New 3-D Bulk Shaped Polycrystalline and Nanocomposite Magnetostrictive Materials*

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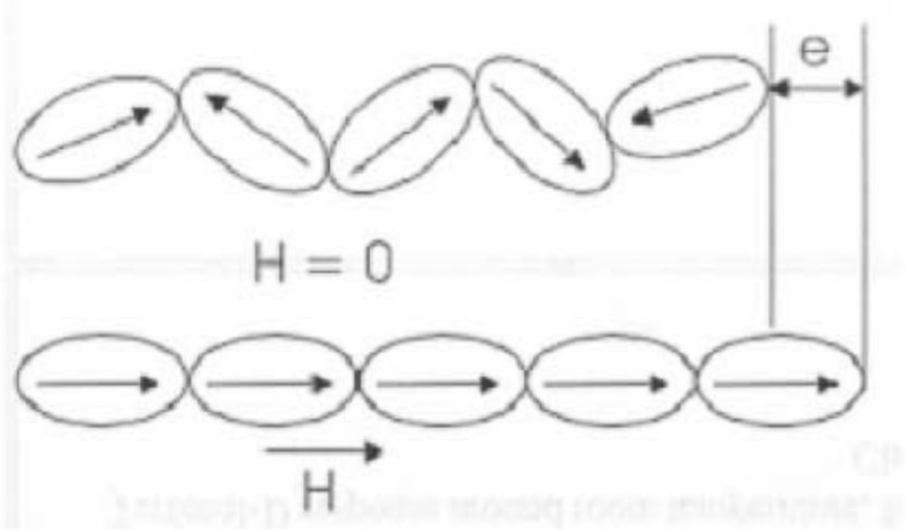
Outlines

- ✓ Magnetostriction
- ✓ Magnetic Sensors and Actuators vs. Smart Materials
- ✓ Fe-(Ga,Al) magnetostrictive alloys
- ✓ (Co,Ni)-Mn-(Ga,Al) magnetostrictive alloys
- ✓ (Fe,Co)-RE-B magnetostrictive materials (RE = Tb, Dy, Sm)
- ✓ Conclusions & Potential Applications

Magnetostriction (1)

Magnetostrictive materials are changing their shape due to the change in the magnetization state of the material.



Although nearly all ferromagnetic materials exhibit a shape change resulting from magnetization change, only those with significant interactions between shape change and magnetization change are suitable for sensors/actuators applications.

Magnetostriction (2)

- ✓ **Magnetostriction** - a consequence of the **magnetoelastic coupling**.
- ✓ Magnetostriction is **an intrinsic property of magnetic materials**, which is for a crystalline material a direction dependent tensor λ_{hkl} mainly caused by the orbital coupling of the magnetic moment.
- ✓ **Linear**, $\frac{\delta l}{l}$, or **volume magnetostriction** $\frac{\delta V}{V}$.
- ✓ **Positive** when the material is elongated **and negative** when is contracted.

Magnetostriction (3)

✓ **Saturation magnetostriction** (λ_s) - the magnetostrictive deformation of a material increases with the applied magnetic field increase and reaches the maximum value.

✓ **Isotropic magnetostriction** = spontaneous deformation “e” is constant in all crystallographic directions.

✓ **Anisotropic magnetostriction** = the sign and value of deformation depend on the crystallographic direction.

Magnetostriction – How to measure it (1)

✓ The magnetostriction can be measured by **direct** and **indirect** methods.

✓ **Direct methods**: with strain gauges, capacitance transducers or interferometers.

- ✓ For crystalline materials the use of strain gauges is most common.
- ✓ The most sensitive method is the capacitance method.

✓ **Disadvantages** of direct methods: they require a special sample preparation and they do not deliver the “true” saturation magnetostriction.

✓ **Indirect methods:** Becker-Kersten method and SAMR method (Small Angle Magnetization Rotation).

- ✓ Becker-Kersten method - the magnetostriction is determined from the stress dependence of the hysteresis loop.
- ✓ SAMR - for soft magnetic ribbons/wires because of the special geometry. Beside the stress dependence of the hysteresis the SAMR method delivers very accurate results. This method can also be used from 4.2 K up to high temperatures.

C. Polak, Thesis, TU Wien, 1992.

Comparison of some methods to measure magnetostriction

Method	Manner	Sensitivity	Remarks
Strain gauges	Direct	$\pm 1 \times 10^{-6}$	Determine $\lambda_{//}$ and $\lambda_{\perp}$ independently, difficult to perform at high temperature
Capacitance	Direct	$\sim \pm 10^{-10}$	Most sensitive method but also difficult to carry out at high temperature
Stress dependence of hysteresis loop	Indirect	$\sim \pm 10^{-8}$	Good for negative and very small value of λ_s
SAMR (Small Angle Magnetisation Rotation)	Indirect	$\sim \pm 10^{-9}$	High sensitivity, suitable for ribbons, usable at all temperature to determine λ_s
Transverse susceptibility	Indirect	$\sim \pm 10^{-9}$	Variation of SAMR method

Magnetic Sensors and Actuators vs. Smart Materials (1)

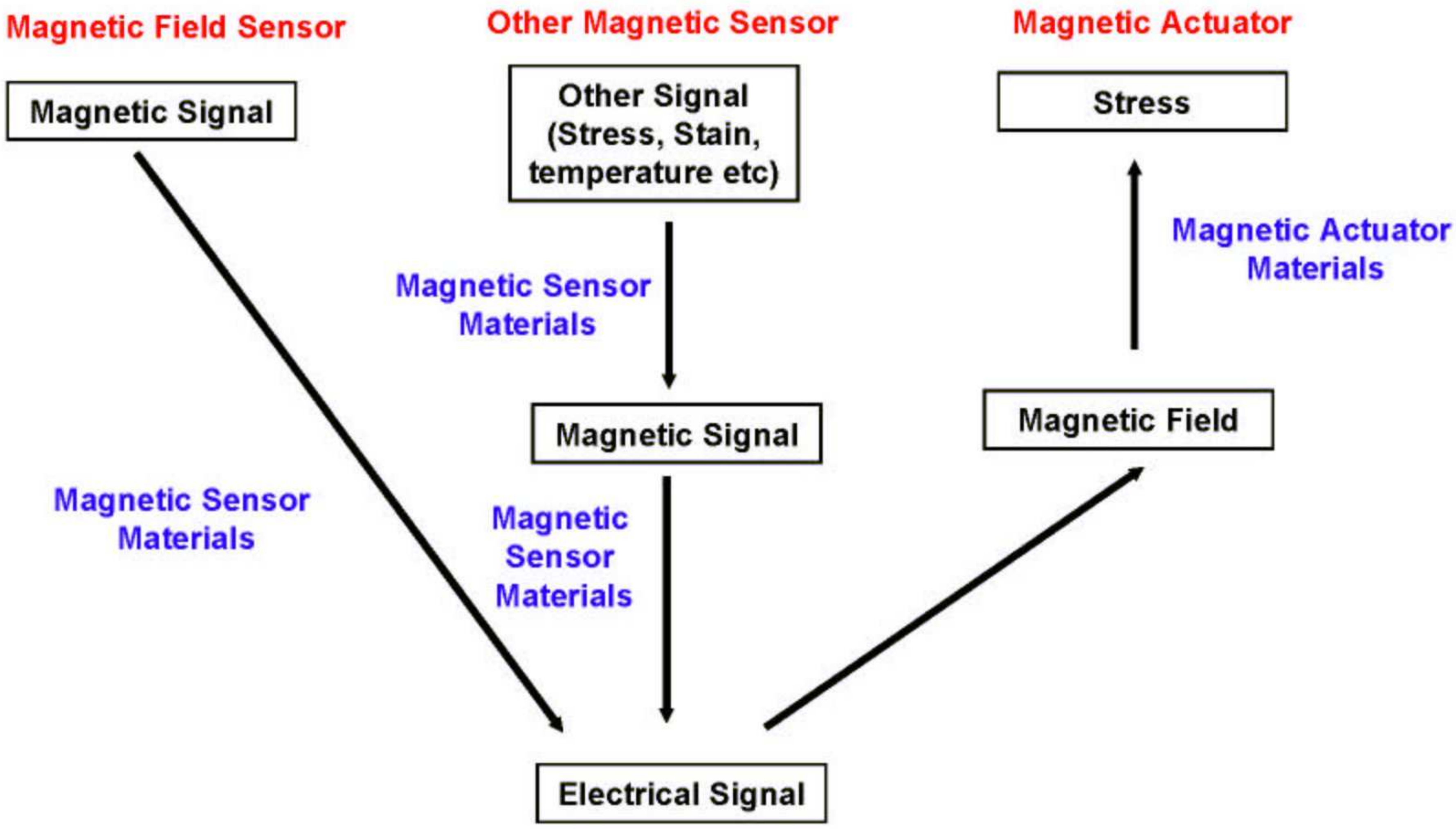
- Both magnetic sensor and actuator materials require strong interaction between the magnetic response and other responses to external factors (resistance, stress, strain, etc.).

- Actuators materials are generally “hard” materials since significant stress is required for actuators to work.

- Magnetic sensors materials can be “soft” materials, BUT high sensitivity and low noise level are important.

- There is no clear “border” between magnetic sensors and actuators materials, and some actuator materials can be used as sensor materials as well.

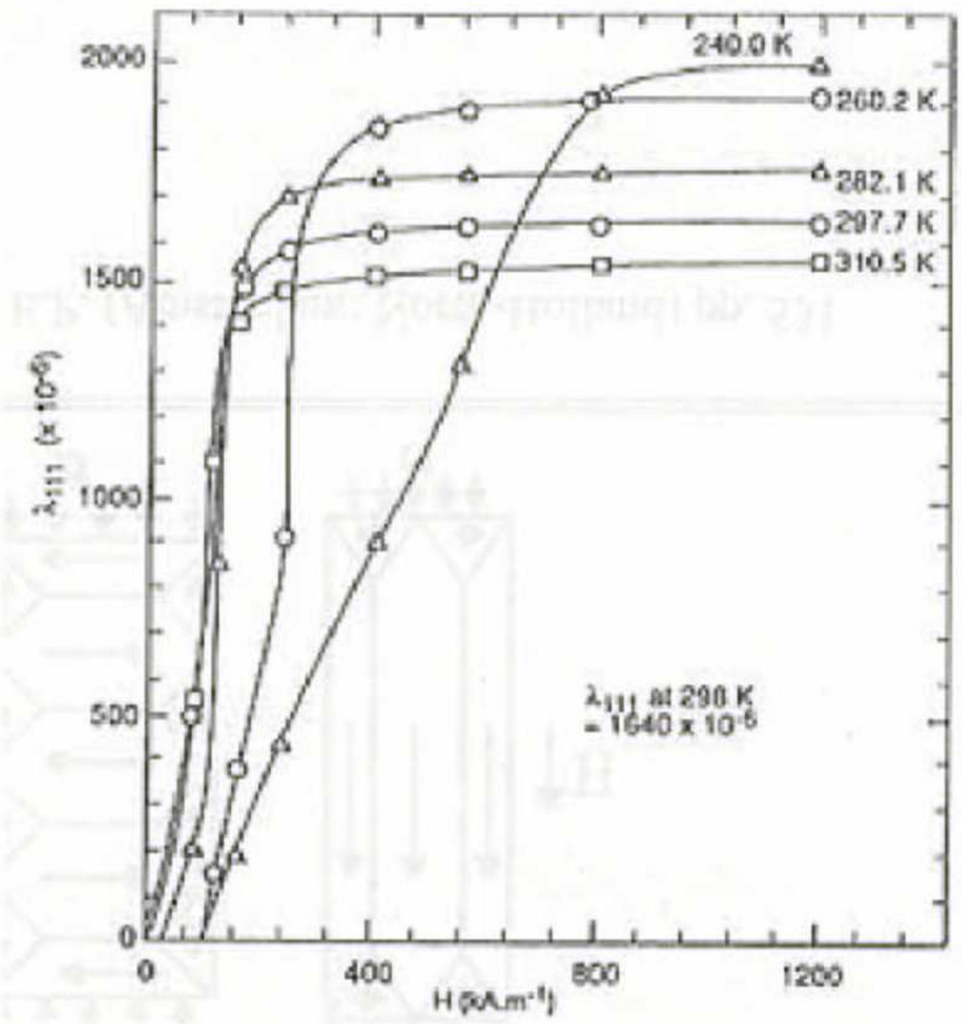
Magnetic Sensors and Actuators vs. Smart Materials



