

EFFECT OF HIGH MAGNETIC FIELD DURING PRIMARY ANNEALING ON TEXTURE OF SILICON STEEL

C.M.B.Bacaltchuk^{1,3}, G.A.Castello-Branco^{1,3}, B. Gault¹, H.Garmestani^{1,2,*}

¹ FAMU-FSU College of Engineering & Center for Materials Research and Technology -1800 East Paul Dirac Drive, Tallahassee, Florida 32310, USA

² Georgia Institute of Technology - Materials Science and Engineering
771 N.W Ferst Drive, Atlanta, GA 30332, USA

³ Centro Federal de Educação Tecnológica -CSF-RJ, Rio de Janeiro, Brazil

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Abstract

Cold rolled silicon steel samples were annealed at 800°C for annealing times varying from 10 to 30 minutes in an inert atmosphere, and in the presence of a 17 Tesla magnetic field oriented parallel to the plane of the sheet. In order to evaluate the effect of the magnetic field, cold rolled samples were annealed at the same conditions as for the magnetic annealing but without the application of the magnetic field. The texture development was analyzed by means of Pole Figure and Orientation Distribution Function using X-Ray diffraction. Magnetic annealing was found to be more effective in enhancing the Goss component in the primary recrystallized microstructure. This finding suggests that silicon steel can be affected by an external magnetic field even when the material is found at its paramagnetic state.

Introduction

Grain non-oriented silicon steel is widely used in the electrical industry. This soft magnetic material has its main technological application in rotating electrical machinery in which the magnetic field is in the plane of the sheet, but the angle between the field and the rolling direction is variable [1]. Magnetic behavior is controlled by factors such as: final texture, average grain size, composition of the steel, purity level, strain, surface oxidation [2]. Texture, or crystallographic preferred orientation, is produced as a consequence of grain boundary migration during annealing (recovery, recrystallization, and grain growth) where new grains in the solid state are formed at the expenses of others. In the case of primary annealing, the driving force for the formation of new grains is the stored energy of the deformed grains. This preferential orientation of the new grains can be a result of: preferred nucleation, in which the preferred activation of some special nuclei determines the final recrystallization texture; or oriented growth, in which only grains having the best orientation relationship to the deformed matrix can grow and form the recrystallization texture [3]. It is believed that the preferred orientation is enhanced by the application of external fields and that the sample position with respect to applied magnetic field direction is significant. Magnetic annealing has been shown to have a significant effect on texture and microstructure evolution in ferrous [4,5,6,7] and non-ferrous alloys [9,10]. It has been noticed that annealing in magnetic fields retards recrystallization and consequently develops a texture different from that formed in the ordinary recrystallization process [4,5,6,7].

Experimental Setup and Procedure

The material used in this investigation was a grain non-oriented (GNO) low silicon steel, rolled at room temperature up to 75% reduction in thickness. The chemical composition of the sample is shown in Table 1. Coupon specimens 5 x 8 x 0.5mm were sampled from the sheet with the longitudinal axis parallel to the rolling direction. The magnetic annealing was carried out in a

cylindrical furnace that was inserted into the 195mm bore of the high field magnet. An alumina sample holder, containing the samples, was inserted inside the furnace and positioned at the center of the magnetic field. The samples were annealed at 800°C for annealing times varying from 10 to 30 minutes in an inert atmosphere, and in the presence of a 17 Tesla magnetic field oriented parallel to the plane of the sheet. The highest available field strength was used in order to maximize its influence on texture development. In order to evaluate the effect of the magnetic field, the cold rolled specimens were annealed at the same conditions (temperature, time and inert atmosphere) as for the magnetic annealing but without any magnetic field. Texture was measured using a Philips X'Pert MPD equipment. Pole figures and ODFs were calculated using PC-Texture 3.0 and PopLA software. Table 2 shows the nomenclature of the samples according to the mode of annealing and annealing temperature.

Table 1. Chemical composition

Material	%Si	%C	%Mn	%S	%N	%Al
Iron-Silicon	0.75	0.003	0.50	0.002	0.003	0.002

Table 2 – Identification of the samples according to their annealing mode and annealing time.

Sample	History
AR	As Received – 75% cold rolled
LM10	After magnetic annealing for 10 minutes
LM15	After magnetic annealing for 15 minutes
LM20	After magnetic annealing for 20 minutes
LM30	After magnetic annealing for 30 minutes
LO10	After ordinary annealing for 10 minutes
LO15	After ordinary annealing for 15 minutes
LO20	After ordinary annealing for 20 minutes
LO30	After ordinary annealing for 30 minutes

