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MAGNETOELASTIC PROPERTIES OF CoFeCrSiB AMORPHOUS RIBBONS – A POSSIBILITY OF THEIR APPLICATION

Jan Bydžovský * — **Mojmír Kollár** * — **Peter Švec** ** — **Luděk Kraus** *** — **Vladimír Jančárik** *

Magnetoelastic properties of amorphous $Co_{71-x}Fe_xCr_7Si_8B_{14}$ ribbons with $x = 2$, 3.3, 4, 6, 8, and 12 were investigated. Suitable composition of amorphous material and annealing conditions with respect to magnetoelastic efficiency and linearity of transfer characteristics and resistance to external magnetic fields in a wide strain interval up to 2000 microstrains were selected. A prototype of two-coil strain sensor based on these materials was tested at different magnetizing conditions. The obtained results show the possibility to use the stress-annealed amorphous ribbon with composition $Co_{69}Fe_2Cr_7Si_8B_{14}$ ($\lambda_s <$ 0) and $Co_{67}Fe_4Cr_7Si_8B_{14}$ ($\lambda_s > 0$) as a potential sensor material for civil engineering applications.

K e y w o r d s: amorphous ribbons, strain sensors, civil engineering

1 INTRODUCTION

Remarkable mechanical properties and extraordinary magnetoelastic coupling makes the amorphous metallic alloys suitable for magnetoelastic transducers, [1]. The sensitivity of magnetoelastic strain sensors is more than thousand times higher in comparison with resistive (wire) gauges. However, the application of magnetoelastic sensors is more complicated because they need AC-current supply. The static magnetoelastic force, pressure, or strain sensors are mostly designed to work as coils using an amorphous ribbon magnetic core. The sensitive parameter, which will increase or decrease its value depending on the sign of magnetostriction constant, is the magnetic permeability of the core. Very sensitive strain sensors were obtained when field-annealed Fe-rich amorphous ribbons with high positive magnetostriction were used [2]. However, due to permeability saturation they could be used only for small strains. To increase the strain range the amorphous magnetic alloys with negative magnetostriction were suggested to use [3]. The application of magnetoelastic sensors in strain and load measurements for civil construction, besides high corrosion resistance, requires a small temperature coefficient, sensor effective length more than 5 cm, resistance to external magnetic fields and a range of measurable strains up to 2000 ppm (microstrains). While the amorphous force and pressure sensors are usually designed as closed magnetic circuits [4, 5], the strain-measuring element, as an open magnetic circuit, yields the problem of considerable sensitivity to external DC magnetic field. In applications where it is hard to provide the magnetic shielding of the sensor with respect to the Earth magnetic field or other stray fields, the use of these high sensitive sensors is limited and appropriate methods of compensation are needed [6]. The stress annealed Co-rich amorphous ribbons, thickness about of 20 μm, are very promising materials to satisfy all the above-mentioned requirements. Stress annealing induces the magnetic anisotropy with easy plane perpendicular to the ribbon axis and clear evidence of wide transverse stripe domain structure perpendicular to the ribbon axis with zigzag type of domain walls [7, 8]. Magnetization reversal takes place by magnetization rotation and the $B(H)$ loops are linear with nearly negligible hysteresis. In this case the magnetic permeability up to saturation does not depend on the exciting field amplitude (or the resultant working field: AC superimposed on DC-bias) and is a function of the applied stress only. In this work we report on magnetoelastic properties of CoFeCrSiB alloys with small positive or negative magnetostriction, which are the best candidates for sensor applications.

2 MAGNETOELASTIC PROPERTIES OF CoFeCrSiB AMORPHOUS ALLOYS

The ribbons with composition $Co_{71-x}Fe_xCr_7Si_8B_{14}$, 6 mm wide, $\approx 20\mu$m thick and with $x = 2$, 3.3, 4, 6, 8, and 12, were prepared by planar flow-casting. The saturation polarization J_S slightly increases with Fe content and the magnetostriction constant λ_S changes from -1×10^{-6} up to $+4 \times 10^{-6}$ (for x from 2 to 12, with zero at $x =$ 3.3, when the coercivity reaches a minimum $H_C < 0.5$ A/m). The effective stress anisotropy field H_K created by external stress σ in ribbons after a stress annealing

* Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Department of Electromagnetic Theory, Ilkovičova 3, 812 19 Bratislava, Slovakia

