# Effect of pinning centres and crystallographic texture on the quasi-static loss of NGO Fe-Si steels

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This study investigates the dependence of the quasi-static magnetic loss on the nature and distribution of domain-wall pinning sites, and the role of the crystallographic texture in commercial NGO silicon steels. Samples were prepared using a process that simulates the industrial batch annealing cycle, magnetically characterized at low and power frequencies, and structurally investigated by XRD and SEM. The study was devoted to the appraisal of the effect on coercivity and quasi-static loss of the combined role of structural heterogeneities, precipitates, and textural features of the sheets after the lamination process. A primary objective of the investigation was to demonstrate that, through an appropriate course of action in the batch annealing cycle, one can modify the density and distribution of pinning sites, resulting in a decrease of coercivity and hysteresis losses. Such a cycle can also be tuned for achieving a high density of grains with the (110) planes aligned with the sheet plane. The interplay between microstructural properties and magnetic behaviour is brought to light by the experiments and interpreted by physical modeling, providing insights into loss optimization for advanced magnetic materials, with implications for energy-efficient electrical motor applications.

Keywords: NGO Fe-Si steels; microstructural properties; magnetic losses.

## 1. Introduction

Many experiments have demonstrated the feasibility of production processes leading to less than 0.3 mm thick NGO Fe-Si laminated steels, having optimised grain size and crystallographic texture. Their magnetic performances are appreciated in several electrical power applications, like inductive cores in transformers, motors, and generators. The present-day requirements of high-efficiency electrical machines call for low-loss magnetic cores, which at power frequencies are critically dependent on the microstructural properties of the employed NGO sheets [1].

The present study focuses on the role played by precipitates, namely the undissolved iron carbides, in the magnetization process and losses. The carbides act as pinning sites for the domain walls, in a way that depends on their size and concentration. We show that these can be controlled and homogeneously distributed during the production process through the accurate design of the batch annealing cycle, which consists of a long-duration soaking at high temperature in $H_2$ atmosphere under relatively slow heating and final cooling steps. A quantitative analysis of the related loss and hysteresis behaviours, taking into account the associated role of the crystallographic texture, is carried out by quasi-static coercive field and hysteresis modelling and the approach to the loss decomposition by the Statistical Theory of Losses.

## 2. Results and discussion

Quasi-static hysteresis loops and energy loss versus frequency were measured by the Epstein test frame (IEC 60404-2) on NGO Fe-Si sheets of thickness (0.34 mm – 0.27 mm) obtained by the previously described batch annealing cycles.

Concurrent structural investigations aimed at assessing the grain structure, the distribution of the precipitates, and the textural properties were performed by Optical Microscopy, Scanning Electron Microscopy, Electron Backscatter Diffraction, and X-ray Diffraction (XRD). A homogeneous grain structure was observed, with large and irregularly shaped grains, having average diameter around 100 µm.

The magnetic behaviour of the NGO steels and the interplay of magnetization processes with grain size, impurities, and crystallographic texture distribution have been elucidated and integrated in a comprehensive perspective. The role of pinning sites and grain boundaries on the quasi-static and dynamic loss properties has been highlighted. Coercivity measurements up to about 300 °C provide evidence of the presence and contribution of the iron carbides [2]. The loss decomposition shows, at the same time, that the microstructural parameters similarly affect the quasi-static and the excess loss components, in accordance with the relationships predicted by the Statistical Theory of Losses.

## References

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