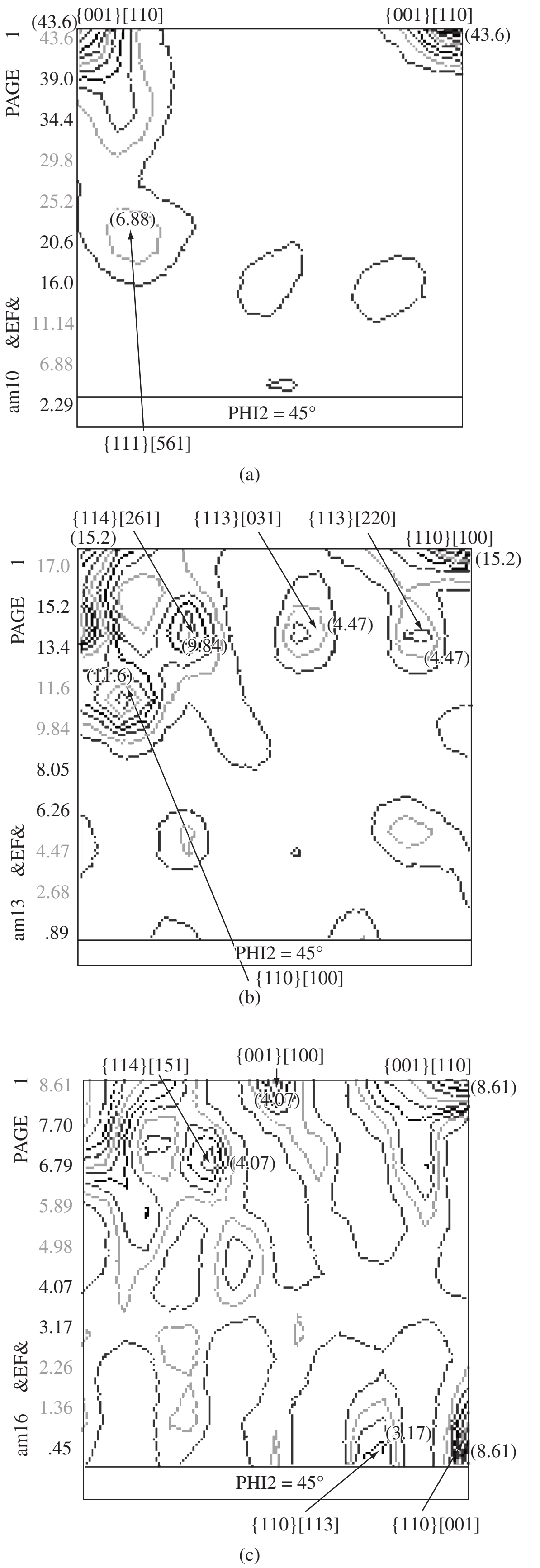


Figure 4. ODFs, section $\varphi_2 = 45°$, for a) A4HR, b) B2HR and c) C2HR samples after temper rolling and annealing at 800 °C. The maximum intensities and J index are 33.84, 12.38, 8.28 and 6.76, 3.75, 2.55, respectively.

