Magnetic Shape Memory Alloys

- Magnetically Induced Martensite (MIM)
- Magnetically Induced Reorientation (MIR)
- Requirements for actuation
- “Exotic” materials

www.adaptamat.com

German Priority Program SPP 1239:
“Modification of Microstructure and Shape of solid Materials by an external magnetic Field”
www.MagneticShape.de
Multiferroics

magnetoelectric effect

magnetic shape memory effect
Anisotropic magnetostriction

- Single ion effect (spin-orbit coupling) – no collective phenomenon

- Strain < 0.24 %
+ High frequency
+ Low magnetic field

Not important for Magnetic Shape Memory Alloys
Martensitic transformation

$T > T_M$:
- Austenite
  (high symmetry)

$T < T_M$:
- Martensite
  (low symmetry)

- No diffusion, reversible
- Twinned microstructure of martensite
- Thermal actuation

$\Rightarrow$ conventional shape memory effect

+ Strain > 5%
+ High forces
- Low frequency
Prototype Ni-Mn-Ga, Shearing

Ni$_{2+x}$Mn$_{1-x}$Ga
L2$_1$

Why are structures instable?
→ Phonon spectra

bcc - sheared
Martensitic transformation of magnets

Modification of structure and shape by a magnetic field

- High magnetic field $>> 1 \text{T}$
- Narrow temperature regime

Ni$_{2.15}$Mn$_{0.81}$Fe$_{0.04}$Ga

Non-magnetic Austenite

Ferromagnetic Martensite

Martensite and Austenite

$\sim 1 \text{K/T}$
Martensitic transformation of magnets

Modification of structure and shape by a magnetic field

- High magnetic field $>> 1 \, \text{T}$
- Narrow temperature regime

Ni$_{2.15}$Mn$_{0.81}$Fe$_{0.04}$Ga

Ferromagnetic Martensite

Non-magnetic Austenite

Magnetic field favors ferromagnetic phase

Clausius Clapeyron:

\[ \frac{dT}{dH} = \frac{\Delta J}{\Delta S} \]

\( \Delta J \): magn. polarization difference in martensite and austenite state

\( \Delta S \): entropy difference

- Magnetic actuation
- Latent heat (magnetocaloric effect): here a problem
New Materials: Inverse Transformation

Ni-Mn-In

Magnetic field favors high temperature austenite because its ferromagnetism is stronger than that of martensite

DSC:

- Shift of $M_S$ by -8 K/T
- Large magnetocaloric effect

Magnetically Induced Austenite (MIA)

Magnetic field favors ferromagnetic phase

Clausius Clapeyron:

\[
\frac{dT}{dH} = \frac{\Delta J}{\Delta S}
\]

\(\Delta J\): magn. polarization difference in martensite and austenite state

\(\Delta S\): entropy difference

Negative \(\Delta J \rightarrow H\) stabilizes austenite
Magnetically Induced Austenite (MIA)

$\text{Ni}_{45}\text{Co}_5\text{Mn}_{36.7}\text{In}_{13.3}$

- Hysteresis may inhibit reversibility!
- Strain ~ 3%
- No anisotropy needed

R. Kainuma et al.  
Ni-Mn-Ga, 7M

At const $T < T_M$

- Easy movement of twin boundaries ($\sim$ MPa)

- Little pinning of twin boundaries at defects
Only highly symmetric twin boundaries are highly mobile. But a collective movement would require to move $10^{23}$ atoms simultaneously...
Dislocation (step + screw) as elemental step of twin boundary movement

„Intrinsic“ Peierls stress to move Burgers vector $\sim 10^{-13}$ Pa

P. Müllner et al., JMMM 267 (2003) 325

S. Rajasekhar, P. J. Ferreira
Scripta Mat. 53 (2005) 817
Magnetically Induced Reorientation (MIR)

Twin boundary movement

No phase transition, affects only microstructure

Requires:
- Non-cubic phase
- High magnetocrystalline anisotropy
- Easily movable twin boundary

++ Strain ≤ 10 % !
+ High frequency
Rotation of magnetization must be avoided

⇒ high magnetocrystalline anisotropy needed
Magnetic field moves twin boundary instead of magnetization rotation
Integral measurement of strain and magnetization

