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Texture Evolution In Fe-1%Si As A Function of High Magnetic Field

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Abstract. The effect of a 1.5T, 15T and 30T magnetic field on texture evolution in Fe-1%Si was investigated by annealing samples for 1 hour at 787°C, (27° above the Curie temperature, T_c = 760°C). The intensity of the Goss texture component increased with increasing field strength accompanied by a drastic increase in grain size.

Introduction

Over the past two decades, magnetic annealing has emerged as a major means of material processing and, has garnered much interest in areas such as grain boundary engineering [1]. Several workers have reported that field annealing effects changes in the texture, grain size distribution, grain boundary character distribution (GBCD), boundary migration, densification rates in powders and phase transformation temperatures [1-10]. Changes in the intensity of texture components have been found to depend on the field strength and direction with respect to the sample, as well as the annealing temperature. For example, Xu found that the intensity of the {111}<112> component increased after magnetic annealing of non-oriented Fe-3%Si samples below the Curie temperature [3]. Similarly, in [1] it was demonstrated that the average grain size of iron-50mol%cobalt ribbons annealed below the Curie temperature increased when the field direction was parallel to the surface of the ribbon. On the other hand, the average grain size decreased when the applied field direction was perpendicular to the surface of the ribbon. Still similar results were reported in [2] where the boundary velocity in a Bi bicrystal changed with the direction of the applied field. More recently it has become possible to perform annealing experiments in fields of 20T and above [2, 4]. Ludtka et al. observed that austenite decomposition is enhanced when samples are cooled in the presence of a 30T field subsequent to zero-field annealing [4]. The aim of this work is similar in concept; here we investigate the effect of magnetic annealing on the microstructure of Fe-1%Si as a function of field strength.

Experimental Methods

Non-oriented electrical steel specimens containing (weight %) Si: 1.12, C: 0.0038, Al: 0.31, Mn: 0.61, and N: 0.003 were used in this study. Samples were produced by a series of thermomechanical treatments including hot rolling at 1206.8°C, followed by hot band annealing in a 100% H_2 atmosphere; the hot end was held at 823.5°C (1540°F) for 18 hours while the cold end was held at 818°C (1530°F) for 1-2 hours in a 100%H_2 atmosphere. The material was subsequently cold rolled to approximately 75.5% reduction in thickness and then annealed at 588.6°C (1117°F) in a 100% H_2 atmosphere, followed by 8% temper rolling. From here on, these samples will be referred to as "As-received" specimens. In addition, other samples were produced by annealing the As-received samples at 787°C for 1 hour in an $H_2$15% + N_2 85% atmosphere. These samples will be referred to as QDA_0T. The average grain size of the As-received and QDA_0T samples were 50μm and 170μm respectively.

Specimens with average dimensions of 8mm×6mm×0.46mm were annealed in the presence of 1.5T, 15T and 30T magnetic fields using the apparatus described in [4]. The experiments were performed in Ar atmosphere followed by quenching in He gas. Field annealed samples were heated at a rate of about 7°C/s up to 787°C and held at that temperature for 1 hour with the applied field parallel to the sample rolling direction. After annealing it was observed that the samples had rotated about 5° with respect to the field direction. Samples were electropolished using perchloric acid solution in order to perform microtexture measurements. An integrated scanning electron microscope (Phillips XL40 FEG) - EBSD mapping system (TexSEM Laboratories, Inc.) was used to obtain crystallographic orientation data from each sample, with a resolution of 20μm.

