Utilizing Neutron Grating Interferometry (nGI) to Study the Effect of Stabilizing Elements in Non-Grain Oriented Electrical Steel

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In the project "STabilized ELectrical Steels for Electric Mobility Project" short STeELS-EM, five partners from various European universities and industry participants work on the development of innovative non-grain oriented (NO) electrical steels. The primary goal of the project is to create fully stabilized NO electrical steel. This involves binding interstitial elements to coarse particles and significantly reducing the formation of fine precipitation. During the course of the project, steel laminations with variation of the initial alloying and subsequent processing steps were produced and thoroughly characterized. The impact of alloying, reheating temperature, cooling, hot-band annealing, intermediate annealing and final annealing on the microstructural features (microstructure, precipitation state and texture) as well as on the magnetic properties has been studied.
As part of the studies, neutron grating interferometry (nGI) has been used to further analyze the produced material samples. The measurements were performed at the ICON beamline of Paul Scherrer Institut (PSI) [1]. NGI is an advanced neutron imaging technique that enables to map neutron scattering under ultra small angles (USANS). This scattering signal is recorded in the dark-field image (DFI) as depicted schematically in Figure 1 [2]. The DFI-signal captured through this method is sensitive to the scattering from magnetic domain boundaries 3-4]. Thus, the DFI is related to the magnetic domain structure of the produced samples. When a magnetic field is present in the ferromagnet, it aligns the domains, thus reducing scattering. This alignment results in on average larger domain structures and subsequently less neutron scattering which in turn manifests in higher DFI-signal. Lower DFI-signal indicates more neutron scattering of more, smaller, i.e. disordered domain structures under weaker fields [5]. In order to magnetize the samples, sheets of 60 mm x 60 mm were clamped with a specialized magnetic yoke consisting of a stack of electric steel sheets equipped with solenoids. This setup is able to replicate magnetization conditions effectively [2]. Within the measurement area, the DFI image gives information on the local magnetization behavior [5-6].

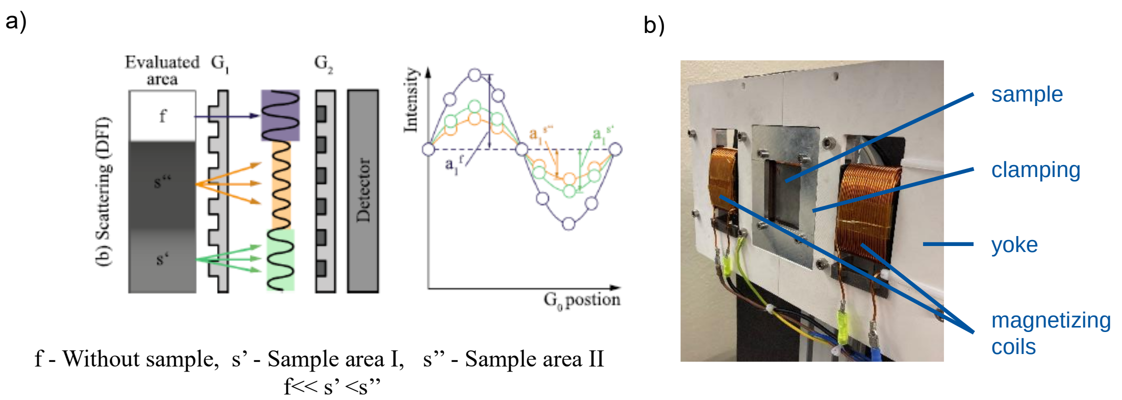

Figure 1. (a) nGI contrast mechanism , neutron scattering that influences the intensity oscillation at the detector during one nGI scan [2] and (b) magnetization yoke.

A total of 25 material states have been studied by nGI measurements which have been processed with the aforementioned process variations regarding annealing temperatures, alloying and cooling methods throughout the processing chain. The results for selected samples are displayed in Figure 2. The magnetic properties were performed on a 60 mm x 60 mm Single Sheet Tester. The permeability is displayed for a frequency of 50 Hz with sinusoidal excitation. The processing parameters of the samples of Figure 2 are displayed in Table 1.
The results presented in Figure 2 indicate that, for the majority of samples, the DFI image correlates with magnetic permeability. General trends can be observed in the DFI images, where a lower DFI value suggests less neutron scattering from domain walls, i.e., easier magnetization. Domain wall pinning is generally influenced by grain boundaries, precipitations, residual stress or dislocations, all of which thereby impact permeability. From the performed measurements it is evident that the DFI image reflects magnetic behavior for the majority of samples.