** Institute of Physics, Slovak Academy of Sciences, Dúbravská cesta 9, 842 28 Bratislava, Slovakia

*** Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Praha 8, Czech Republic

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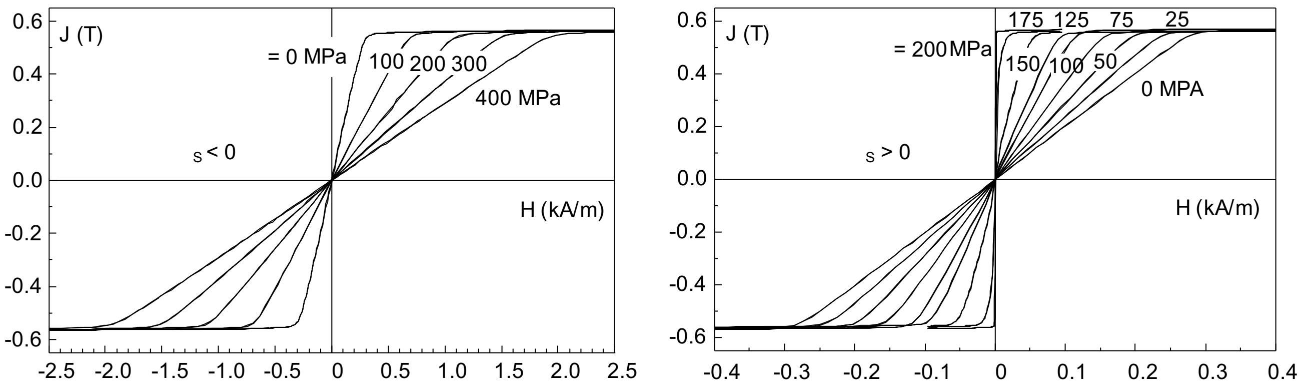

Fig. 1. The influence of applied stress on the static hysteresis loops of stress-annealed amorphous ribbons. $Co_{69}Fe_2Cr_7Si_8B_{14}$ with negative magnetostriction (left) and $Co_{67}Fe_4Cr_7Si_8B_{14}$ with small positive magnetostriction (right). Both annealed at 350 °C 1 hour at applied stress $\sigma_A = 200$ MPa.

process can be expressed as

$$H_K = H_{K0} - \frac{3\lambda_S \sigma}{J_S}. \tag{1}$$

where the anisotropy field H_{K0} induced by stress annealing is proportional to the annealing stress σ_A and only slightly depends on the alloy composition.

The alloys with $x > 4$, annealed at 350° C and under applied stress σ_A up to 700 MPa, due to a relatively large positive magnetostriction, reach $H_K = 0$ at applied critical strees $\sigma_C = 2K/(3\lambda_s)$ of about 175 MPa. Since larger anisotropy constant than $K \approx 335\ \mathrm{J/m^3}$ can hardly be induced in this type of alloys, for a sensor working up to 2000 microstrains, as required in civil engineering applications, λ_s should not exceed value of $+0.6 \times 10^{-6}$. Parameters of as-quenched samples with $x = 2$ (representative of negative magnetostriction) and of composition with $x = 4$ (with low positive magnetostriction) and thickness d are summarized in Table 1.

Table 1. Parameters of as-quenched CoFeCrSiB amorphous ribbons, *) after annealing 1h/350 °C

Composition	d (μm)	J_S (T)	H_C (A/m)	λ_S (ppm)
$Co_{69}Fe_2Cr_7Si_8B_{14}$	19.7	0.56	2.9	- (0.6÷1.03)
$Co_{67}Fe_4Cr_7Si_8B_{14}$	17.6	0.58	0.4	+ 0.33 *)

Stress-annealing, for 1 hour at 350 °C , was done in a radiation furnace with about 14 cm long temperature plateau. The $J(H)$ loops of open samples (typically 40 cm long) were measured under applied stress using an automated DC hysteresis loop tracer. The magnetization characteristics are shown in Fig. 1.

