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Synthesis and characterization of magnetic shape memory materials

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Synthesis and Characterization of Magnetic Shape Memory Materials

by

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Abstract

Magnetic shape memory alloys give significant recoverable strain due to the reorientation of martensite plates by the motion of twin boundaries as a result of an applied magnetic field. The presence or extent of the effect is a function of such variables as the martensite morphology, the mobility of twin boundaries, the volume magnetostriction, and the magnetic susceptibility. The effect can occur at high frequencies and at easily achievable temperatures. These materials thus show great promise for use in actuators and sensors for a variety of applications. An introduction to this class of materials is provided, and preliminary work to synthesize and characterize nickel-based magnetic shape memory materials is described.

Synthesis and Characterization of Magnetic Shape Memory Materials

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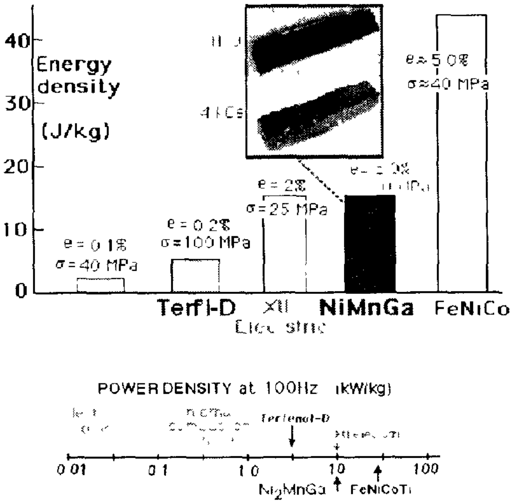
Outline

- Introduction
  - Active materials and their applications
- Magnetic properties of matter
  - Background
  - Paramagnetism and ferromagnetism
- Magnetostriction
  - Mechanism of magnetostriction
  - Limitations
- Magnetic shape memory materials
  - Background - martensite formation and morphology
  - Mechanism of MSM effect (Ni_2MnGa, FeNiCoTi)
- Preliminary work

Introduction - active materials

- Active materials are used to:
  - activate switches (close circuits)
  - effect changes in a structure
    - helicopter rotors
    - biomimetic active hydrofoils
- Requirements of active materials:
  - sensible operating temperatures
  - large strains
  - high frequencies
  - strength and toughness
- Classes of active materials:
  - electrostrictives
  - magnetostrictives
  - magnetic shape memory

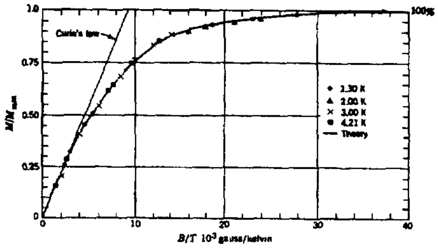


Magnetic properties of matter

- Simplest magnetic structure = magnetic dipole
  - *Examples.* current loop, bar magnet, solenoid, elementary particles
  - electron ⇒ “spin” magnetic moment + “orbital” magnetic moment
- Magnetic dipole moment (μ)
  - N & S poles which are inseparable and are not sharply defined
  - Dipole experiences a torque when exposed to an applied $\mathbf{B}$ ($\tau = \mu \times \mathbf{B}$)

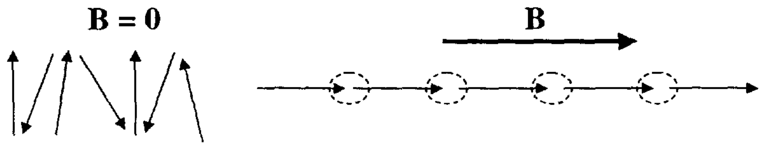
Paramagnetism and ferromagnetism

- PARAMAGNETISM
  - In most atoms and ions, $\Sigma\mu_{electron} = 0$ $\Rightarrow$ non-magnetic
  - In some cases, the magnetic moments do not cancel completely so the atom / ion has an overall magnetic moment.
    - Elementary dipoles tend to align in an applied field **BUT** thermal agitation interferes
      - $\mu_{max} = N\mu$ (N = # of atoms, μ = atomic magnetic moment)
      - In practice, $\mu_{actual} << \mu_{max}$
    - Magnetization **M** = magnetic dipole moment per unit volume (**M** = μ / V)