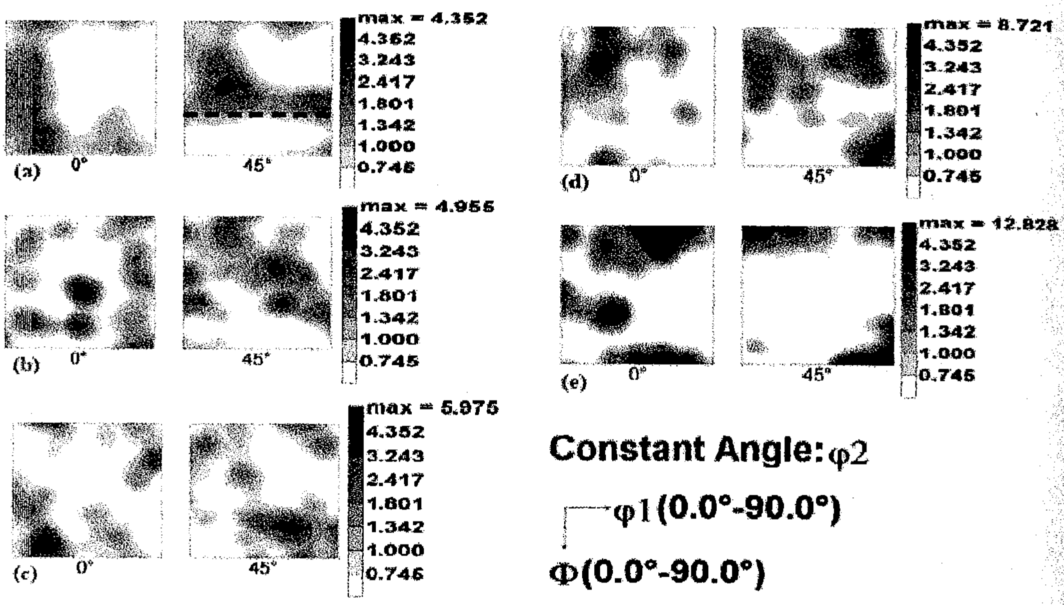

Fig. 1: 0° and 45° sections of the Orientation Distribution Function (ODF) for (a) As-received, (b) QDA_0T, (c) Field annealed 1.5T, (d) Field annealed 15T and (e) Field annealed 30T samples. The dashed line denotes the position of the γ fiber in the 45° section. The Goss components are located at $(\phi_1, \Phi, \phi_2) = (0°, 45°, 0°)$ and $(90°, 90°, 45°)$.

Results

The As-received material showed a weak preference for grains with the {110}<001> Goss orientation located at the $(\phi_1, \Phi, \phi_2) = (0°, 45°, 0°)$ and $(90°, 90°, 45°)$ positions in Fig. 1(a) while the dominant component in the QDA_0T material was found to lie between $(111)[\bar{3}21]$ and $(111)[0\bar{1}1]$. The intensity of the Goss component increased with increasing field strength while the reverse is true for components along the γ fiber. In fact, increasing the field strength to 30T severely decreased the intensity of most of the components along the γ fiber. On the other hand, the intensity of the (90°, 90°, 45°) variant of the Goss component increased to greater than 12 times that expected in a completely random material. Strong peaks were also observed for the $(001)[1\bar{1}0]$ and $(001)[\bar{1}\bar{1}0]$ located at (0°, 0°, 45°) and (90°, 0°, 45°) respectively, as illustrated in Fig. 1(e).

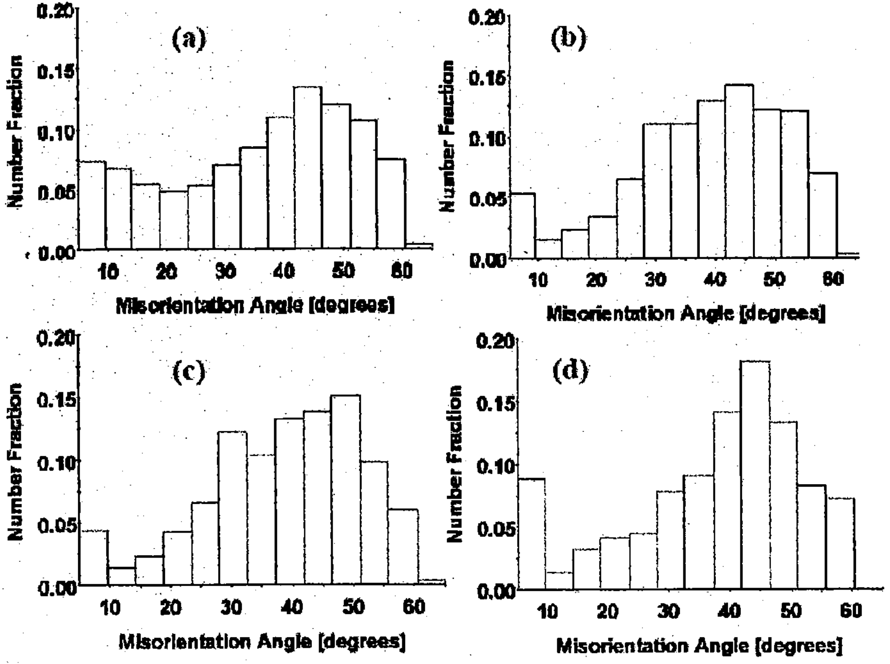

Fig. 2: Misorientation angle distributions for (a) As-received, (b) Field annealed 1.5T (c) Field annealed 15T and (d) Field annealed 30T samples.

