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# Modeling of additive manufactured materials magnetic behavior

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# Outline

- 1 INTRODUCTION
  - Definitions and scope
  - Additive manufacturing of soft/medium magnetic materials
  
- 2 MAGNETIC BEHAVIOR
  - Definitions and basic properties
  - Magnetomechanics
  - Some specificities of AM materials magnetic behavior
  
- 3 MODELING OF AM MATERIALS MAGNETIC BEHAVIOR
  - Typical scales
  - Gibbs free energy at the magnetic domain family scale
  - Stochastic modeling, localization, homogenization
  - Some results
  
- 4 CONCLUSIONS

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  - Some results
  
- 4 **CONCLUSIONS**

# INTRODUCTION

## Definitions and scope

### **Strong increase of AM materials and structures**

- Many available materials
- Most alloys with dominant Fe, Ni, Co: get neutral, desired or suffered magnetic state
- Relationship between magnetism and additive manufacturing: recent topic [1, 2]
- Mainly metallic materials even if ferrimagnetic/antiferromagnetic/magneto-rheologic materials could be considered

### **Many possible materials however**

- Only ferromagnetic materials considered in this talk
- Possible extension to other magnetic orders
- Possible extension to other physics: SMA, ferroelectrics

# INTRODUCTION

## Definitions and scope

### Many possible materials remain

- Soft magnetic materials: FeSi, FeCo, FeNi, Ni, *electrical steels*
- Medium magnetic materials: all carbon steels from ferritic/ferrito-pearlitic to quenched/aged martensitic alloys
- Medium magnetic materials: ferritic, martensitic and (unstable) austenitic stainless steels (Fe-Cr-Mn)
- *Hard magnetic materials*
- *Magnetic shape memory alloys*
- *Magneto-caloric materials*
- ...

### Only soft/medium ferromagnetic materials considered in this talk

- Below Curie temperature of course...
- Boundary electromagnetic phenomena not considered

# INTRODUCTION

Soft/medium ferromagnetic materials

## Interest of AM for these materials?

- Wide range of chemical composition / gradient
- Prototyping
- Lightening of structures (lattices)
- Complex designs (where conventional machining fails)
- Repairing

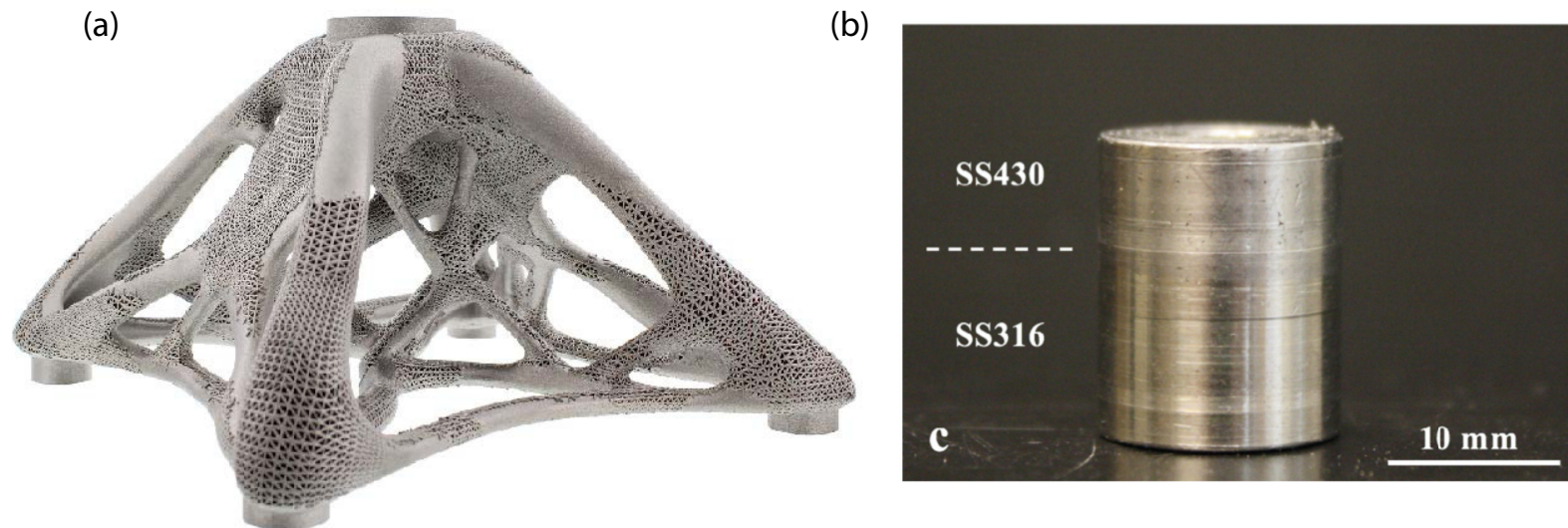


Figure 1: (a) Optimized AM structure [3]; (b) AM with composition gradient [4].

# INTRODUCTION

Soft/medium ferromagnetic materials

## AM Techniques

- Powder bed fusion by energy source: laser in the case of selective laser melting (SLM) or an electron beam in electron beam manufacturing (EBM)
- Directed energy deposition (DED) and binder jetting
- Stress-relief, sintering or homogenization heat treatment

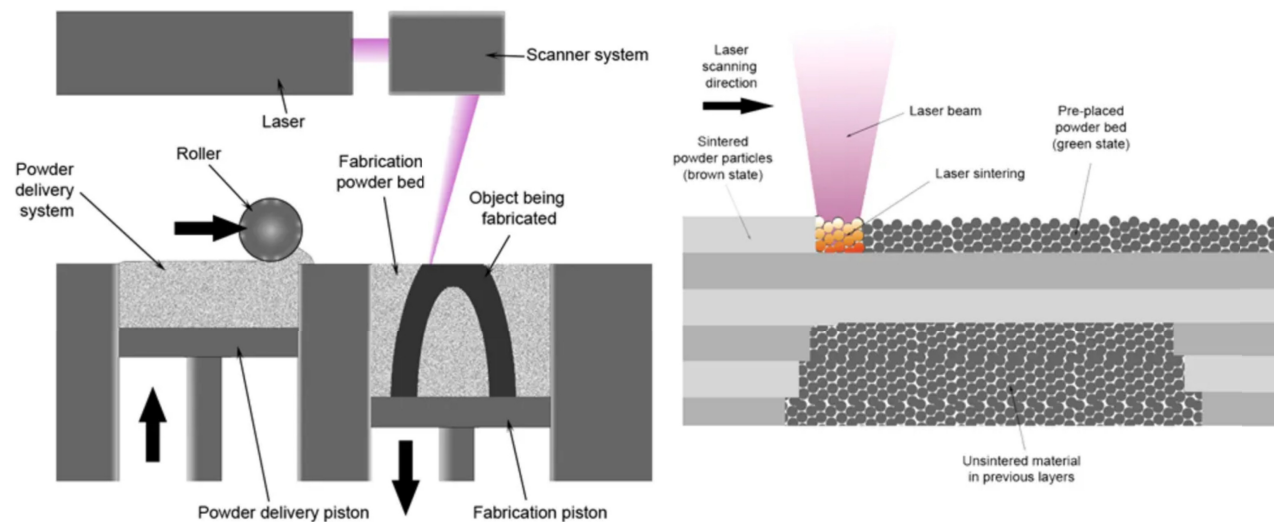


Figure 2: Powder bed fusion technique and SLM [5].



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# MAGNETIC BEHAVIOR

Definitions and basic properties

## Ferromagnetic behavior

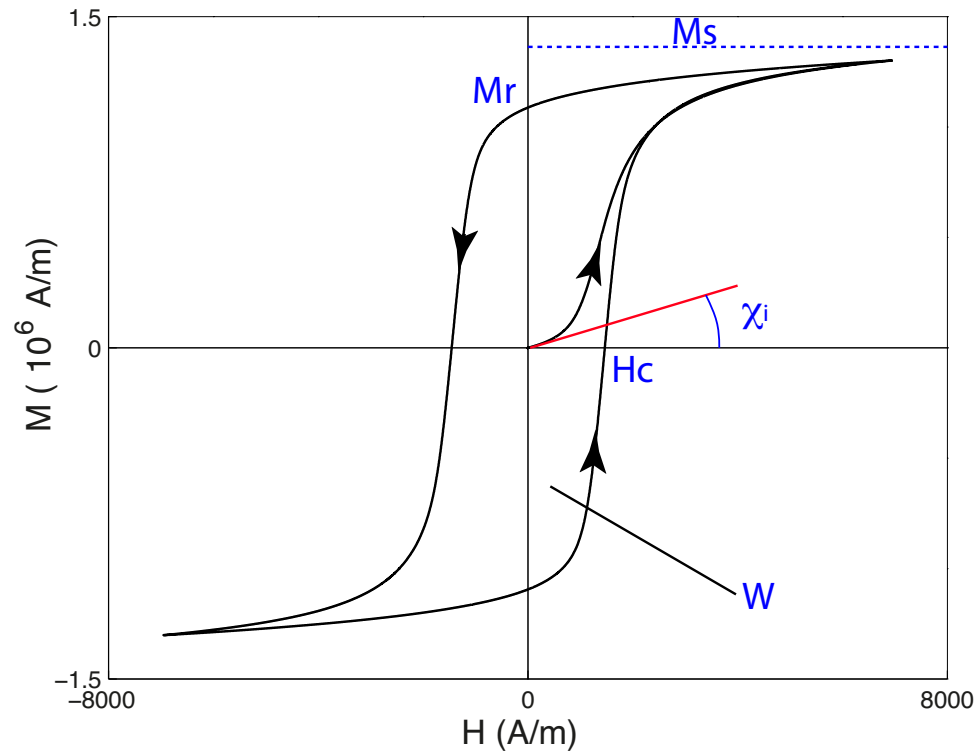


Figure 3: Cyclic magnetic behavior of carbon steel and main quantities [6].

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) \quad \vec{M} = \chi(H)\vec{H}$$

# MAGNETIC BEHAVIOR

Definitions and basic properties

## Ferromagnetic domains

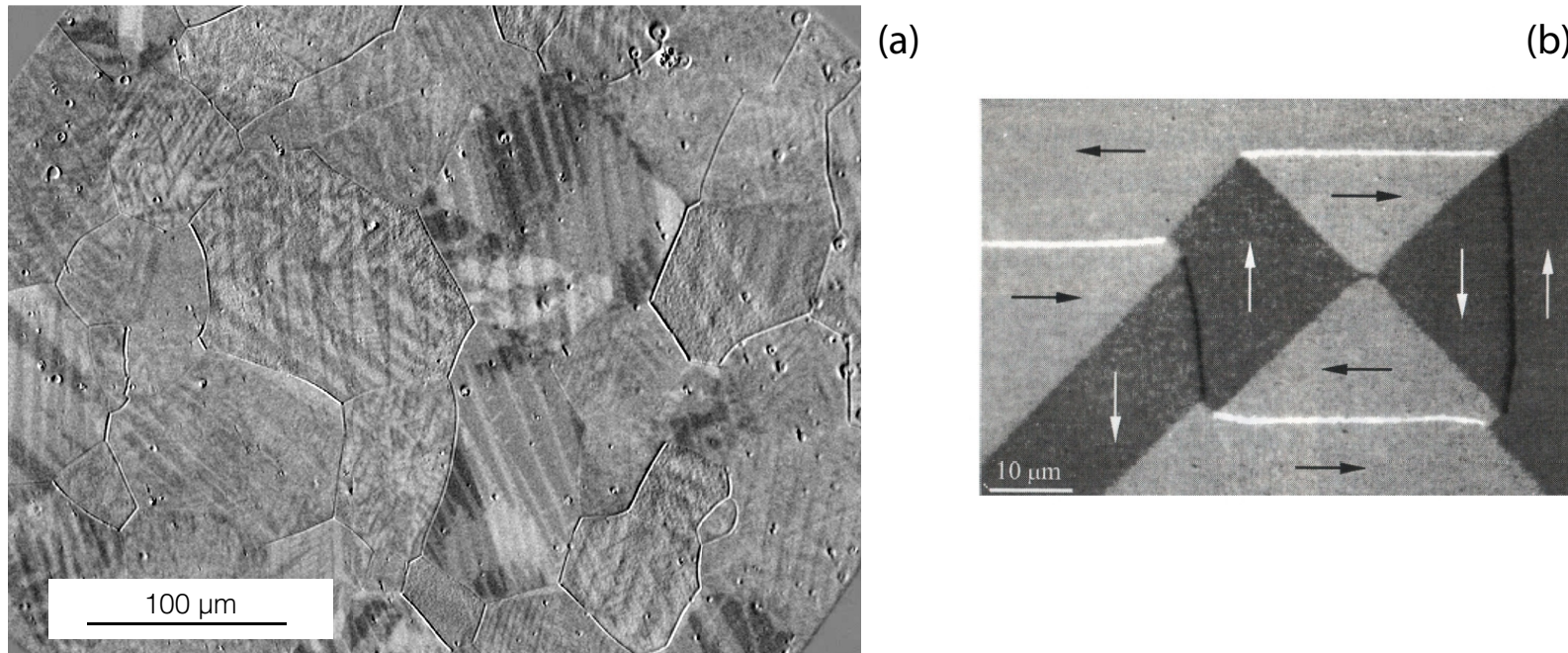


Figure 4: (a) Fe-27%Co sheet [7]; (100)-oriented silicon-iron crystal [8] - Kerr microscopy.