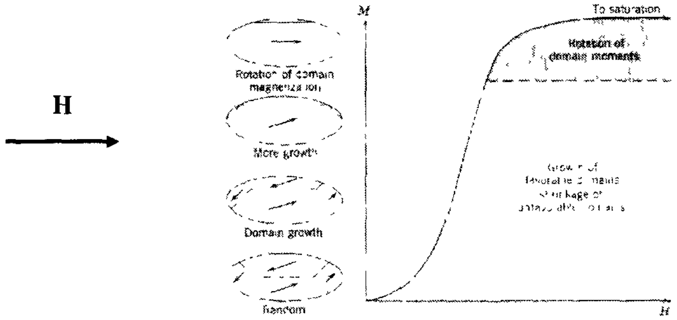
Paramagnetism and ferromagnetism

- FERROMAGNETISM
  - Fe, Co, Ni can achieve a high degree of magnetic dipole alignment even at elevated temperatures.
  - This effect is due to "exchange coupling" between adjacent atoms, which causes the magnetic alignment to be "locked-in "
  - Exchange coupling disappears above the Curie Temperature (1043 K for Fe)



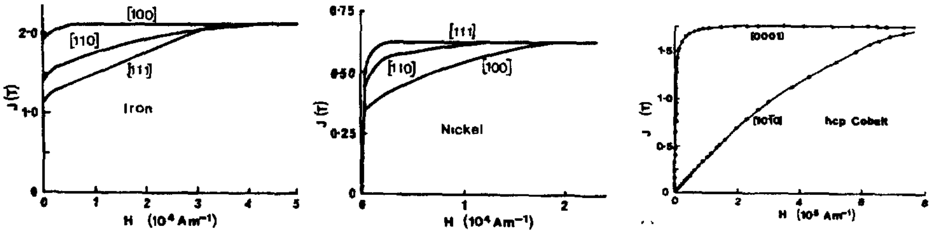
Magnetization of ferromagnetic materials

- Saturation magnetization is generally achieved at very high applied field $\mathbf{B}_0$.
  - Magnetic domains - regions in which magnetic dipoles are aligned
- When a magnetic field is applied:
  - Favorably oriented domains grow at the expense of unfavorably oriented domains.
  - Orientation direction of dipoles in a domain can become closer to the field direction.



Ferromagnetism

- Magnetization curves are anisotropic
  - There is an easy direction of magnetization

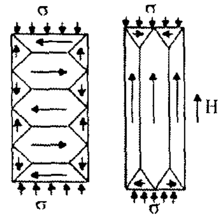


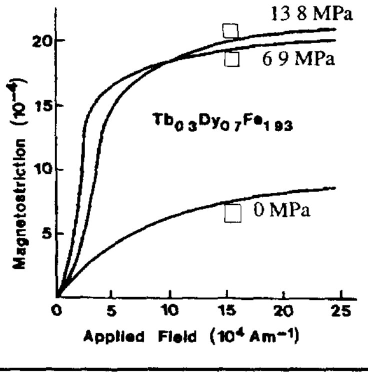
Magnetostriction

- When the magnetic electron spin dipole moments of the atoms in a solid are aligned, the length of the bonds between the atoms changes.
  - Shape and volume of a ferromagnetic solid change as it is magnetized.
- Magnetostriction = reversible strain along the axis of magnetization.
  - Usually saturates at the same time as magnetization
  - Anisotropic because:
    1) The magnetization curve is anisotropic
    2) Elastic properties are anisotropic.
  - Appears to provide the clearest magnetic indication of the stress state of a sample.

Magnetostriction - limitations

- Saturation magnetostriction is relatively low (max < 1%).
- Large fields are needed to induce appreciable strains (2 kOe)
- Useful frequency range is limited by development of eddy currents
- Materials are very brittle in tension.
- Terfenol-D - must be mechanically biased in compression.

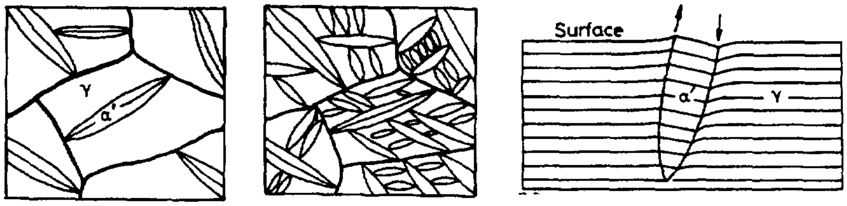




Material	Saturation magnetostriction λ_s (10^{-6})
Iron	−7
Fe−3 2% Si	+9
Nickel	−33
45 Permalloy, 45% Ni−55% Fe	+27
82% Ni−18% Fe Permalloy	0
Permendur, 49% Co−49% Fe−2% V	+70
87% Fe−13% Al Alfer	+30
Magnetite, Fe_3O_4	+40
Cobalt ferrite, $CoFe_2O_4$	−110
Cobalt ferrite, $Co_{1\ 1}Fe_{1\ 9}O_4$	−250
$SmFe_2$	−1560
$TbFe_2$	+1753
$Tb_{0\ 3}Dy_{0\ 7}Fe_{1\ 93}$ (Terfenol D)	+2000
$Fe_{66}Co_{18}B_{15}Si_1$ (amorphous)	+35
$Co_{72}Fe_3B_6Al_3$ (amorphous)	0

