Strain sensors based on stress-annealed Co_{69}Fe_{2}Cr_{7}Si_{8}B_{14} amorphous ribbons

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Abstract

An application of the sensors in strain and load measurements for outdoor applications requires both high corrosion resistance and independence of measuring signal on long-term moisture of the surroundings. One of the best candidates for this field of application is a magnetoelastic sensor using the amorphous magnetic ribbons with negative magnetostriction. Two-coil strain sensors based on stress-annealed Co_{69}Fe_{2}Cr_{7}Si_{8}B_{14} amorphous magnetic ribbons were designed, fabricated, and evaluated. Their sensitivity is much more higher compared with resistance gauges, allowing low-price electronic portable equipment for outdoor measurements.

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1. Introduction

Remarkable mechanical properties and extraordinary magnetoelastic coupling makes the amorphous metallic alloys suitable for magnetoelastic transducers [1,2]. High homogeneity with neither grain boundaries nor dislocations greatly enhances their elastic limit. This allows a high stress (strain) to be applied within the elastic reversible range. Commonly Fe-rich amorphous alloys, in form of thin ribbon, with high positive magnetostriction λ_{S} (∼=+30 ppm) are very suitable for mechanical stress sensors, [3]. Nevertheless they can be used only for relatively small strain range because of the saturation effect. When the desired range of strain measurement is more than 1000 ppm, the amorphous alloys with negative magnetostriction are preferable [2]. To improve the linearity of sensor transfer characteristics an induced transversal magnetic anisotropy is used. Stress-annealing Co-rich alloys with applied tensile stress along the ribbon axis induces a magnetic anisotropy with an easy plane perpendicular to the ribbon axis [4]. Magnetization reversal then takes place by rotation only, that ensures negligible hysteresis and nearly linear magnetization characteristics.

2. Magnetic and magnetoelastic properties of CoFeCrSiB amorphous ribbons

Ribbons 6 mm wide and approximately 20 μm thick were prepared by planar flow casting and afterwards continuously stress-annealed in a radiation furnace (1 h at temperature 380 °C). The representative magnetic and magnetoelastic parameters of stress-annealed samples are summarized in Table 1.

The effective anisotropy field H_{K} of the ribbon is magnetized with magnetic field parallel with the ribbon axis can be expressed as

\[ H_{K} = H_{K0} - \frac{3\lambda_{p}\sigma}{J_{S}} + H_{KS}, \]

where the anisotropy field H_{K0} is induced by stress-annealing and H_{KS} the shape anisotropy field, J_{S} the saturation value of magnetic polarization and σ the applied stress. The stress induced anisotropy field H_{K0} is proportional to annealing tensile stress σ_{A}, and slightly depends on the alloy composition. This dependence for Co_{69}Fe_{2}Cr_{7}Si_{8}B_{14} can be approximately described by the relation: H_{K0} = 1.7σ_{A} (A/m, MPa). The shape anisotropy field (demagnetizing field)

\[ H_{KS} = \frac{N_{S}}{\mu_{0}} \]

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Table 1
Parameters of Co$_69$Fe$_{2}$Cr$_{7}$Si$_{8}$B$_{14}$ ribbon after annealing for 1 h at 350$^\circ$C at different $\sigma_A$.

<table>
<thead>
<tr>
<th>$\sigma_A$ (MPa)</th>
<th>$J_s$ (T)</th>
<th>$H_C$ (A/m)</th>
<th>$H_K$ (A/m)</th>
<th>$\lambda_S$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.56</td>
<td>2.9</td>
<td>175</td>
<td>(-0.6 to 1.03)</td>
</tr>
<tr>
<td>150</td>
<td>2.45</td>
<td>250</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$J_s$ is the magnetic polarization of saturation, $H_C$ the coercivity and $\lambda_S$ the magnetostriction constant of the amorphous alloy.

is proportional to the demagnetizing coefficient along the ribbon axis $N$. This varies in a range from 27 to 72 A/m with the length of the ribbon from 150 down to 60 mm, which are reasonable values from application point of view in civil engineering constructions.

