

Depth-sensitive characterization of surface magnetic properties of as-quenched FeNbB ribbons

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The longitudinal magneto-optical Kerr effect (MOKE) is used to study the surface magnetic properties of as-quenched FeNbB ribbons. MOKE surface hysteresis loops measured from both ribbon sides confirm different magnetic behavior. Wheel ribbon side shows heterogeneous (crystalline/amorphous) properties, thickness of crystalline phase (about 3 nm) was established by comparing the measured magneto-optical angles of Kerr rotation and ellipticity at different incident angles with the theoretical model. Effective crystalline phase observed at shiny ribbon side is harder (coercive field about 40 Oe) than that on wheel side and penetrates deeper into the material volume. Its thickness 1.3 μm estimated from the weight reduction of the ribbon during surface etching is in good agreement with cross-section image obtained using the scanning electron microscopy (SEM). The sources of magnetoelastic anisotropy were identified in the bulk as well as on the ribbon surface using the magneto-optical Kerr microscopy.

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1 INTRODUCTION

Amorphous and nanocrystalline Fe-based ribbons are systematically studied for many years due to excellent soft magnetic properties. Their progress and applicability has rapidly grown in seventies of 20th century, when the commercial production of the amorphous alloys called the metallic glasses (Metglass) began. Especially the Metglass alloys with the compositions Fe-B and Fe-B-Si exhibited much lower coercive force and higher magnetic permeability in comparison to other soft magnetic materials [1–4]. Further development and improvement of magnetic softness and thermal stability was discovered at materials with heterogeneous (crystalline / amorphous) structure often called nanocrystalline soft magnetic materials. The best known commercial alloys are NANOPERM, FINEMET, and HITPERM [5,6]. As a consequence the nanocrystalline soft magnetic materials showed great potentials in many industrial applications like the transformer cores, the switched-mode power supplies, the ground fault interrupters or the magnetic sensors [7–9].

Present technological trends in investigations of nanocrystalline materials are mainly focused on the improvement of their magnetic and mechanical properties, decreasing the size of crystalline grains, controlling the volume ratio between the crystalline and amorphous phases, eliminating the surface corrosions, and the surface magnetic domains observations that correspond to the anisotropy distribution. Mentioned properties can be achieved in ribbon

as-quenched state as well as by sufficient postpreparation treatment like the annealing at sufficient temperatures, annealing in applied magnetic field or by stress applications [10–13]. Moreover, there are introduced new material compositions originating by adding new elements (Ni, Mn, Mo) to the traditional Fe-based nanocrystalline alloys [14–16]. Hence there is a need to use advanced surface and bulk sensitive methods and investigate the depth profile of the magnetic properties in the near-surface region of these alloys.

Recently we investigated the surface and bulk magnetic properties of as-quenched FeNbB ribbons prepared by planar flow casting [17]. Main emphasis was devoted to the surface sensitive methods like the magneto-optical Kerr effect (MOKE) and the conversion electron Mössbauer spectroscopy (CEMS). Due to lower searching depths of both methods (MOKE – 30 nm, CEMS – 200-300 nm) [18] we detected the contribution of thin crystalline phase close to the ribbon wheel side, i.e. the side in direct contact with quenching wheel. X-ray diffraction (XRD) measurements shown that crystallites are highly (2 0 0) textured. Moreover, after 10 s of etching in diluted HNO₃, which corresponded to removing about 50 nm from the ribbon wheel side, the sharp α -Fe diffraction peak disappeared and only broad amorphous peaks were observed. Consequently the influence of the annealing on the crystalline phase and ribbon anisotropy was studied in Ref. [19].

In this paper we continue in our studies on the as-quenched FeNbB ribbons and our attention is focused on three main problems. Firstly, we try to estimate more precisely the thickness of crystalline phase from the ribbon wheel side. To solve this problem we use the surface-sensitive method based on the measurement of complete complex longitudinal Kerr effect at variable incident angle [19]. Secondly, we investigate in details the shiny ribbon side, i.e. the

side in contact with the air during preparation process. It seems that thicker crystalline phase observed from the shiny side by the XRD and the CEMS methods is exchange-biased with the soft amorphous bulk [20]. Hence the study of the thickness and magnetic properties of such layer is important for understanding the bias phenomenon in these materials. Finally we deal with the anisotropy distribution on the ribbon surface using the magneto-optical Kerr microscopy.

2 EXPERIMENTAL

10 mm wide and 28 μm thick as-quenched $\text{Fe}_{80.5}\text{Nb}_{6.9}\text{B}_{12.6}$ ribbons were prepared by conventional planar method and additionally spark-cut to the 9 mm discs to eliminate the in-plane shape anisotropy. MOKE experimental setup based on differential intensity method consists of the semiconductor laser working at wavelength of 670 nm, the polarizer, the quarter-wave plate used as retarder, the Wollaston prism, and two photodiodes [19]. Approximately circular laser spot about 0.5 mm in diameter was focused on the center of the circular sample. The magneto-optical angles of Kerr rotation $\theta_{Ks,p}$ without the retarder and Kerr ellipticity $\epsilon_{Ks,p}$ using the quarter-wave plate for *s*- and *p*-polarized light are measured at different incident angles. The longitudinal hysteresis loops detecting the magnetization component in the sample plane and in the plane of incidence are obtained [21]. We did not observe any polar (out of plane) component of magnetization. All measurements were done at room temperature and in an open air.

SEM digital images of the sample cross-section were obtained from both ribbon sides by PHILIPS XL-30 scanning electron microscope. Images were taken at