Properties of Different Smart Materials

Material	Material Type	Maximum Strain (%)	Actuation Voltage (V)	Relative Response Speed	Curie Temperature (K)
$Tb_{0.3}Dy_{0.7}Fe_{1.9}$ (Terfenol-D)	Magnetostrictor	0.16-0.24	< 15	Fast	653
KelvinAll® (EMERGEN)	Magnetostrictor	0.14-0.2	< 15	Fast	660
Fe-Ga (Galfenol)	Magnetostrictor	0.013-0.025	< 15	Fast	~923
Ni-Mn-Ga	Ferromagnetic Shape Memory Alloy (FSMA)	5	> 50	Fast	~380
Ni-Ti (Nitinol)	Shape Memory Alloy (SMA)	> 5	10-20	Slow	N/A
PZT	Piezoelectric	0.12	> 1000	Fast	N/A
P(VDF-TrFE)	Electroactive polymer	4	10-100	Medium	N/A

- ✓ The fabrication of highly efficient integrated magnetostrictive sensors, actuators and transducers requires the availability of magnetoelastic materials with high magnetostriction and low saturation fields in different shapes, depending on the final application.
- ✓ Terfenol-D is the most used magnetostrictive material for magnetostrictive actuators and transducers;
- ✓ magnetostrictive metallic glasses are preferred for sensors applications;



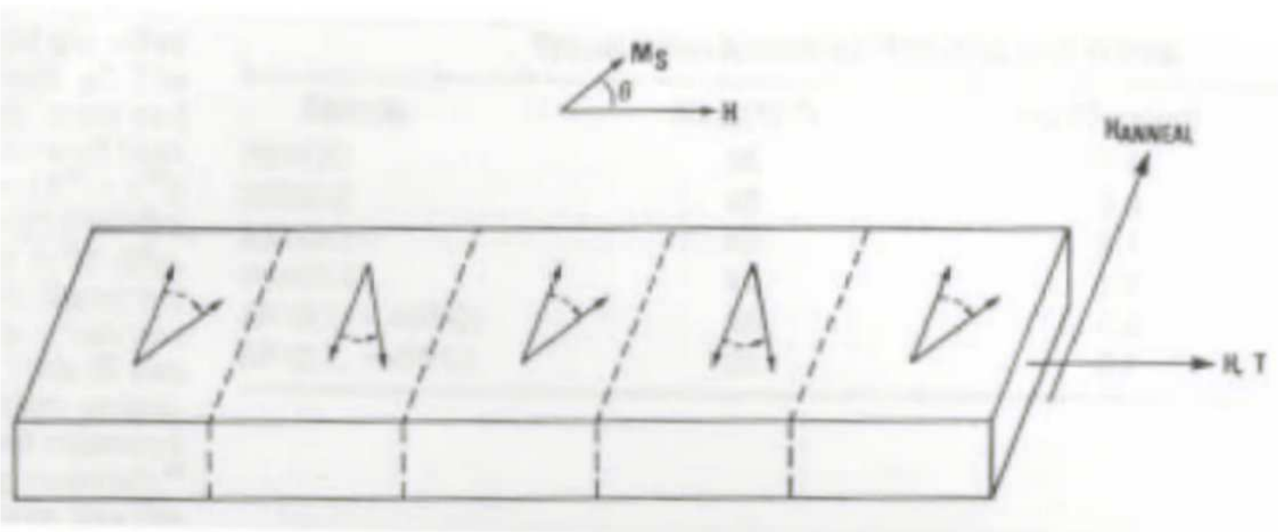
TERFENOL-D: Courtesy of ETREMA Inc.

The highest room temperature magnetostriction of a pure element is Co, which saturates at 60 ppm.

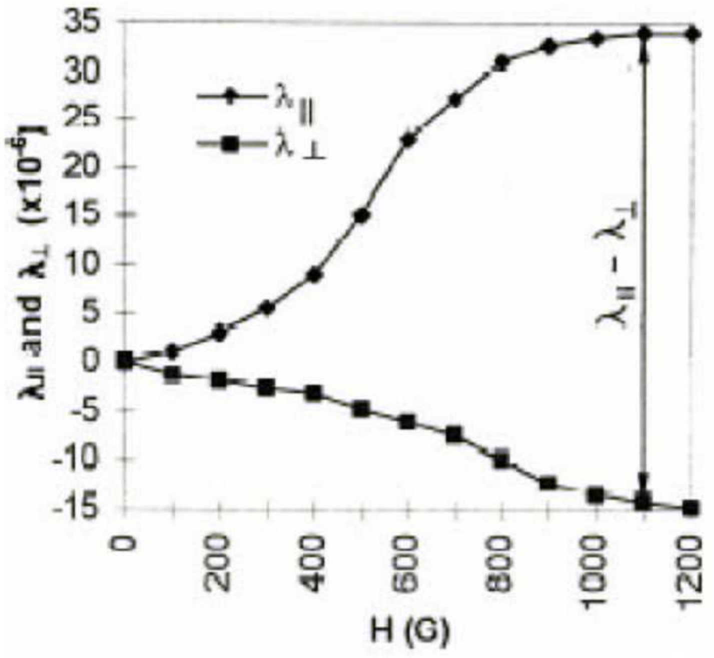
METGLAS (Fe-based alloy), discovered in early 1980s, is a good sensor material with an amorphous structure.

Why amorphous? The amorphous structure of METGLAS makes it have a smaller anisotropy energy compared with magnetocrystalline materials.

Annealing METGLAS in a magnetic field produces a well-defined anisotropy direction but with the smallest possible magnitude of anisotropy energy.



Magnetic moments rotate, without any domain wall motion.



$Fe_{70}B_{20}Si_6C_4$

Source composition	$Fe_{70}B_{20}Si_6C_4$	Ni
Thickness (Å)	8500	8000
σ_s (emu/g)	134	52
k_u (erg/g)	2.5×10^3	-7.0×10^4
T_C (°C)	338	362
λ_s ($\times10^{-6}$)	32	−30
$b^{\gamma,2}$ ($\times10^6$ dyne/cm^2)	−82	45
D ($\times10^{-10}$ G^{-1})	375	250
$\Delta E/E$	0.58	0.12

D = dλ/dH - the rate at which the strain is developed with respect to the applied field.

Ferromagnetic METGLAS can effectively increase magnetostriction than crystalline materials, at the same magnetic field level.

H. Chiriac et al., Sensors and Actuators 81 (2000) 166.

TERFENOL

1. Cubic C15 structure
2. Large magnetostrictive strains of the order of 0.1 % at and above RT
3. Brittle, large field for saturation, expensive Tb and Dy

METGLAS

1. Amorphous
2. Low saturation magnetostriction (30×10^{-6} for $Fe_{81}B_{13.5}Si_{3.5}C_2$)
3. Low field for saturation, large magnetomechanical coupling coefficient

New materials to combine the advantages of both materials.

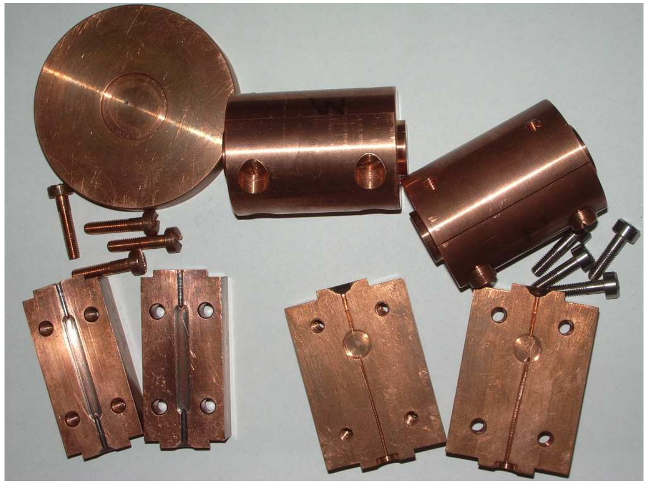
Very recently, 2 new alternatives appeared:

- Fe-(Ga,Al) alloys, as single crystals and melt-spun ribbons
- Ni-Mn-Al and Co-based magnetic shape memory alloys (MSMs)

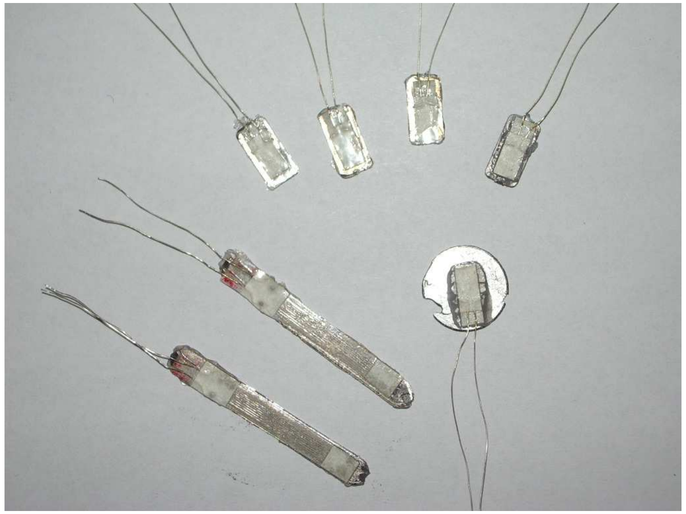
Fe-(Ga,Al) system

(Galfenol Alloys)

