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Survival of Goss grains during cold rolling of a silicon steel single crystal

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Abstract. A silicon steel single crystal with initial Goss orientation, i.e. the {110}<001> orientation, was cold rolled up to 89 % thickness reduction. Most of the crystal volume rotates into the two symmetrical equivalent {111}<112> orientations. However, a weak Goss component is still present after high strain, although the Goss orientation is mechanically instable under plane strain loading. Two types of Goss-oriented crystal volumes are found in the highly deformed material. We suggest that their origin is different. The Goss-oriented regions that are observed within shear bands form during the cold rolling process. In contrast, those Goss-oriented crystal volumes that are found inside of microbands survive the cold rolling.

Introduction

Grain-oriented Fe3%Si steel is a soft magnetic material that is used for iron cores in electrical transformers. It is characterised by a sharp {110}<001> texture, referred to as Goss texture, which develops during secondary recrystallisation in the industrial production process. The origin of the Goss component is in the hot rolling stage, where due to high friction and the resulting shear deformation, the Goss orientation develops close to the sheet surface. The Goss orientation is inherited through the cold rolling and primary recrystallisation process. Finally, during the secondary annealing treatment, some of the Goss grains grow abnormally leading to the sharp Goss texture.

This study aims to investigate the evolution of the microstructure during cold rolling, because in this stage the nucleation sites for the primary recrystallisation of Goss grains are provided. In particular, it is investigated how the Goss-oriented crystal volumes evolve during cold rolling, and how some of the original Goss orientation survives the deformation process although it is known to be instable under plane strain deformation conditions [1-3]. In order to increase the chance to observe Goss grains in the material throughout the deformation process, single crystals of Goss orientation were used as a starting material.

Experimental Method

The experimental procedure of this study comprises growing and subsequent cold rolling of a Goss-oriented single crystal. The starting material for the growth experiment was an industrially hot rolled silicon steel strip containing 3.2 % Si and MnS as inhibitor as used for the production of conventional grain-oriented electrical steel. In the subsequent cold rolling experiment, the single crystal sheet with a thickness of 2.20 mm was cold rolled without lubrication in a laboratory rolling mill with a roll diameter of 105 mm, a roll velocity of 10 m/min, and a load of 120 kN. In 14 passes the sheet was rolled to a thickness of 0.25 mm corresponding to a total engineering thickness reduction of $\varepsilon = 89$ % (true logarithmic strain of $\varphi = 2.2$). The texture and microstructure of the deformed material was then investigated by automatic crystal orientation mapping based on electron backscatter diffraction (EBSD) in a scanning electron microscope.

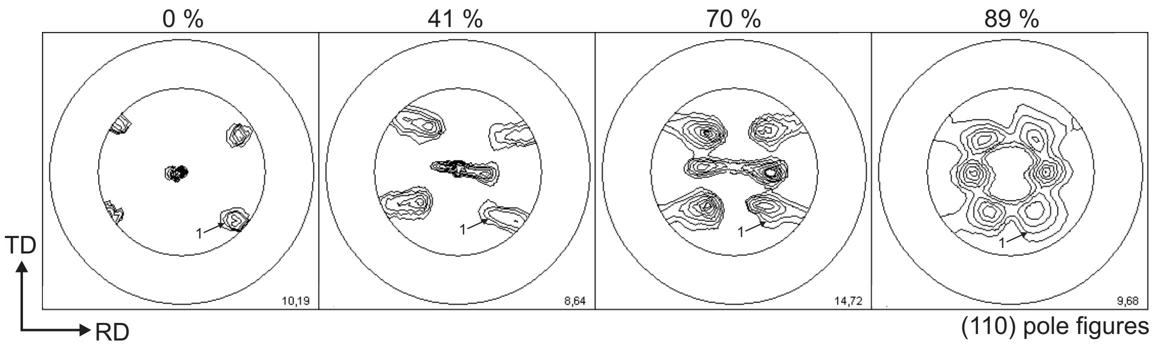

Fig. 1: Texture evolution during cold rolling of an initially Goss-oriented single crystal. (110) pole figures obtained by x-ray diffraction for samples with a thickness reduction of 0 %, 41 %, 70 %, and 89 %, respectively. The {110}<001> orientation rotates 35° around the <110> crystal direction, which is parallel to the transverse sample direction, in both directions into two symmetrically equivalent {111}<112> orientations. TD: transverse direction; RD: rolling direction. The intensity scale for the drawn isolines is logarithmic; the isoline with intensity 1 is indicated by an arrow; the maximum intensity for each sample is given in the lower right corner.