Results and Discussion

The so called Goss texture, $\{110\}[100]$, is a very attractive component of texture in magnetic materials since it has the highest permeability direction, $\langle 100 \rangle$, parallel to the rolling direction and the $[110]$ direction, which is an intermediate permeability direction, parallel to the normal direction $[10,11]$. On the other hand, the gamma fiber, $\{111\}\langle uvw \rangle$, is detrimental for the magnetic properties of silicon steel since $\{111\}$ is the lowest permeability direction. Fig 1 shows the $\phi = 0^\circ$ and $\phi = 45^\circ$ Orientation Distribution Function sections for the cold rolled sample (a) as well as for the samples annealed with (b-e) and without an applied magnetic field (f-i). The cold rolled texture, characterized by an intense $\{001\}\langle 110 \rangle$ component of texture and a strong α fiber (direction $\langle 110 \rangle$ parallel to the rolling direction) and γ fiber (direction $\langle 111 \rangle$ parallel to the normal direction), changed dramatically after annealing. For both annealing conditions, with and without the magnetic field, after recrystallization there was an increase in strength of the η fiber ($\langle 100 \rangle$ parallel to the rolling direction) and the maximum peak shifted from the α to the γ fiber. It is known that grains with Goss orientation are formed mainly at in-grain shear bands in $\{111\}\langle 112 \rangle$ deformed grains [2,12]. For that reason the volume fraction of $\{111\}\langle 112 \rangle$ grains decreases with the recrystallization. Similar results on silicon steels have been reported by others [2,12,13,14]. Fig.1, $\phi = 0^\circ$ ODF sections, shows that for the magnetic annealed samples, the texture development did not change much with the change in annealing time, however when comparing the samples annealed with field and without the field the difference in texture, number of counters and maximum values, can be seen. Fig.2 shows the intensity of Goss component before annealing and after annealing with and without an applied magnetic field. Magnetic annealing showed to be more effective in

increasing the volume fraction of crystals with their $\{110\}$ planes parallel to the sheet surface and $\langle 100 \rangle$ direction parallel to the rolling direction.

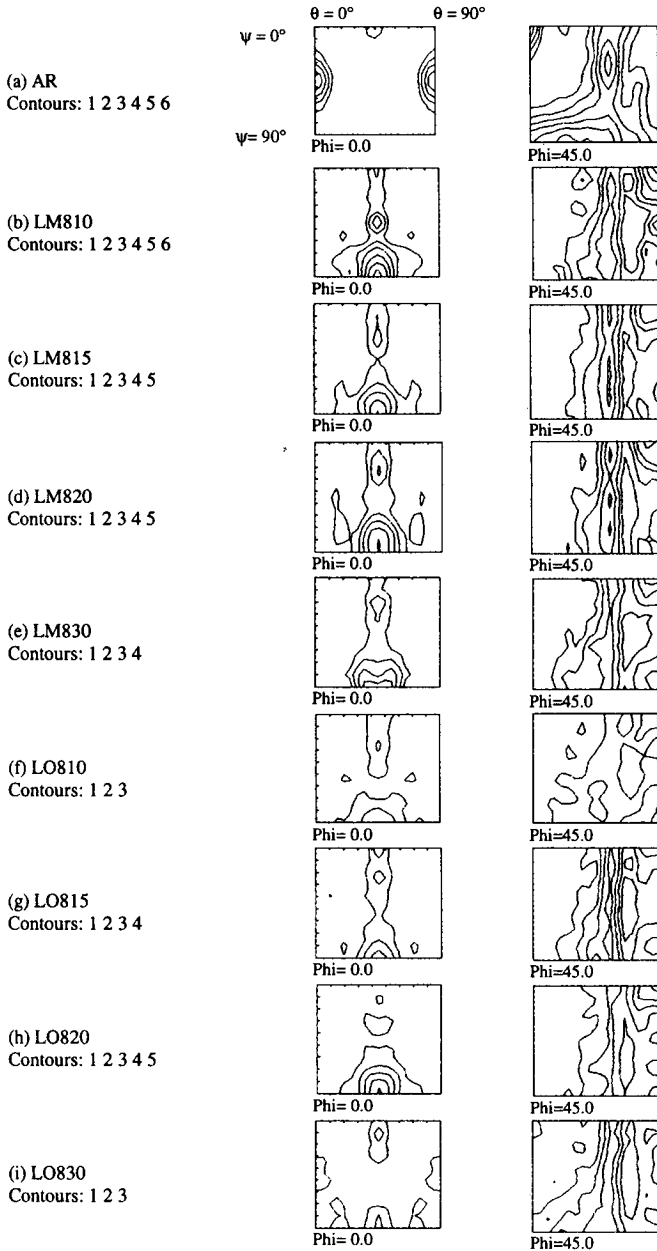


Fig. 1. $\phi = 0^\circ$ and $\phi = 45^\circ$ ODF sections, Roe notation, for the samples: a) cold rolled; annealed with magnetic field for b) 10 min., c) 15 min., d) 20 min., e) 30 min. and annealed without magnetic field for f) 10 min., g) 15 min., h) 20 min., i) 30 min.