"GALFENOL is the latest magnetostrictive material to be invented, and is currently under development. Originally invented in 1998 by the Magnetic Materials Group at NSWC-CD, GALFENOL is slowly emerging into the real world. While its magnetostriction is only 1/3rd to 1/4th that of Terfenol-D, GALFENOL is a much more robust material allowing it to be used in harsh mechanically harsh environments with minimal shock hardening." (ETREMA Products, Inc. website)

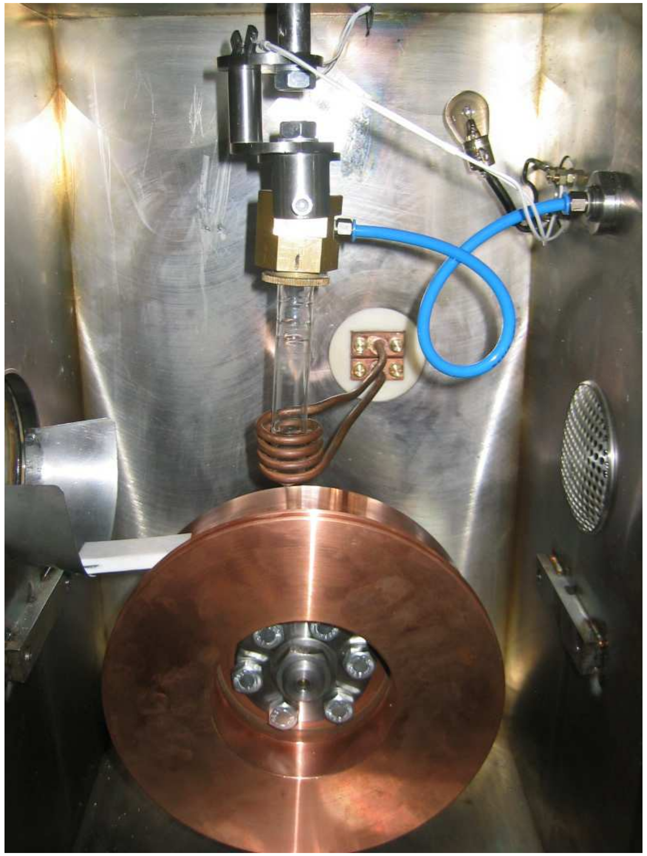


3-D shaped $Fe_{100-x}(Ga,Al)_x$ polycrystalline magnetostrictive alloys (x = 13÷30) as thin plates of 12*6*0.5 mm and 40*5*1 mm, rods (6 mm$^{\phi}$ and 40 mm long) and bars 3*3*10 mm^3.



Magnetostriction measured by the electrical resistance strain gauge technique.

Melt-Spun Ribbons Preparation



- Ribbon samples were produced by melting 3 grams of ingot with an induction coil in a partial argon atmosphere and ejecting the melt onto a rotating copper wheel at a wheel speed of 35 m/s.

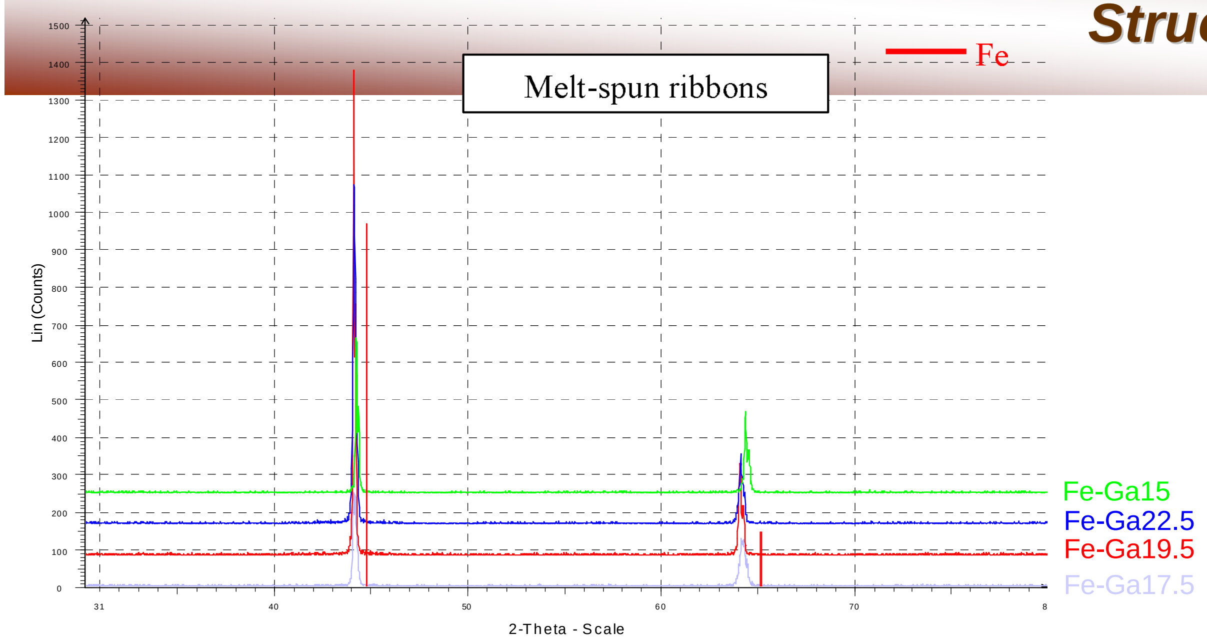
- Isothermal heat treatment was performed on some ribbon samples at 1000^0C for 72 hours and then:

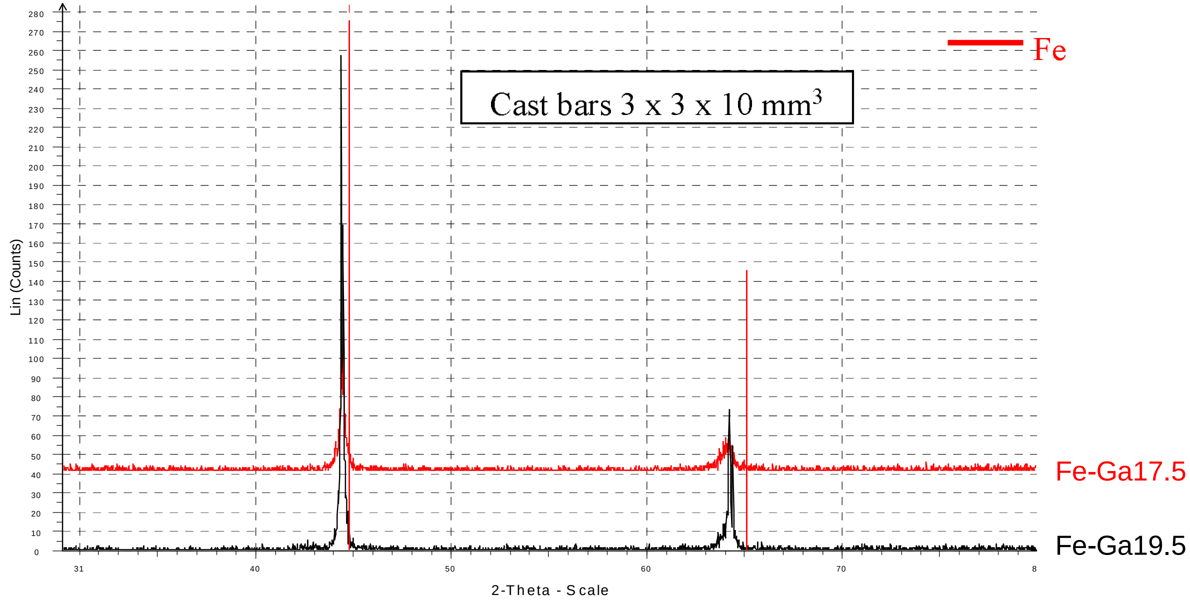
  - slow quenched to RT, OR

  - slow quenched to 800^0C, then water quenched.

- Ribbons were evacuated in a quartz tube and then sealed with approximately one atmosphere of argon at the annealing temperature.

Structure



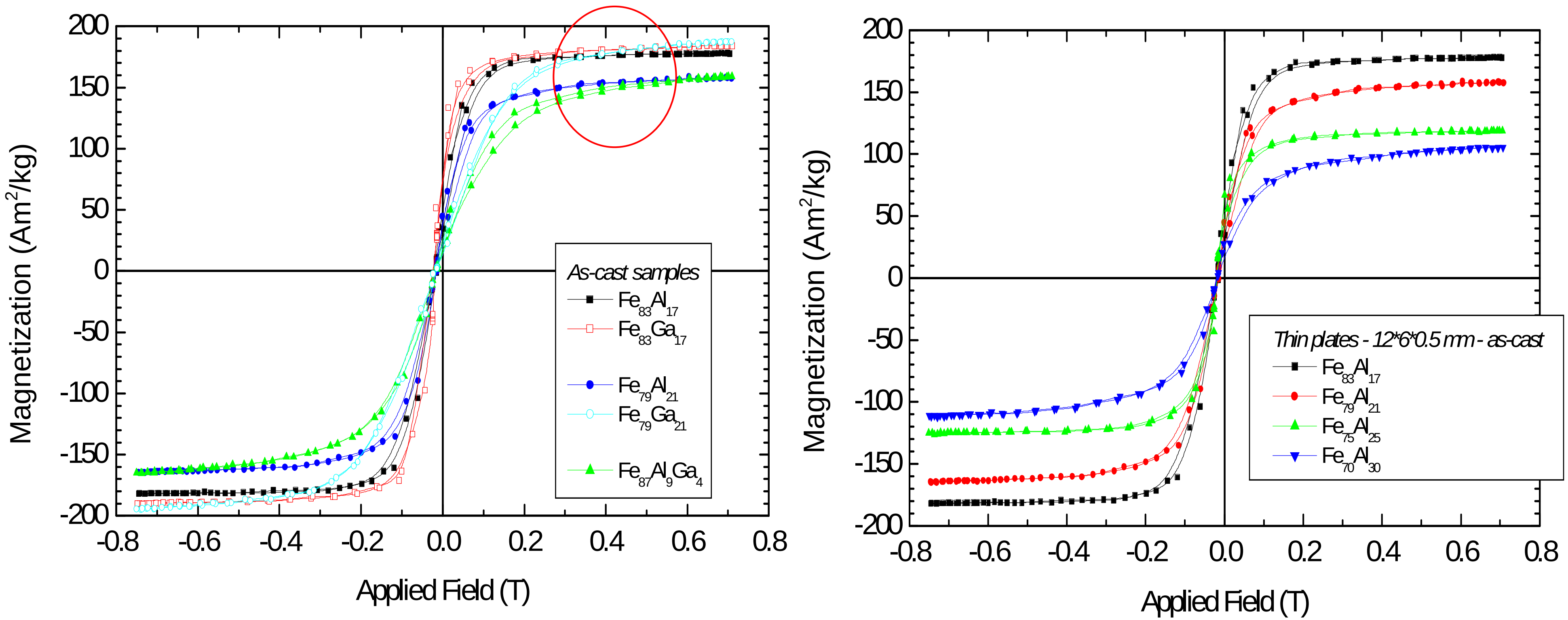


Investigated using both the conventional X-ray diffractometer and the high energy X-rays synchrotron radiation (ID11 @ ESRF Grenoble)

The XRD patterns of as-quenched melt-spun ribbons and bulk shaped samples don‘t show any texture.

