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Coupling of multi-scale investigation methods to study microstructural related magnetic properties and domain structure of electrical steel material

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The magnetic properties of electrical steel are determined by microstructural characteristics, e.g., crystallographic orientation, grain boundaries and lattice defects. These characteristics affect both macroscopic magnetic properties and microscopic domain processes. While fundamental relationships between individual material parameters and magnetic behavior are well established, their complex interactions under realistic magnetization conditions remain insufficiently understood. In this work, a coupled multi-scale experimental approach is presented to investigate microstructure-related magnetic properties of electrical steel. The methodology combines global magnetic measurements with local microstructural characterization and observation of magnetic domain evolution during magnetization. Oligocrystalline samples are employed as model systems to provide a controlled microstructure with a limited number of well-defined grains and grain boundaries. Furthermore, samples are subjected to deformation. The presented approach establishes a direct link between microstructure, domain structure and magnetic properties and contributes to an improved understanding of magnetization mechanisms in electrical steel.

***Index Terms*—electrical steel; magnetic domains, mini-SST, deformation**

I. Introduction

THE MATERIAL used to build the magnetic core of electrical machines is a decisive factor for the efficiency of electrical energy conversion. Iron silicon (FeSi) electrical steel is conventionally used to increase and guide the magnetic flux in transformers and rotating electrical machines. A fundamental understanding of material properties, e.g. grain size, alloying, sheet thickness or crystallographic texture has been established. This fundamental understanding is used to adjust the manufacturing of electrical steel strip to improve magnetic properties of electrical steels [1-3].

In practice, the required understanding of electrical steel magnetization behavior needs to go far beyond the current understanding. Numerous effects are overly simplified or neglected in the standardized testing of electrical steel according to DIN EN 60404 such as rotating magnetization, complex residual stress stated [4] or dislocations or non-sinusoidal excitations [5] as well as the testing methods themselves [6]. The magnetization behavior is influenced by numerous interactions and nonlinearities between material parameters and excitation parameters. Until now, a detailed understanding of individual microstructural features and their effects on the magnetic properties of electrical steel is still incomplete. This is not only important for the optimization of electrical steel material but also for the design and simulation of advanced electrical drive systems. Only with a better understanding improved material models of the magnetization behavior and frequency dependent losses can be enabled.

II. Methods

A first step of the research was the development of a miniature single sheet tester (Mini-SST), which, due to its small size, is capable of investigating differently oriented single, bi- or oligo-crystals [7]. In previous studies, the influences of orientation, grain boundaries, and deformation on magnetic properties could be examined independently of one another [8]. Once further of these relationships are decoded, both non-oriented and grain-oriented polycrystalline industrial electrical steel strip can also be better understood.

What has been missing so far, however, is the investigation of the domain processes responsible for magnetization which link the microstructural effects to the global magnetic characteristics. These processes are recorded and analyzed during the magnetization process using a specialized domain tester in combination with the Mini-SST and X-ray diffraction (XRD) to identify the crystal structure of various positions of the samples.

TABLE I
Studied Samples

Sample Name	Sample Dimensions Length x width x thickness	Optical micrograph
Sample 1 (B8)	26.43 mm x 9.98 mm x 0.436 mm	
Sample 2 (B9)	26.41 mm x 9.95 mm x 0.466 mm	
Sample 3 (B11)	30.59 mm x 10.19 mm x 0.347 mm 20% deformation	

The domain tester system enables the recording of domain evolution with a spatial resolution of at least 30 µm, a field of view of 18 × 12 mm, and frame rates of up to 1 kHz. The domain tester is designed to match the geometry of the Mini-SST. The C-shaped magnetizing yoke used mirrors the symmetric design of the Mini-SST, thereby generating comparable magnetic field distributions in the sample holder. This allows the results to be coupled with the global magnetic measurements from the previously described Mini-SST.

The samples studied in this paper were taken form a cylindrical, macroscopic oligo-crystal produced according to the vertical Bridgman-Stockbarger method. Slices for the characterization were cut from the grown crystal along the grown direction by electrical discharge machining (EDM). The final surface was reached through etching with nitric acid (100 ml HNO_3, 150 ml H_2O). Sample 1 and 2 are as-cut, with different volume fractions of the three grains. Sample 3 is further deformed with 20 %. A summary is given in Tab.1. For sample 3 only part of the sample is displayed as it elongated due to the deformation.

III. Results

A. Magnetic Measurements

Magnetic measurements are performed at three frequencies, 50 Hz, 400 Hz and 1000 Hz. In Fig.1, the magnetization curves at 400 Hz are displayed for the three samples. Even though, samples are cut from the same oligo-crystal and cut in the same orientation, the magnetization curves show different behavior. This is on one hand due to the different volume ratio of the different crystallographic orientations and on the other hand, in case of sample 3, combination of the different volume fraction and additional deformation. Sample 1 has the easiest magnetization whereas sample 2 and three have harder magnetization. Results were processed according to the method in [8] to account for different geometrical dimensions.

B. Orientation and Domain Structure

The crystallographic orientation of the different grains and local distribution was observed via XRD. The largest sample portion on samples 1 and 2 is attributed to the 100-direction, as can be seen from measurements on the positions highlighted in Fig. 2. Positions 1, 2 and 5 exhibit a clear (100)-direction. Therefore, it is plausible why sample 1 has the easiest magnetization as it has the largest fraction of the easy magnetization direction. Position 4 is close to 100-direction. Position 3 has a (322)-orientation that is close to an (111)-orientiation.

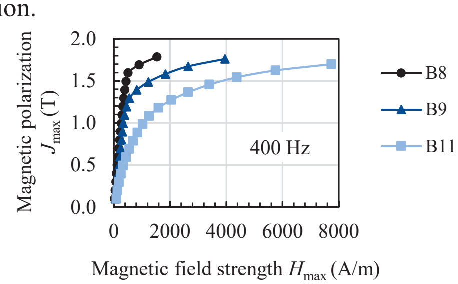

Fig. 1. Magnetization curves at 400 Hz for the three samples measured on the Mini-SST.

Fig. 2. Positions of XRD measurements.

In Fig 3. Results of the domain viewer are displayed exemplarily. In both cases the results are zoomed in on the grain with (332)-orientation. It can be observed that the domain structure changes drastically with the deformation that was performed.

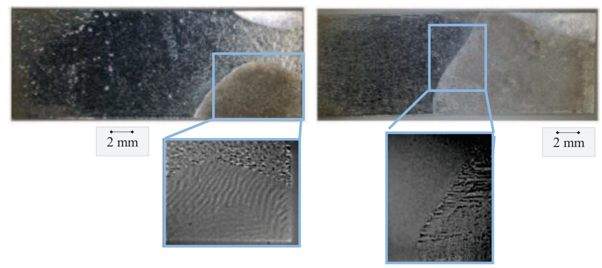

Fig. 3. Optical micrographs and domain tester results of sample B8 (left) and deformed B11 (right).

IV Conclusions

Based on the determined microstructural parameters (local crystal orientation, grain boundary character and deformation), the domain structure and global magnetic properties correlations can be derived between the initial magnetic domain configuration and magnetization processes. The results of this multi-scale investigation approach contribute to an improved understanding of magnetization mechanisms in electrical steel.

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