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Effect of deformation and annealing on the microstructure and magnetic properties of grain-oriented electrical steels

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Abstract

The effect of plastic deformation and subsequent annealing on the magnetic properties and microstructure of a grain-oriented (GO) electrical steel has been studied. True strain (ε) from 0.002 to 0.23 was applied by rolling in two directions, rolling (RD) and transverse (TD). The deterioration of power losses varies according to the direction of deformation. Annealing the strained material—at 800 °C/2 h—leads to a recrystallization and restored magnetic properties. The main components of annealed-textures are around 15–35° from those of deformed-textures for both RD and TD. Rolling along {1 1 0} ⟨0 0 1⟩ direction leads to the development of deformation twins.

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Keywords: Electrical steels; Plastic deformation; Recrystallization

1. Introduction

In production of distribution transformers, one of used techniques is to coil the grain oriented (GO) sheets—cutting them in layers—and annealing. The corner radius can be as small as 30 mm leading to a reasonably large plastic deformation in the sheet. In presented study, the controlled strain was applied by rolling, and deterioration of magnetic properties after forming and their restoration by a subsequent annealing are evaluated together with the associated microstructural changes.

2. Experimental

True strain (ε) from 0.002 to 0.23 was applied by rolling, in two directions, rolling direction (RD) and transverse direction (TD), of a 3.2% GO Silicon steel with the Goss texture (1 1 0) [0 0 1]. The magnetic properties were measured in a Soken single sheet tester model DAC-BHW-5. Deformed structures were observed by SEM equipped EBSD system (Philips XL30 with TSL system). ODFs of deformed and annealed sheets were calculated from {1 1 0}, {2 0 0}, {2 1 1} and {3 1 0} polefigures measured by X-ray diffraction in a Shimadzu Difractometer XRD6000 using CuKα radiation.

3. Results and discussion

After applying deformation, the magnetic properties are strongly deteriorated (see Figs. 1 and 2), in a pattern that has been shown to occur in non-oriented steels [1,2]: a large increase in losses after a very small straining (less than 1%) followed by a less steep linear increase in losses for larger strains. The differences between the behaviour shown in Figs. 1 and 2 can be explained by the microstructure. In transverse direction TD, the crystallographic orientation of grains is {1 1 0} ⟨1 1 0⟩, while for rolling direction RD it is {0 0 1} ⟨1 1 0⟩.

The magnetic hardening after rolling may be described using an analogy to Ludwik's description [2] of the mechanical hardening: $P = P_0 + k\varepsilon^n$, where P are power losses, P_0 are power losses without a plastic deformation, k

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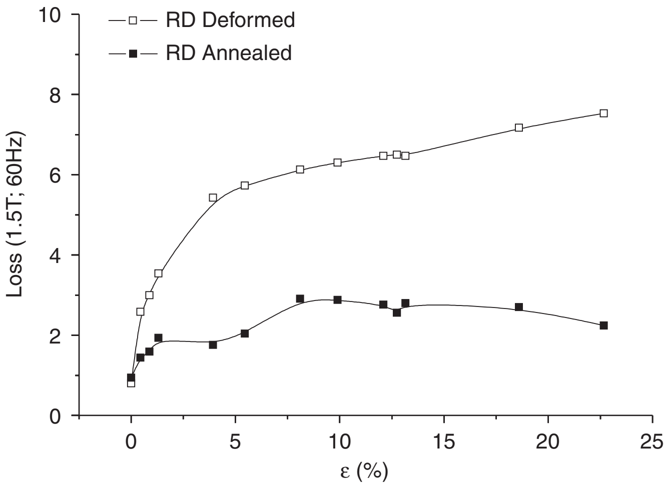

Fig. 1. Magnetic loss as function of the true strain at samples rolled in the rolling direction (RD).

