Determination of saturation magnetostriction of amorphous Fe-Co-P-B ribbons: comparison of various methods

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Abstract. We present and compare results of measurement of saturation magnetostriction constants of amorphous ribbons Fe₈₀ₓCoₓP₁₄B₆ (x = 23, 25, 28, 32, 40 at.%) and the reference Fe₄₀Ni₄₀P₁₄B₆ specimen employing Narita and Becker-Kersten methods. We also modified a strain gauge-based method to enable measurements of complete magnetic field dependence of magnetostriction coefficients.

1. Introduction

This work aims the measurement of saturation magnetostriction coefficients in amorphous rapidly quenched Fe₈₀ₓCoₓP₁₄B₆ (x = 23, 25, 28, 32, 40 at.%) ribbons. Two methods were employed: Narita small-angle magnetization rotation [1] and Becker-Kersten-O’Dell saturation of strained specimen [2,3]. In Narita method, experimental magnetic field dependence of the amplitude of the second harmonic nicely fits to the theory thus yields the most reliable results. In the Becker-Kersten method, the results are less convincing since features of experimental hysteresis M-H loops do not allow one to define accurately the value of magnetic field required to saturate metallic glass samples.

Both above mentioned methods cannot provide the information concerning the dependence of magnetostriction on applied field and its hysteretic behaviour. For this reason, we modified a strain gauge-based method to enable measurements of complete magnetic field dependence of magnetostriction coefficients.

2. Theory

2.1. Narita method

In the original Narita method, metallic glass ribbon is exposed to the saturation under longitudinal magnetic field $H_\parallel$ and additional transversal sinusoidal magnetic field $H_\perp$ oriented parallel to the plane of the ribbon. Time variation of transversal magnetic field causes such small-angle rotation of magnetization vector that, during one oscillation period of transversal field, longitudinal component of magnetization changes with a double frequency. As a result, the second harmonic signal appeared in receiving solenoidal coil.

To calculate the amplitude of this signal, Narita used the following expression for energy density:
Here $M_s$ is the saturation magnetization (determined from $M - H||$ magnetization curves), $N_\perp$ and $N_{||}$ are ribbon’s demagnetizing factors, $\lambda_s$ is the saturation magnetostriction, $\sigma$ is applied tensile stress, $\theta$ is the angle between magnetization vector and ribbon’s axis. Minimization of energy $E$ with the respect to $\theta$ yields the following expression for the electromotive force:

$$E = -H_l M_s \cos \theta - H_\perp M_s \sin \theta + 3/2 \lambda_s \sigma \sin^2 \theta + 1/2 M_s^2 (N_\perp \cos^2 \theta + N_{||} \sin^2 \theta)$$ \hspace{1cm} (1)

$$e_{2f} = 2\pi/c N \cdot S \cdot M_s \cdot \omega \cdot \sin^2 \theta \sin 2\omega t, \quad \sin \theta_{\max} = H_{\perp,\max} / (H_{||} + H_k + H_s).$$ \hspace{1cm} (2)

Here $c$ is light velocity, $N$ – is the number of turns in receiving coil, $S$ – area of cross-section of the sample, $\omega$ – frequency, $H_k = 3\lambda_s \sigma / M_s$, $H_s = M_s (N_\perp - N_{||})$. Since $1/\sqrt{e_{2f}}$ is proportional to $(H_{||} + H_k + H_s) / H_{\perp,\max}$, we obtain $H_k$ and $\lambda_s = H_k M_s / 3 \sigma$ when plotting $1/\sqrt{e_{2f}}$ against $H_{||}$ for various values of $\sigma$.

2.2. Becker-Kersten method

In the original Becker-Kersten method [2], negative saturation magnetostriction constant is obtained from the series of hysteresis $M - H$ loops recorded at different tensile tensions $\sigma$ applied to a ribbon. $\lambda_s$ is determined from $H_k$ assumed to be a magnitude of applied field that magnetizes ribbon up to saturation. Since $H_k$ is not well defined, O’Dell [3] modified the method and suggested to settle $H_k$ as a field required to reach 90% of saturation. Finally, saturation magnetostriction is expressed as follows:

$$\lambda_s = 1/3 M_s \times dH_k / d\sigma.$$ \hspace{1cm} (3)

2.3. Strain gauge method

In [4] and [5], the authors determined $\lambda_s$ by measuring the strain of magnetic samples arisen at applied magnetic field. In the present work we follow this method and measured the strain of the ribbon exposed to various tensile tensions $\sigma$ and pulsed magnetic field.

3. Experimental Arrangement

The details of fabrication of Fe-Co-P-B series of rapidly quenched ribbons with the cross section of $1 \times 0.03$ mm$^2$ have been published elsewhere [6,7]. Our amorphous Fe$_{40}$Ni$_{40}$P$_{14}$B$_6$ ribbon and commercial Ni wire with the diameter of 0.3 mm were served as reference samples.

For the measurements, we used Keithley 2400 SourceMeter and L6D-C3-3kg-0.4B single point load cell (calibrated output voltage is 238 mV/N). Their precision was sufficient to observe changes of output voltage of the strain gauge caused by applying of magnetic field. To suppress the drift of the output signal, pulsed modulation of the magnetic field and averaging of the results were employed. In calculations we used Young’s modulus to be equal to 43 GPa for Fe-Co-P-B ribbons.

