



# Effect of a DC transverse magnetic field on the magnetization dynamics in FeCuNbSiB ribbons and derived nanostructured powder cores



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## ABSTRACT

The paper aims to give a comprehensive account of DC transverse bias magnetic field influence on the dynamic magnetization processes in Fe<sub>73</sub>Cu<sub>1</sub>Nb<sub>3</sub>Si<sub>16</sub>B<sub>7</sub> soft magnetic ribbons and nanostructured powder cores based on ribbon precursor. These materials were extensively investigated using an approach of impedance spectroscopy from the viewpoint of complex permeability spectra, which offer the indirect insight into magnetization mechanisms and their frequency relaxation. In order to analyze the dynamic nature of domain wall magnetization mechanism, we carried out complex permeability measurements under combined influence of three independent variables, i.e. magnetizing frequency, various driving AC and DC bias magnetic fields. From this ample matrix of results, it has been found that the DC bias smaller than some critical field can increase the real part of complex permeability in the case of as-quenched and annealed ribbon. Nonetheless, the higher fields play a role of additional anisotropy and consequently domain wall damping mechanism. For nanocrystalline compacted powder cores, only the damping influence of DC transverse field was observed. The results are compared in detail and possible mechanisms of domain wall movement damping are proposed and discussed.

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## 1. Introduction

In a preceding paper [1], we investigated the influence of AC measuring magnetic field on the magnetization processes and their dynamics in FeCuNbSiB soft magnetic ribbons and two compacted powder cores based on this type of rapid-solidified alloy. The reversible and irreversible domain wall relaxation processes were successfully recognized in as-quenched and annealed ribbon and the collective relaxation process was observed in powder cores. Moreover, the effects of increasing AC field amplitude on the relaxation frequencies and domain wall movement dynamics were scrutinized and compared from the view of used form of the material, i.e. amorphous, nanocrystalline alloy in the form of ribbon and consequently as powder particles compacted into the ring-shaped cores. This analysis has been performed by the study of complex permeability spectra obtained using the impedance spectroscopy [2] of the samples over wide frequency band. The complex permeability,  $\mu = \mu' - i\mu''$ , consisting of real ( $\mu'$ ) and

imaginary ( $\mu''$ ) part, includes the thorough magnetic response information of the sample on the exciting AC magnetic field of increasing frequency,  $H_{AC} = H_m \cos(\omega t)$ , where  $H_m$  is its amplitude. The domain walls pinned on pinning centers (mechanical strains, defects, surface edges, inclusions, structure imperfections, precipitates etc.) and driven by small AC field possess a similar dynamics as membranes under mechanical pressure and can be reversibly bulged. Magnetic fields, higher than pinning field  $H_p$ , can cause the irreversible jumps of domain walls. The third main magnetization mechanism is the magnetization rotation, which is able to follow AC field up to the highest frequencies because of the fastest dynamics. From the complex permeability spectra, one can retrieve the dynamic properties of dominant magnetization processes and, furthermore, separate magnetization processes using the AC fields of different amplitude and frequency.

Recent studies, which have been conducted on thin Fe- and Co-based soft magnetic ribbons [3–8], ferrites [9–11], ferrite-type composites [10,12,13] and thin ferromagnetic wires [14], have shown that the DC magnetic field applied on the sample along different directions can significantly affect the permeability of ferromagnet due to the changes in its domain structure. Therefore,

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the understanding of the magnetic response in a material exposed to AC fields of various frequencies under DC bias conditions is necessary for the possible applications as magnetic active parts for electric motors, transformers, magnetic sensors etc.

In the last few years there has been a growing interest [15–21] in the physical properties investigation of powder materials prepared by the milling of ribbons or the mechanical alloying of initial elements and then processed by several powder metallurgy methods into the bulk form. The shape diversity of possible core components for industry applications is the main advantage of this group of magnetic materials. For our study, we have chosen Finemet-type alloy commercially available as Vitroperm® 800 ( $\text{Fe}_{73}\text{Cu}_1\text{Nb}_3\text{Si}_{16}\text{B}_7$ ). To the authors' knowledge, DC bias field effect on the complex permeability in nanostructured powder  $\text{FeCuNbSiB}$  cores has not yet been investigated.

Therefore, the purpose of present paper is a systematic study of DC field influence on the relaxation processes concerning the domain walls in this type of materials, i.e. in ribbons and compacted powder cores obtained by the milling of amorphous ribbon precursor. The research is carried out by means of complex permeability measurements as a function of three independent variables,  $\mu = \mu'(f, H_m, H_{DC}) - i \mu''(f, H_m, H_{DC})$ , where  $f$  is the magnetizing frequency of AC magnetic field  $H_{AC}$  of amplitude  $H_m$  and  $H_{DC}$  is the DC bias magnetic field intensity. It allows us to see a complete image of magnetization processes contributing to the total magnetization in the light of their frequency relaxation under AC driving magnetic field in the absence/presence of bias DC field. An approach of complex permeability concept to magnetization processes investigation offers quite sensitive method of indirect and non-destructive evaluation of magnetic material. Other techniques, e.g. magneto-optical Kerr effect-based observation of dynamic magnetization reversal, can be used in a narrower frequency band and also have the limitations regarding the repeatability and the studied material due to the testing of surface domain structure. On the contrary, the complex permeability can be straightforwardly determined from the whole volume of the sample and thus gives a total information on the material. Furthermore, the impedance spectroscopy offers high-precision measurement in specified AC magnetic field of broad-band frequency.