$$\vec{M}_\alpha = M_s \vec{e}_\alpha = M_s \gamma_i \vec{e}_i$$

# MAGNETIC BEHAVIOR

## Definitions and basic properties

### Ferromagnetic domains - interaction with defects

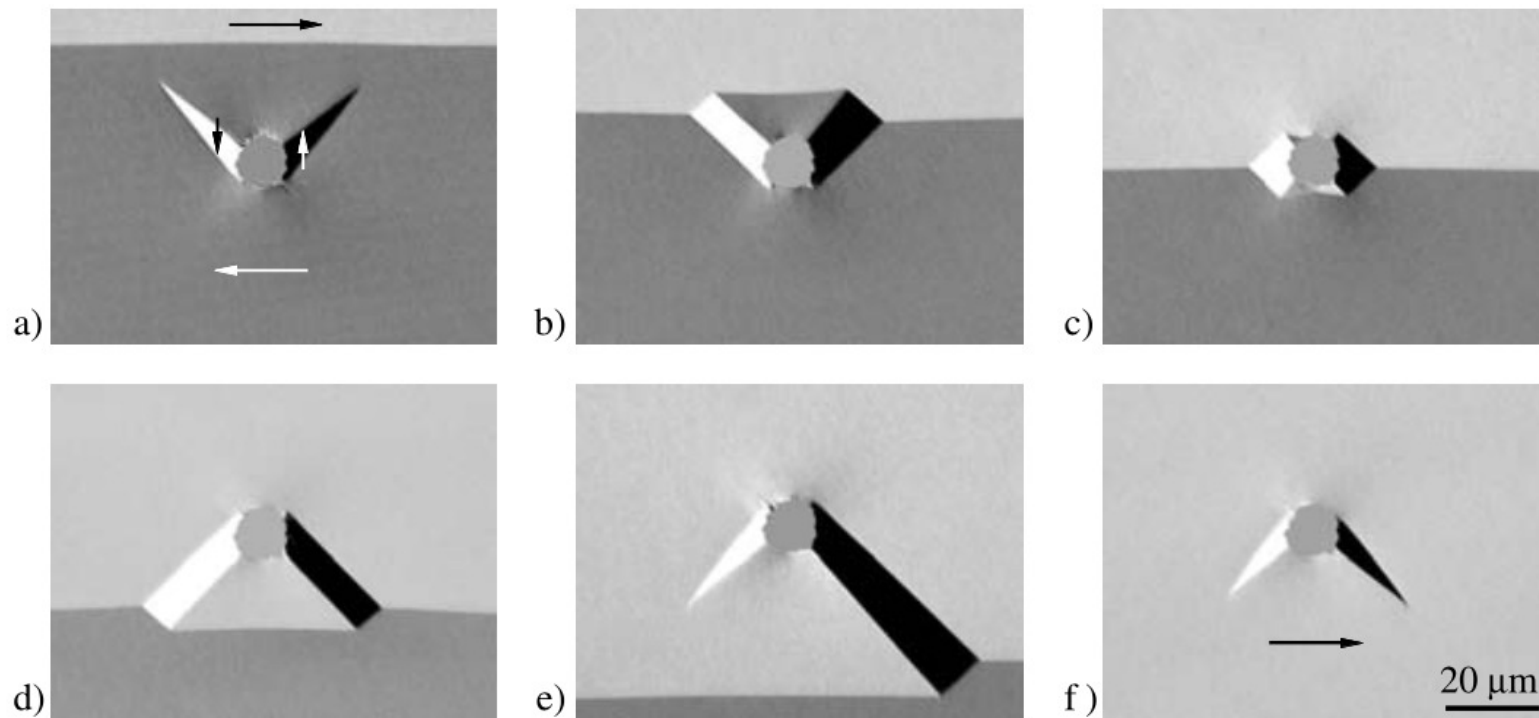


Figure 5: Defect / 180° domain wall interaction / silicon-iron crystal [8] - Kerr microscopy.

=> Magnetostatic and magnetoelastic interactions

# MAGNETIC BEHAVIOR

## Definitions and basic properties

### Anisotropy

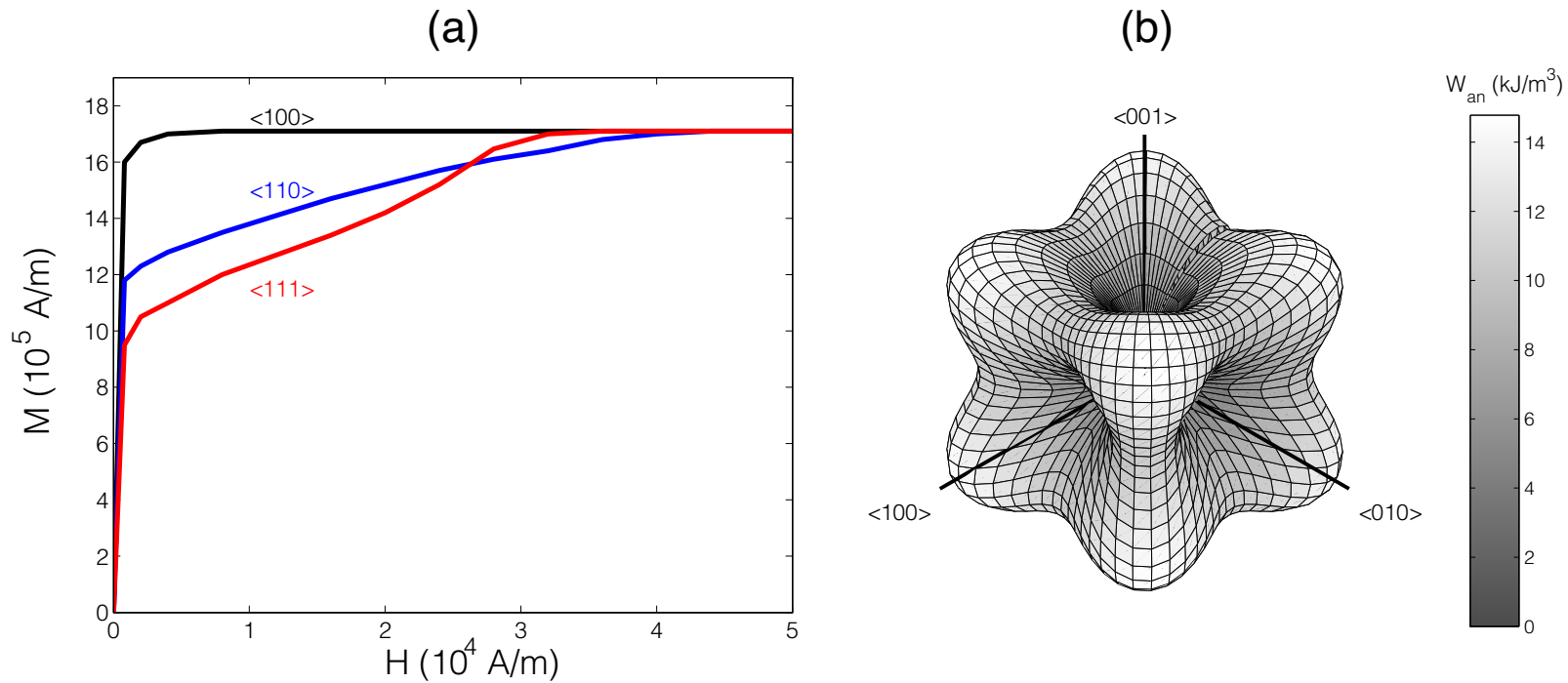


Figure 6: Magnetic crystalline anisotropy of pure iron: (a)[9]; (b)[10].

$$\psi_{\alpha} = K_0 + K_1(\gamma_1^2 \gamma_2^2 + \gamma_1^2 \gamma_3^2 + \gamma_2^2 \gamma_3^2) + K_2 \gamma_1^2 \gamma_2^2 \gamma_3^2$$

# MAGNETIC BEHAVIOR

Definitions and basic properties

## Composition

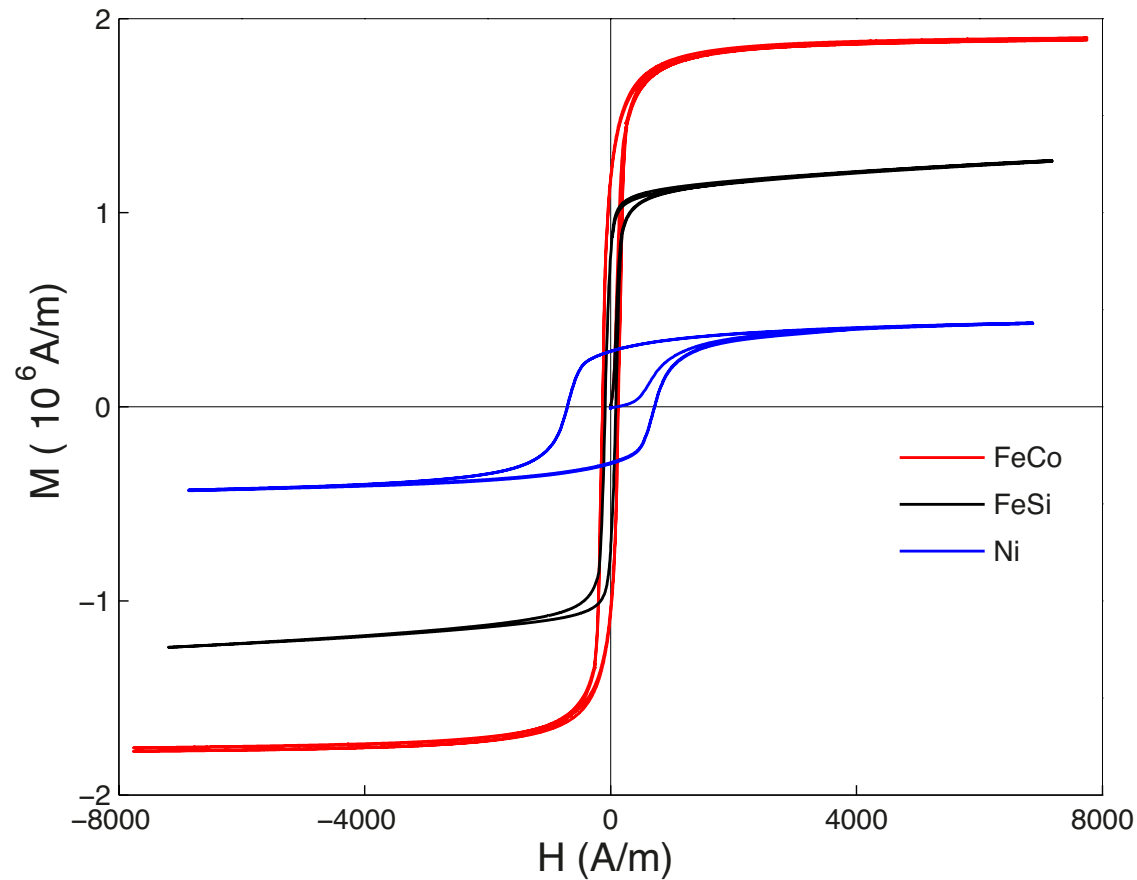


Figure 7: Composition dependent magnetic behavior [11].

# MAGNETIC BEHAVIOR

Definitions and basic properties

## Composition / phases

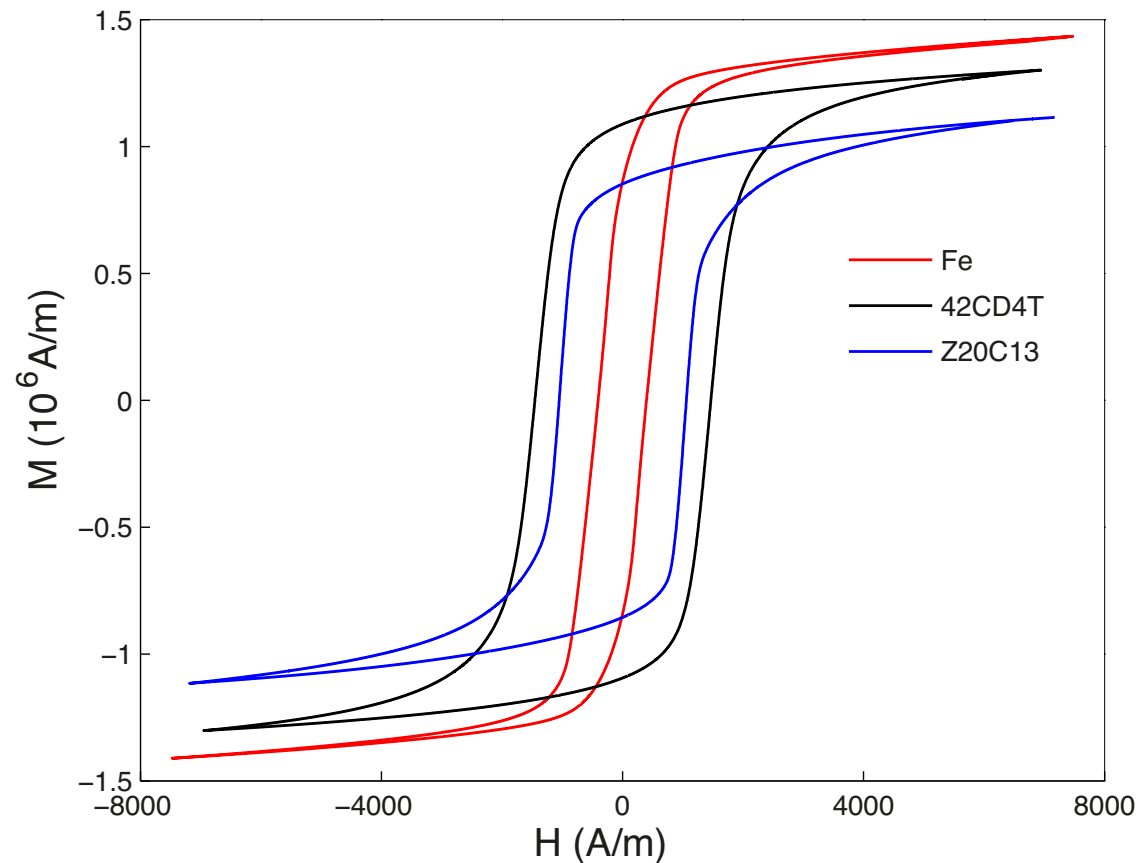


Figure 8: Composition/phases dependent magnetic behavior [6].