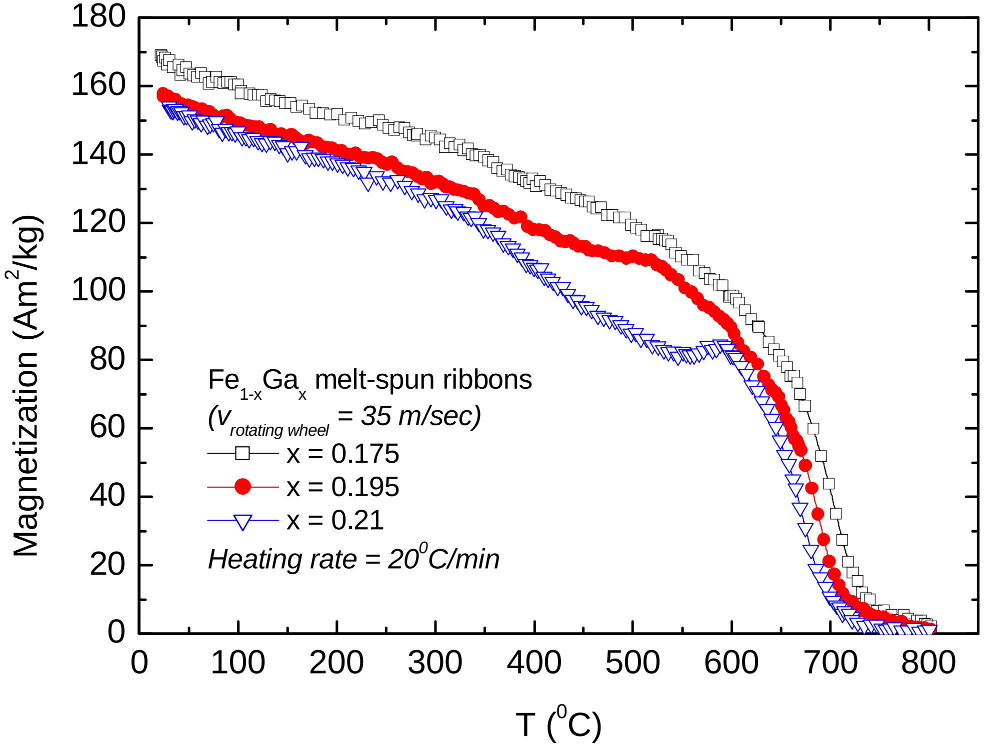
In addition, to the primary reflection at ~ 44^0 (110) and ~ 64^0 (200), none reflections corresponding to the DO_3 phase are observed.

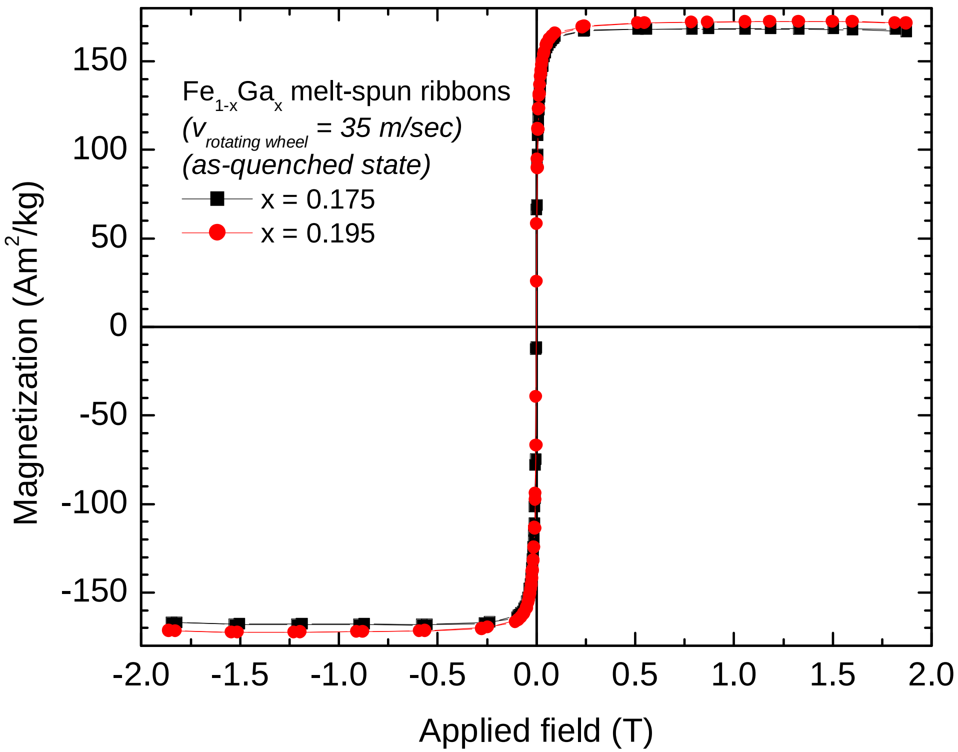
Magnetic Behavior



*M-H loops of Fe-Ga, Fe-Al and Fe-Ga-Al thin plates (12*6*0.5 mm) in the as-cast state.*

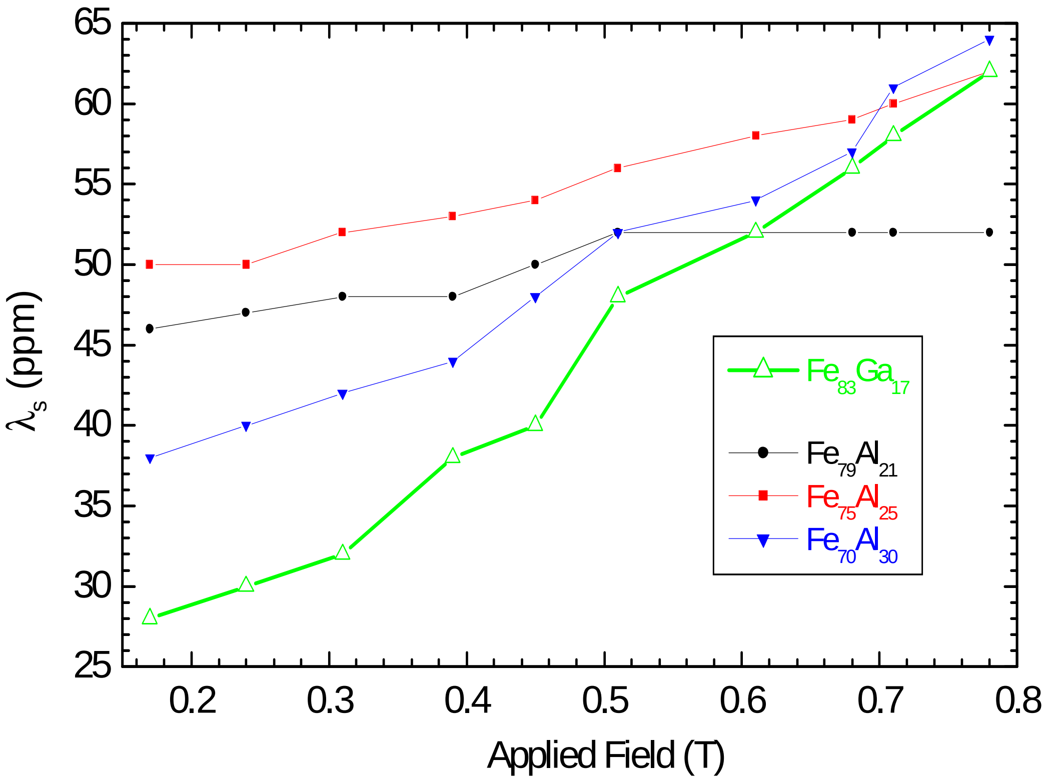
M-T and M-H curves





The thermomagnetic measurements confirm the existence of bcc Fe (A2 phase), with an additional magnetic transition at around 500^{0}C for $Fe_{79}Ga_{21}$ melt-spun ribbons.

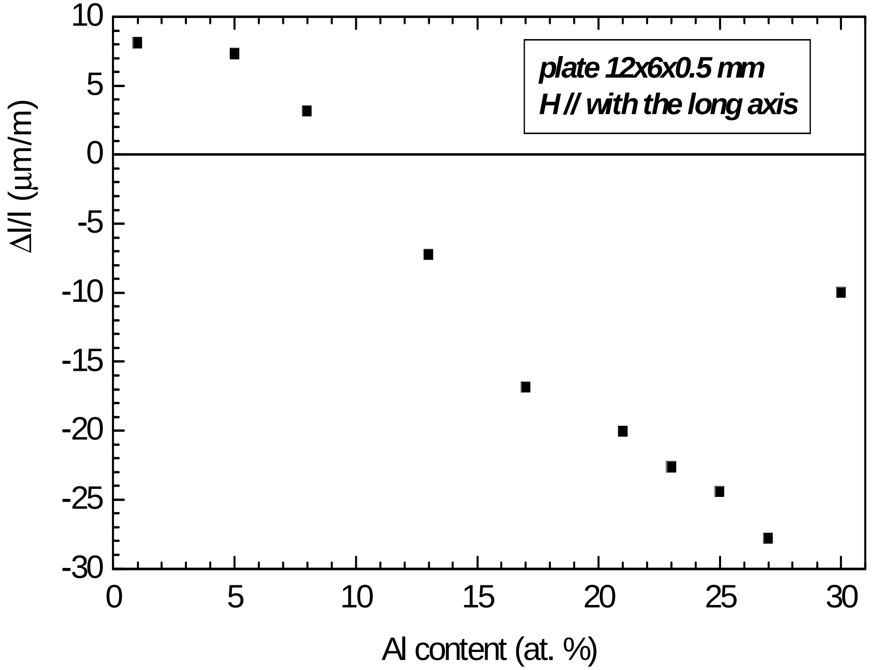
Very soft magnetic materials.