Results

Texture and Microstructure during cold rolling. The bulk texture evolution during cold rolling of the initially Goss-oriented single crystal was investigated using x-ray diffraction. In the course of the deformation process the Goss-oriented single crystal rotates 35° around the <110> crystal direction, which is parallel to the transverse direction (TD) of the sheet, in both directions into two symmetrically equivalent {111}<112> components (Fig. 1). The orientation distribution function for the highest deformed material, as determined by EBSD, is shown in Figure 2 for two sections through the Euler space. The strongest components are the two {111}<112> orientations (Fig. 2a), but the data also show that a weak Goss component is still present after 89 % thickness reduction (Fig. 2b). The evolution of the microstructure was studied in detail using EBSD [4].

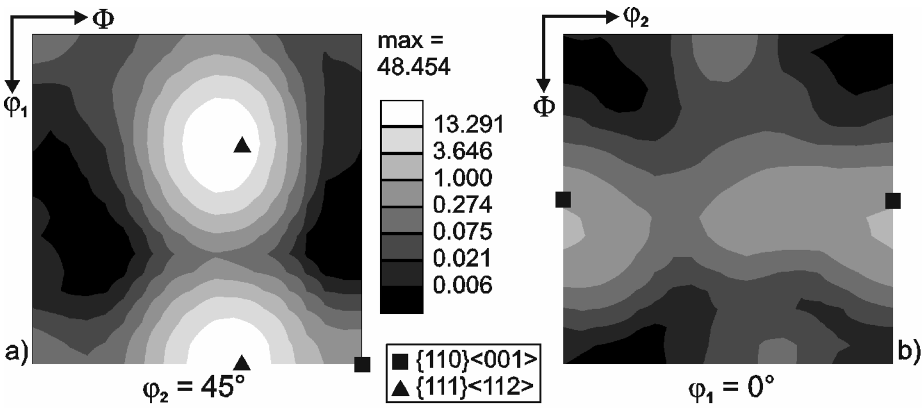

Fig. 2: Texture of the 89 % deformed material. Orientation distribution function diplayed in a $\varphi_2 = 45°$ (a) and a $\varphi_1 = 0°$ section (b) through the Euler space. The texture components with the highest intensities are the two symmetrically equivalent {111}<112> components (a). In addition, a weak Goss component is observed, with a texture intensity of about 1 (b). Note that the texture intensity scale is logarithmic.

Development of Goss-oriented regions during cold rolling. After the highest deformation degree of 89 %, most of the remaining Goss-oriented crystal volume is surrounded by high-angle grain boundaries. After smaller strains of 70 %, some of the Goss-oriented regions are already surrounded by high-angle grain boundaries. Other Goss-oriented regions, however, partly reveal a continuous orientation gradient to the surrounding {111}<112> matrix and partly form high-angle grain boundaries. The high-angle grain boundaries mostly show an orientation difference of about 35°, which is the misorientation between the Goss and the {111}<112> orientation. These new grain boundaries develop parallel to the transverse direction and are inclined between 10° and 20° to the rolling direction.