# MAGNETIC BEHAVIOR

## Definitions and basic properties

### Grain size

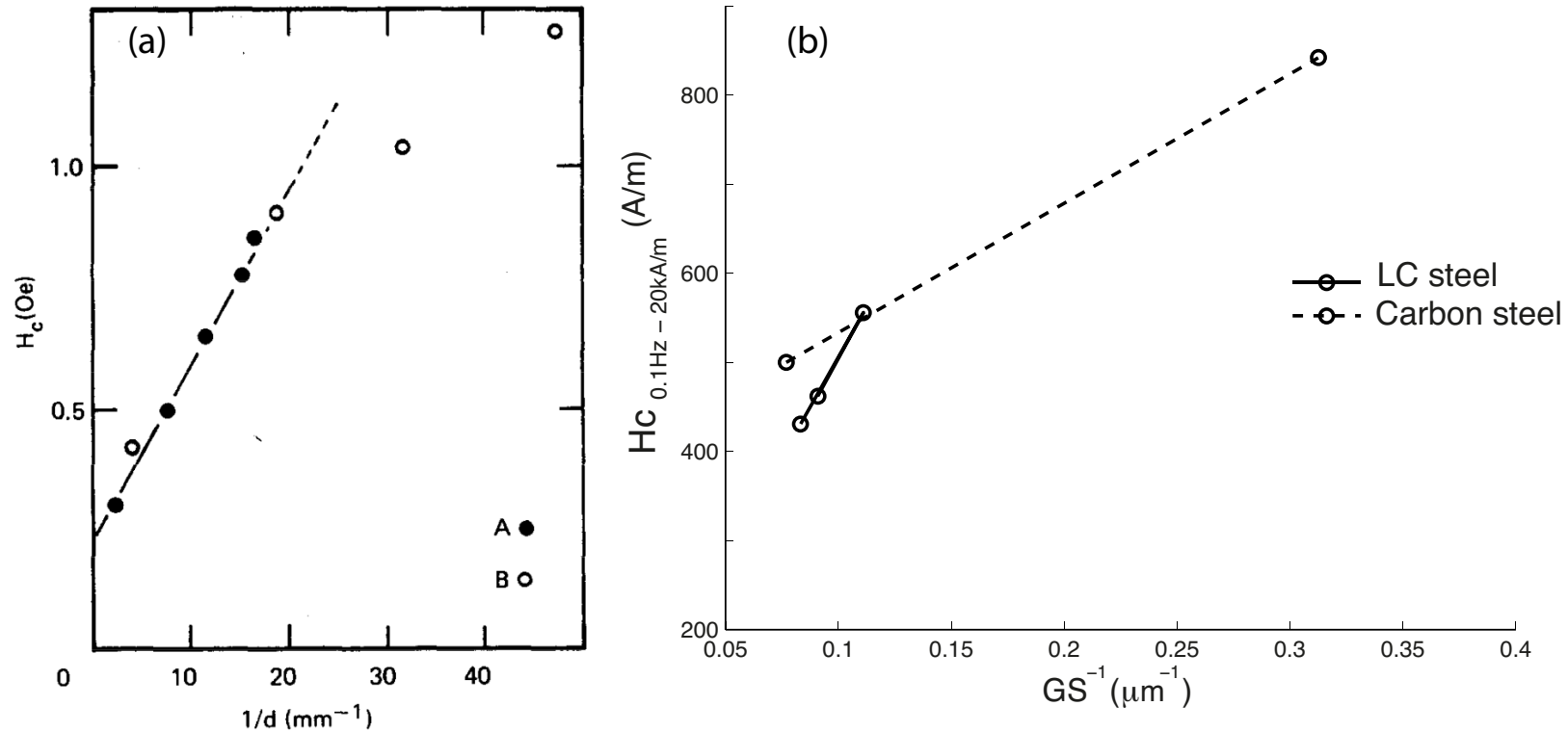


Figure 9: (a) Coercive field vs. GS [12]; (b) Coercive field vs. GS HS-Steels [6].



# MAGNETIC BEHAVIOR

Magnetomechanics

## Magnetostriction

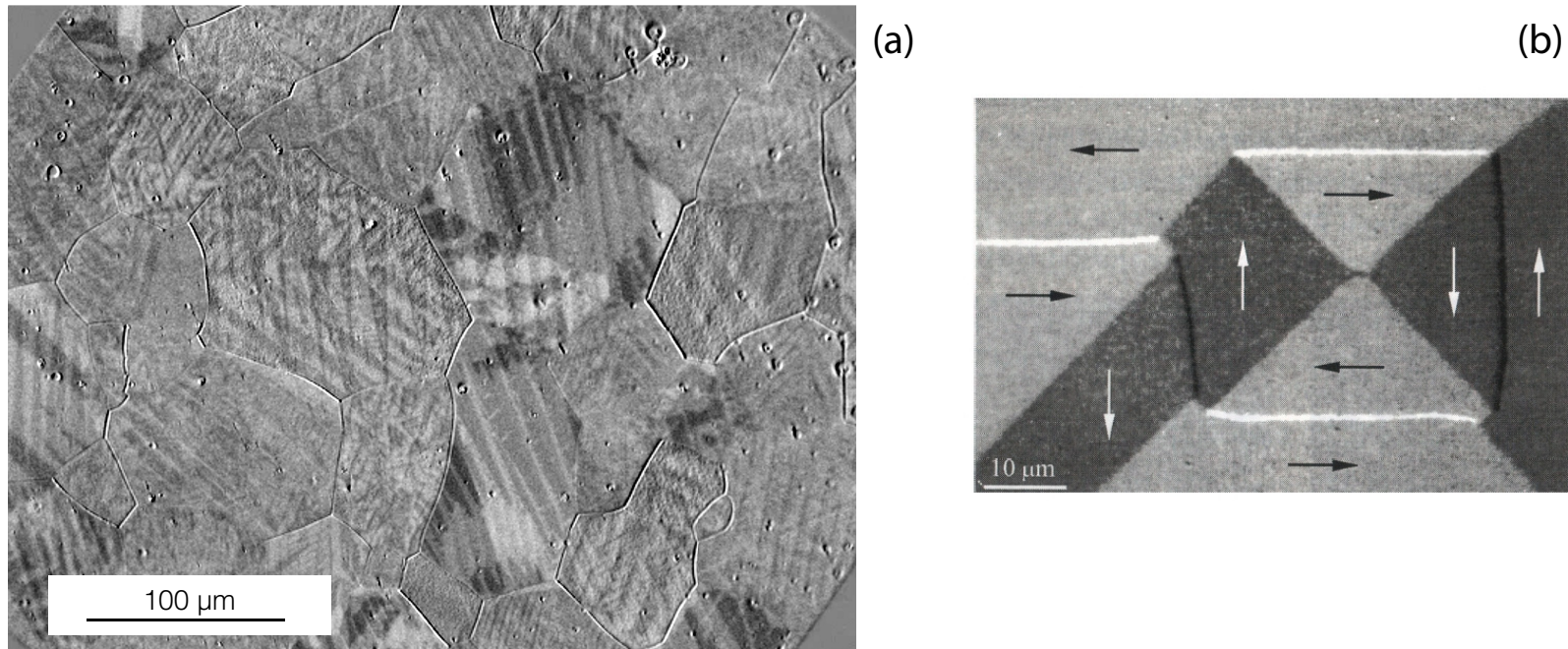


Figure 10: (a) Fe-27%Co sheet [7]; (100)-oriented silicon-iron crystal [8] - Kerr effect

$$\vec{M}_\alpha = M_s \vec{e}_\alpha = M_s \gamma_i \vec{e}_i$$

# MAGNETIC BEHAVIOR

## Magnetomechanics

### Magnetostriction

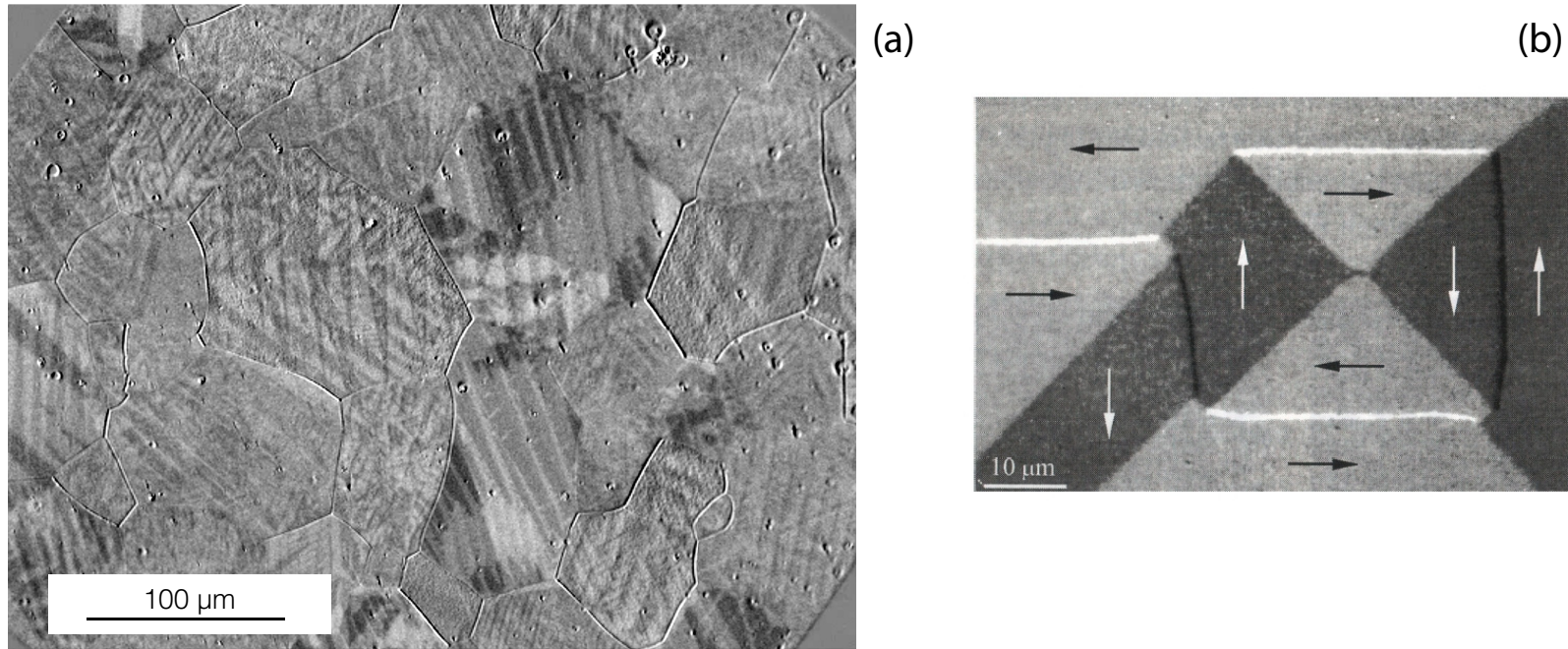


Figure 11: (a) Fe-27%Co sheet [7]; (100)-oriented silicon-iron crystal [8] - Kerr effect

$$\vec{M}_\alpha = M_s \vec{e}_\alpha = M_s \gamma_i \vec{e}_i \quad \epsilon_\alpha^\mu = \frac{3}{2} \begin{pmatrix} \lambda_{100}(\gamma_1^2 - \frac{1}{3}) & \lambda_{111}\gamma_1\gamma_2 & \lambda_{111}\gamma_1\gamma_3 \\ \lambda_{111}\gamma_1\gamma_2 & \lambda_{100}(\gamma_2^2 - \frac{1}{3}) & \lambda_{111}\gamma_2\gamma_3 \\ \lambda_{111}\gamma_1\gamma_3 & \lambda_{111}\gamma_2\gamma_3 & \lambda_{100}(\gamma_3^2 - \frac{1}{3}) \end{pmatrix}$$