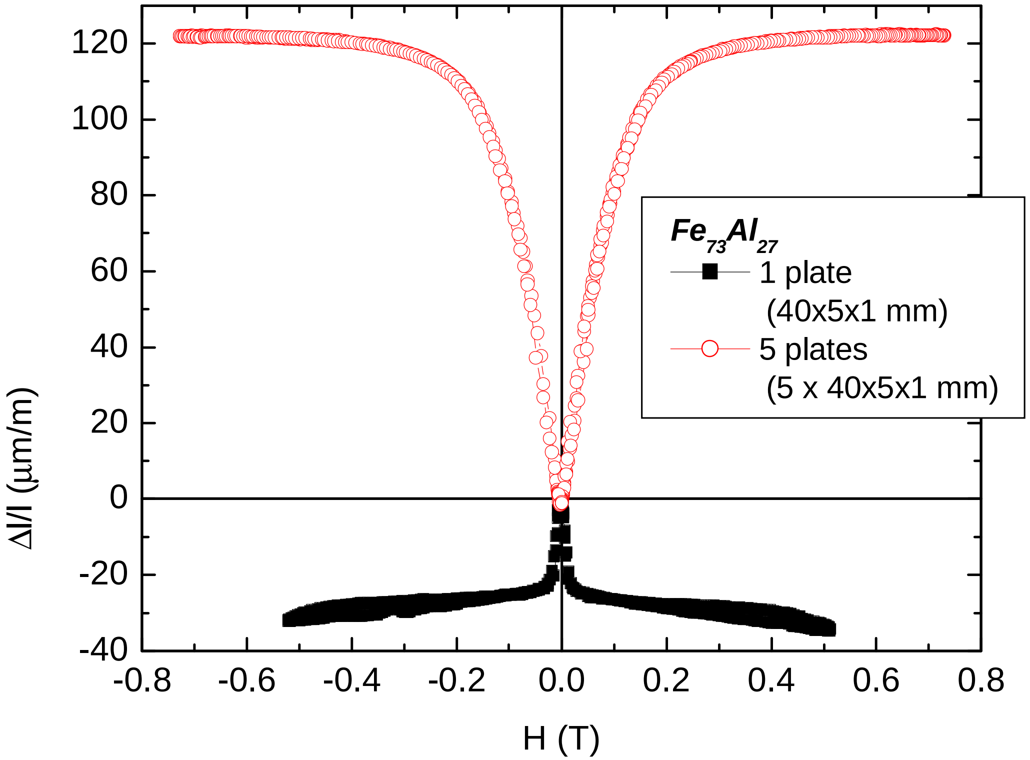
$$\lambda_s = \frac{2}{3}(\lambda_{//} - \lambda_{\perp})$$

*Magnetostriction versus applied magnetic field for Fe-Ga and Fe-Al thin plates (12*6*0.5 mm).*

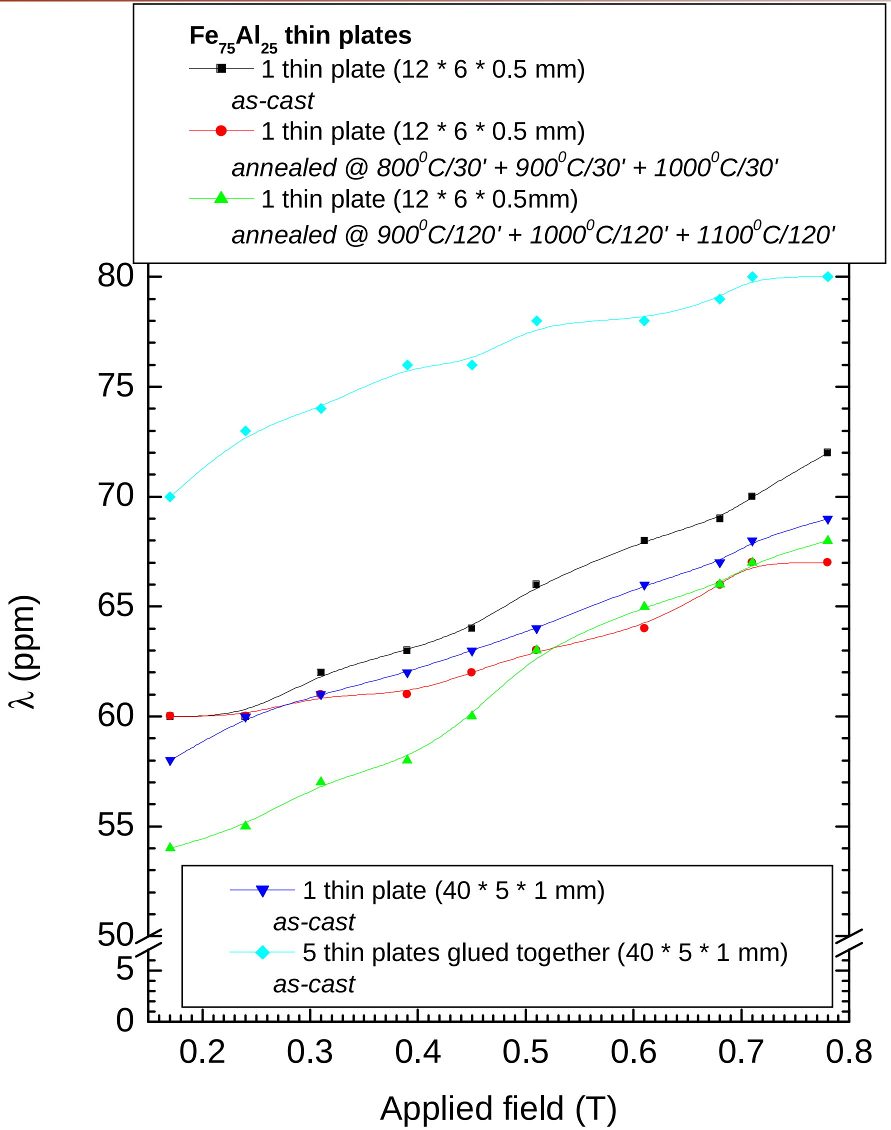
Magnetostriction



The magnetostriction is changing the sign from positive to negative when the Al content increases.

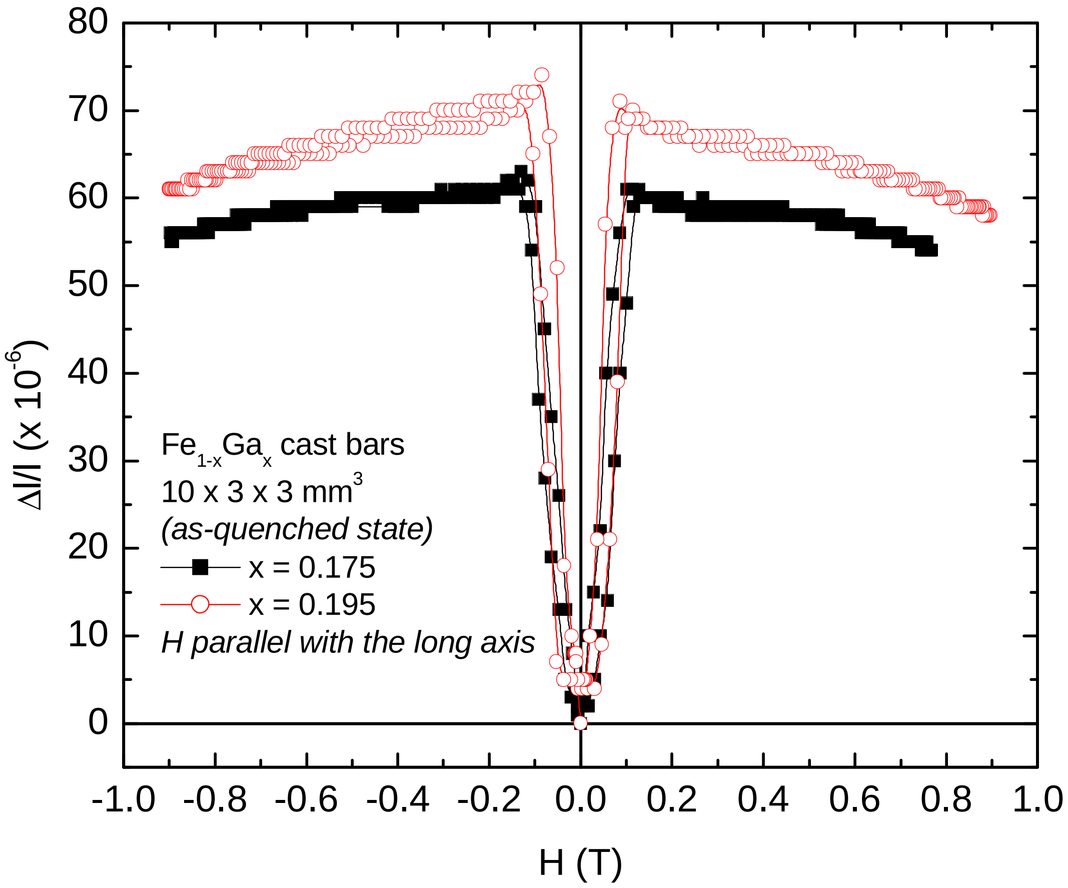


Magnetostriction as a function of the number of thin plates.



Magnetostriction as a function of the thickness, number of thin plates measured at once and applied treatments.

Magnetostriction

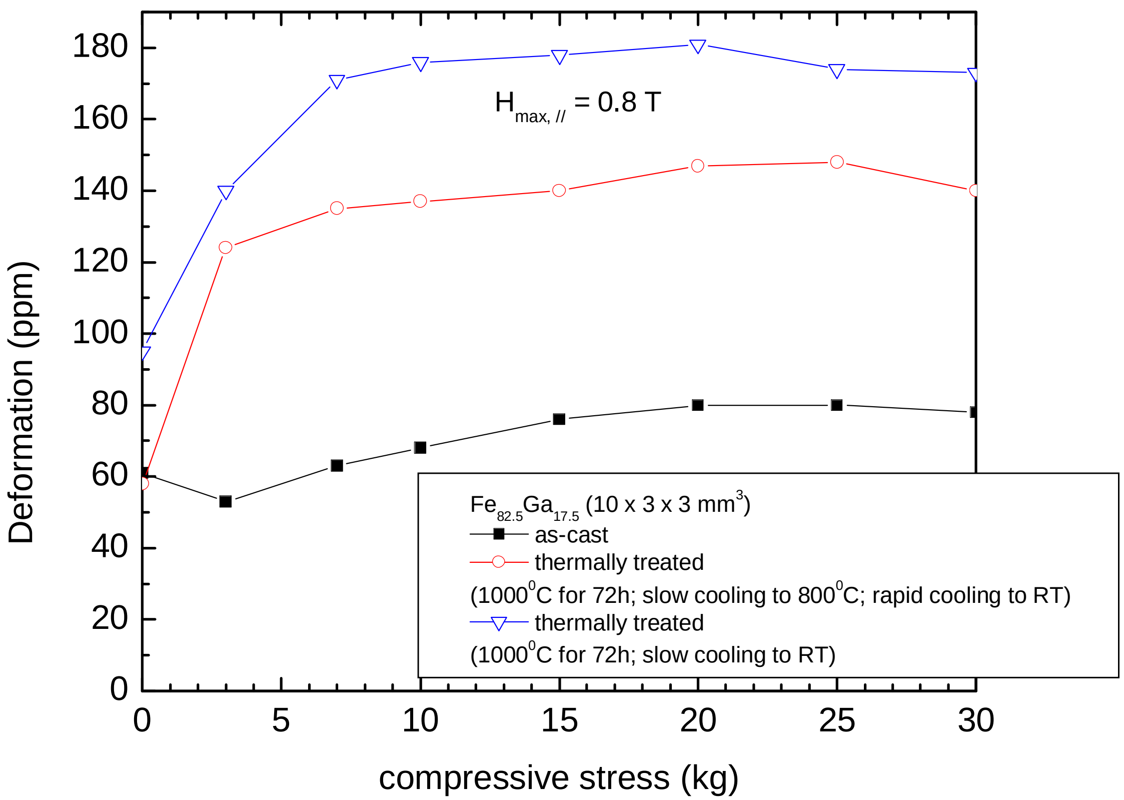


Very soft magnetic materials.