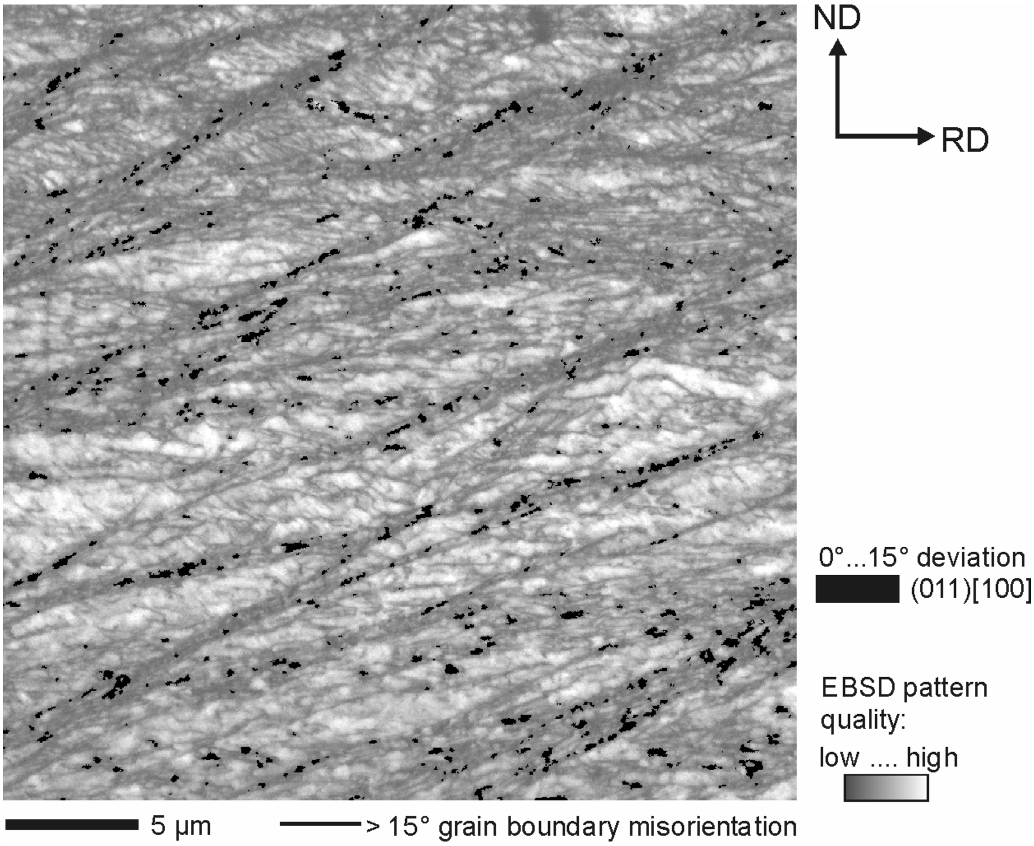

Fig. 3: Goss-oriented regions inside of shear bands in the 89 % deformed material. EBSD pattern quality map (gray scale) showing shear bands as regions with low EBSD pattern qualities. The shear bands are inclined by 29° to 36° to the rolling direction. In addition, Goss-oriented regions are marked in black.

Occurrence of Goss-oriented regions in shear bands and in microbands. Shear bands formed in cold rolled samples with thickness reductions of 77 % and higher [4,5]. When viewed on longitudinal sections, the shear bands are initially inclined by 29° to 36° to the rolling direction, with smaller inclination angles additionally occurring at higher strain [5]. We observed that the inclination direction of the shear bands is dependent on the particular {111}<112> orientation in which they develop [5]. Assuming that the shear band plane is parallel to the transverse sheet direction, we found that it coincides with one {110} plane in both {111}<112> orientations. The texture inside the shear bands consists of the Goss orientation and the two symmetrical {111}<112> components with varying intensities, but no additional orientations appear [5]. These two observations, i.e. the correlation of shear band inclination and crystal orientation and the occurrence of a limited number of texture components inside the shear bands, reveal the crystallographic nature of the observed shear bands. Therefore, we assume that we deal with so-called copper-type shear bands that develop due to geometrical softening as described by Dillamore et al. [6].

We found two types of Goss-oriented crystal volumes in the 89 % deformed material. Most of the Goss-oriented regions are situated inside of shear bands (Fig. 3), which develop at high strain. However, Goss-oriented crystal volumes are also observed inside of microbands (Fig. 4). The observed microbands have a width of about 0.5 µm and their interior is characterised by an EBSD pattern quality that is significantly higher than that within the shear bands.