# MAGNETIC BEHAVIOR

Magnetomechanics

## Magnetostriction

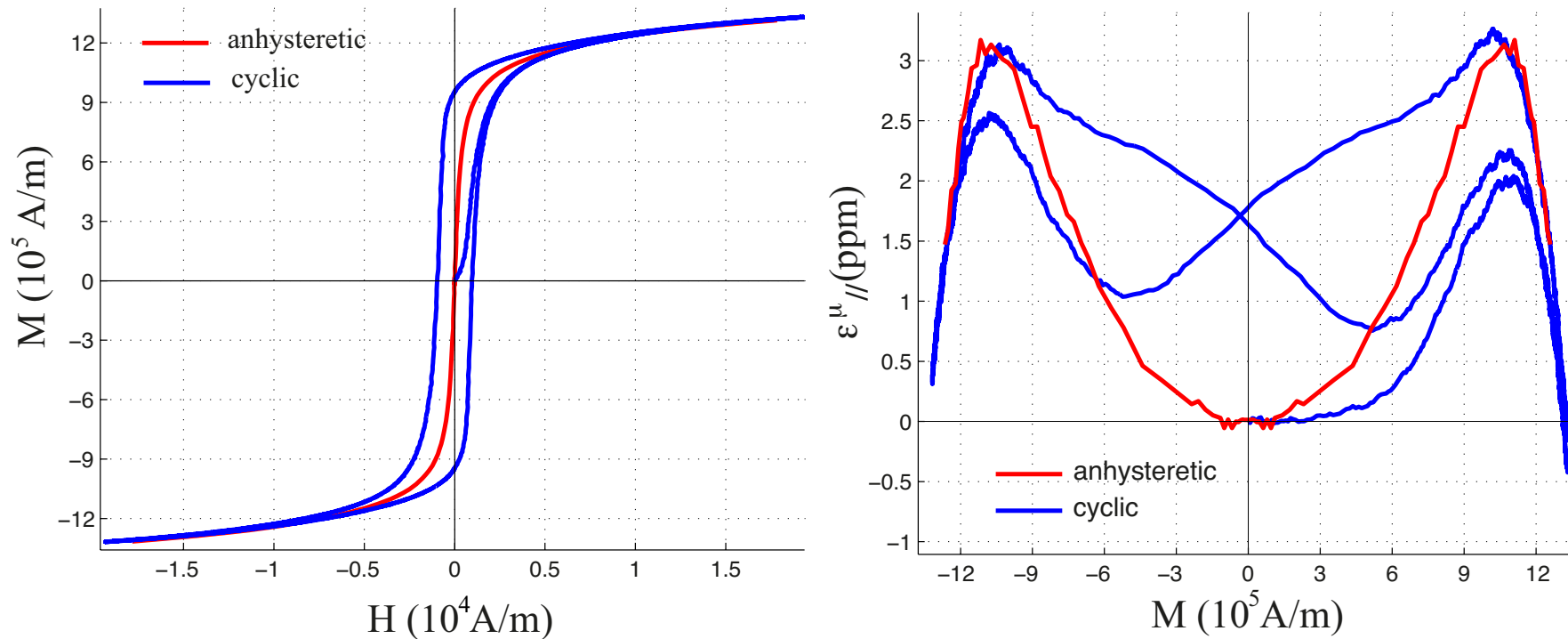


Figure 12: Magnetic vs. magnetostrictive behavior - DP600 steel- [13].

# MAGNETIC BEHAVIOR

Magnetomechanics

## Constant stress, variable magnetic field

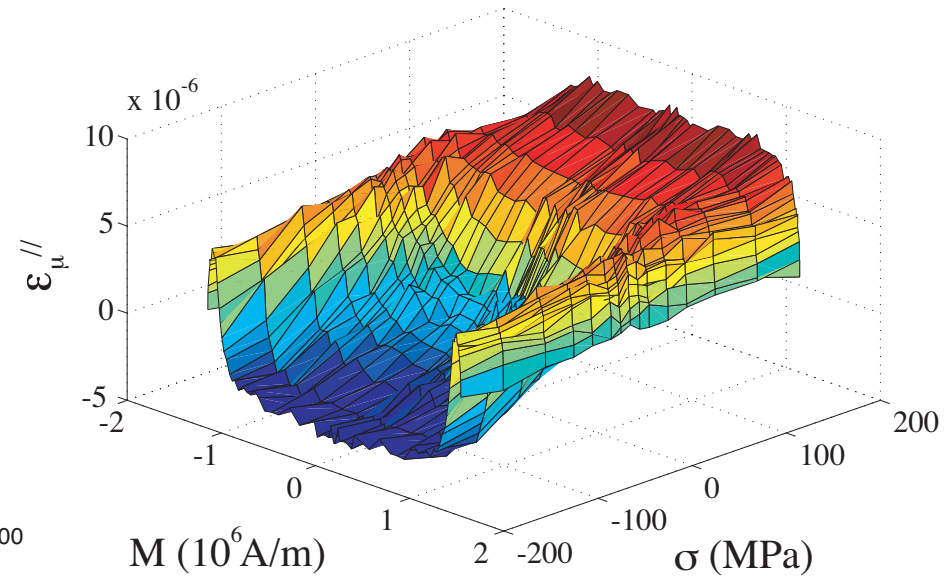
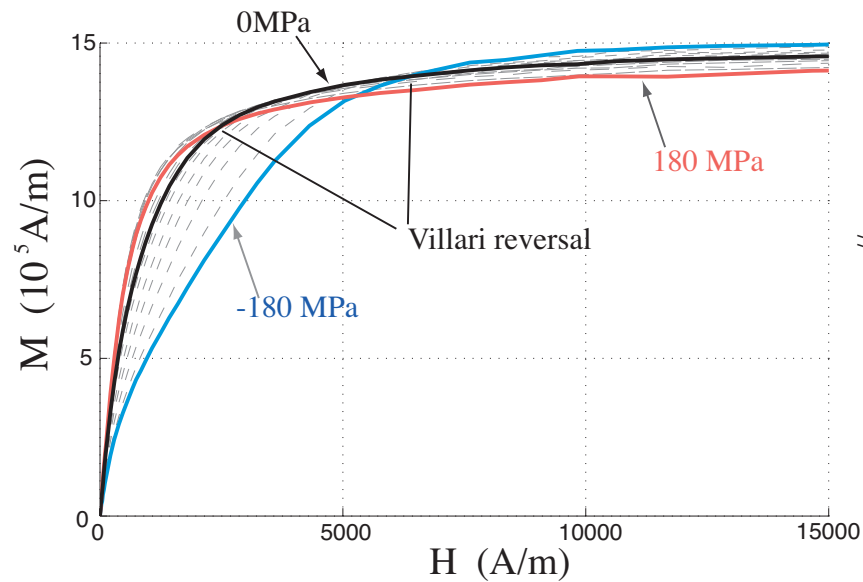


Figure 13: Stress influence on magnetic and magnetostrictive behavior of a low carbon steel [14].

$$\vec{M}(\vec{H}, \sigma)|_{\sigma} \quad \epsilon_{\mu}(\vec{H}, \sigma)|_{\sigma}$$

# MAGNETIC BEHAVIOR

Magnetomechanics

## Constant magnetic field, variable stress

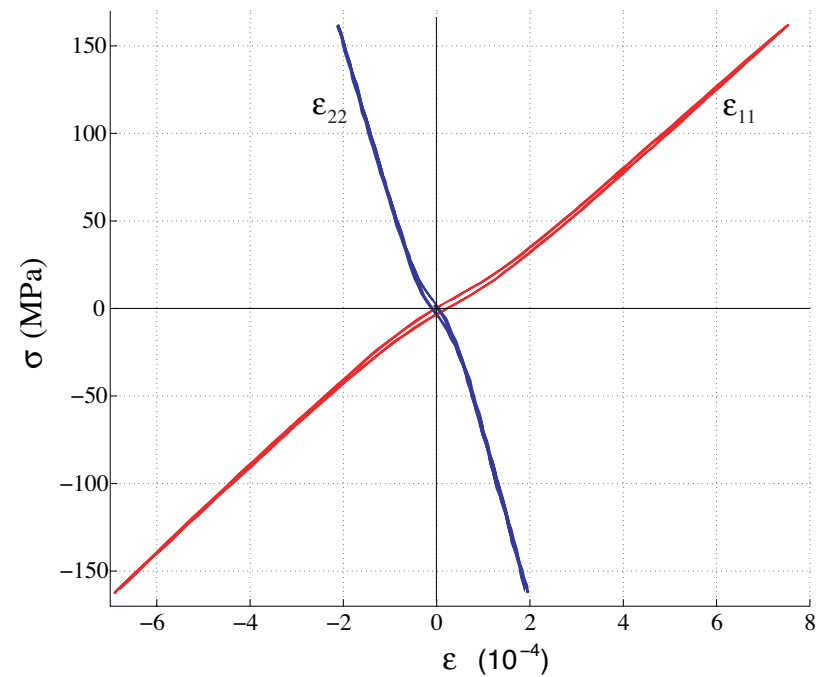
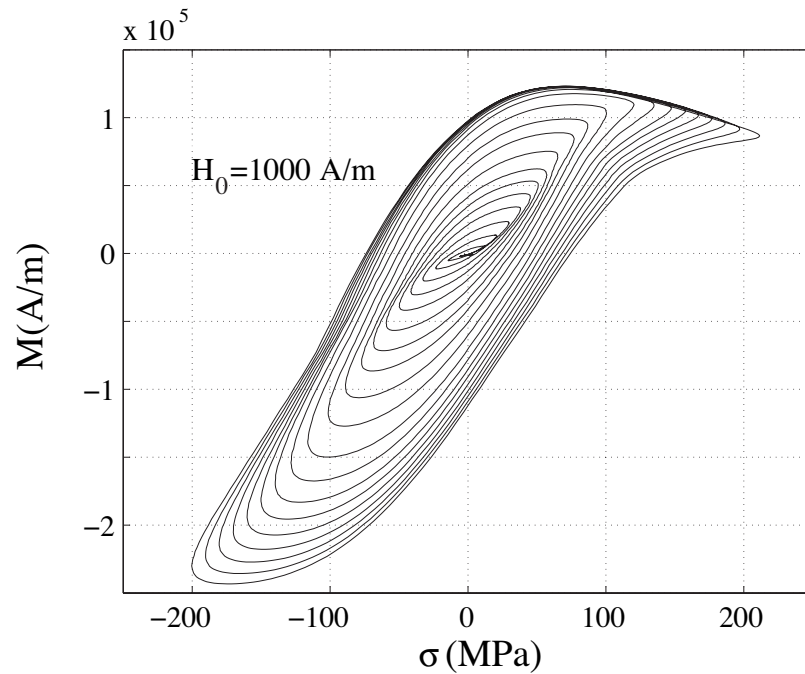


Figure 14: Piezomagnetic behavior and  $\Delta E$  effect - low carbon steel and Fe-Co - [15, 16].

$$\vec{M}(\vec{H}, \sigma) \Big|_{\vec{H}} \quad \epsilon = \epsilon_e(\sigma) + \epsilon_\mu(\vec{H}, \sigma) \Big|_{\vec{H}}$$