By assuming that the induced transverse anisotropy ensures magnetization process prevailingly by magnetization rotation, the dependence of magnetic permeability on the applied stress is described by equation

$$\mu = \mu_0 + \frac{J_S^2}{(2K - 3\lambda_S \sigma)} \tag{2}$$

where $\sigma \geq 0$ for tensile stress. The sensitivity of permeability on external stress is then given by

$$\frac{\partial \mu}{\partial \sigma} = \frac{3\lambda_S J_S^2}{(2K - 3\lambda_S \sigma)^2}. \tag{3}$$

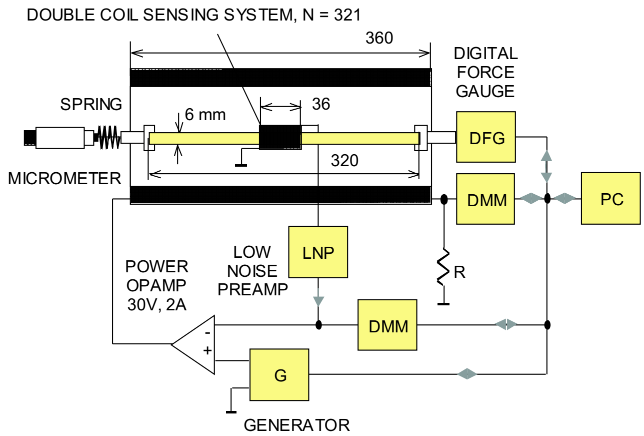

Fig. 2. Set-up for AC characteristics measurement.

The disadvantage of materials with positive magnetostriction is that they can work only to the critical tensile stress, as mentioned above

$$\sigma_c = \frac{2K}{3\lambda_S}. \tag{4}$$

When using an amorphous ribbon as the core of a coil we define the so-called "impedance figure of merit", F [2] characterizing the magnetoelastic sensitivity of sensor as

$$F = \frac{\Delta Z / Z_{(0)}}{\Delta \varepsilon} = \frac{E}{\mu_{(0)}} \frac{\partial \mu}{\partial \sigma} = \frac{6\lambda_S K E}{(2K - 3\lambda_S \sigma)^2} \tag{5}$$

where $\Delta Z = Z_{(\sigma)} - Z_{(0)}$ is the change of the coil impedance after tensile stress was applied causing ribbon elongation $\Delta\varepsilon = {}^{\sigma}/_{E}$, here $\mu_{(0)}$ is the permeability at no stress condition and E is the Young modulus.

Table 2. Parameters of CoFeCrSiB ribbons after annealing 1h/350 °C

Composition - annealing temperature/applied stress	σ_c (MPa)	Magnetoelastic efficiency	Standard deviation	Relative permeability
$Co_{69}Fe_2Cr_7Si_8B_{14}$ - 350 °C /0 MPa	> 375	16.8×10^3	-	310 - 10 200
$Co_{69}Fe_2Cr_7Si_8B_{14}$ - 350 °C /100 MPa	> 375	2.78×10^3	0.1684	300 - 2 200
$Co_{69}Fe_2Cr_7Si_8B_{14}$ - 350 °C /200 MPa	> 375	1.73×10^3	0.0784	420 - 1 740
$Co_{69}Fe_2Cr_7Si_8B_{14}$ - 350 °C /300 MPa	> 375	0.84×10^3	0.0488	270 - 730
$Co_{67}Fe_4Cr_7Si_8B_{14}$ - 350 °C /200 MPa	150	16.2×10^3	-	1820 - 28 000
$Co_{67}Fe_4Cr_7Si_8B_{14}$ - 350 °C /400 MPa	> 375	7.58×10^3	0.0675	850 - 15 000
$Co_{67}Fe_4Cr_7Si_8B_{14}$ - 350 °C /700 MPa	> 375	0.36×10^3	0.0176	525 - 900

The samples, 30 cm long ribbons, were measured in a 34 cm long solenoid at frequency of 5 kHz in a conventional measuring set-up shown in Fig. 2. All presented measurements were performed at a sine waveform of the flux density with a constant amplitude while the applied stress was changed. Experimental results of the reluctivity change with applied tensile stress are shown in Fig. 3. The range of applied stresses up to 375 MPa is identical with the strain $\varepsilon \approx 2000$ ppm, supposing the value of $E = 185$ GPa. The effect of saturation at $\sigma_C \approx 150$ MPa is well visible in the case of $CoFe_4CrSiB$ alloy stress-annealed at $\sigma = 200$ MPa. Other parameters characterizing the magnetoelastic efficiency $(\mu(\sigma)/\mu(0) - 1)/\Delta\varepsilon$, and linearity of the transfer characteristics as well as the standard deviation from a linear fit, are summarized in Tab. 2. These parameters were identified at $B_m = 50$ mT and the relative permeability changes coincide with the changes of external stress up to 375 MPa.