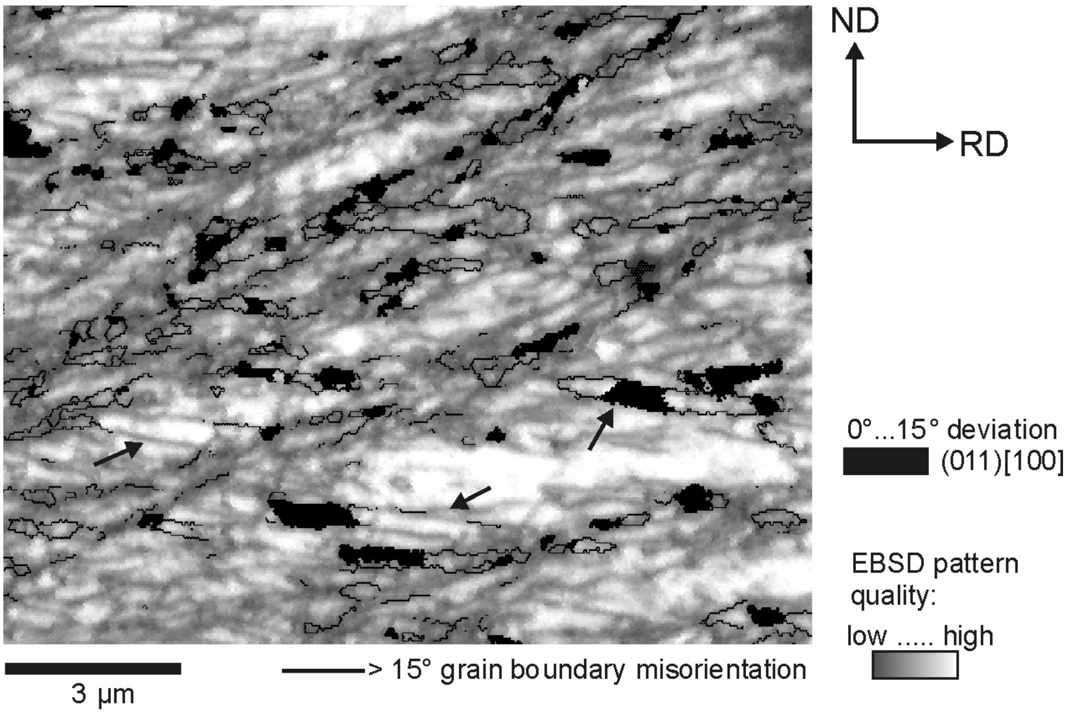

Fig. 4: Goss-oriented regions inside of microbands in the 89 % deformed material. EBSD pattern quality map (gray scale) and Goss-oriented regions (black). Some microbands are marked with arrows. In addition, shear bands are visible.

Discussion

We discuss the stability of the remaining Goss-oriented crystal volumes with respect to two possible types of mechanism [4]: firstly, the development of the Goss orientation in shear bands, and secondly, a microband mechanism that causes some small Goss-oriented crystal volumes not to rotate, although the Goss orientation is mechanically instable under plane strain deformation.

Development of Goss-oriented regions within shear bands. The role of shear bands in the context of the Goss texture formation in silicon steel was already investigated by Haratani et al. [7] and Ushioda and Hutchinson [8]. However, they could not resolve the microstructure of the shear bands in the cold rolled state. In our investigation, we observe that a part of the Goss-oriented regions that are found after high strain is aligned within shear bands (Fig. 3), indicating that this crystal orientation newly forms due to the local shear deformation in the shear bands. We suggest that at first, the initial Goss orientation rotates to the two {111}<112> orientations. Subsequently at higher deformation degrees, when the shear bands are formed, the {111}<112> orientations rotate *back* to the Goss orientation due to the local shear strain state. The alternative possibility that the Goss orientation survives within the shear bands can be excluded because the shear bands first form after most of the Goss-oriented material has disappeared.

Goss-oriented regions between microbands and the development of high-angle grain boundaries. After high strain, Goss-oriented material is not only found inside of shear bands, i.e. in regions with a high dislocation density as indicated by the low EBSD pattern quality, but also in regions inside of microbands, which are characterised by a lower amount of lattice distortion. In this section, a model assumption is outlined explaining the observation of stable Goss-oriented regions inside of microbands as well as the development of high-angle grain boundaries between the {110}<001> orientation and surrounding {111}<112> orientations.

In order to make an estimate about the slip systems that are dominant during the transverse lattice rotation from the {110}<001> into the {111}<112> crystal orientations we used a full constraint Taylor model. For the determination of the Taylor factor, the active slip systems, and the corresponding shear strain for each slip system, the 12 {110}<111> and the 12 {112}<111> slip systems are taken into consideration. The Taylor-type calculations yield that during the whole deformation and rotation process, one slip system is particularly active (Fig. 5). Moreover, a discontinuous transition of the second and third active slip systems to other active slip systems takes place after a rotation of 10° (Fig 5).

The described microstructural observations combined with the results obtained from the Taylor-type calculation gave reason to propose the following model to explain the survival of the Goss orientation in microbands. During the first deformation stage, microbands develop because slip occurs mainly on one glide system (Fig. 6a). After some deformation, a transition takes place to another set of active slip systems. The microband walls, which developed earlier, now act as a barrier for the motion of the dislocations on the newly active slip systems causing the dislocations to pile up at the microband walls (Fig. 6b). At locations where the width of the microbands is small, further dislocation activity is impeded inside the microbands due to these pile-ups (Fig. 6c). Therefore, no further lattice rotation takes place within the microbands. By this process, the Goss orientation might survive within small crystal volumes and high-angle grain boundaries develop around the Goss orientation when the lattice rotation continues in the region next to the microband. The presented model assumption explains the survival of the initial Goss orientation in small crystal volumes due to a *microband mechanism*, i.e. no back rotation of the crystal lattice is involved in this process. This is in contrast to the origin of the Goss-oriented regions inside the shear bands.