# MAGNETIC BEHAVIOR

Magnetomechanics

## Plastic straining

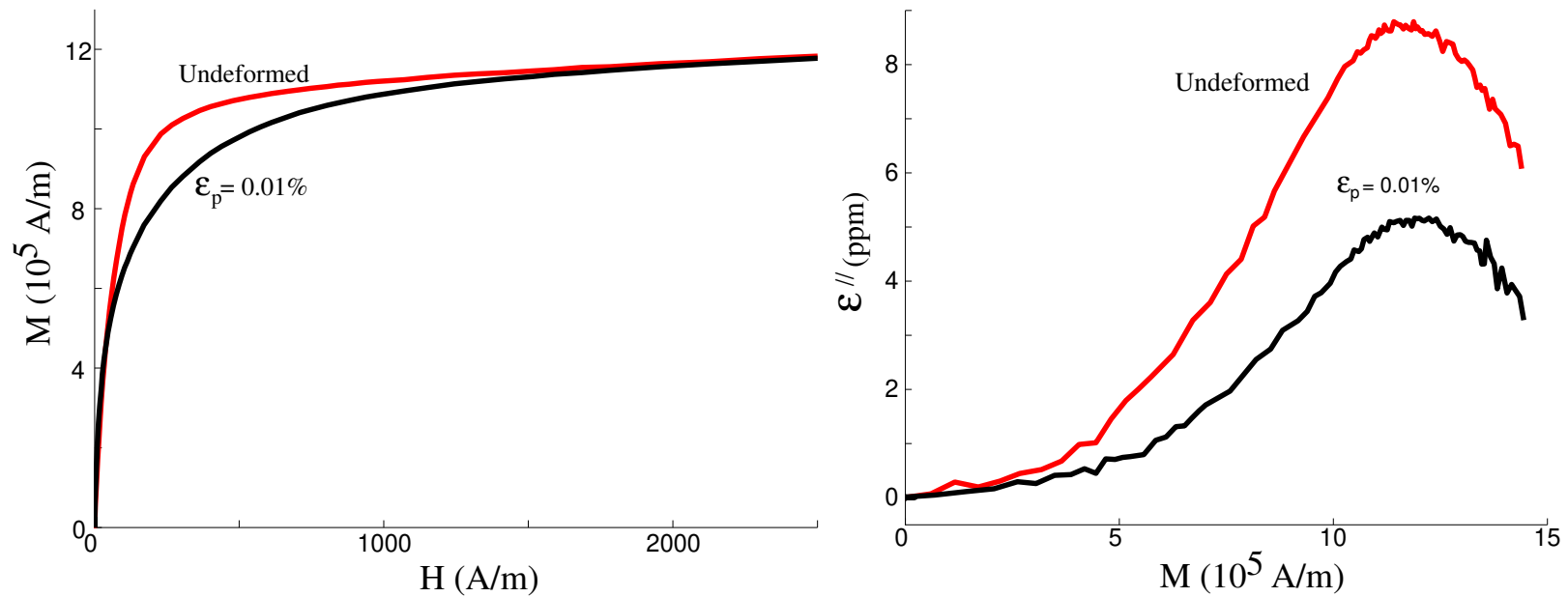


Figure 15: An hysteretic magnetic behavior of NO Fe-3%Si w/wt plastic strain [13]

$$\vec{M}(\vec{H})|_{\epsilon_p} \quad \epsilon_{\mu}(\vec{H})|_{\epsilon_p}$$

# MAGNETIC BEHAVIOR

Magnetomechanics

## Plastic straining

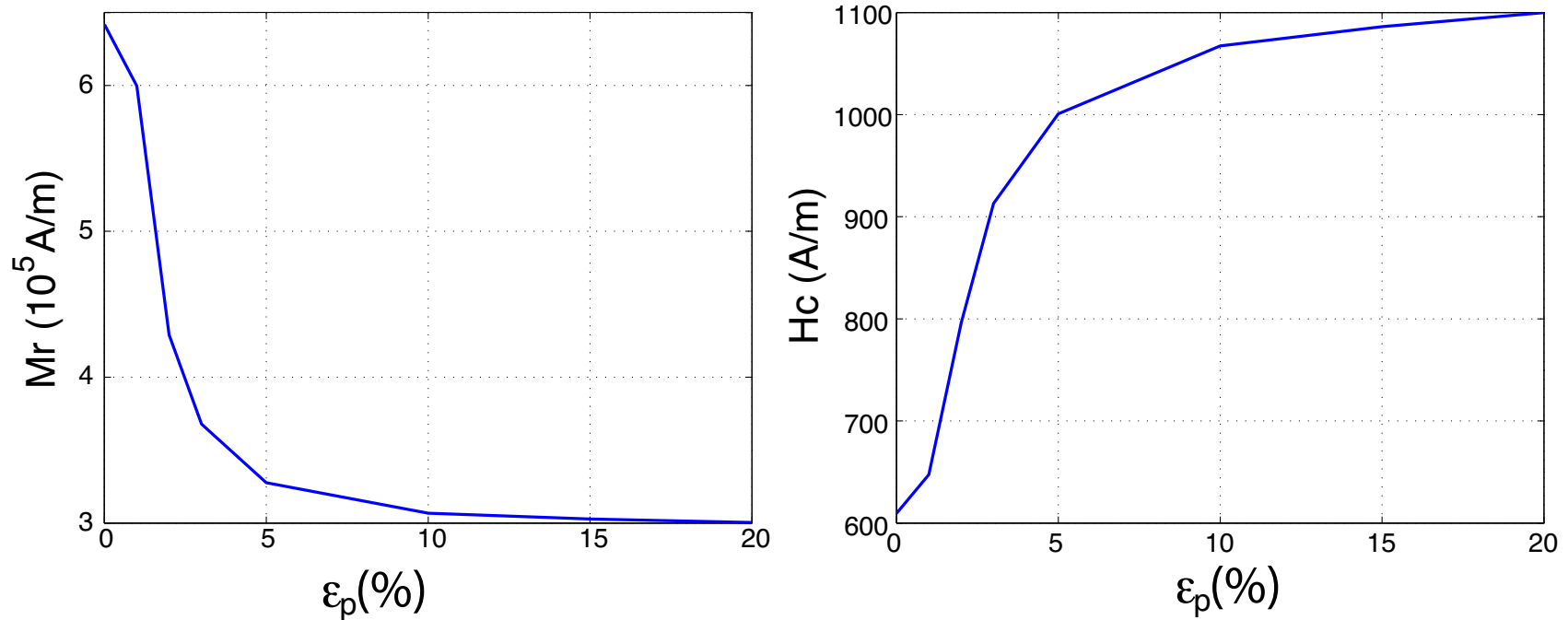


Figure 16: Remanent magnetization and coercive field evolution with large plastic strain - pipeline steel [17]

$$M_r(\epsilon_p)|_{H=0}$$

$$H_c(\epsilon_p)|_{M=0}$$

# MAGNETIC BEHAVIOR

Some specificities of AM materials magnetic behavior

## EM boundary effects - demagnetization

- Porosities
- Cracks
- Surface finish

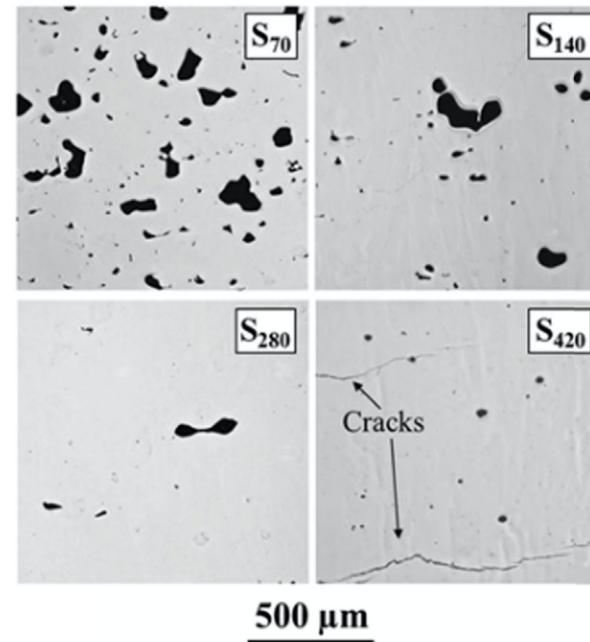
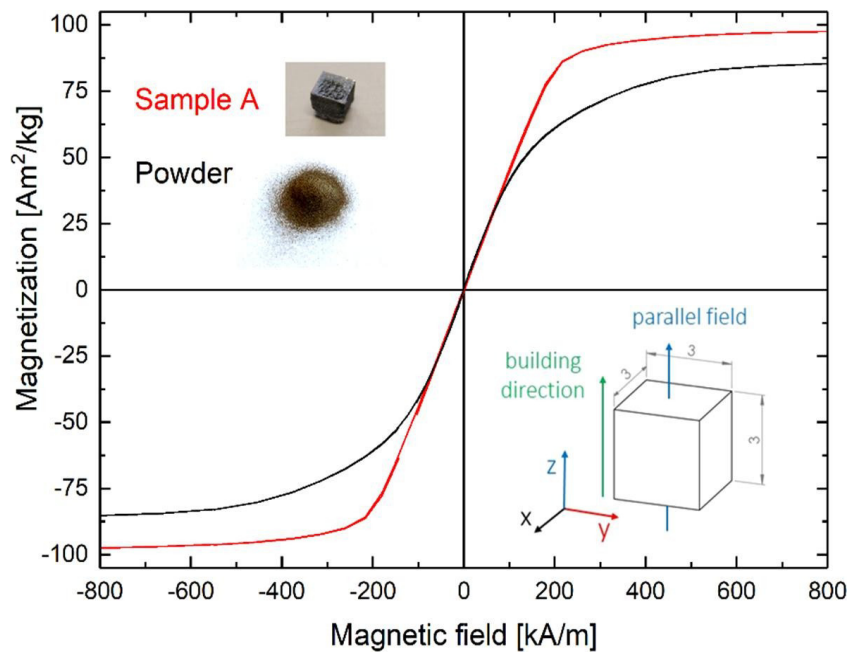


Figure 17: (a) Powder vs. sintered material [18];(b) porosities function of beam energy [2].



# MAGNETIC BEHAVIOR

Some specificities of AM materials magnetic behavior

## Metallurgical (process) issues I

- Chemical heterogeneities / unexpected phases
- Residual stresses, cracks

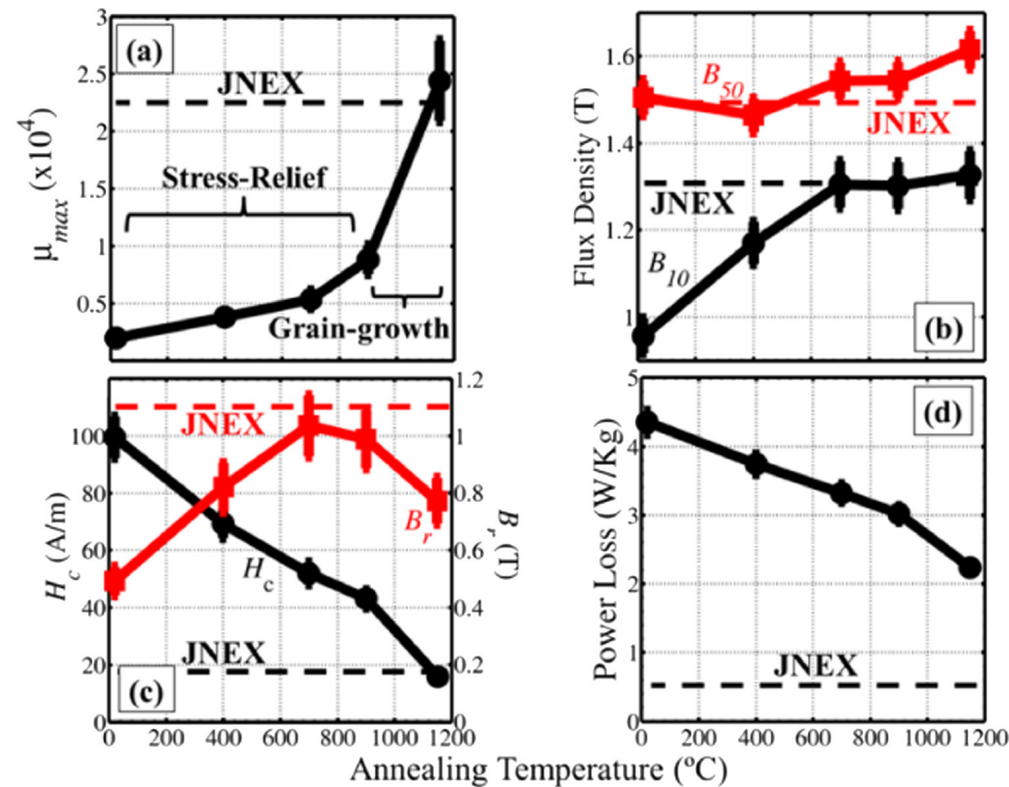


Figure 18: Effect of thermal annealing on properties [2].

# MAGNETIC BEHAVIOR

Some specificities of AM materials magnetic behavior

## Metallurgical (process) issues II

- Crystal texture
- Crystal defects, plasticity

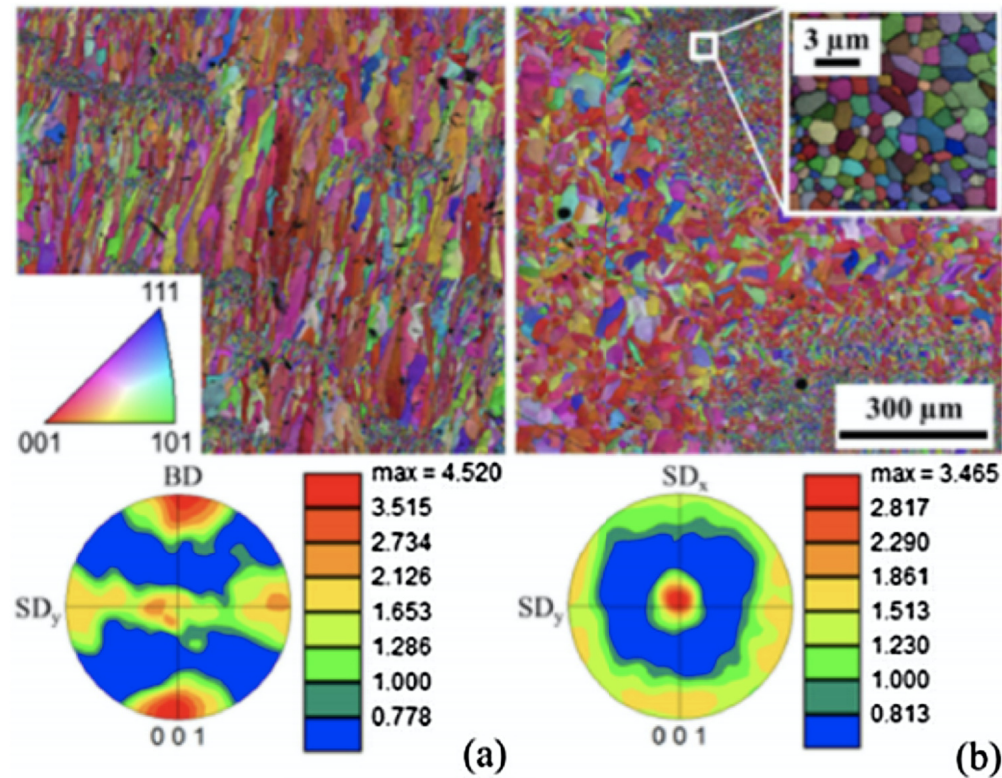


Figure 19: macro and micro texture of FeSi AM parts [1].