When the length of the 6 mm wide ribbon is more than 340 mm the shape anisotropy field can be neglected, if compared with the stress induced anisotropy. Then the dependence of the magnetic susceptibility $\chi$ on the applied stress is described by equation

$$\chi(\sigma) = \chi(0) \left(1 + \frac{3|\lambda_S|}{2K_0} \sigma \right) = \chi(0) \left(1 + C \frac{\sigma}{\sigma_A}\right),$$

where $K_0$ is anisotropy constant of the stress induced anisotropy and $C$ is a dimensionless constant. The measured values of normalized dynamic reluctivity $\nu$ changes with the applied tensile stress $\sigma$ for different stress-annealing conditions $\sigma_A$ are shown in Fig. 1.

The range of applied stresses $\sigma$ up to 375 MPa corresponds to strains $\varepsilon \approx 2200$ ppm and satisfies the conditions of reversible magnetoelastic effects.

Experimental results were obtained with homogeneously magnetized 320 mm long amorphous ribbon at a frequency of 5 kHz and sinusoidal flux density with a constant amplitude $B_m = 80$ mT.

The negligible hysteresis and nearly linear dynamic magnetization characteristics ensure independence of sensor output signal on external magnetic field without need for special magnetic shielding or sophisticated methods of electronic compensation [5]. The value of coercivity depends on internal stresses that are eliminated by the annealing stress $\sigma_A$ higher than 50 MPa. The linearity of dynamic magnetization characteristics with applied tensile stress as parameter is illustrated in Fig. 2.

Increasing the applied tensile stress increases also the range of the linearity of the dynamic magnetization characteristic. The influence of the ribbon length on the linearity of dynamic magnetization characteristics, for $\sigma = 0$ MPa, is shown in Fig. 3.

![Fig. 1. Change of normalized reluctivity of the stress-annealed ribbons with applied tensile stress.](image1)

![Fig. 2. Change of dynamic magnetization characteristic of continuously stress-annealed ($\sigma_A = 100$ MPa) ribbon with applied tensile stress as a parameter.](image2)

![Fig. 3. Change of the slope and linearity of dynamic hysteresis magnetization characteristics with the ribbon lengths. The sample was continually annealed at an applied tensile stress of 150 MPa.](image3)
Shortening of the ribbon causes the shape anisotropy field \( H_{K_S} \) to grow and on the other hand, results in a widening of the range where the branch of the magnetization characteristic is almost linear with respect to the applied magnetic field intensity. However, this is on account of the sensor sensitivity due to increase of effective anisotropy caused by a higher demagnetizing field (cf. curves in Fig. 1).

3. Two-coil strain sensor characteristics

Static magnetoelastic force or strain sensors are mostly designed to work as unloaded transformers with an open magnetic core, which is realized with an amorphous magnetic ribbon. The value of magnetic reluctivity of the core increases with the applied tensile stress for magnetic alloys with negative magnetostriction. For materials with a linear dynamic magnetization curve, small hysteresis and permeability \( \mu_r \gg 1 \), the voltage in the secondary (sensing) winding as a function of the strain \( \varepsilon \) can be expressed by the relation [6]

\[
U_2 = A \omega J_2 S K_2 \frac{\varepsilon_\lambda}{3E S \mu_0},
\]

where \( \omega \) is the angular frequency of sinusoidal magnetizing current \( I_{mag} \) in primary (magnetizing) winding, \( E \) the Young’s modulus and constant \( A \) takes into account both the demagnetizing effect and packing factor of the ribbon inside the sensing coil. If the induced voltage \( U_2 \) is kept constant, the magnetizing current as an output signal is then proportional to the strain \( \varepsilon \).

Since the designed strain sensor is an open magnetic circuit, it is necessary to take into account the problem of a considerable sensitivity to external magnetic fields. This problem can be overcome when dynamic magnetization characteristic is linear in the range of resultant (exciting AC superimposed on external disturbing) magnetic field. The influence of external DC disturbing magnetic field on the output signal of the sensor was tested for a zero applied stress when the linearity of dynamic magnetization characteristic is critical. The shape anisotropy of an 85 mm long ribbon with induced perpendicular anisotropy and cross-effect of acting magnetic fields ensure that the influence of the perpendicular component of the external magnetic field to the ribbon axis is negligible. The improvement of the measurement accuracy with an applied longitudinal DC external field due to the effect of the annealing stress \( \sigma_A \) is demonstrated in Fig. 4. The same effect of improving the measurement accuracy can be obtained after an appropriate bias stress is applied.

The prototype of a sensor with ribbon core 85 mm long, primary winding \( N_1 = 460 \) and secondary winding \( N_2 = 120 \), was mounted on a brass beam and subjected to a defined deformation, see Fig. 5.