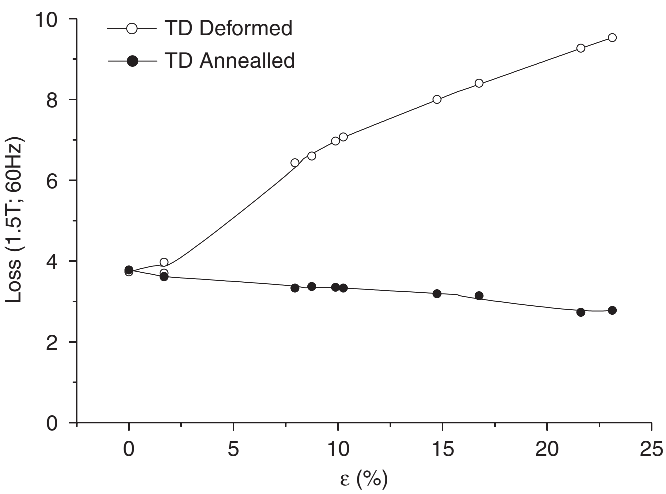

Fig. 2. Magnetic loss as function of the true strain at samples rolled in the transverse direction (TD).

is an experimental constant and n is the hardening exponent. For rolling in RD, we have found $n = 0.34$ and for rolling in TD, $n = 0.71$. This difference can be related to the Taylor work-hardening factor [3], which is 2.1 for Goss orientation (1 1 0) [0 0 1], and 4.2 for the {1 1 0} ⟨1 1 0⟩ orientation [4]. Higher the Taylor factor, larger tend to be the amount of dislocations after the plastic deformation for a given crystallographic orientation, with dislocations increasing coercive field and losses, due the pinning of domain walls. The annealing (at 800 °C for 2 h) promotes the decrease of losses, as showed in Figs. 1 and 2, and this is due to a reduction of dislocation density [5] during the annealing, where metallurgical phenomena like the recovery and recrystallization take place.

Annealing at 800 °C for 2 h leads to a complete recrystallization of samples with straining above 8% in both cases, RD and TD , and to a decrease in grain size and disappearance of the strong Goss texture (see Figs. 3–6). With less than 8% of deformation, the recrystallization is "incomplete", with some grains recrystallized and others not (some grains only "recovered", i.e. dislocations were annihilated due to annealing [5]). Incomplete recrystallization can result in a significant reduction of the dislocation density, also significantly reducing the losses.

As we can see in Fig. 3, the rolling in RD with $\varepsilon = 0.23$ still keeps the major Goss (1 1 0) [1 0 0] component,

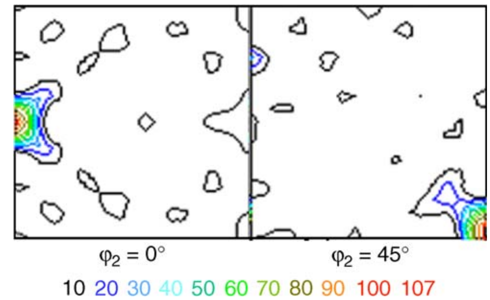

Fig. 3. ODF of sample strained in RD, $\varepsilon = 0.23$.

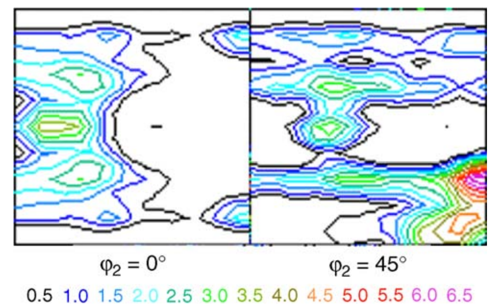

Fig. 4. ODF of annealed sample ($\varepsilon = 0.23$ on RD).