## 2. Experimental procedure

The initial material for the preparation of studied samples was the amorphous alloy of nominal composition  $\text{Fe}_{73}\text{Cu}_1\text{Nb}_3\text{Si}_{16}\text{B}_7$  (at.%) in the form of ribbon, which was produced via melt spinning technique (commercial material Vitroperm® 800, provided by Vakuumschmelze GmbH & Co. KG Hanau, Germany). We started by the investigation of two ribbon samples: in original amorphous state and annealed one in nanocrystalline state. Then two powder bulk ring-shaped cores were prepared by the hot uniaxial compaction of two types of powders produced by the milling and cryomilling of as-quenched ribbon. The powder core R consists of the powder milled at room temperature and core L was consolidated from powder obtained by cryomilling, i.e. milling after the cooling to the temperature of liquid nitrogen. The powders differed in the morphology and mean size of particles. Cryomilling resulted in smaller particles due to the higher brittleness of the ribbon at lower temperature. Our previous studies [22,23] showed that particle size of more than 95% of particles after milling at room temperature is from 50  $\mu\text{m}$  to 300  $\mu\text{m}$ , but cryomilled powder has smaller particle sizes, from 20  $\mu\text{m}$  to 150  $\mu\text{m}$ . The DSC traces of the as-quenched  $\text{Fe}_{73}\text{Cu}_1\text{Nb}_3\text{Si}_{16}\text{B}_7$  ribbon, milled powder and cryomilled powder revealed a sharp single exothermal crystallization peak at  $T = 525^\circ\text{C}$  [22]. This peak corresponds to the crystallization of  $\alpha\text{-Fe-Si}$  phase and therefore the annealed ribbon sample,

introduced as described above, can be regarded as nanocrystalline. Finally, the both powder cores were annealed to prepare nanostructured bulk material with as optimal as possible soft magnetic properties as it outcomes from our earlier experience [22]. The detailed description of the samples preparation is provided in our previous paper [1].

The frequency dependencies of real and imaginary parts of complex permeability were determined by the impedance spectroscopy (in the frequency range from 100 Hz to 40 MHz) using an impedance analyzer (HP 4194A) equipped with a test fixture (Agilent 16047D), which converts four-terminal pair impedance measurement to a two-terminal configuration [24]. For this purpose, the toroidal coils of several turns around the ring samples were prepared and connected to the test fixture. We used an experimental approach, synthetically described in Ref. [1], based on the high-accuracy keeping of measuring AC current amplitude, i.e. AC magnetic field amplitude applied to the sample, at the constant value in the studied frequency band by PC software control. The main limitations of our apparatus concerning the setting up of desired AC magnetic field amplitude value are the range of RMS voltage (0.01–1.00 V) supplied by impedance analyzer and sample dimensions.

The DC bias magnetic fields of various strengths,  $H_{DC}$ , were generated by the Helmholtz coils ( $H_{DC} \leq 5 \text{ kA/m}$ ) and Weiss type electromagnet ( $H_{DC} \leq 500 \text{ kA/m}$ ) energized by a programmable DC power supply (Agilent E3634A). The sample under test was inserted in the center of Helmholtz coils or between central zones of north and south electromagnet pole. The DC field intensity was measured in the vicinity of a sample by a microprocessor controlled gaussmeter (Hirst Magnetic Instruments GM08). DC fields were applied along the rotation axis of toroidal samples, i.e. perpendicularly to the circular measuring AC magnetic field created by AC current from impedance analyzer. All the measurements were performed at room temperature. Before the measurements, the toroidal samples were carefully demagnetized from technical saturation using 40 Hz signal of continuously descending amplitude.

## 3. Results and discussion

### 3.1. Magnetization dynamics in as-quenched and annealed ribbon

We have started with the investigation of the role of an increasing DC bias transverse magnetic field on the complex permeability parts of two ribbon samples. Figs. 1 and 2 present the complex permeability spectra of as-quenched and annealed  $\text{Fe}_{73}\text{Cu}_1\text{Nb}_3\text{Si}_{16}\text{B}_7$  ribbon, respectively, under several different DC magnetic fields ranging from 0 up to several tenths of kA/m. All these spectra were measured at very small amplitude of exciting AC magnetic field of  $H_m = 0.14 \text{ A/m}$  during the frequency sweep. In the absence of DC field, the real part of permeability for as-quenched ribbon, Fig. 1(a), exhibits a plateau up to 300 kHz and then drops to small values. Together with this behavior in real part  $\mu'$ , the imaginary part  $\mu''$  reaches a peak at relaxation frequency of about 3.8 MHz, Fig. 1(b). That is probably mostly connected to the domain wall relaxation and the domain walls are fully relaxed above this frequency. The frequencies at the maximum of imaginary parts of complex permeability in thin soft magnetic ribbons of various compositions recently studied have also been attributed to such effects [8]. For annealed ribbon without bias field, Fig. 2, we can see the stability of real part permeability up lower frequencies than for as-quenched one. For the DC fields  $H_{DC} \leq 15 \text{ kA/m}$  applied on the as-quenched ribbon, we can observe the progressive increase of real part of permeability, as shown in Fig. 1(a). Higher fields than this critical field (further marked as  $H_{cr}$ ) result in the significant

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