# MAGNETIC BEHAVIOR

Some specificities of AM materials magnetic behavior

## Production of high silicon content Fe-Si alloy

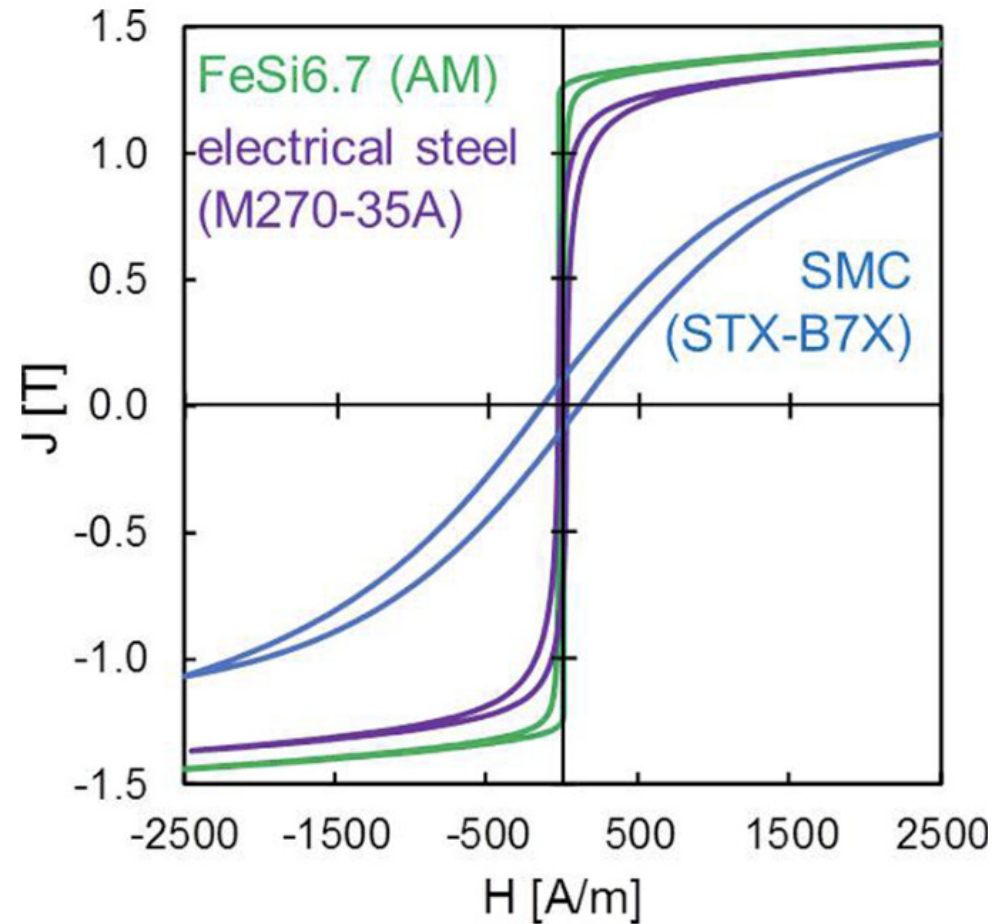


Figure 20: Fe-6,5%Si produced by AM after annealing [19].

# MAGNETIC BEHAVIOR

Some specificities of AM materials magnetic behavior

## Main modeling difficulties

- Crystallographic texture
- Residual stresses (order I and II)
- Micro/macro segregations and unexpected phases

**To be addressed by a multiscale magneto-mechanical modeling**

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- Typical scales
- Gibbs free energy at the magnetic domain family scale
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- Some results

## 4 CONCLUSIONS

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

## Typical scales

- Magnetic domains
- Grains and phases
- RVE

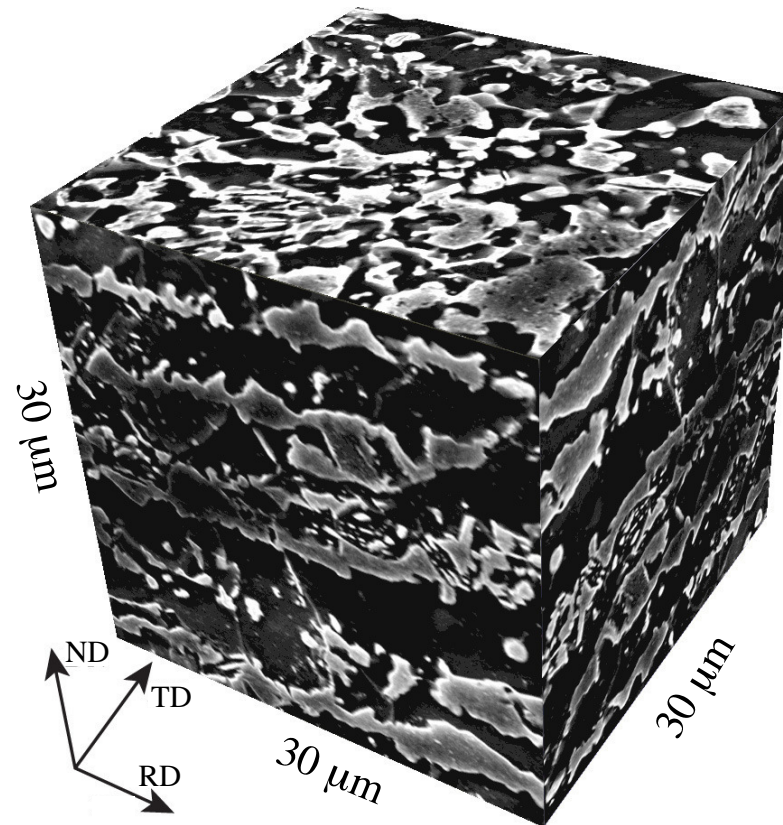


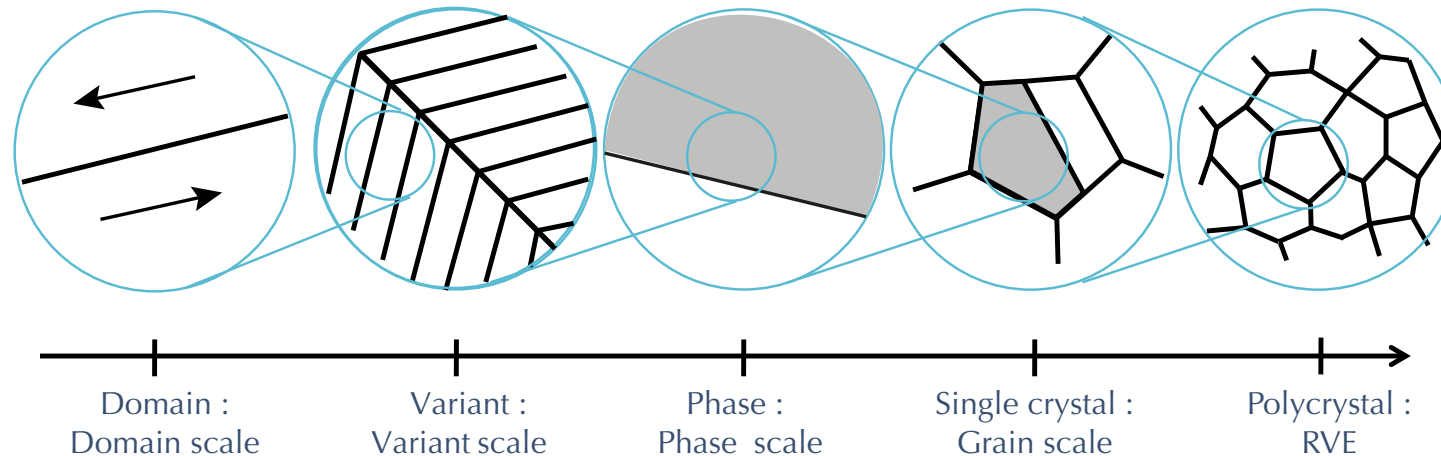
Figure 21: Microstructure of DP600 [20].

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

## Typical scales

### Multiscale modeling: [10, 21, 22]

- Different scales involved depending on the problem



- RVE - representative volume element = polycrystal (ODF)
- $g$ : grain scale
- $\varphi$ : phase family scale
- $\phi$ : variant family scale
- $\alpha$ : magnetic domain family scale

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

- first step: build an energy function at the domain scale where anisotropic crystallographic phenomena are significant and some fields can be simplified.
- second step: energy conservation at the local scale (energy density)
- constant velocity - removal of kinetic energy and associated power density (Body forces, Maxwell forces)
- direct relationship between the variation of internal energy density and power sources:

$$du_{\alpha} = dh_{\alpha} + T_{\alpha} ds_{\alpha} + \sigma_{\alpha} : d\epsilon_{\alpha} + \vec{H}_{\alpha} \cdot d\vec{B}_{\alpha}$$

Control variables: entropy, strain, and magnetic induction



# MODELING OF AM MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

More usual control variables: temperature, stress, and magnetic field

- free Helmholtz energy density

$$\psi_\alpha = u_\alpha - T_\alpha s_\alpha$$

- magnetic free enthalpy

$$k_\alpha = \psi_\alpha - \vec{H}_\alpha \cdot \vec{B}_\alpha$$

- Gibbs free energy (mechanical free enthalpy)

$$g_\alpha = k_\alpha - \sigma_\alpha : \epsilon_\alpha$$

Since chemical bound is constant over a domain inside a phase, this leads to:

$$dg_\alpha = -s_\alpha dT_\alpha - \epsilon_\alpha : d\sigma_\alpha - \vec{B}_\alpha \cdot d\vec{H}_\alpha$$

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

Consequences:

- Entropy density, strain and magnetic induction finally derive from the Gibbs free energy function following

$$s_\alpha = -\frac{\partial g_\alpha}{\partial T_\alpha} \quad \vec{B}_\alpha = -\frac{\partial g_\alpha}{\partial \vec{H}} \quad \epsilon_\alpha = -\frac{\partial g_\alpha}{\partial \sigma_\alpha}$$

- Definition of Gibbs free chemical, mechanical and magnetic energy densities separately

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

- Gibbs free chemical energy:

$$g_{\alpha}^T(T_{\alpha}) = h_{\alpha} - T_{\alpha}s_{\alpha} = h_{\alpha} - T_{\alpha}s_{\alpha}^0 + \rho_{\alpha}c_{\alpha}^p(T_{\alpha} - T_{\alpha}^0 + T_{\alpha}\ln(\frac{T_{\alpha}^0}{T_{\alpha}}))$$

- Gibbs free mechanical energy

$$dg^{\sigma}(\sigma_{\alpha}) = -\epsilon_{\alpha} : d\sigma_{\alpha}$$

Two sources of deformation: elastic + inelastic of *multiphysic* origin (thermal expansion, magnetostriction, phase transformation...) - small perturbations hypothesis

$$\epsilon = \epsilon_{\alpha}^e + \epsilon_{\alpha}^l$$

$$g_{\alpha}^{\sigma}(\sigma_{\alpha}) = -\frac{1}{2}\sigma_{\alpha} : \mathbb{C}_{\alpha}^{-1} : \sigma_{\alpha} - \int_{\mathbb{0}}^{\sigma_{\alpha}} \epsilon_{\alpha}^l : d\sigma$$

→ Integration CANNOT be simplified without assumptions on inelastic strain / stress relationship

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

- Gibbs free magnetic energy

Usual simplification by physicians: magnetization  $\vec{M}$  instead of magnetic induction  $\vec{B}$  since  $\vec{M} = \vec{0}$  in vacuum

$$\vec{B} = \mu_0(\vec{H} + \vec{M})$$

$$\vec{H}_\alpha = -\frac{\partial g_\alpha}{\partial \vec{B}_\alpha} = -\frac{\partial g_\alpha}{\mu_0 \partial \vec{M}_\alpha}$$

$$g_\alpha^H(\vec{H}_\alpha) = \psi_\alpha(\vec{M}_\alpha) - \mu_0 \vec{H}_\alpha \cdot \vec{M}_\alpha$$

→ Expression of Helmholtz magnetic energy  $\psi_\alpha$  CANNOT be simplified without assumptions on magnetization homogeneity

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

Taylor expansion of the Helmholtz magnetic energy  $\psi_\alpha$  that must be an even function of magnetization (magnetic behavior odd function)

$$\psi_\alpha(\vec{M}_\alpha) = \vec{M}_\alpha \cdot \mathbf{P}_\alpha \cdot \vec{M}_\alpha + \vec{M}_\alpha \otimes \vec{M}_\alpha : \mathbb{P}'_\alpha : \vec{M}_\alpha \otimes \vec{M}_\alpha + \vec{M}_\alpha \otimes \vec{M}_\alpha \otimes \vec{M}_\alpha : \mathbb{P}''_\alpha : \vec{M}_\alpha \otimes \vec{M}_\alpha \otimes \vec{M}_\alpha$$

- Magneto-elastic coupling ?

