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Journal of Magnetism and Magnetic Materials 304 (2006) 183–186
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Overview of Microstructure and Microtexture Development in Grain-oriented Silicon Steel

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Abstract

This paper outlines the development of the microstructure and microtexture of grain-oriented silicon steel during the industrial production process. In particular the evolution of the Goss orientation was studied in industrial material as well as in single crystal experiments.

PACS: 61.14.−x; 75.50.Bb; 81.40.Ef; 92.10.Ns

Keywords: Grain-oriented silicon steel; Goss orientation; EBSD

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1. Introduction

The grain-oriented silicon steel is a soft magnetic material that is used as the core material in electrical transformers. It is characterized by a pronounced Goss texture, i.e. a $\{110\}\langle 0\,0\,1\rangle$ preferred crystal orientation. This sharp texture develops due to a discontinuous or abnormal Goss grain growth during a high-temperature annealing at the end of the industrial production process. Although it is a matter of intensive basic and applied research since more than 50 years, there is no general agreement on the origin of preferred growth of the Goss grains. It is known, however, that the inheritance of Goss orientation from early production stages plays an important role, as it was shown by Böttcher and Lücke in Ref. [1] who removed the Goss-containing surface layer of the hot rolled material with the result that abnormal Goss grain growth did not take place after further processing. Therefore, in this contribution we intend to outline the evolution of the Goss orientation in industrially processed grain-oriented silicon steel along the various production stages, i.e. hot rolling, cold rolling, primary annealing, and secondary annealing. Furthermore, experiments are described in which the evolution of a Goss-oriented single crystal was tracked during the cold rolling and primary annealing in order to gain more information on the origin of abnormal Goss grain growth. All observations the of microstructure and microtexture were carried out by means of a high resolution and high speed EBSD (electron backscatter diffraction) analysis system (TSL OIM software; JEOL 6500F field emission gun scanning electron microscope) that allows to map very large areas, in order to detect the very rare Goss grains, as well as to precisely reconstruct the microstructure of heavily deformed samples.

2. Microstructure and microtexture evolution

2.1. Hot rolling

Industrial material: During hot rolling the Goss orientation originates due to shear deformation close to the strip surface [1–5]. Our microtexture measurements revealed some quite large Goss grains without visible substructure (Fig. 1). However, other Goss grains are much smaller, reveal a substructure or an orientation gradient.

Single crystal experiments: The idea of our single crystal experiments is visualized in Fig. 2: we grabbed one of the Goss grains in the hot rolled material and deformed and

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doi:10.1016/j.jmmm.2006.02.116

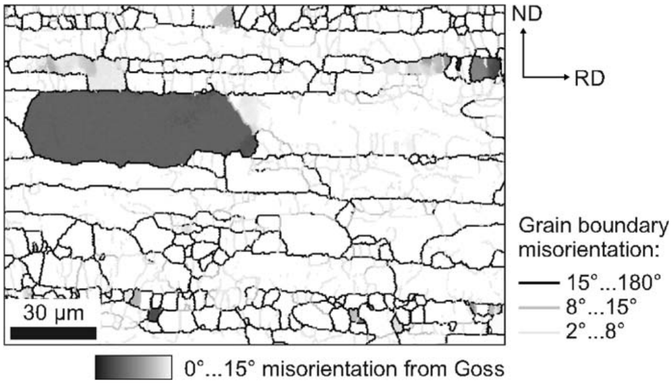

Fig. 1. Large Goss grain in industrially hot rolled silicon steel. Crystal orientation map including grain boundaries. RD: rolling direction; ND: normal direction.

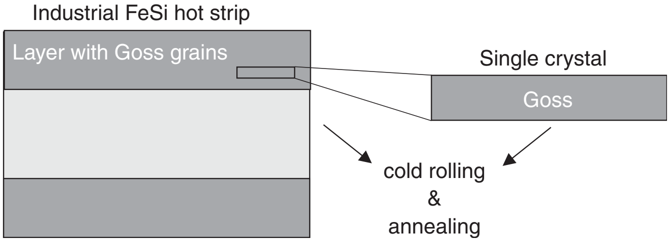

Fig. 2. Idea of single crystal experiments.

annealed it in the same way as it was done with the industrial polycrystalline silicon steel. Experimentally this was done by growing a macroscopic Goss-oriented single crystal ($20\times 50\times 2.2\,\mathrm{mm}^3$) which was then used for cold rolling [6,7] and annealing experiments.