3 TWO–COIL STRAIN SENSOR

The prototype of a two-coil strain sensor, with magnetizing and pick-up coils 44 mm and 22 mm long, was tested in the strain range up to 10^3 ppm. The sensor with effective length of 60 mm (Fig. 4) was strained by means of a support brass beam, 400 mm long, fixed at his both of ends and bent by a force applied to its center, [6]. The brass beam bearing the sensor was placed into a system of two-pair rectangular coils, designed to generate DC-magnetic field in the sensor ribbon plane. By measuring the flexure Δz in the center of the beam, we can directly determine the strain

$$\varepsilon\left({}^{l}\!/_{2}\right) = {}^{\Delta l}\!/_{l} = 6\frac{h\Delta z}{l^2}. \tag{6}$$

Here l and h are the length and thickness of the brass beam, respectively. Comparative (calibration) measurements were performed also with bridge connected wire strain gauges and different distances between them.

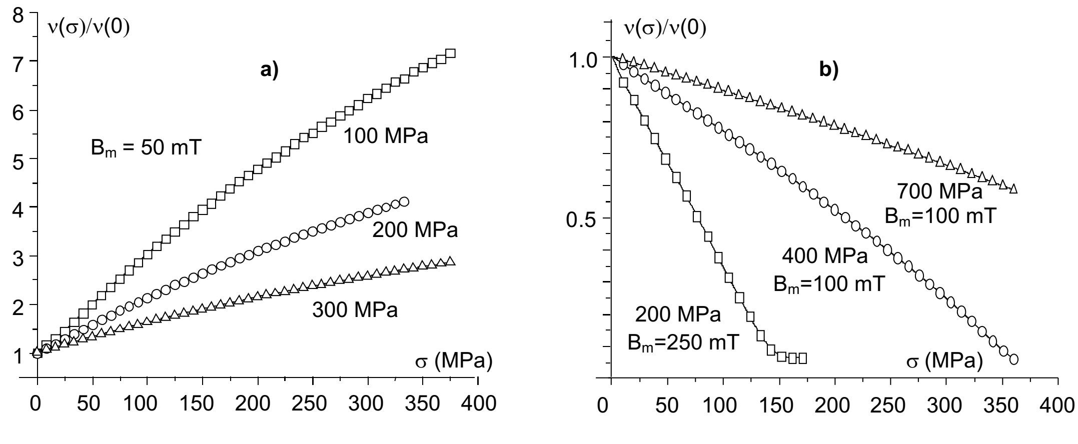

Fig. 3. Change of normalized reluctivity of the stress-annealed amorphous alloys with applied tensile stress: a) $Co_{69}Fe_2Cr_7Si_8B_{14}$ at induction amplitude of 50 mT, b) $Co_{67}Fe_4Cr_7Si_8B_{14}$ at two different induction amplitudes 100 mT and 250 mT.

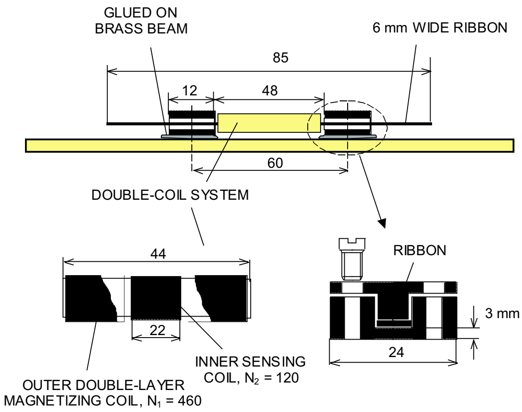

Fig. 4. The prototype of a two-coil sensor mounted on a brass beam subjected to a deliberate deformation.