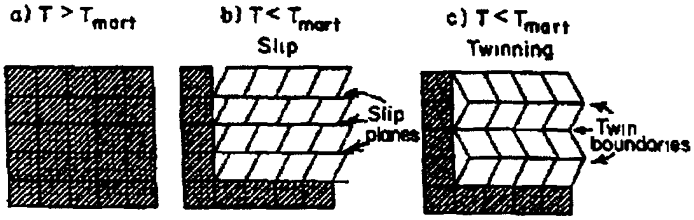
Magnetic Shape Memory Effect (MSME)

- **Magnetostriction** - expansion or contraction of interatomic bonds (elastic,0.2%)
- **MSME** - movement of twin boundaries in twinned martensite (plastic, 6%)
- Martensite:
  - Forms by a diffusionless transformation (no change in composition)
    - steels, nickel aluminum bronzes, NiMnGa, FeNiCoTi
  - Transformation from cubic to tetragonal structure
  - Transformed region appears coherent with the surrounding parent phase.
    - The habit planes are macroscopically undistorted, and are often irrational



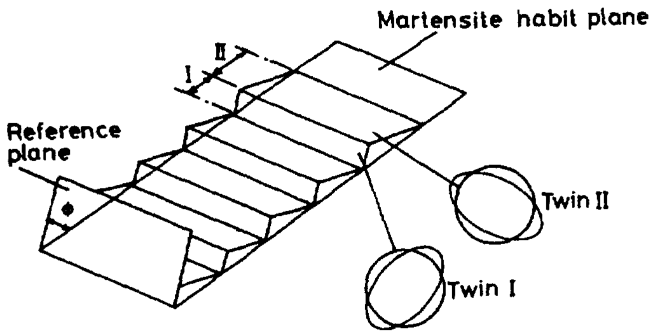
Martensite crystallography

- How do the invariant planes arise ???
- The strain on nucleation of a martensite region within the parent phase is accommodated (elastic energy is minimized) by a shear deformation:
  - slip
  - formation of an ensemble of twin variants
    - internally twinned martensite
    - more likely in a lath-type martensite morphology



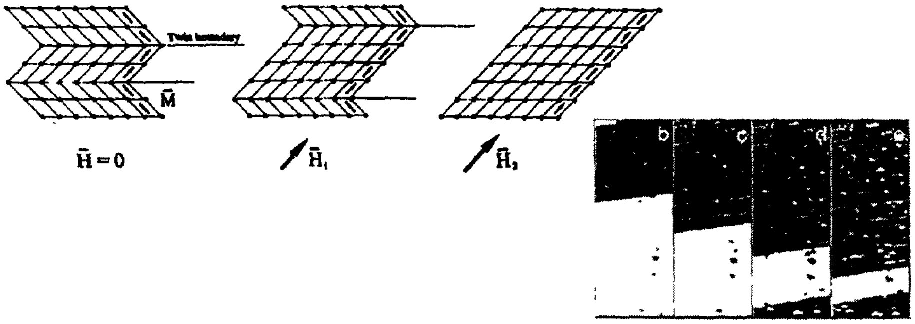
The magnetic shape memory effect

- If one twin type is favored over the other, the habit plane and the shape of the martensite plate must change.
- In MSM materials, there is a field-induced redistribution of the twin variants in the martensite.