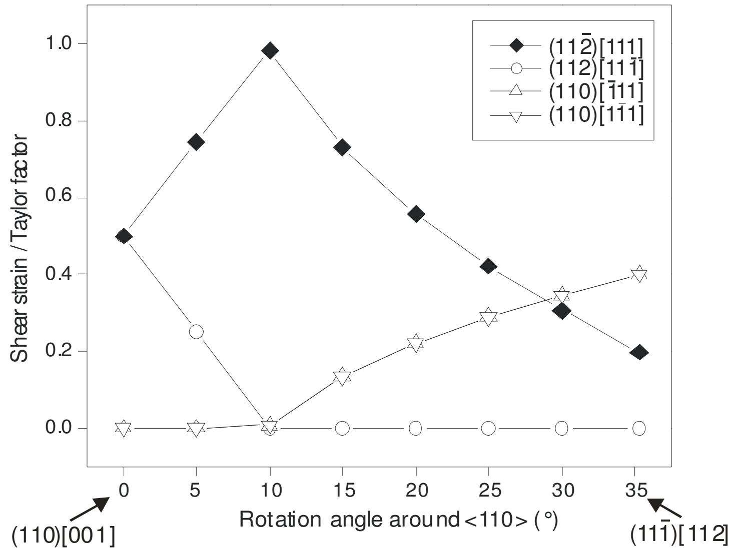

Fig. 5: Shear strain normalized by the Taylor factor as a function of rotation from (110)[001] to (11-1)[112] around the <110> crystal direction. The shear strain is concentrated on only one slip system. After 10° rotation the second and third active slip system changes. The Taylor-type calculations were performed with 24 slip systems for a bcc crystal.

Summary and Conclusions

A silicon steel single crystal with {110}<001> crystal orientation was cold rolled and the evolution of the Goss orientation during rolling deformation was investigated using EBSD.

(1) The texture after cold rolling up to 89 % thickness reduction is characterised by two strong symmetrically equivalent {111}<112> components. In addition, a weak {110}<001> component is still present though the Goss orientation is mechanically instable under plane strain loading.

(2) In the highly deformed material, most remaining Goss-oriented regions are situated inside of *shear bands*. However, Goss-oriented crystal volumes are also found inside of *microbands*. We suggest that their origin is different. One type of Goss-oriented regions newly form at higher deformation degrees due to shear deformation within the shear bands. The Goss-oriented regions that are found outside of the shear bands are suggested to survive during plane strain deformation in small regions within microbands. We propose that the microband walls act as barriers for dislocation glide on other glide systems. Due to dislocation pile-ups further rotation of Goss-oriented volumes is impeded and the Goss orientation survives.

3) The sharp Goss orientation that develops during secondary recrystallisation in industrially processed silicon steel has its origin in the hot rolling process. In this study, we observed two types of Goss-oriented regions after cold rolling of an initially Goss-oriented single crystal. Provided that our results on single crystals can be transferred to polycrystalline material, it might be concluded that the Goss-oriented regions that are found in microbands and that are assumed to be stable during cold rolling, have special significance for the formation of Goss grains in the primary recrystallised material, and, consequently, for the abnormal growth of Goss grains during secondary recrystallisation. If the newly formed Goss-oriented regions within the shear bands were specifically relevant, then the removal of the surface layer would not change the formation of Goss grains during primary recrystallisation as it was described in literature [9-11].

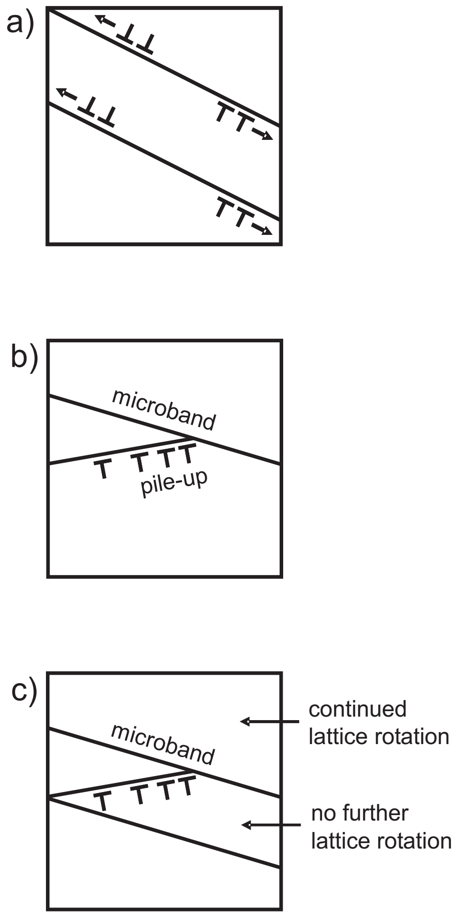

Fig. 6: Scheme of the model explaining the survival of Goss-oriented crystal volumes in regions inside of microbands.

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