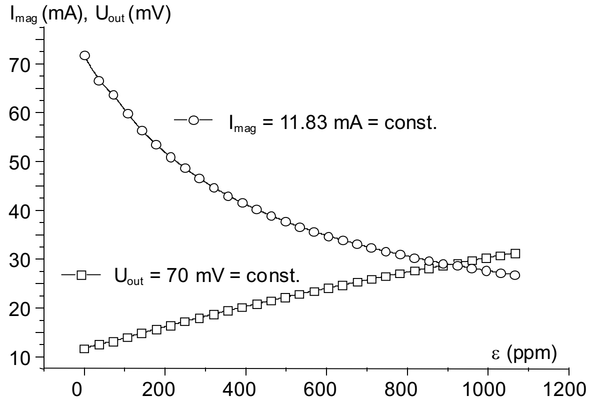

Fig. 5. Sensor output signals as function of measured strain for different magnetizing conditions.

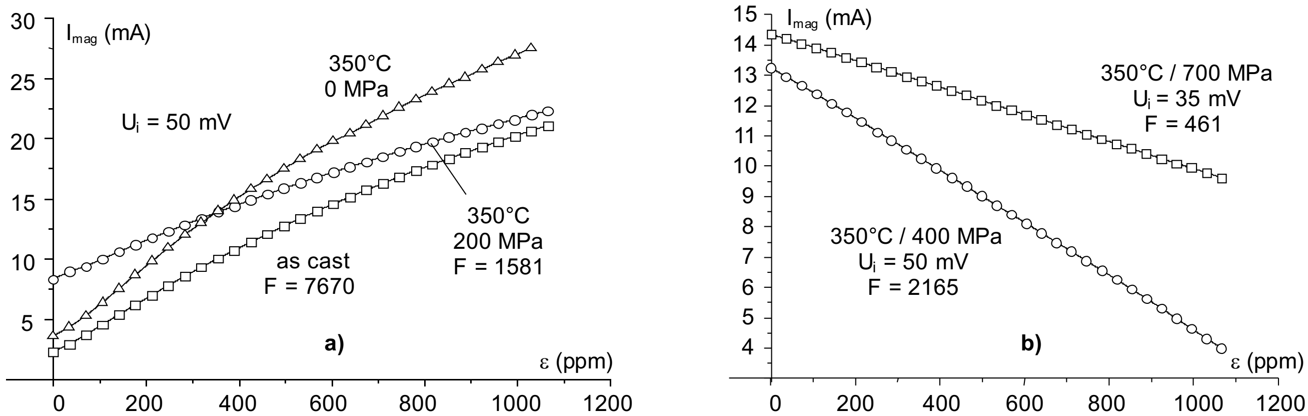

Fig. 6. The transfer characteristics of the two-coil strain sensor for different core materials: a) $Co_{69}Fe_2Cr_7Si_8B_{14}$ with $\lambda_s < 0$, b) $Co_{67}Fe_4Cr_7Si_8B_{14}$ with $\lambda_s > 0$.

The linearity of magnetizing characteristics and the low hysteresis of stress-annealed ribbons provide a nearly linear dependence of the coil inductance on the effective permeability and good measurement reproducibility. It means we can express the inductance of the magnetizing coil as $L = C\mu_{eff}$ (the coil effective permeability takes into account the demagnetizing effect). For materials with $\mu_r >> 1$, the voltage induced in the pick-up coil is then

$$U_i \cong \frac{\omega C J_S^2}{(2K - 3\varepsilon\lambda_S E)} I_{mag} \qquad (7)$$

where ω is the angular frequency of sinusoidal magnetizing current. If the induced voltage is kept constant (by a feedback loop), the magnetizing current I_{mag}, as the output signal, is proportional to the applied strain ε. On the other hand with magnetizing current kept constant, the output signal (voltage induced in the pick-up coil) is a nonlinear function of the applied strain, Fig. 5.

The exciting current I_{mag} as a function of the strain ε at the brass beam upper surface for different core materials is in Fig. 6.

The influence of a DC-magnetic field on the output signal of the magnetoelastic sensors of different lengths was investigated in detail [9] and a method of its elimination was proposed [6]. The found independence of the output signal on DC magnetic field component perpendicular to the ribbon axis was ascribed to a large demagnetizing factor along the (small) width of the ribbon. Due to nonlinear magnetizing characteristics of as-cast, as well as of the samples annealed without stress, the influence of DC magnetic field component parallel to the ribbon axis on the change of permeability is too high.