4. Results and Discussion

Figure 1 presents the time dependent output voltage response of a strain gauge upon the rectangular pulses of longitudinal magnetic field applied to the ribbon. Pulses of the electrical current have a negative polarity and gradually decreased amplitude. Output strain gauge voltage $U_{\text{tens}}$ contains instantaneous response pulses superimposed upon the continuous voltage drift. The latter one indicates the increase of the length of the ribbon caused by a train of input pulses.
Figure 1. Time dependence of applied magnetic field (current in solenoidal coil $I$) and the output strain gauge’s voltage $U_{tens}$.

Figure 2 shows dependence of magnetostriction coefficient $\lambda$ as a function of the amplitude of magnetic field pulses for the ribbon experienced different static tensile strain. The instantaneous changes of strain increase with the increase of magnetic field and saturate at ca. 20 Oe. Influence of magnetic field clearly decreases for highly strained ribbon.

Figure 2. Dependence of magnetostriction coefficient $\lambda$ on the amplitude of pulsed magnetic field in Fe$_{52}$Co$_{28}$P$_{14}$B$_6$ ribbon experienced different static tensile strains $U_{tens}$.

Figure 3 depicts the dependence of the amplitude of magnetic field response $\Delta U_{tens}^{\max}$ and calculated magnetostriction coefficient $\lambda$ on the static tensile stress $\sigma$ for ribbons with a different content of Co substituent.
Figure 3. Dependence of magnetostriction coefficient $\lambda$ upon the static tensile stress $\sigma$ at saturating pulsed magnetic fields for different ribbons.

Also, we made an attempt to measure the hysteresis of magnetostriction by cycling the current $I(t)$ in solenoidal coil up to saturation (see figure 4). Sufficiently smooth curves $\Delta U_{\text{tens}}(t)$ were obtained after averaging. For amorphous ribbons, hysteresis of $\Delta U_{\text{tens}}(t)$ vs. $H(t)$ is almost invisible in figure 5. On the contrary, the butterfly-like hysteresis curve was observed in figure 6 for Ni wire with a clear time retarding of the output signal.

![Graph of magnetostriction coefficient vs. static tensile stress](image1)

Figure 4. Time dependence of applied magnetic field (current in solenoidal coil $I$) and output strain gauge’s voltage $U_{\text{tens}}$ during the measurement of hysteresis of magnetostriction.

Table 1 collects results of the measurements of saturated magnetostriction. For Fe$_{40}$Ni$_{40}$P$_{14}$B$_6$, $\lambda_s$ obtained by Narita method is close to the value from the literature: $12.6 \times 10^{-6}$ [1,4]. Results for Becker-Kerston method are less reliable due to the arbitrariness when parameterizing the hysteresis $M$-$H$ curves.
### Table 1. Results of measurement of $\lambda_s$

| Sample          | $\mu_0 M_s$ [T] | $\lambda_s \times 10^6$ (Narita) | $\lambda_s \times 10^6$ (Becker-Kersten) | $\lambda_s \times 10^6$ (strain gauge) |
|-----------------|-----------------|----------------------------------|----------------------------------------|----------------------------------------|
| Fe$_{40}$Ni$_{40}$P$_{14}$B$_6$ | 0.85            | 17.2                             | 17                                     | 4.4                                    |
| Fe$_{57}$Co$_{23}$P$_{14}$B$_6$  | 1.6             | 30.9                             | 5.4                                    | 11.4                                   |
| Fe$_{55}$Co$_{25}$P$_{14}$B$_6$  | 1.4             | 47.1                             | 1.75                                   | 11.8                                   |
| Fe$_{52}$Co$_{28}$P$_{14}$B$_6$  | 1.4             | 35.9                             | 10                                     | 12.9                                   |
| Fe$_{48}$Co$_{32}$P$_{14}$B$_6$  | 1.45            | 38.2                             | 22                                     | 15.1                                   |
| Fe$_{48}$Co$_{32}$P$_{14}$B$_6$  | 1.4             | 52.8                             | 16                                     | 19.1                                   |

**Figure 5.** Absence of apparent hysteresis for amorphous metallic glass Fe$_{52}$Co$_{28}$P$_{14}$B$_6$ ribbon.

**Figure 6.** Butterfly-like hysteresis for Ni wire.

### 5. Conclusions
Saturation magnetostriction constants were measured by various methods and compared to each other. Strain gauge method was modified to enable determination of complete magnetic field dependence of magnetostriction coefficients.
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References
[1] Narita K, Yamasaki J and Fukunaga H 1980 IEEE Trans. Magn. 16 435-439
[2] Becker R and Kersten M 1930 Zeitschrift für Physik 64 660-681
[3] O'Dell T H 1981 Phys. Stat. sol. (a) 68 221-226
[4] Tsuya N, Arai K and Ohsaka T 1978 IEEE Trans. Magn. 14 946-948
[5] Takaki H and Tsuji T 1956 J. Phys. Soc. Jpn. 11 1153-1157
[6] Hollmark M, Tkatch V I, Grishin A M and Khartsev S I 2001 IEEE Trans. Magn. 37 2278-2280
[7] Tkatch V I, Grishin A M and Khartsev S I 2002 Mater. Sci. Eng. A 337 187-193