Low magnetic fields to achieve the saturation magnetostriction.

H parallel with the bars long axis (casting axis).

Strain vs. force (stress)



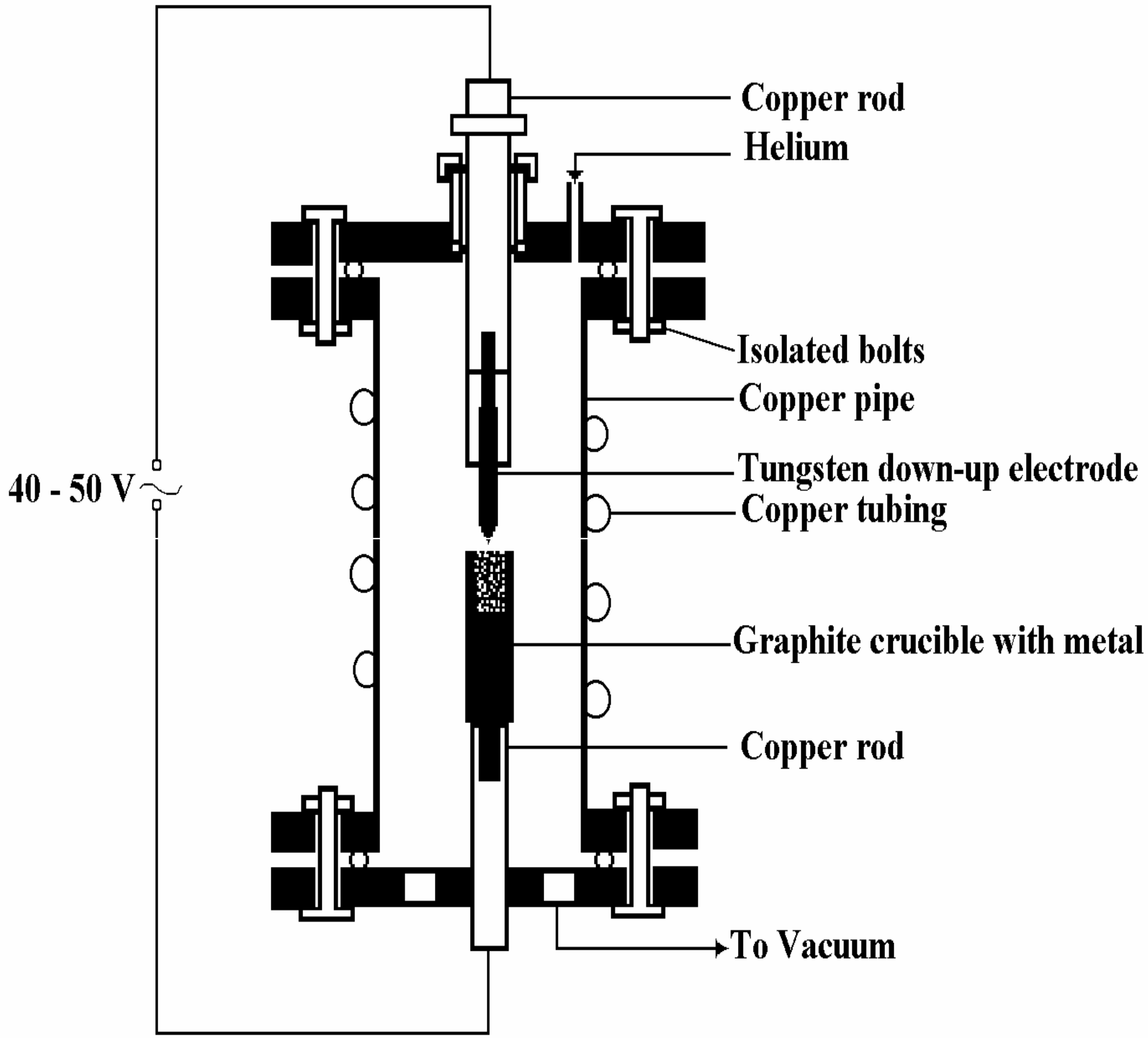
The value of λ_s increases gradually to 160÷180 ppm, depending on composition (the maximum value is smaller for higher contents of Ga), when applying an external compressive stress of 3÷5 MPa. Over this compressive stress value, the strain remains constant.

Paper DR-09, MMM Conference, Tampa, FL, 5-9 November 2007

Fe-Ga and Fe-Al composites – Samples Preparation

- $Fe_{100-x}Ga_x$ (x = 17; 20) and $Fe_{100-x}Al_x$ (x = 20; 24) nanopowders prepared by arc-discharge method;
- nanopowders embedded in Poxipol® commercial resin (resistance to water, outdoor conditions and many corrosive agents), CTM polymer, electrostrictive polymers and polyurethane;
- different concentrations (10 ÷ 30 wt. %) of metallic nanopowders into the resin layer (t = 3 ÷ 5 mm);
- magnetostriction of the composite layers measured by the electrical resistance strain gauge technique.

Fe-Ga and Fe-Al composites - Nanopowders Preparation

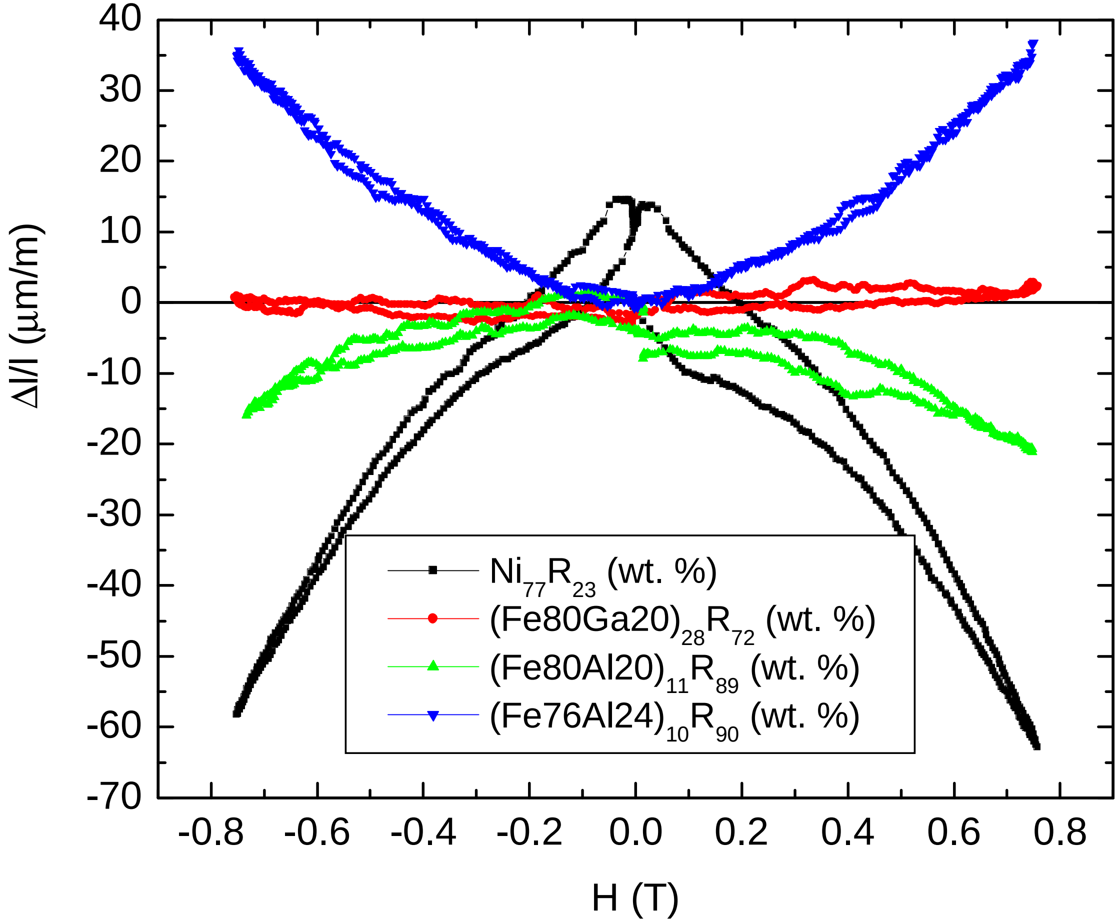


Arc discharge (modified Kratschmer-Huffman carbon arc method)

Composition	**$Fe_{83}Ga_{17}$**		**$Fe_{80}Ga_{20}$**	**$Fe_{80}Al_{20}$**		**$Fe_{76}Al_{24}$**	
Nanopowders average size (nm)*	386	323	425	440	352	359	198
σ_s (emu/g)	1.26	2.3	81	76	54	41	26

** The size distribution of nanoparticles was determined by Dynamic Light Scattering (DLS) technique, using a MICROTRAC Nanotrac 252 Particle Size Analyser.*

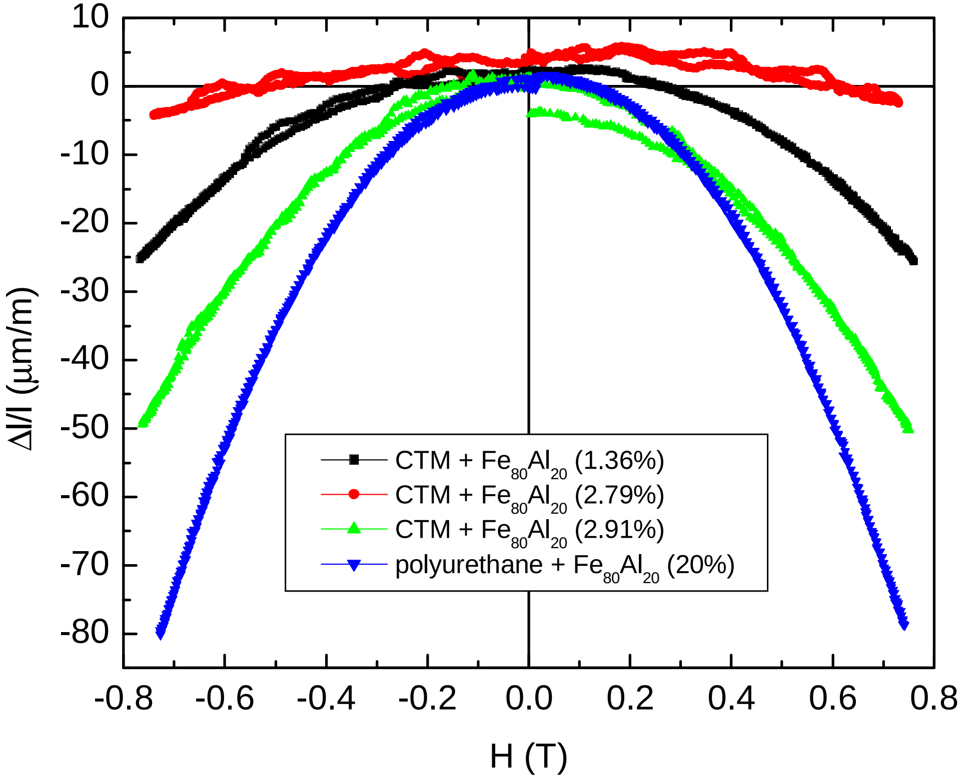
Fe-Ga and Fe-Al composites - Magnetostriction