The magnetic shape memory effect

- The MSM effect is only appreciable if the magnetic anisotropy is sufficiently high
  - It is easier to re-orient the crystal than to rotate the magnetization away from the easy axis
  - More likely to move twin boundaries than to rotate the magnetization within the unfavorably oriented internal twins



Factors affecting the MSM effect

- Alloying elements
  - hinder twin boundary motion
  - stabilize martensite phase
  - favor lath or plate martensite morphology
  - affect T_C and M_S temperatures

Work output $\propto \frac{M_S^2H^2}{4Ce_0^2}\left(1-\frac{M_SH}{4K_u}\right)$

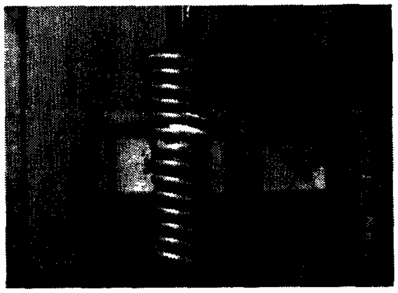
- Plastic deformation prior to martensite formation
  - affect martensite morphology (heterogeneous nucleation)

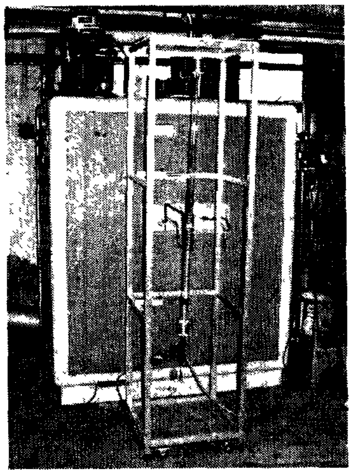
Stress is limited by M_SH

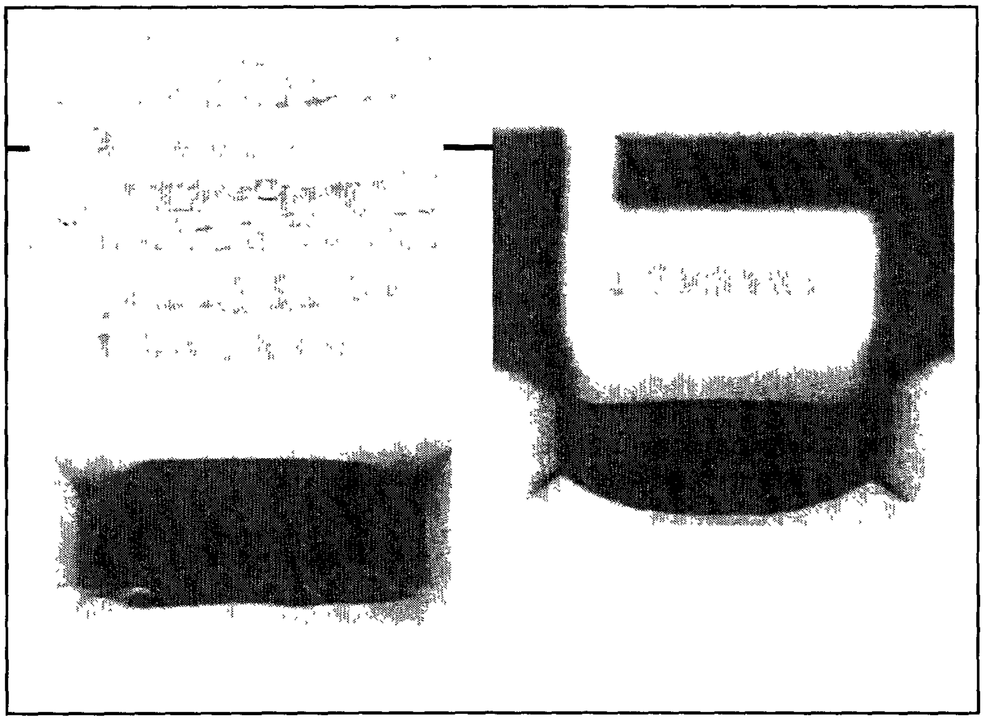
- Prior austenite grain size
  - limit size of martensite laths
- Crystallographic texture
  - max strain for highly textured material (single crystal)
- Mechanical bias
  - max strain if starting structure consists only of unfavorable twin variant