→ Taylor expansion as well - of 1st order in stress (keeping stiffness independent of stress)

$$\psi_\alpha^{\sigma H}(\vec{M}_\alpha, \boldsymbol{\sigma}_\alpha) = -\vec{M}_\alpha \cdot \mathbb{E}_\alpha : \boldsymbol{\sigma}_\alpha \cdot \vec{M}_\alpha$$

$\mathbb{E}_\alpha$  4th order magnetostriction tensor

$$\vec{M}_\alpha \mathbb{E}_\alpha \cdot \vec{M}_\alpha = \vec{M}_\alpha \otimes \vec{M}_\alpha : \mathbb{E}_\alpha = \boldsymbol{\epsilon}_\alpha^\mu$$

homogeneous to a deformation → MAGNETOSTRICTION tensor

→ **Scale choice allows different expressions of magnetostriction tensor**

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

At scale  $\alpha$  of cubic symmetry:

- constant magnetization norm: *saturation* magnetization

- $\vec{M} = M_s \gamma_i \vec{e}_i$

- $\vec{M} \otimes \vec{M} = M_s^2 \begin{pmatrix} \gamma_1^2 & \gamma_1 \gamma_2 & \gamma_1 \gamma_3 \\ \gamma_1 \gamma_2 & \gamma_2^2 & \gamma_2 \gamma_3 \\ \gamma_1 \gamma_3 & \gamma_2 \gamma_3 & \gamma_3^2 \end{pmatrix}$

- simplification of local magnetostriction tensor using 3 constants (cubic symmetry) minus 1 (incompressibility)

$$\epsilon_{\alpha}^{\mu} = \frac{3}{2} \begin{pmatrix} \lambda_{100}(\gamma_1^2 - \frac{1}{3}) & \lambda_{111}\gamma_1\gamma_2 & \lambda_{111}\gamma_1\gamma_3 \\ \lambda_{111}\gamma_1\gamma_2 & \lambda_{100}(\gamma_2^2 - \frac{1}{3}) & \lambda_{111}\gamma_2\gamma_3 \\ \lambda_{111}\gamma_1\gamma_3 & \lambda_{111}\gamma_2\gamma_3 & \lambda_{100}(\gamma_3^2 - \frac{1}{3}) \end{pmatrix}$$

$\lambda_{100}$  et  $\lambda_{111}$ : deformation measurement along 2 crystalline axes

- simplification of local Helmholtz energy (cubic symmetry)

$$\psi_{\alpha} = K_0 + K_1(\gamma_1^2\gamma_2^2 + \gamma_2^2\gamma_3^2 + \gamma_3^2\gamma_1^2) + K_2(\gamma_1^2\gamma_2^2\gamma_3^2)$$

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

- + free deformation associated with phase transformation: defined at the variant or phase scale

$$\epsilon_{\alpha}^{tr} = \begin{pmatrix} \epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{12} & \epsilon_{22} & \epsilon_{23} \\ \epsilon_{13} & \epsilon_{23} & \epsilon_{33} \end{pmatrix}$$

- total inelastic deformation

$$\epsilon_{\alpha}^I = \epsilon_{\alpha}^{\mu} + \epsilon_{\alpha}^{tr}$$

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Gibbs free energy at the magnetic domain family scale

At scale  $\alpha$  of cubic symmetry  $\rightarrow$

- Gibbs free energy final expression

$$g(T_\alpha, \vec{H}_\alpha, \boldsymbol{\sigma}_\alpha) = h_\alpha - T_\alpha s_\alpha^0 + \rho_\alpha c_\alpha^p (T_\alpha - T_\alpha^0 + T_\alpha \ln(\frac{T_\alpha^0}{T_\alpha})) + K_1(\gamma_1^2 \gamma_2^2 + \gamma_2^2 \gamma_3^2 + \gamma_3^2 \gamma_1^2) + K_2(\gamma_1^2 \gamma_2^2 \gamma_3^2) - \mu_0 M_s \vec{H}_\alpha \cdot \vec{\gamma}_\alpha - \frac{1}{2} \boldsymbol{\sigma}_\alpha : \mathbb{C}^{-1} : \boldsymbol{\sigma}_\alpha - \boldsymbol{\sigma}_\alpha : \boldsymbol{\epsilon}_\alpha^I$$

- Localization procedures: loading  $L(T, \boldsymbol{\sigma}, \vec{H})$

$$L \rightarrow L_g \rightarrow L_\varphi \rightarrow L_\phi \rightarrow L_\alpha$$

Including self-consistent homogenization schemes



# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Stochastic modeling, localization, homogenization

## Stochastic modeling, localization

- state parameters:
  - volume fraction of domains, inside a variant, inside a phase, inside a grain.
  - magnetization orientation of a domain family
- constitutive equation: Boltzmann function (at equilibrium solution of stochastic problem)

$$f_{\alpha} = \frac{\sum_{\phi} \sum_{\alpha} \exp(-A.g_{\alpha})}{\sum_{\varphi} \sum_{\phi} \sum_{\alpha} \exp(-A.g_{\alpha})} \frac{\sum_{\alpha} \exp(-B.g_{\alpha})}{\sum_{\phi} \sum_{\alpha} \exp(-B.g_{\alpha})} \frac{\exp(-C.g_{\alpha})}{\sum_{\alpha} \exp(-C.g_{\alpha})}$$

- Local Gibbs free energy minimization to get the magnetization orientation

$$\vec{\gamma}_{\alpha} = \min(g_{\alpha}(\vec{\gamma}, T_{\alpha}, \vec{H}_{\alpha}, \sigma_{\alpha}))$$

- variant fraction

$$f_{\phi} = \frac{\sum_{\alpha} \exp(-A.g_{\alpha})}{\sum_{\phi} \sum_{\alpha} \exp(-A.g_{\alpha})} \frac{\sum_{\alpha} \exp(-B.g_{\alpha})}{\sum_{\phi} \sum_{\alpha} \exp(-B.g_{\alpha})}$$

- phase fraction

$$f_{\varphi} = \frac{\sum_{\phi} \sum_{\alpha} \exp(-A.g_{\alpha})}{\sum_{\varphi} \sum_{\phi} \sum_{\alpha} \exp(-A.g_{\alpha})}$$

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Stochastic modeling, localization, homogenization

## Identification, homogenization

- Physical parameters and ODF
- Identification ( $A, B, C$ )
  - anhysteretic initial susceptibility
  - DSC
  - anhysteretic mechanical loading
- Boundary effects
  - demagnetization field (surface effect)
  - initial configuration (inherited from forming process)
- Averaging operations

$$\vec{M} = \sum_{\varphi} f_{\varphi} \vec{M}_{\varphi} = \sum_{\varphi} f_{\varphi} \sum_{\phi} f_{\phi} \vec{M}_{\phi} = \sum_{\varphi} f_{\varphi} \sum_{\phi} f_{\phi} \sum_{\alpha} f_{\alpha} \vec{M}_{\alpha}$$

$$s = \sum_{\varphi} f_{\varphi} s_{\varphi} = \sum_{\varphi} f_{\varphi} \sum_{\phi} f_{\phi} s_{\phi} = \sum_{\varphi} f_{\varphi} \sum_{\phi} f_{\phi} \sum_{\alpha} f_{\alpha} s_{\alpha}$$

$$\epsilon = \sum_{\varphi} f_{\varphi} \epsilon_{\varphi} = \sum_{\varphi} f_{\varphi} \sum_{\phi} f_{\phi} \epsilon_{\phi} = \sum_{\varphi} f_{\varphi} \sum_{\phi} f_{\phi} \sum_{\alpha} f_{\alpha} \epsilon_{\alpha}$$

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Some results

## • Anisotropy

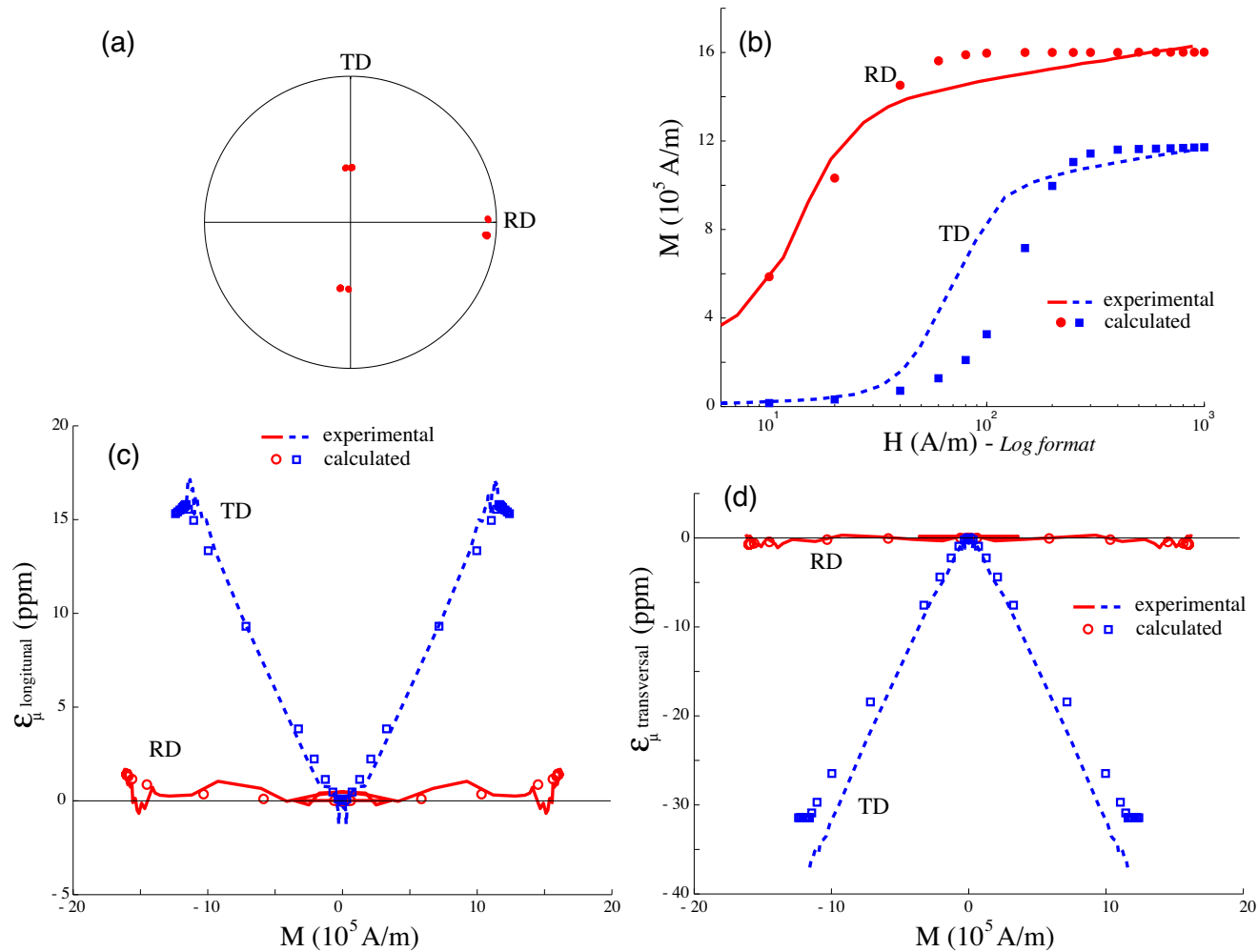


Figure 22: Experiment vs. modeling - GO SiFe alloy [22].