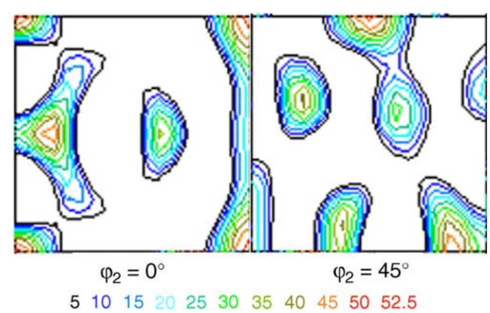

Fig. 5. ODF of strained sample ($\varepsilon = 0.23$ on TD).

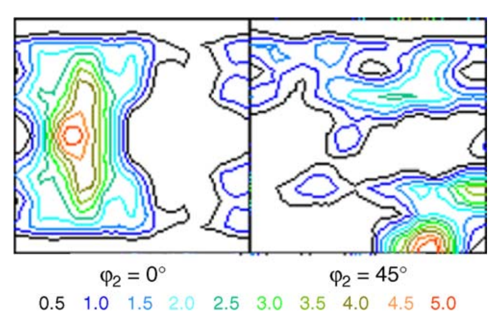

Fig. 6. ODF of annealed sample ($\varepsilon = 0.23$ on TD).

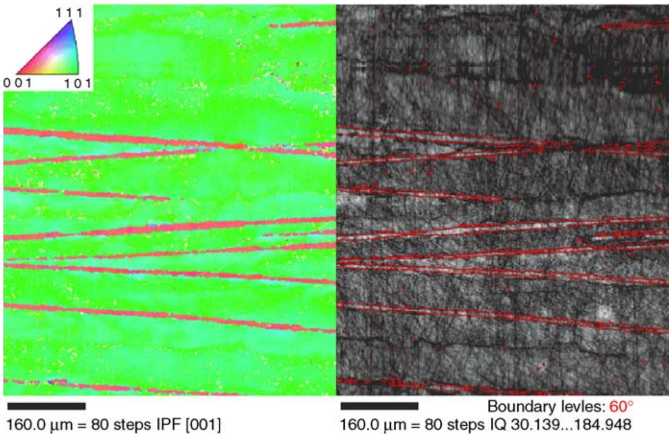

Fig. 7. Deformation twins in the sample strained to 23% in the rolling direction (RD).

introducing a component of the alpha fibre. After the annealing, we observed randomization of texture (Fig. 4), with new recrystallization components around 15–35° from the initial orientation. We observed (Fig. 5) that plastic deformation at TD was much more effective in rotating Goss original orientation than rolling in RD. In the same way as previously observed, comparing Fig. 3 with Fig. 4, the main components of the TD recrystallization texture (Fig. 6) are around 15–35° from the initial orientation (Fig. 5), a result also previously found for non-oriented electrical steels [6]

Steels typically present the deformation bands after a plastic deformation at room temperature, as can be found in textbooks [5]. However, it was observed that specifically for straining in orientation $\{1\,1\,0\}\ \langle 0\,0\,1\rangle$, and unlike the typical behaviour for most of other textures [5], the deformation twins appeared (Fig. 7). The deformation twins [7] were observed in OIM-EBSD image (Fig. 7) around orientation $(1\,2\,9)\ [-3\,-3\,1]$, which is near the rotated cube orientation ($\{0\,0\,1\}\ \langle 1\,1\,0\rangle$). The 60° miss-orientation determined by OIM (Fig. 7) confirms they are the deformation twins. (Note: an angle of ~60° is a necessary condition to the structure be a twin. The orientation $(1\,2\,9)\ [-3\,-3\,1]$ is around 60° from Goss $(1\,1\,0)\ [0\,0\,1]$).

4. Conclusions

The deterioration of power losses in deformed GO steels varies according to the deforming directions. The difference between the power losses behavior after deformation along RD and TD can be explained by observation of the microstructure. A subsequent annealing partially restores the magnetic properties—thanks to metallurgical phenomena, like recovery and recrystallization. The main components of the annealed textures are around 15–35° from those of deformed textures in both sheets deformed along RD and TD. Deforming along $\{1\,1\,0\}\ \langle 0\,0\,1\rangle$ causes development of the deformation twins.

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