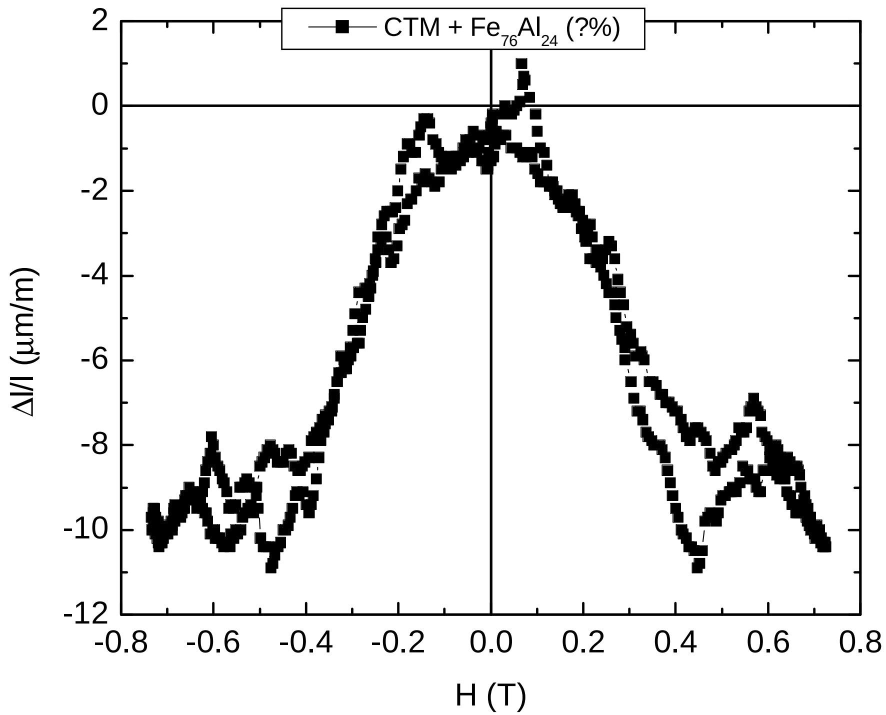


Nanopowders embedded in Poxipol® resin.

Ni nanoparticles size is ranging between 250 and 500 nm.

Nanopowders embedded in CTM and polyurethane

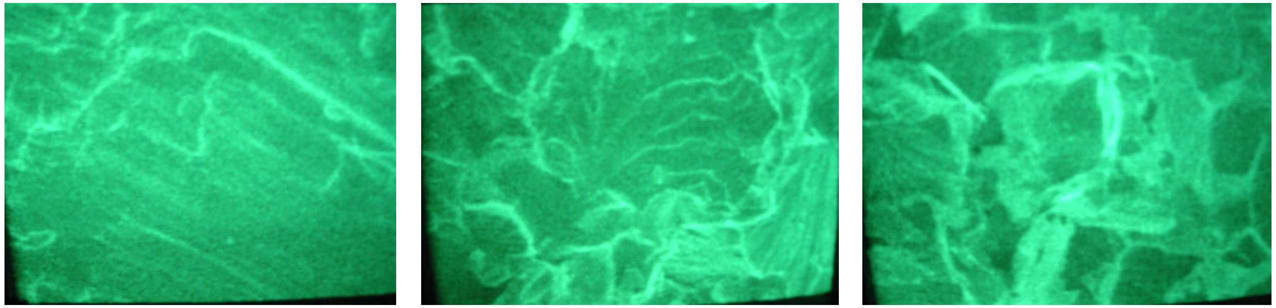




(Co,Ni)-Mn-(Ga,Al) system

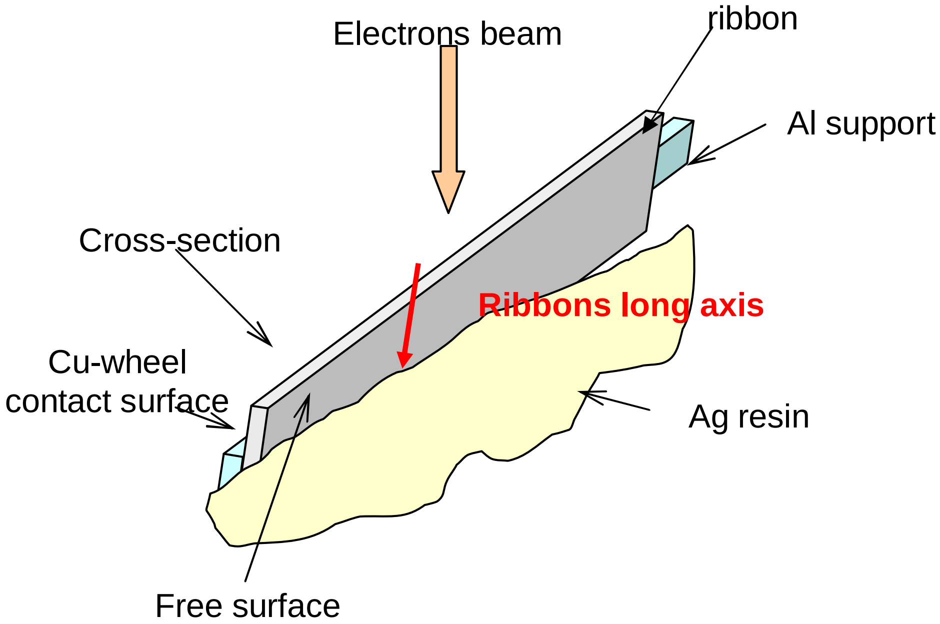
- melt-spun ribbons (25 μm thickness)
- 3-D bulk shaped samples (12 x 6 x 0.5 mm)
- composites

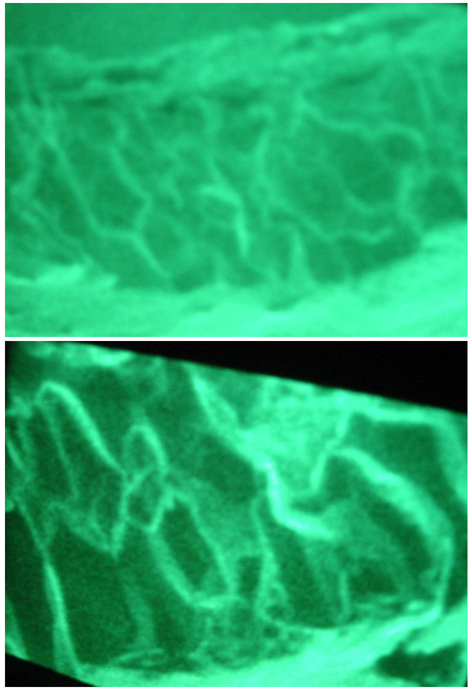
Samples morphology



SEM images taken on the cross-section of the $Co_{38}Ni_{33}Al_{29}$ thin plate.

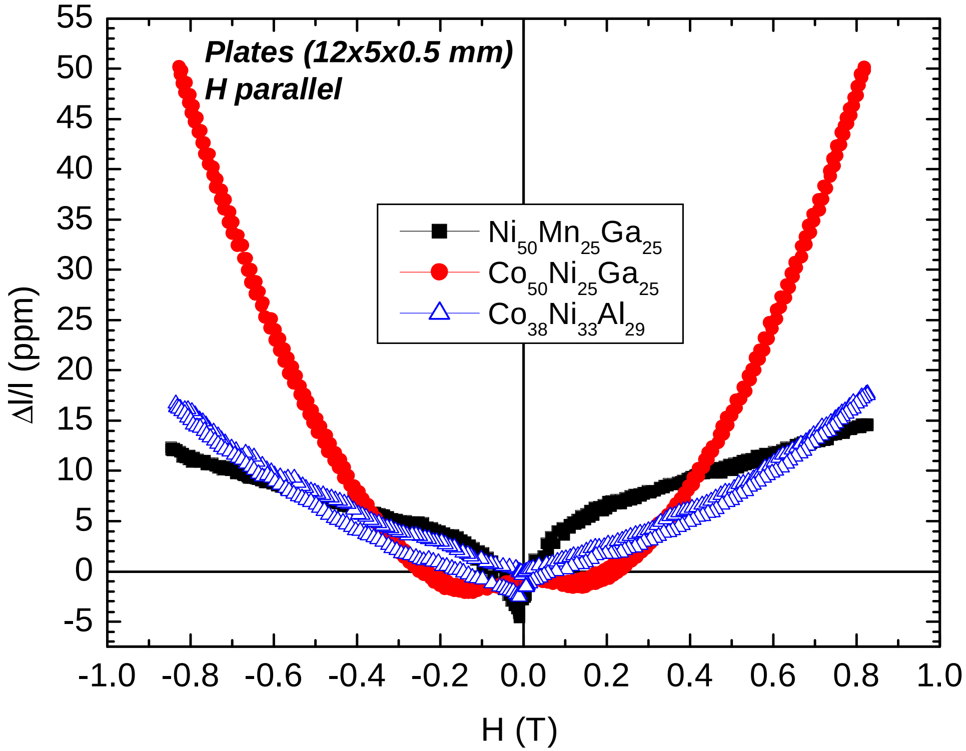
The images do not indicate any preferential direction of the grains.