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Some results

- Constant stress, variable magnetic field

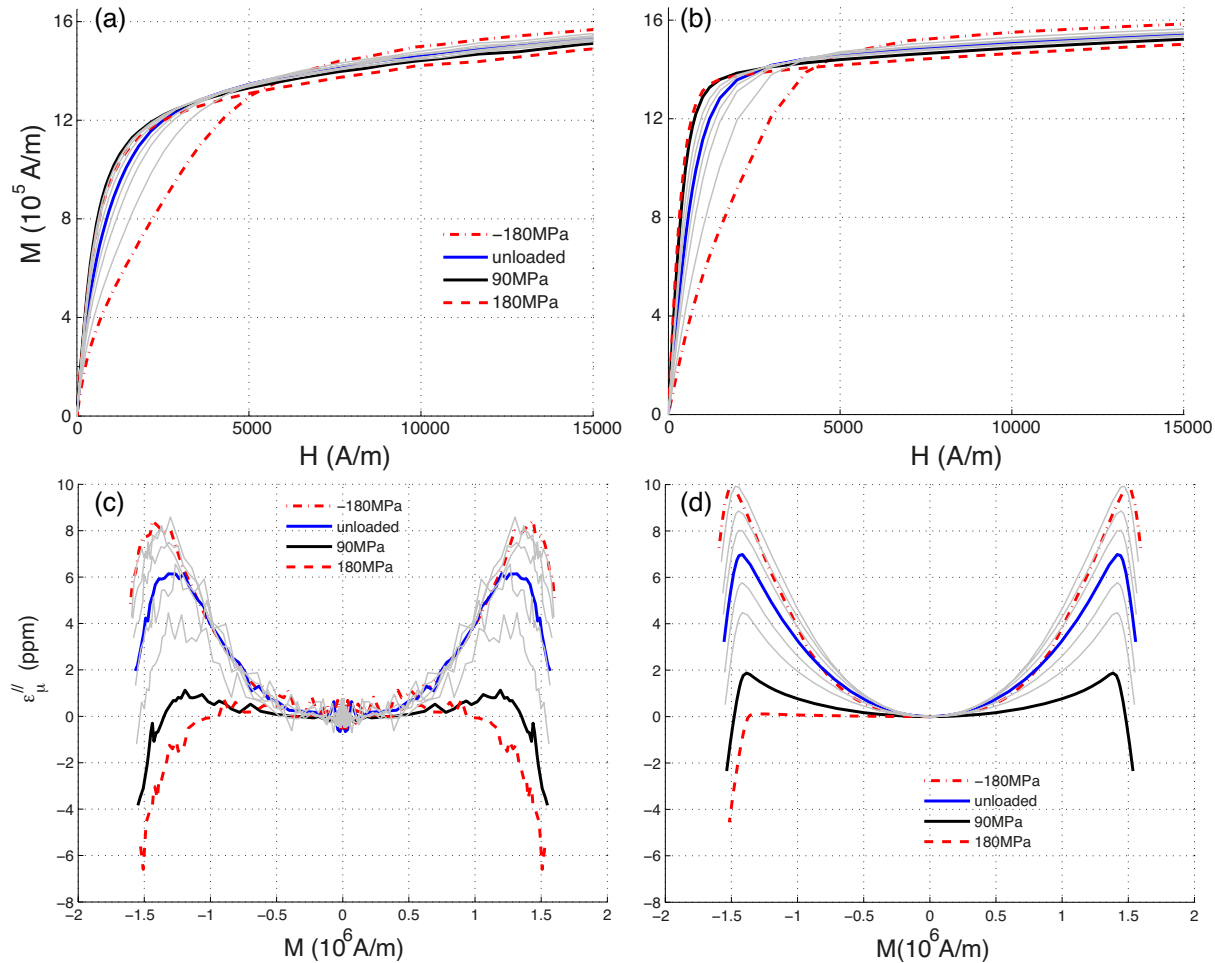


Figure 23: Experiment vs. modeling - LC steel at constant stress [22].

# MODELING OF AM MATERIALS MAGNETIC BEHAVIOR

Some results

- Constant magnetic field, variable stress

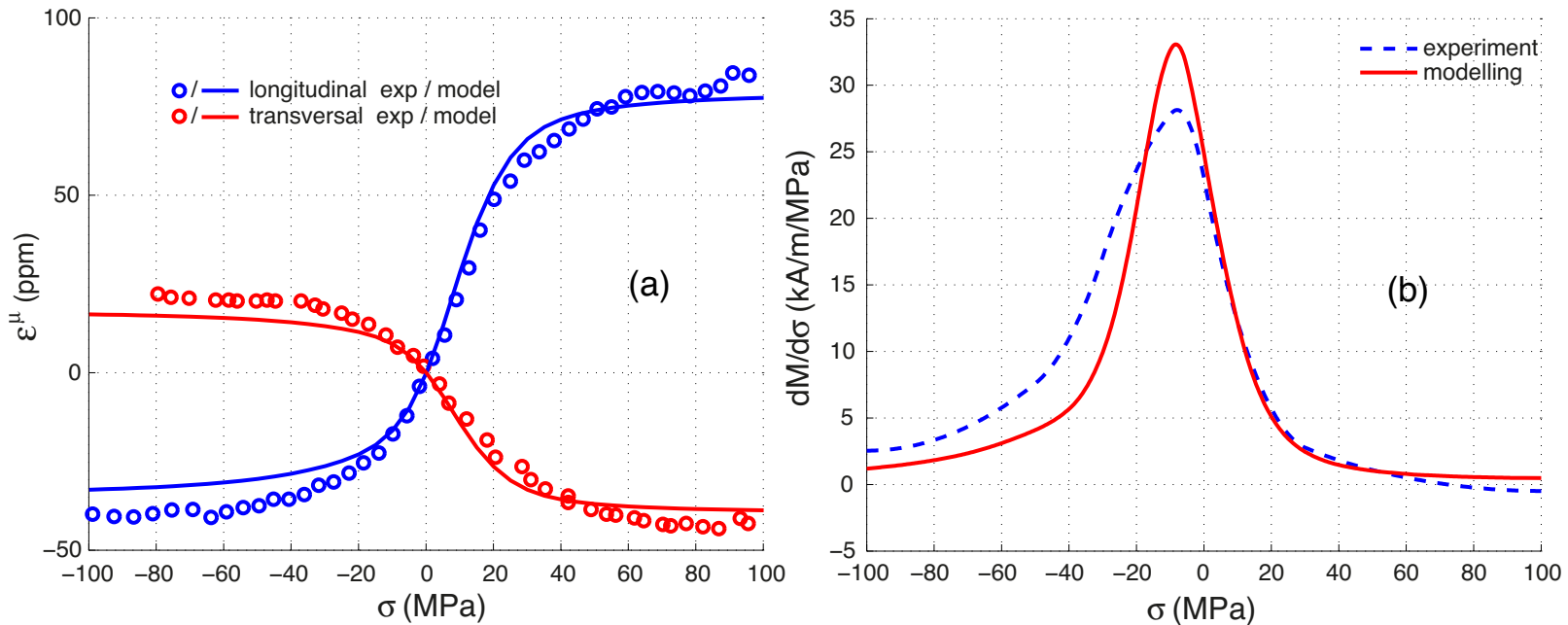


Figure 24: Experiment vs. modeling - FeCo at constant magnetic field [22].

# Outline

- 1 INTRODUCTION
  - Definitions and scope
  - Additive manufacturing of soft/medium magnetic materials
  
- 2 MAGNETIC BEHAVIOR
  - Definitions and basic properties
  - Magnetomechanics
  - Some specificities of AM materials magnetic behavior
  
- 3 MODELING OF AM MATERIALS MAGNETIC BEHAVIOR
  - Typical scales
  - Gibbs free energy at the magnetic domain family scale
  - Stochastic modeling, localization, homogenization
  - Some results
  
- 4 CONCLUSIONS

# CONCLUSIONS

- Multiscale coercive field description (Hauser's model [24])
- Micromagnetics for smart AM magnetic structures [25]
- NDE of AM structure by magnetic/mechanical inspection [24]

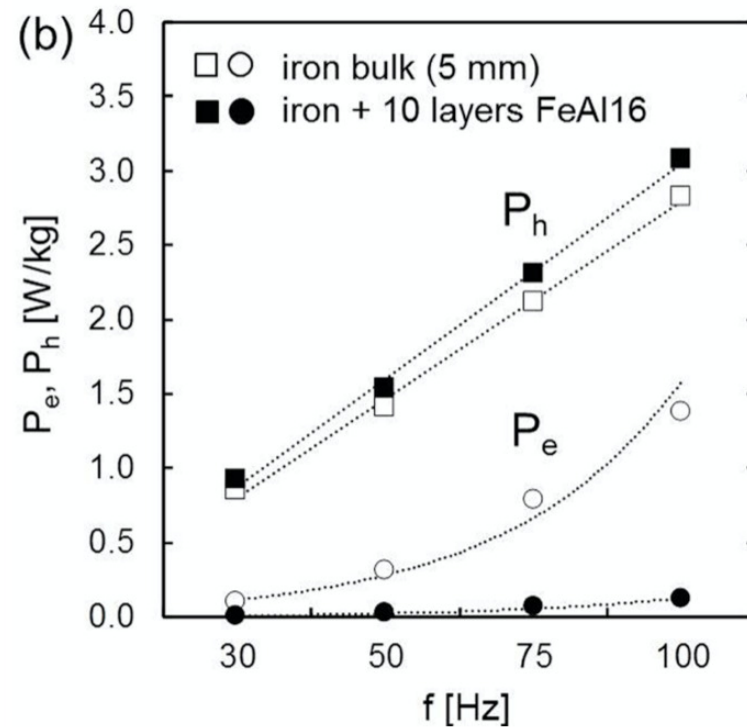
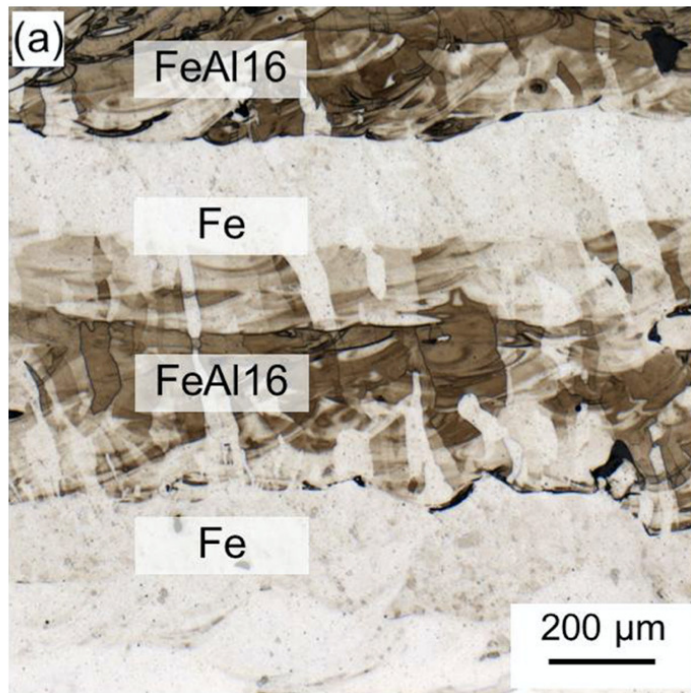


Figure 25: AM multilayer with variable resistivity - Eddy currents reduction [23].

## CONCLUSIONS

- Multiscale coercive field description (Hauser's model [24])
- Micromagnetics for smart AM magnetic structures [25]
- NDE of AM structure by magnetic/mechanical inspection [24]

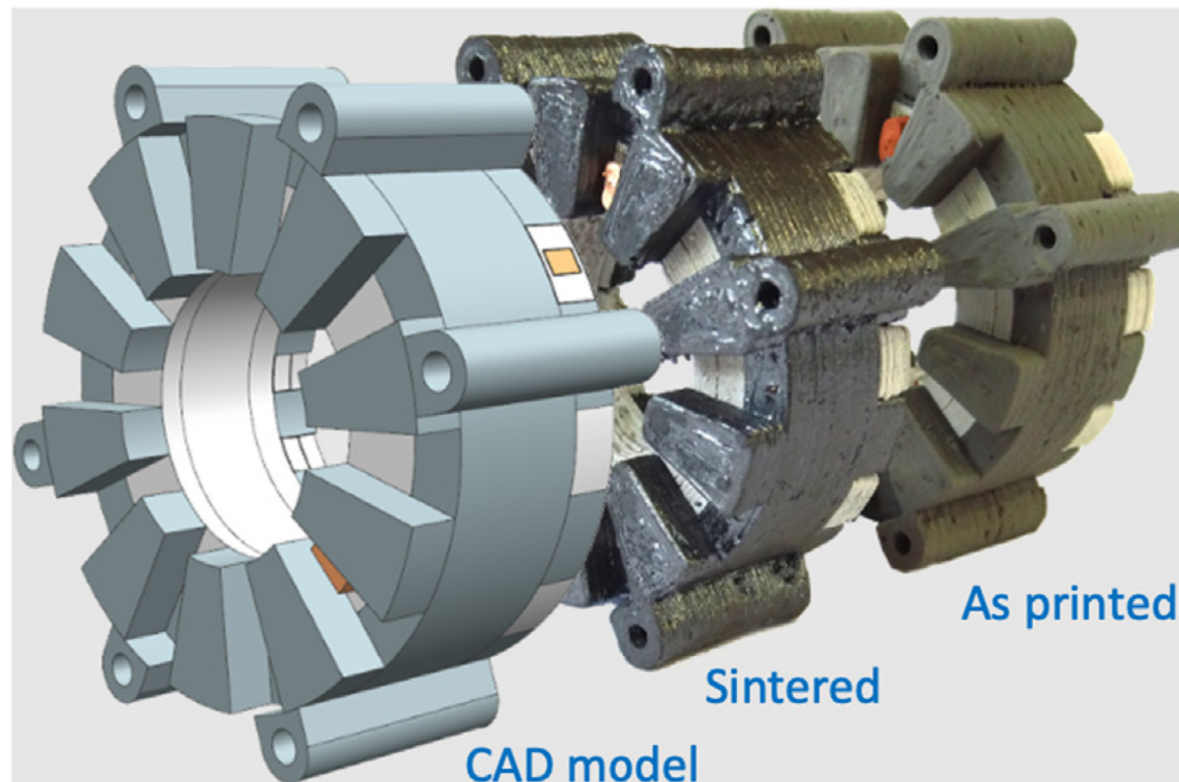


Figure 26: AM multilayer of rotor shaft [2].





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