2.2. Cold rolling

Industrial material: As already known from earlier studies on industrially cold rolled silicon steel, the major texture components after cold rolling are the α-fibre and the γ-fibre [1,8,9,4]. However, our microtexture measurements revealed that small Goss-oriented areas are also present in the cold rolled microstructure. The area fraction of the Goss orientation is about 1% taking into account a maximum misorientation from exact Goss of 15°. This weak Goss component was not detected in earlier studies due to the lower resolution of the X-ray diffraction compared to the EBSD technique. Furthermore, we observed that the occurrence of Goss-oriented areas was restricted to regions with orientations close to $\{111\}\langle 1\,1\,2\rangle$ (Fig. 3). Most of the Goss grains were aligned along shear bands, however, very few Goss grains appeared to occur in less strained areas outside of shear bands.

Single crystal experiments: Cold rolling of a Goss-oriented single crystal resulted in a crystal rotation into the two symmetrically equivalent $\{111\}\langle 1\,1\,2\rangle$ texture components as already reported by Dunn [10]. But we found that Goss-oriented areas were still present in the highly strained material with a fraction of 2.2–2.6%, although the Goss orientation is not stable under plane strain deformation [9,11]. In particular, we observed two types of Goss grains (Fig.4). Goss grains inside of shear bands newly formed during deformation at high strain. Whereas we supposed that those Goss grains that were found between microbands were retained during cold rolling [6,7].

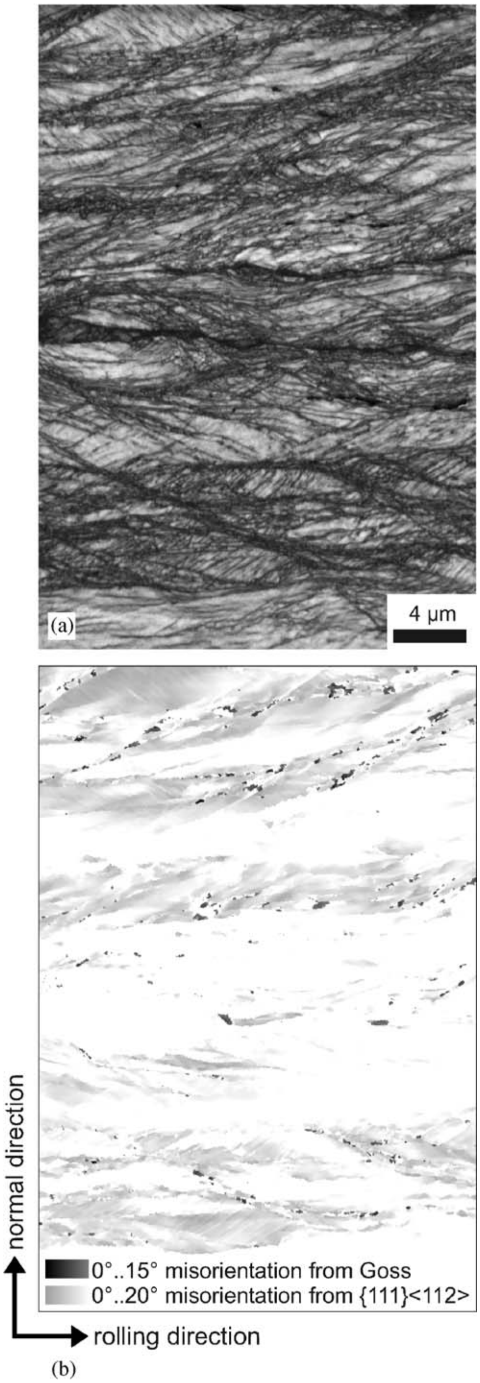

Fig. 3. Industrial silicon steel: (a) Microstructure with characteristic shear bands. EBSD pattern quality map: darker areas represent a higher dislocation density; (b) Crystal orientation map. The Goss-oriented areas occur only next to $\{111\}\langle 1\,1\,2\rangle$-oriented areas.

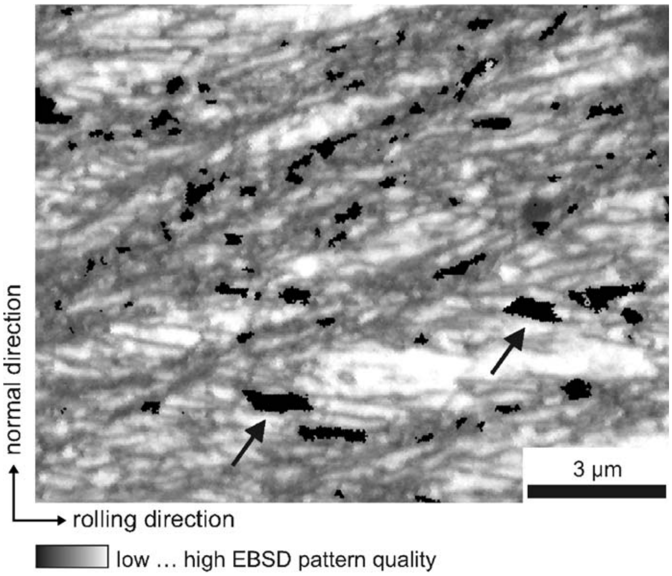

Fig. 4. Single crystal experiments. Goss-oriented areas in a 89% deformed, originally Goss-oriented single crystal. The Goss grains are situated both inside of shear bands and between microbands (arrows). EBSD pattern quality map; Goss-oriented areas are marked in black.