To eliminate the "dead-zone" in both cases the amorphous ribbon was prestressed with a bias tensile stress of 60 MPa.

![Fig. 4. Influence of the longitudinal external DC magnetic field on measuring error \( \delta \) of a two-coil sensor for 85 mm long cores with different annealing stress \( \sigma_A \). A zero bias stress was applied.](image)

The induced voltage \( U_2 = 25 \) mV corresponds to flux density amplitude \( B_m = 80 \) mT. The efficiency characterizing the sensitivity of the sensor to the elongation (strain) \( \varepsilon \) is usually given by a relation

\[
F = \frac{\Delta M_{rel}}{\varepsilon},
\]

where \( \Delta M_{rel} \) is the relative change of measured value. In the case of a strain gauge the measured quantity is the resistance of wire, the parameter \( F \) is about 2. For the designed prototype of the two-coil magnetoelastic sensor \( F \) reaches the average value of 1350 and 1050 for \( \sigma_A = 100 \) and 150 MPa, respectively. The resulting exciting current \( I_{mag} \) as a function of the strain for the cores with different annealing stresses \( \sigma_A \) is shown in Fig. 6. Basic electrical scheme with feedback ensures a constant induced voltage, independent on strain, as shown in Fig. 7.

The ribbon sensor is excited by a sine signal with high frequency stability, derived from CPU timing circuits. Stability of the voltage at the secondary winding of the sensor

![Fig. 5. The experimental setup.](image)
coil \( N_2 \) is provided via a negative feedback using passive RC filters (LPF) and PI controller. The voltage measured on resistor \( R \) in the primary winding of the sensor \( N_1 \) is led to the CPU for further processing. This measuring system is capable of controlling more than one sensor at a time, using multiplexors (not shown in Fig. 7) in a master/slave mode of operation.

In order to test the performance of the sensors under a deformation in a general \( x, y \) direction, four sensors were fixed onto a cylindrical plastic rod in parallel direction with its length under 90°, allowing to investigate simultaneously also the effects of compression and elongation of the rod. The sensors were applied in a prestressed state corresponding to \( \sim 50\% \) of the expected maximal strain range (\( \sim 1000 \text{ ppm} \)). The scheme of such arrangement is shown in Fig. 8. Signal output of all four sensors for the case of deformation in \( x \)-direction (sensors \( X_1 \) and \( X_2 \) active) is shown in Fig. 9.

While the active sensors exhibit the corresponding signal change, the sensors in perpendicular positions (\( Y_1 \) and \( Y_2 \)) exhibit almost no effect. Different signals for the state with no deformation is due to the inaccuracy of application of prestressing during sensor fixation.

The effect of a deformation in a general \( x, y \) direction is shown in Fig. 10, where the pairs of lines correspond to a deformation of magnitude \((x, y)\) applied in both axes perpendicular to the rod length and to a corresponding \( x \) or \( y \) component of the same magnitude. Only the sensors \( X_1 \) and \( Y_1 \) were used. The results indicate that in a prestressed state the sensors are capable of measuring both elongation and compression effects in a general \( x, y \) direction, showing excellent additiveness and low sensitivity even for deformations in off-ribbon axes.
and compression. It is also clearly visible that the effect of off-axis deformation has negligible influence on the signal output. Thus, using even two sensors it is possible to obtain information on the direction and magnitude and sign of the general \( x-y \) deformation in the plane perpendicular to the direction of the attached ribbon sensors.

4. Conclusions

Selected amorphous Co-based ribbons in stress-annealed state provide excellent sensor material for strain sensors with high sensitivity, high and simple signal output and low sensitivity to environmental effects such as corrosion, temperature or humidity. The use of special pickup arrangement and the corresponding electronics combined with multiple-sensor arrangement allows advantageous measuring of wide interval of strains, including their direction.

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References


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Jan Bydžovský was born in Nový Bydžov, Czechoslovakia, in 1944. He graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, from Solid State Physics branch, in 1967. He received his PhD degree in theory of electromagnetism in 1981. Since 1987 he has been with the Department of Electromagnetic Theory at his Alma Mater, first as a research fellow, later as Lecturer. In 1995 he was appointed Associate Professor. He lectures electromagnetic theory and magnetic measurements. His research interests are focused on investigations of ferromagnetic properties of materials.

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