Ni-Mn-Ga 5M


- Moderate switching field $H_S < 1$ T
Setup of a linear actuator

- **H=0**
- **H₁**
- **H₂**
- **H₃**
- **F**
Magnetic Shape Memory Alloys

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Beneficial conditions for MIR

Intrinsic properties (composition, phase)
- High martensitic transformation temperature $\Rightarrow$ high application temperature
- High magnetocrystalline anisotropy $\Rightarrow$ avoids rotation of magnetization
- High magnetization $\Rightarrow$ high blocking stress
- Large maximum strain $\varepsilon_0 = 1 - \frac{c}{a}$

Extrinsic properties (microstructure, texture)
- High strain $\varepsilon < \varepsilon_0$
- Low switching field $H_S < H_A$
- Easily moveable twin boundaries $\Rightarrow$ rubber like behavior

Aim: high strain in low magnetic fields
What is essential for the MSM effect?

- Martensitic transformation
- Ferromagnetism
- High uniaxial magnetocrystalline anisotropy
- High magnetostriction
- Chemical ordering

Not fulfilled for:

- Tb, Dy, $ReCu_2$
- $ReCu_2$, $La_{2-x}Sr_xCuO_4$
- $Fe_{70}Pd_{30}$, Ni-Mn-In
- Ni-Mn-Ga
- $Fe_{70}Pd_{30}$, Tb, Dy
Anisotropic magnetostriction

Constrained 5M NiMnGa single crystals

$\lambda_S = -50$ ppm

- Not appropriate to describe threshold like switching (Reorientation or Martensitic transformation)

Fe$_{70}$Pd$_{30}$

- **Austenite**: fcc
- **Martensite**: fct, c/a <1
  - two easy axis $||$ a

- No uniaxial anisotropy needed
- No chemical ordering

R.D. James, M. Wuttig
Phil. Mag. 77 (1998) 1273

J. Cui, T.W. Shield, R.D. James,
Acta Mat. 52 (2004) 35

- no martensitic transformation
- orthorhombic (pseudohexagonal, 3 variants)

\[ H \parallel c, \, T = 40 \text{ K} \]

- Canted magnetic order

\[ M(\mu_B/\text{f.u.}) \]

- 1.5% strain at 3.2 T by reorientation
La$_{2-x}$Sr$_x$CuO$_4$ (LSCO)

- Orthorhombic, twinning in ab plane, b axis (red domains) aligns parallel to magnetic field
- Antiferromagnetic, weak ferromagnetic moment

H = 14 T
RT
1% strain

Dy single crystal at 4 K

8% strain in Tb (40 T, 4K)


- Pure elements

Magnetic field favors high temperature austenite because its ferromagnetism is stronger than that of martensite.

- No significant magnetocrystalline anisotropy (cubic ferromagnet)

DSC:

- Magnetically weaker (Martensite)
- Magnetically stronger (Austenite)

Magnetic Shape Memory Alloys

Martensite (SMA)

FMSMA

Magnetic Ordering

NiMnGa FePd Fe₃Pt Dy Tb La₂₋ₓSrₓCuO₄ ReCu₂

NiMnIn FeNiGa CoNiGa
### Magnetic Shape Memory Alloys

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![Diagram of magnetic shape memory alloys](image_url)
Martensitic and Ferromagnetic

Crystallographic variants

Coupled by magneto-
Crystalline anisotropy

Magnetic domains

F

→

H

Short axis aligned by stress

Domain and variant movement
→ local mechanism

Magnetization direction aligned by field
Martensitic and Ferromagnetic

Crystallographic variants

Coupled by magneto-crystalline anisotropy

Magnetic domains

Short axis aligned by stress

Magnetization direction aligned by field

Kerr microscopy:

Twin boundaries (Variant boundaries, grain boundaries)

90° and 180° Domain boundaries

B1: J. McCord, R. Schäfer, *IFW Dresden*
Magnetic Shape Memory Alloys

Magnetically Induced Martensite (MIM)
- Little constrains on microstructure
- No magnetocrystalline anisotropy needed

Forces?
- High fields > 1 T
- Works only at the vicinity of martensitic transformation
- Magnetocaloric effect inhibits high frequency

Magnetically Induced Reorientation (MIR)
- Rubber like behavior needed
- High magnetocrystalline anisotropy
- Low forces
- Moderate fields < 1 T
- Works below martensitic transformation
- High frequency (kHz) possible