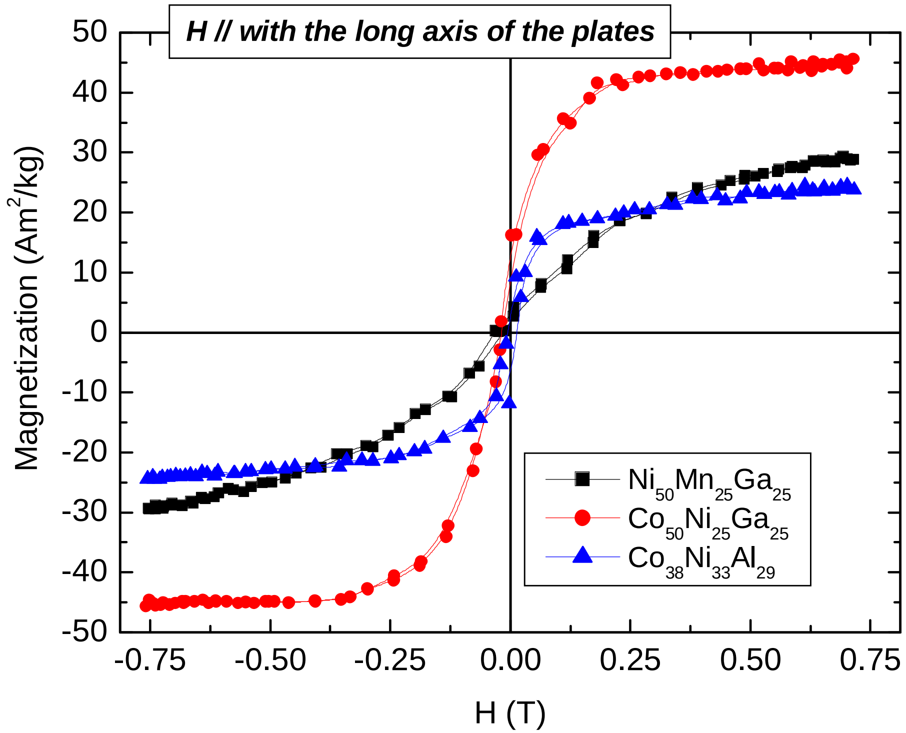




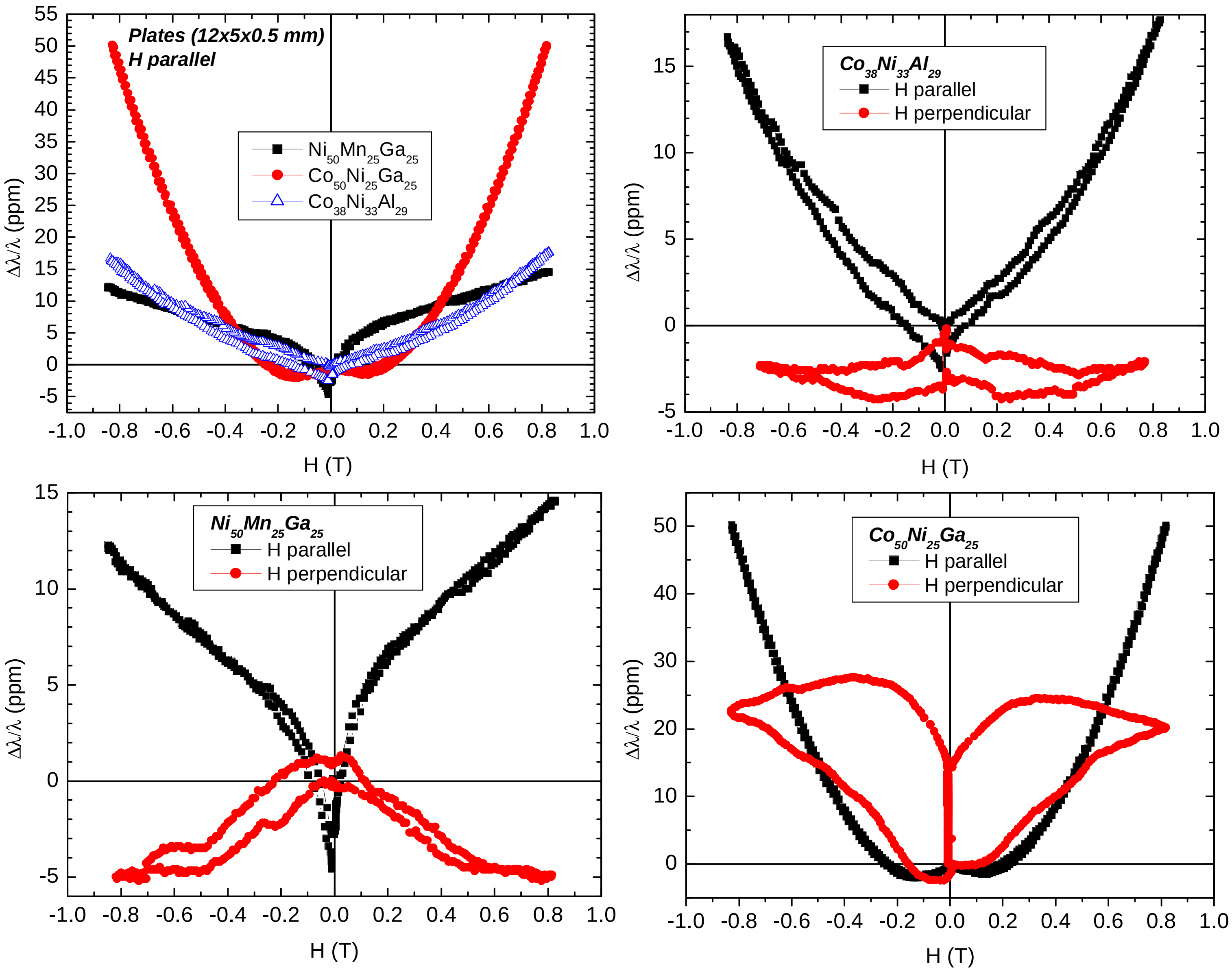
SEM images taken on the cross-section of the $Co_{38}Ni_{33}Al_{29}$ melt-spun ribbons.

λ-H and M-H curves for NiMnGa, CoNiGa and CoNiAl thin plates

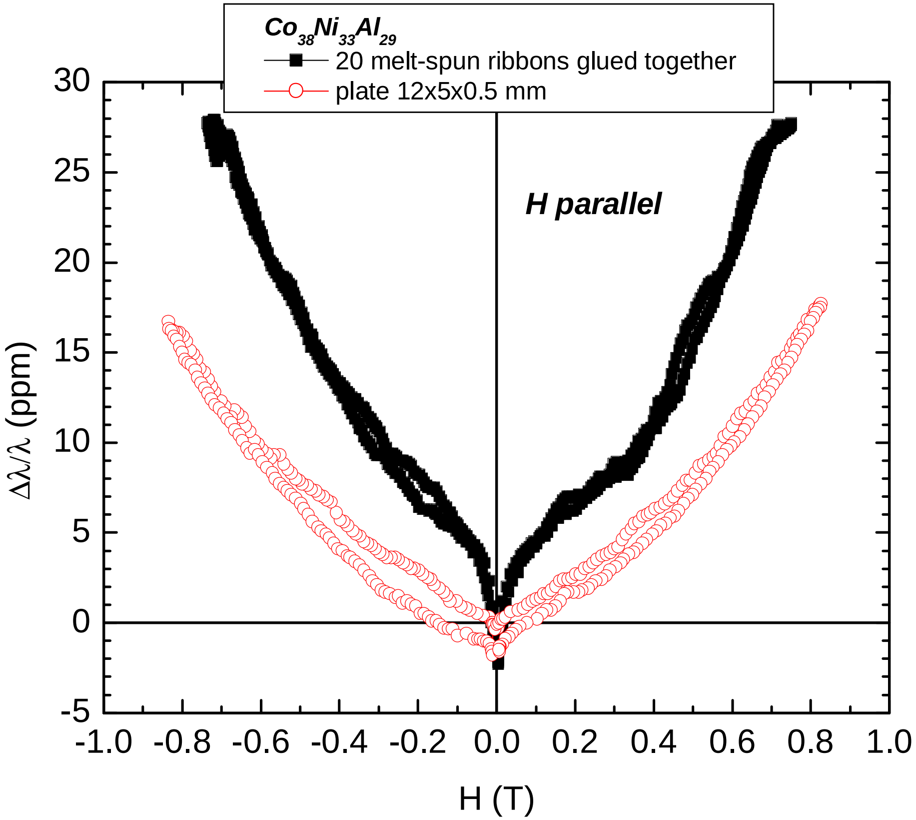


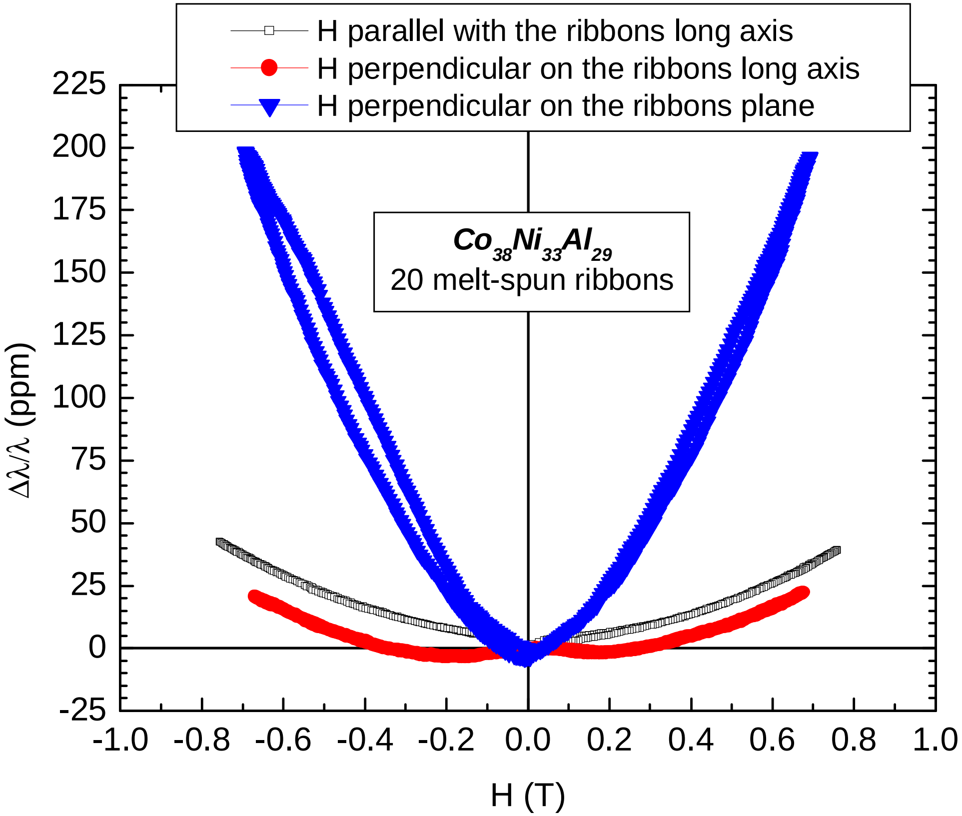


λ-H curves for NiMnGa, CoNiGa and CoNiAl thin plates



Magnetostriction as a function of the sample's shape and direction of the applied field





Conclusions

Despite the fact that λ_s is not comparable with Terfenol-D values, there are other important facts which can be considered for applications:

a. all samples are polycrystalline,

b. easy to prepare and reproducible (efficient and low cost),

c. not fragile and brittle,

d. the magnetoelastic properties can be further improved by tailoring the composition and treatment to be applied.

Potential applications: **in aeronautics and automotive industry**