However, there were samples that exhibited behavior deviating from the expectations. Further analysis within the project consortium on microstructure, texture and the utilization of advanced testing methods will be conducted to establish correlations between the nGI measurements, magnetic performance and the processing conditions as well as efforts concerning the stabilizing elements.

Table 1. Processing variations for samples displayed in Figure 2.

Sample	Alloy		Hot Rolling		Hot band Annealing	Annealing	
	Ti	Si	Reheat. Temp.	Cooling Temp.		Intermediate	Final
S3 - E	no Ti added	high Si	1050	700	NOHBA	1050	1000
S4 - A	no Ti added	high Si	1250	700	NOHBA	1050	1000
S6 - D	no Ti added	low Si	1250	Water quenched	NOHBA	950	1000
S7 - F (I)	no Ti added	low Si	1050	700	NOHBA	950	1000
S8 - F (II)	no Ti added	low Si	1050	700	HBA	950	1000
S10 - H	no Ti added	low Si	1050	Water quenched	NOHBA	950	1000
S11 - TF	Ti added	low Si	1050	700	NOHBA	1100	1070
S12 - TA	Ti added	high Si	1250	700	HBA	1125	1080
S20 - TH	Ti added	low Si	1050	Water quenched	NOHBA	1100	1070
S22 - TG	Ti added	high Si	1050	AC	NOHBA	1125	1070
S24 - TE	Ti added	high Si	1050	700	NOHBA	1125	1070
S25 - TD	Ti added	low Si	1250	Water quenched	NOHBA	1100	1080

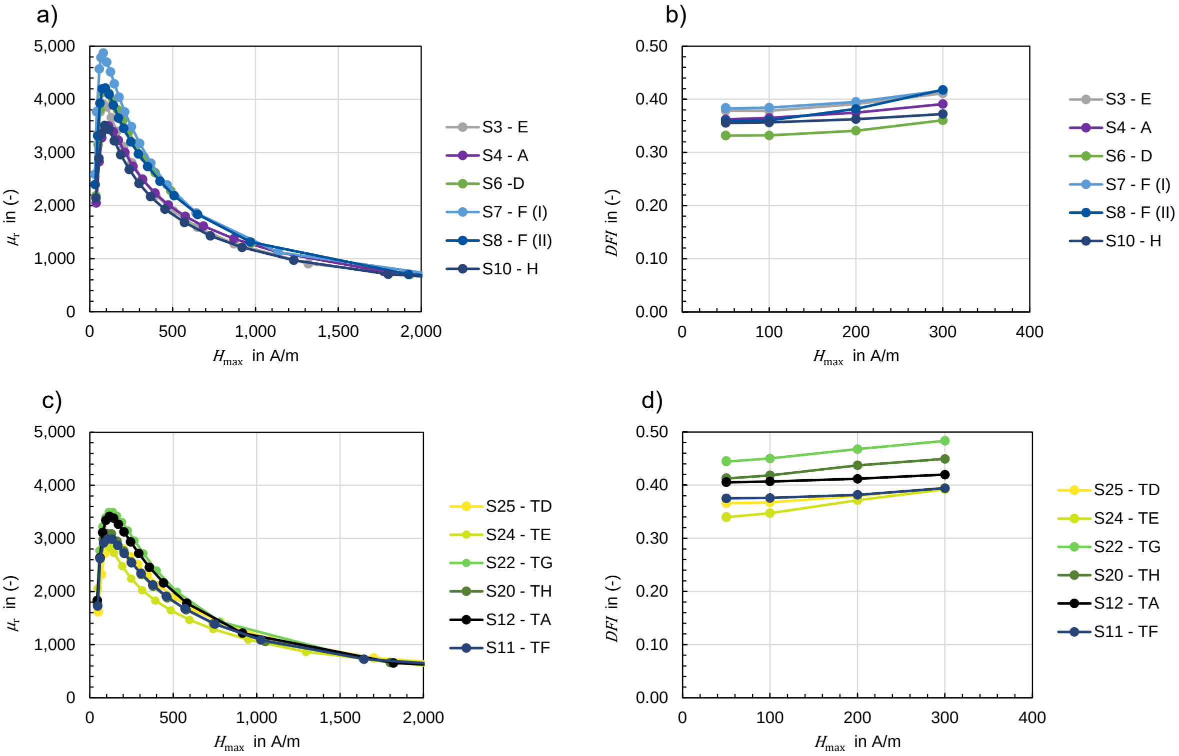

Figure 2. Permeability at 50 Hz measured on a Single Sheet Tester for samples a) without Ti added and c) with Ti added and DFI signal as a function of magnetic field strength for samples b) without Ti added and d) with Ti added.

References

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