

Abstract

This dissertation addresses the development, processing, and comprehensive characterization of Fe–Co–B based nanocrystalline soft magnetic alloys designed for high-frequency and high-power energy conversion systems. The study follows a structured research methodology that spans alloy design, rapid solidification, controlled annealing, and multi-scale structural and magnetic characterization.

The work begins with $\text{Fe}_{67}\text{Co}_{20}\text{B}_{13}$ and $\text{Fe}_{84,5-x}\text{Co}_x\text{Nb}_5\text{B}_{8,5}\text{P}_2$ ($x = 0, 5, 10, 15, 20$ at. %) alloy design and preparation under a protective atmosphere, followed by careful melting and casting into pre-alloyed ingots. The alloys were processed into thin ribbons using the melt-spinning technique, where the optimization of wheel speed, ejection pressure, and melt temperature was crucial for achieving homogeneous ribbon, free of macroscopic defects. The reproducibility of ribbon production was essential for ensuring consistent magnetic behavior in subsequent processing steps.

Thermal and thermo-magnetic treatments were systematically performed using both conventional tube furnaces and a custom-built ultra rapid annealing (URA) and continuous ultra rapid annealing (cURA) system, enabling precise control of heating rates and annealing times. The application of transverse magnetic fields during conventional annealing, with intensities up to 140 kA/m, was used to induce well-defined uniaxial magnetic anisotropy. This approach proved to be effective in aligning magnetic domains, reducing core losses, and optimizing permeability for high-frequency operation. The application of ultrarapid annealing systems is an effective approach in achieving high saturation induction $> 1,8$ T, through a controlled crystallization in an alloy without elements responsible for nucleation and crystal growth control.

A broad range of analytical techniques was employed to investigate the structural evolution of the alloys. Differential scanning calorimetry (DSC) and differential thermal analysis (DTA) were used to determine crystallization onset, transformation enthalpies, and activation energies, allowing for the definition of safe annealing windows that suppress the formation of magnetically hard boride phases. Density measurements were conducted to verify the absence of porosity and to calculate specific losses of analyzed ribbons.

X-ray diffraction (XRD) analyses provided phase identification and quantification of crystallization progress, while *in-situ* transmission electron microscopy (TEM) enabled analysis of nucleation and grain growth under controlled heating conditions. Mössbauer spectroscopy played a key role in elucidating hyperfine field distributions and detecting subtle structural rearrangements in the local atomic environment. It confirmed the participation of cobalt in the bcc- (Fe, Co) lattice and revealed the progressive alignment of magnetic moments induced by field-assisted annealing.

The magnetic characterization was performed on several levels. Curie temperature measurements were used to determine the thermal stability and operational limits of the materials. Magneto-optical Kerr effect (MOKE) microscopy provided a direct visualization of domain structures, confirming the formation of elongated domains along the easy axis induced by external fields. Hysteresis loop measurements and primary magnetization curves were recorded over a wide frequency range up to 400 kHz, allowing for detailed analysis of coercivity, remanence, and energy losses as a function of composition and processing conditions.

To capture the dynamic response of the alloys, broadband measurements of complex magnetic permeability were conducted up to 110 MHz. These experiments revealed the frequency roll-off behavior, enabling the determination of the cut-off frequency and the optimization of alloy composition for minimal power loss under high-frequency excitation.

The study demonstrates that through a combination of alloy design, rapid solidification, thermo-magnetic processing, and advanced structural and magnetic characterization, it is possible to tailor microstructure and magnetic response to meet the requirements of modern energy conversion technologies. The proposed methodology establishes a framework for engineering next-generation nanocrystalline magnetic materials capable of surpassing the limits of conventional soft magnetic alloys and enabling further miniaturization and efficiency gains in high-frequency power systems.

In the implementation phase, a series of cores based on the $\text{Fe}_{64.5}\text{Co}_{20}\text{Nb}_3\text{B}_{8.5}\text{P}_2$ alloy was produced and deployed in ENRX's prototype line of induction heaters. Preliminary calculations for the $\text{Fe}_{67}\text{Co}_{20}\text{B}_{13}$ alloy confirmed its application potential in electric motors. In trials of rapid heat treatment on the cores, a saturation induction of 1.99 T and a coercivity of 51 A/m were achieved.