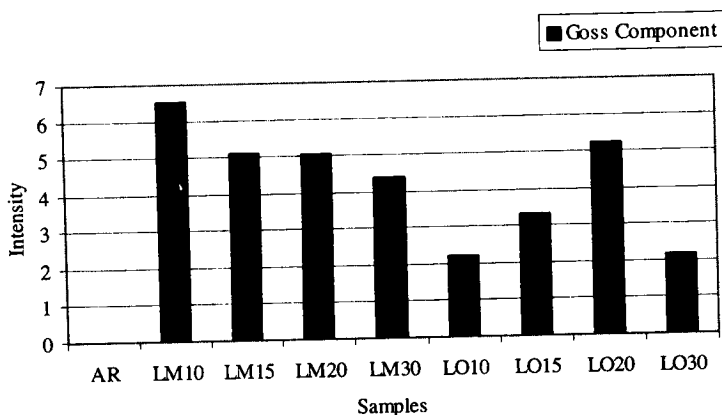


Fig. 2. Intensity of Goss component ($\{110\}\langle 001\rangle$) before annealing and after annealing with and without an applied magnetic field.

From the results shown in Figures 1 and 2, it appears that an external magnetic field enhances the growth of the Goss even at a temperature above the Curie temperature. Similar results were also found by Tsurekawa et al. [15] when sintering iron powder, in the paramagnetic range, in the presence of a magnetic field. As mentioned by Tsurekawa et al. [15], a possible explanation for the magnetic effect observed above the Curie temperature is that the magnetic moments are forced to orient along the magnetic field direction by an external magnetic field against the thermal motion of the atoms, which tends to randomize the directions of any moments that may be aligned. The forced magnetic ordering together with the magnetocrystalline anisotropy may provide a driving force for selective grain growth even above the Curie temperature.

Besides Goss component, the gamma fiber, $\{111\}\langle uvw\rangle$, is also another group of texture components to be examined when magnetic efficiency is required. Figure 3 shows the intensities on the gamma fiber after both magnetic and ordinary annealing. The results in Fig. 1 ($\phi = 45^\circ$ ODF sections) and Fig. 2 show that the gamma fiber decreased after both magnetic and ordinary annealing. Annealing without magnetic field, however, was more effective, on the average, in decreasing the volume fraction of crystals with their $\{111\}$ planes parallel to the sheet surface. A similar result was found by Xu and co-workers [16] when working with a 3% silicon steel sample.

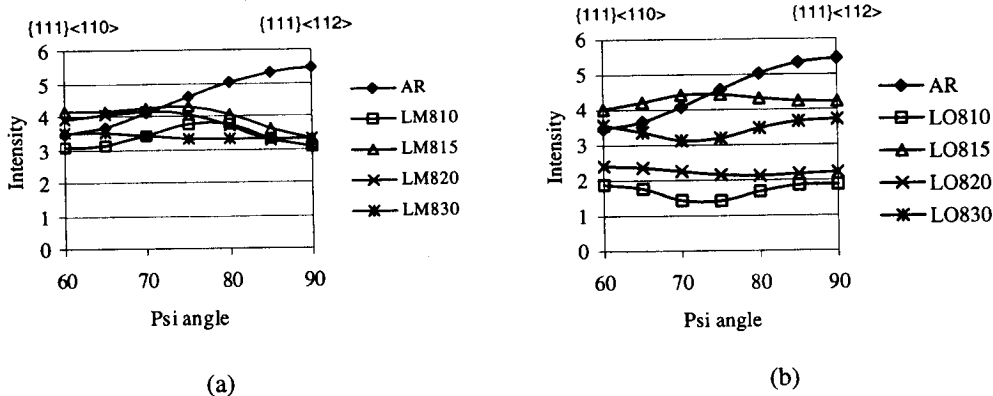


Figure 3 – Variation in intensity along the gamma fiber (a) after annealing in a magnetic field and, (b), after annealing without an applied magnetic field.

Conclusion

Magnetic field applied during primary annealing was found to increase the strength of $\{110\}\langle 001 \rangle$ component of texture and to decrease $\{111\}$ axis orientation. The intensity of the Goss component increased from zero, in the cold rolled state, to 6.5 times random after annealing for 10 minutes. The highest intensity of the Goss component found during the ordinary annealing was 5.2 times random after annealing for 20 minutes. For all the other annealing times (10, 15 and 30 minutes) annealing without magnetic field has shown to be less effective in increasing the volume fraction of Goss component.

The reduction of the intensity of the gamma fiber was more pronounced after ordinary annealing than after annealing in the presence of a magnetic field.

Even in the paramagnetic state (800°C), the magnetic field still affected texture development as evident from the intensification of the Goss component. This finding suggests that grain boundary migration in FeSi can be affected by magnetic field even above the Curie temperature, where spontaneous magnetization and magneto-crystalline anisotropy is no longer present.

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