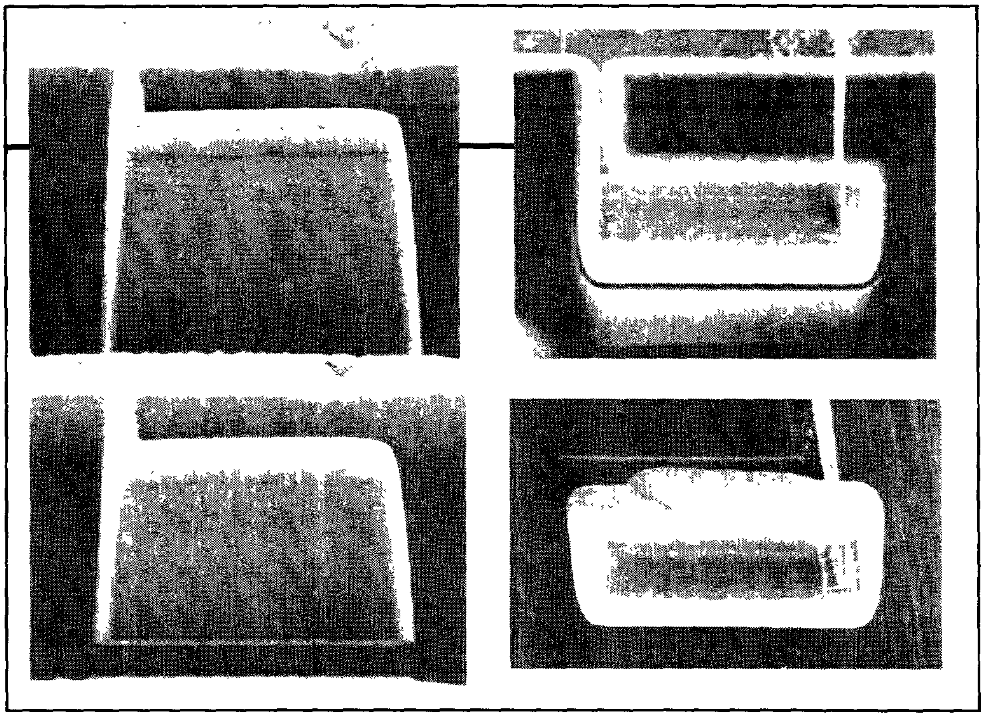
Preliminary work

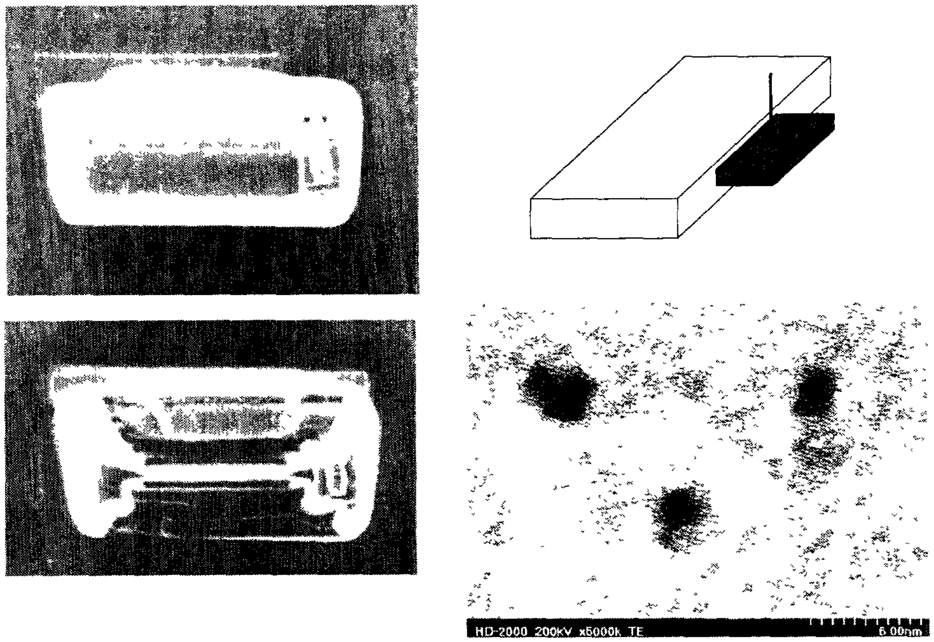
- Goal: to produce and test magnetostrictive and MSM materials
  - Polycrystals
  - Directionally solidified samples
- Made polycrystalline NiMnGa, FeAlGa
- Setup for directional solidification
- First lattice images of Terfenol-D











Summary - magnetostriction vs. MSM effect

- Field-induced strain is due to different processes.
  - MSM - twin boundary motion
    - Strain is tied to the crystallography
  - Magnetostrictives
    - Strain is tied to M (magnetization rotates relative to crystallography)
- Effects of magnetocrystalline anisotropy
  - MSM materials - field-induced strains increase with increasing magnetocrystalline anisotropy
  - Magnetostrictives - field-induced strains decrease with increasing magnetocrystalline anisotropy
- Saturation magnetization
  - Critical to both mechanisms
- Potential strains and energy density
  - MSM materials - up to ≈6% predicted, ≈715 kJ m^{-3}
  - Magnetostrictives - up to ≈0.2% achieved, ≈120 kJ m^{-3}