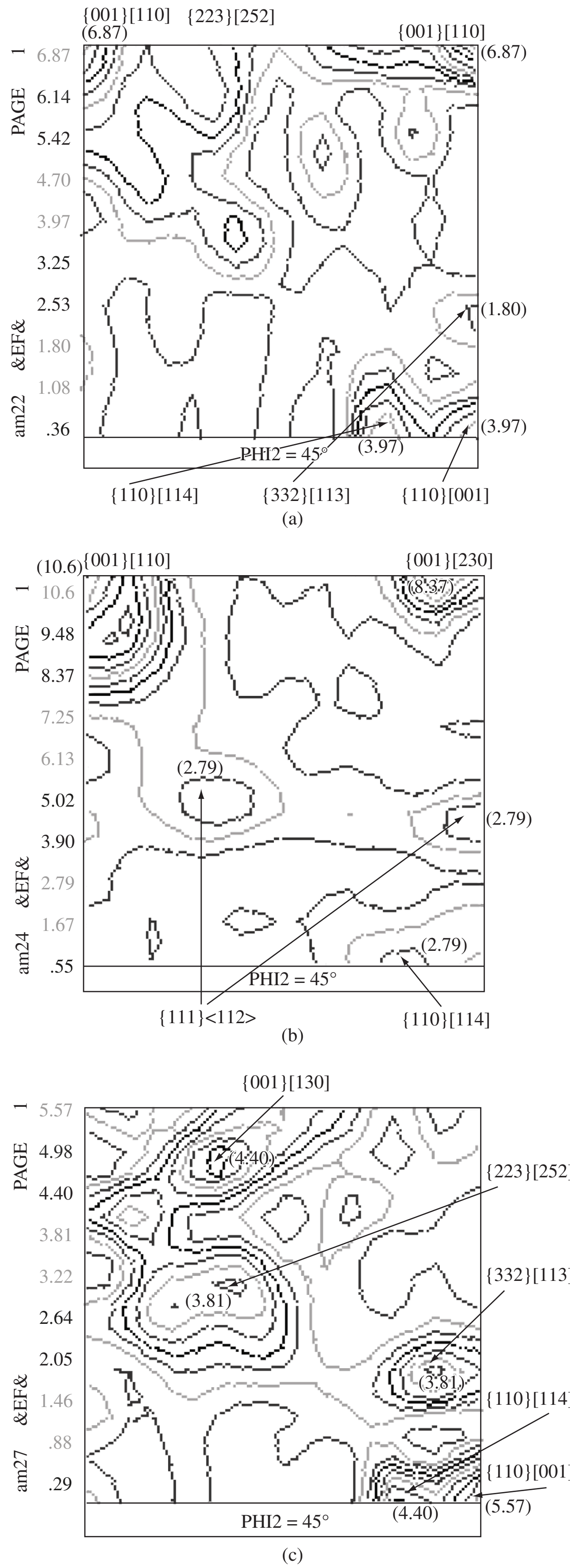
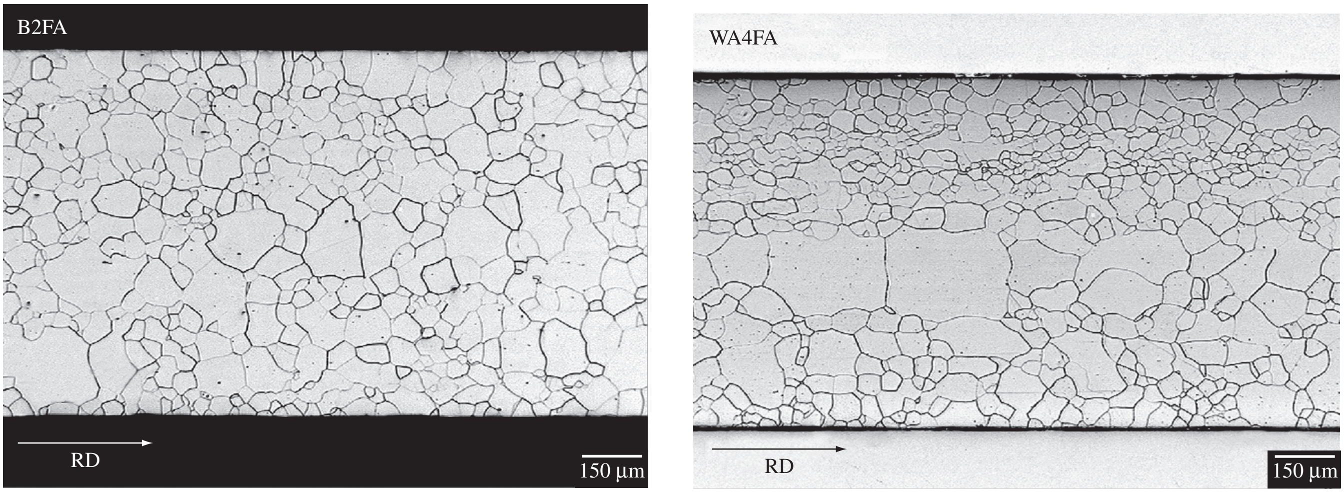


Figure 5. ODFs, section $\varphi_2 = 45°$, for a) B2FA, b) B4FA and c) C4FA samples after final annealing. The maximum intensities and J index are 6.95, 10.72, 5.66 and 1.93, 3.10, 2.14, respectively.



(a) (b)

Figure 6. Micrographs of final annealing at 1000 °C: a) B2FA with hot-band annealing, and b) WA4FA without hot-band annealing.

Table 3. Magnetic measurements and average grain size of B2FA, B4FA and C4FA samples.

Sample	Thickness (mm)	$P_{15/60}$ ($W.kg^{-1}$)	J_{50} (T)	$\mu_{r15/60}$	Average grain size (μm)
B2FA	0.92	3.6	1.69	961	62.3
B4FA	0.94	3.4	1.71	864	68
C4FA	0.93	3.55	1.72	1098	87.4

of resistivity (ρ ($\mu\Omega m$) = $0.12 + 0.11 (C_{Si+}C_{Al})$)[5] shows that addition of aluminum led to an increase of the electrical resistivity. Therefore, observing the Table 3 it can be noted that the sample B4FA with higher Al content presented smaller loss in relation with sample C4FA. The comparison between magnetic loss values of samples B2FA and B4FA shows the grain size influence, where the larger grain (sample B4FA) presented the smaller magnetic loss.

4. Conclusions

The microstructure of all the hot rolled samples presented partially recrystallized ferritic bulk, which is common for low-carbon steel with a high silicon content (above 2.5 wt. (%) Si). The addition of Mn and Al in the samples with hot-band annealing led to larger grain size in the final annealed state being the addition of Mn more effective.

The presence of a Goss orientation peak after hot-band annealing was attributed to deformation bands in the hot rolled microstructure. The presence of coarse grains before cold rolling gave rise to an increase of the Goss orientation after final annealing.

Additions of Al and Mn gave rise to fiber <001>//ND after final annealing, which is in agreement with the theory of oriented growth.

It was observed that the coarse grain size and addition of Al decreased the magnetic losses.

Acknowledgments

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