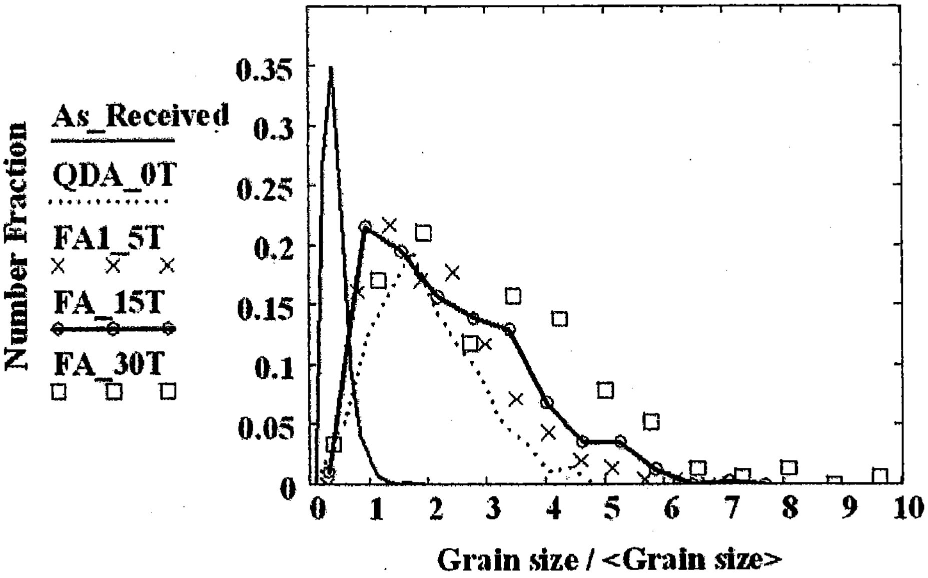

Fig. 3: Grain size distribution in all samples. The x-axis shows the ratio of the actual to the average grain size obtained by averaging the combined data from all samples. FA1_5T, FA_15T and FA_30T denote samples annealed with 1.5T, 15T and 30T field strengths respectively.

The misorientation angle distributions are displayed in Fig. 2. All are similar to the Mackenzie distribution [11] associated with randomly oriented (cubic) materials except with a larger fraction

of low angle grain boundaries. There is no significant change in the distributions when the As-received material is compared to samples annealed in the presence of the magnetic field.
Significant grain growth occurred in all annealing cycles. The grain size data from all five samples were combined and averaged. The average grain size of all samples was found to be 116μm. The x-axis of Fig. 3 shows the ratio of the actual to the averaged grain size. The distribution broadens with increased field strength to reveal that samples annealed with a 30T field had some grains whose size were approximately 10 times the average value. 35% of all grains in the As-received materials were approximately half of the average size. 19% of grains in the QDA_0T samples were twice the average but did not exceed 5 times the average grain size.

Discussion

Though the field annealed samples did not exhibit a strong preference for a single orientation, the results are consistent with those presented in [4] and [8] with regards to the increased intensity of certain texture components after field annealing. It is evident that field annealing increased the intensities of the {110}<001> Goss component. The initial presence of the γ fiber stems from this being a texture typical of rolled bcc metals [12]. The increase in the intensity of the Goss texture component suggests that this is a preferred low energy orientation of crystals that undergo magnetic annealing for this time and temperature.
It is not unreasonable to think that the 8% temper rolling imparted different amounts of strain to certain grains based on their specific orientations and, an external field changes the grain growth kinetics of these crystals as compared to an anneal without a field. At this point it should be emphasized that the QDA_0T samples were annealed in a reducing $H_2$15% + N_2 85% atmosphere that decarburizes the material and therefore removes precipitates from the grain boundaries [13]. However, the field annealing was performed in an inert Ar atmosphere which means that decarburization did not occur. The effect of the magnetic field is therefore highlighted here since one would expect that boundaries free of precipitates should migrate faster and further than those experiencing drag. The fact that the grain sizes increased so drastically during magnetic annealing suggests that the field had a considerable effect on grain boundary migration and hence the grain growth kinetics. With only increased intensities in the Goss components, it is not surprising that the misorientation angle distribution in each case looks very similar. The large percentage of high angle boundaries is attributed to the fact that the material is not dominated by a single crystal orientation in which case, the fraction of low angle boundaries is expected to be significantly higher. The results may also be explained in terms of the effect of annealing temperature as follows: the application of a 30T magnetic field stabilizes the ferromagnetic phase with respect to the paramagnetic phase *via* the Zeeman energy $\mu\vec{\mathbf{M}}\bullet\vec{\mathbf{H}}_a$ [14]. The Curie temperature is the temperature at which a ferromagnetic phase becomes paramagnetic with no applied external magnetic field. The well known tails to the measured magnetization versus temperature plots show that some amount of order of the magnetic moments exists above the Curie temperature when an external field is applied to the ferromagnetic material. The recent modeling performed by Joo et al. demonstrated that even the paramagnetic ferrite to austenite transformation occurs at a higher temperature when a magnetic field is applied [15]. This effect of the applied magnetic field may account for the fact that the texture did not decrease as in the case of the QDA_0T samples. The growth of the Goss oriented grains is also understandable from a magnetocrystalline anisotropy viewpoint. Crystals with the Goss orientation, {110}<001>, are oriented along the magnetically easy axes of the material. Since the field was applied parallel to the [100] rolling direction then less energy is required to align the Goss oriented crystals with the field direction and hence, their growth is favored [14]. Experiments will be conducted in the same atmosphere (Ar) without the field to determine whether or not the environment affects texture development. Anneals at a higher temperature will also be performed to investigate whether the field has any effect on texture components during annealing at temperatures much higher than the Curie temperature.

Summary

The effect of magnetic annealing at 787°C with field strengths of 1.5T, 15T and 30T on texture and grain boundary character development in a Fe-1%Si alloy was investigated. The intensity of the Goss texture component increased with increasing field strength. The grain size increased with increasing field strength, suggesting that the magnetic field accelerates grain growth under these conditions.

Acknowledgments

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