Study of inverse magnetostrictive effect in metallic glasses \( \text{Fe}_{80-x}\text{Co}_x\text{P}_{14}\text{B}_6 \)

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Abstract. The paper presents the possibility to build a tension gauge capable to discriminate different kinds of deformations: compression and twisting (induced by torsion strain) based on the magnetoelastic effect in new metallic glasses \( \text{Fe}_{80-x}\text{Co}_x\text{P}_{14}\text{B}_6 \). Applied loads increase coercive field \( H_c \), saturation induction \( B_s \) and rectangularity of magnetic hysteresis loop. For example, hysteresis loop traced for 1 mm narrow, 50 cm long and 30 \( \mu \)m thick \( \text{Fe}_{40}\text{Co}_{40}\text{P}_{14}\text{B}_6 \) straight ribbon subjected to longitudinal stress of 346 MPa shown increased \( B_s \) from 1.24 to 1.7 T and squareness from 0.55 to 0.88 compared to unloaded specimen. For twisting, on the contrary, both squareness and coercive field vary whereas the value of \( B_s \) remains unchanged.

1. Introduction

Magnetic properties of rapid quenched \( \text{Fe}_{80-x}\text{Co}_x\text{P}_{14}\text{B}_6 \) metallic glasses surpass characteristics of \( \text{Fe}_{40}\text{Ni}_{40}\text{P}_{14}\text{B}_6 \) magnetosoft material (Metglas 2826) widespread in the commercial market. Really, the maximum relative differential permeability of as quenched \( \text{Fe}_{80-x}\text{Co}_x\text{P}_{14}\text{B}_6 \) ribbons is about 110000, the saturation induction \( B_s = 1.45 \) T, quasistatic coercive field as low as 4 A/m, Curie temperature above 700 K, significantly higher thermal stability due to increased by 60 K crystallization temperatures, low hysteresis loss of about 0.26 W/kg in the saturation mode at frequency of 100 Hz [1-3].

Magnetostriction and inverse magnetostrictive (magnetoelastic) effect have been thoroughly investigated only in some polycrystalline magnetic materials. Due to versatile functional properties amorphous magnetic materials promise many practical applications. Besides high magnetoelastic coupling, they exhibit large elastic thresholds, which permit the application of much larger stresses not accompanied by plastic deformations.

The aim of this article is to report experimental results on magneto-mechanical effect in amorphous rapidly quenched ribbons with different \( \text{Fe}_{80-x}\text{Co}_x\text{P}_{14}\text{B}_6 \) compositions.

2. Experimental

Series of \( \text{Fe}_{80-x}\text{Co}_x\text{P}_{14}\text{B}_6 \) \((x = 25, 32, 35 and 40 \text{ at.} \%)\) ribbons were meltspun onto the massive copper wheel from the RF-melted superheated master ingots. X-ray diffraction reveals amorphous structure in as-cast specimens containing the superposition of bcc \( \alpha\)-Fe-Co and bct \( (\text{Fe},\text{Co})_3(\text{P},\text{B}) \) nuclei with a characteristic size as small as 1.6 nm. Both isothermal and isochronal annealing of ribbons in protective atmosphere lead to the predominant growth of bcc \( \alpha\)-Fe-Co 20-30 nm-sized crystals within the amorphous metallic matrix [4].

Characteristics that quantify magnetoelastic phenomenon were obtained from the series of hysteresis \( B-H \) loops recorded for \( \text{Fe}_{80-x}\text{Co}_x\text{P}_{14}\text{B}_6 \) ribbons under applied external stresses. Due to very high magnetic permeability, special precautions were undertaken to choose a proper orientation of ribbons in 30 cm long primary and 5 cm long two secondary (pick-up and reference) solenoidal coils of the
magnetometer. It is determined by actual magnetic declination of 12.764° E and relatively high magnetic inclination of 74.797° in Petrozavodsk city (Karelian Republic, Russia – Latitude: 61°46'59"; Longitude: 34°19'59").

Schematic of experimental setup to record hysteresis loops under applied stresses is shown in Fig. 1. Magnetometer contains the external coil which generates the magnetic field and internal receiving coils. The specimen under test is placed in one of two receiving coils connected in series and electrically in opposition. Signal from the receiver coils is integrated with the use of an active integrator. The upper end of the tape is fixed on the stand, and the bottom one is loaded by hanging a certain weight.

Figure 1. Installation for the measurement setup.