The change of magnetizing characteristics with stress changes this influence also. Generally, the influence of DC magnetic field on the output signal with increasing tensile stress increases for materials with positive magnetostriction and decreases for materials with negative magnetostriction. This effect for a two-coil sensor prototype with $Co_{69}Fe_2Cr_7Si_8B_{14}$ as-cast ribbon core is illustrated in Fig. 7. The influence of DC magnetic field on the output signal of stress-annealed samples is negligible up to the amplitude of the resultant exciting magnetic field less than 0.9 H_K, as defined by (1), due to linear magnetizing characteristics. The independence of the magnetic permeability of the disturbing magnetic field plays a very important role in applications and allows the measurement of sensor impedance by modified AC bridges with high resolution, [3].

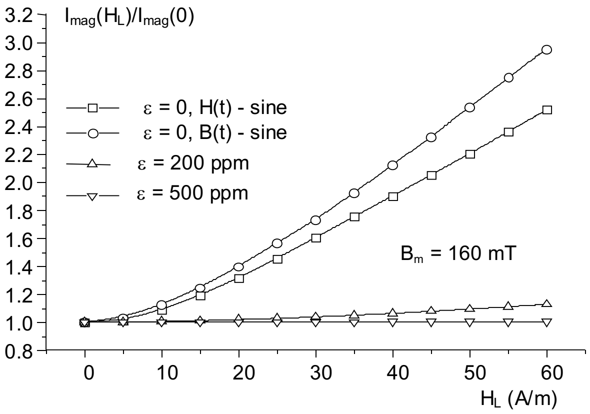

Fig. 7. Influence of longitudinal DC magnetic field H_L on the magnetizing current two-coil sensor with $Co_{69}Fe_2Cr_7Si_8B_{14}$ as cast ribbon core, 6 mm wide and 19.4 μm thick.

5 CONCLUSION

The obtained results show the possibility to use both selected materials as potential candidates for application as strain sensors in civil engineering. The transverse magnetic anisotropy, induced by stress-annealing, was used to improve the sensor transfer characteristics. This thermal treatment gave a possibility to use the positive magnetostriction materials with high linearity of transfer characteristics and wide range of measured strain. The independence of sensor output signal of the disturbing magnetic field without shielding combined with their high corrosion resistance make possibilities of outdoor application more attractive.

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Jan Bydžovský (Doc, Ing, PhD) was born in Nový Býdžov, Czechoslovakia, in 1944. He graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava from Solid State Physics branch, in 1967, and received the PhD degree in Theory of Electromagnetism, in 1981. Since 1967 he has been with the Department of Electromagnetic Theory at his Alma Mater, first as a research worker, later as a teacher. In 1995 he was appointed Associate Professor. He teaches electromagnetic theory and magnetic measurement. In research he is involved in investigation of ferromagnetic materials properties.

Mojmír Kollár (Ing, PhD), born in Ružomberok, Czechoslovakia, in 1945, graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in solid state physics, in 1968. He received the PhD degree in electromagnetic theory from the same university in 1985. At present time he works as a reader at the Department of Electromagnetic Theory. The main fields of his research and teaching activities are circuit and electromagnetic field theory, particularly the bulk ferromagnetic phenomena.

Peter Švec (Ing, PhD), born in Bratislava, Czechoslovakia, in 1955, graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, from Solid State Physics branch, in 1979, and received the PhD degree in Physics in 1986. At present he is with the Institute of Physics, Slovak Academy of Sciences. His research field is the physic of metals, recently namely phase transformations in metal-metalloid glassy systems

Vladimír Jančárik (Doc, Ing, PhD) was born in Bratislava, Czechoslovakia, in 1965. He graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava from Solid State Physics branch, in 1988, and received the PhD degree in Theory of Electromagnetism, in 1996. Since 1988 he has been with the Department of Electromagnetic Theory, from 2001 appointed Associate Professor for electromagnetic theory. He teaches electric circuits, magnetic measurement and electronic devices. In research he is involved in computer controlled measuring systems particularly those of magnetic material properties.

Luděk Kraus (Ing, PhD), born in Frýdek-Místek, Czechoslovakia, in 1945, graduated from the Faculty of Nuclear and Technical Physics, Czech Technical University in Prague in Solid State Physics. Since 1968 he has been with the Institute of Physics, Academy of Sciences of the Czech Republic in Prague. He received the PhD degree in Experimental Physics in 1980 from the same institute. His main field of interest are the magnetic properties of amorphous and nanogranular materials.