2.3. Primary annealing

Industrial material: After primary recrystallization the Goss orientation forms a minor texture component in high permeability grade material and is a one of the main texture components in conventional grade silicon steel. In both grades, the major texture component is the γ-fibre e.g. Ref. [3]. Microtexture analysis showed that the Goss grains are not larger than other grains, i.e. they do not have a size advantage during secondary annealing [12].

Single crystal experiments: In contrast to the industrially processed material, in the deformed and annealed originally Goss-oriented single crystal, the Goss orientation is the strongest texture component. Our microstructure analysis revealed that the Goss grains between the microbands are likely to form nuclei for primary recrystallization. The Goss grains inside of shear bands mostly disappeared.

2.4. Secondary annealing

Industrial material: During the final high temperature annealing, normal grain growth is inhibited by particle pinning of grain boundaries e.g. Ref. [3]. However, some of the Goss grains that are present in the primary recrystallized material can unpin and grow abnormally giving rise to the formation of a sharp and strong Goss texture.

3. Origin of abnormal Goss grain growth

Abnormal Goss grain growth can be due to a growth selection or an oriented nucleation mechanism. Most existing models of abnormal Goss grain growth propose a growth selection mechanism based on special grain boundary properties, that are e.g. the $\Sigma 9$ grain boundary theory [13,14] or the high angle grain boundary theory [15]. However, these theories cannot explain all experimental observations on abnormal Goss grain growth as it was recently outlined by Zaefferer and Chen [16]. Thus, we assume that there is another, probably an oriented nucleation mechanism leading to abnormal Goss grain growth. We suspect that the Goss grains are characterized by a special microstructure, e.g. dislocation structure, which originates in the early production stages and is inherited through the production process. Our search for special microstructural properties of Goss grains is facilitated by the use of single crystals as the starting material, because in this case the number of Goss grains is higher in the cold rolled and in the primary recrystallized states.

4. Discussion

Our EBSD investigations rendered possibly a detailed analysis of the microstructure and microtexture of particularly the deformed state of silicon steel. We found that in the cold rolled industrial material Goss-oriented areas only occurred in the neighborhood of $\{111\}\langle 1\,1\,2\rangle$ grains. This observation implied that findings from our single crystal experiments, where the texture components were only Goss and $\{111\}\langle 1\,1\,2\rangle$, can possibly be transferred to polycrystalline material. In the industrial material, most of the Goss grains were aligned along shear bands, but some appeared not to be related to shear bands. This was consistent with our observation on the originally Goss-oriented single crystal material. In this case after deformation two types of Goss grains were found: in shear bands and between microbands. The Goss grains in shear bands newly developed during deformation. Whereas those between microbands were retained during cold rolling. Their primary recrystallization behaviour was also different. The Goss grains between microbands formed the recrystallisation nuclei, whereas the Goss grains in the shear bands mostly disappeared during annealing. This observation is in contrast to that of Ref. [8] who stated the formation of new Goss-oriented crystals in shear bands. This indicates that possibly some ideas about the formation of Goss grains have to be revised.

5. Summary

In this study the evolution of the microstructure and microtexture of silicon steel was investigated using EBSD. In particular the development of the Goss orientation was tracked in both industrial material and single crystal material. A study on the evolution of the Goss orientation throughout all production stages is important with regard to the question of the origin of abnormal Goss grain growth, because the Goss orientation originates during hot rolling and is inherited to the final secondary annealing. For the industrial material, we found that the occurrence and the amount of the Goss orientation is related to the

{111}⟨1 1 2⟩ orientation. The most important finding for the single crystal was that two types of Goss grains occurred in the cold rolled state, which also showed different primary recrystallization behaviour. We supposed that results obtained from single crystal experiments can be transferred to industrial material and that they offer the potential to investigate the microstructure of individual Goss grains helping to solve the question of the origin of abnormal Goss grain growth.

Acknowledgment

Financial support by ThyssenKrupp Electrical Steel GmbH is gratefully acknowledged.

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