3. Results and discussion

1 mm wide and 30 µm thick Fe$_{80-x}$Co$_x$P$_{14}$B$_6$ ribbons were subjected to mechanical stresses. We neglected the change of ribbon’s cross-section under load and calculated mechanical stress $\sigma$ dividing applied force by cross-sectional area of the ribbon.

Series of hysteresis loops under different linear mechanical loads applied along ribbons is shown in Figs. 2 a,b. They illustrate experimental data for glass composition Fe$_{45}$Co$_{35}$P$_{14}$B$_6$ at magnetizing field up to $H_{\text{max}} = 450$ A/m and for Fe$_{55}$Co$_{25}$P$_{14}$B$_6$ metallic glass at $H_{\text{max}} = 2200$ A/m. Two insets for graphs show that saturation induction $B_s$ increases with a load growth in both cases. It is notable that at low loads the dependences $B_s(\sigma)$ have a linear region to approximately $\sigma = 100$ MPa and then saturate with $B_s$ remaining almost constant. At the same time, coercive field $H_c$ slightly increases under strain deformation for both samples.
Figure 2. a - Series of hysteresis loops for Fe_{45}Co_{35}P_{14}B_{6} ribbon at magnetizing field up to $H_{\text{max}} = 450$ A/m for different linear mechanical loads. b - Hysteresis loops for Fe_{55}Co_{25}P_{14}B_{6} ribbon at $H_{\text{max}} = 2200$ A/m.

Besides the increase of saturation magnetization $B_{s}$, growth of mechanical load results in changing the shape of hysteresis loop. Loop squareness $B_{s}/B_{\text{rem}}$ is a useful parameter to quantify the change of magnetic properties. Here $B_{\text{rem}}$ is a remnant induction remaining at $H = 0$. Fig. 3 depicts a series of hysteresis loops for Fe_{48}Co_{32}P_{14}B_{6} metallic glass. Inset to Fig. 3 presents loop’s squareness and saturation induction $B_{s}$ as functions of mechanical load. In contrast to $B_{s}(\sigma)$, there is a small initial region where the squareness seems to be independent on the load.

Figure 3. Series of hysteresis loops for Fe_{48}Co_{32}P_{14}B_{6} metallic glass at magnetizing field up to $H_{\text{max}} = 300$ A/m with different mechanical loads applied along the ribbon. Inset shows the dependences of hysteresis loop’s squareness and saturation induction $B_{s}$ on mechanical stress $\sigma$.

Under applied linear stress of 346.3 MPa, the saturation induction $B_{s}$ increases from 1.24 to 1.7 T, loop’s squareness also increases from 0.55 to 0.9, whereas the coercive field remains practically unchanged. 3D plot in Fig. 4 summarizes both dependencies of magnetic induction $B$ in Fe_{48}Co_{32}P_{14}B_{6} glass on magnetic field $H$ and applied linear stress $\sigma$. 
Figure 4. 3D plot for the field and stress dependent magnetic induction $B(H, \sigma)$.

We found that magnetic response in magnetosoft rapidly quenched Fe$_{80-x}$Co$_x$P$_{14}$B$_6$ ribbons depends also on the type of applied mechanical stress. Twisting deformations result in dramatic increase of coercive field. Fig. 5 demonstrates this effect as a series of hysteresis loops for Fe$_{48}$Co$_{32}$P$_{14}$B$_6$ metallic glass ribbons subjected to a torsional stress.

Figure 5. Series of hysteresis loops in Fe$_{48}$Co$_{32}$P$_{14}$B$_6$ ribbon magnetized up to $H_{\text{max}} = 400$ A/m and twisted at different angles.
As clearly seen in Fig. 5, opposite to longitudinal strain the torsion deformations as high as 20.6 °/cm result in huge growth of coercive field $H_c$ from 27.5 A/m up to 60 A/m and significant increase of squareness from 0.29 to 0.85, whereas the saturation induction $B_s$ being practically unchanged.

4. Conclusions

Presented results show that different mechanical stresses have significant influence on the shape of hysteresis loops in metallic glasses Fe$_{80-x}$Co$_x$P$_{14}$B$_6$. Magnetoelastic effect manifests itself by growth of coercive field $H_c$, saturation induction $B_s$ and loop’s squareness under applied longitudinal mechanical load. Under twisting, on the contrary, saturation magnetization remains constant whereas both coercive field $H_c$ and loop’s squareness experience a rapid increase. These observations testify possibility to discriminate different types of mechanical deformations and to build a multicomponent strain gauge based on magnetosoft Fe$_{80-x}$Co$_x$P$_{14}$B$_6$ metallic glasses.

References

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