

-----

-----  
-----

# Establishing process-structure-properties relationships of soft ferromagnetic alloys produced by advanced manufacturing techniques

Andrew Kustas

Materials, Physical, and Chemical Sciences Departments, Sandia National Laboratories, Albuquerque, NM, 87123

Oak Ridge National Laboratory Seminar

10-20-17



# Acknowledgements

## Purdue University (Shear-processing of Fe-Si):

**Advisors:** Prof. Kevin Trumble and Prof. Srinivasan Chandrasekar, Center for Materials Processing and Tribology

**Colleagues/Mentors:** Prof. David Johnson, Prof. Matthew Krane, Dr. Kevin Chaput, Prof. Dinakar Sagapuram, Dr. Mert Efe, Dr. Alex Plotkowski, Dr. Kyle Fezi, Dr. Mitchell Wood, Dr. Logan Kearney, Mr. Travis Thornell

Grants: NSF-CMMI-1100712 and 1363524, NSF-IIP-1237866, Bilstrand Dissertation Fellowship, and U.S. Army Research Office Award W911NF-15-1-0591

## SNL (AM of ferromagnetic alloys):

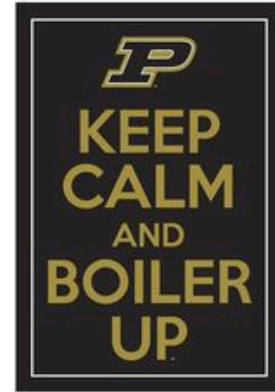
Laboratory Directed Research and Development (LDRD) Program:

1. Exploratory Express LDRD provided start-up funding
2. Born Qualified AM Grand Challenge LDRD

**Postdoc Mentor:** Dr. Nicolas Argibay

**Manager:** Dr. Anton Sumali

**Colleagues/Mentors:** Dr. Donald Susan, Dr. Kyle Johnson, Mr. Shaun Whetten, Mr. Dave Keicher, Dr. Mark Rodriguez, Dr. Daryl Dagel, Dr. Joseph Michael, Dr. R. Allen Roach (PI of BQ), Bonnie McKenzie, and Alice Kilgo.



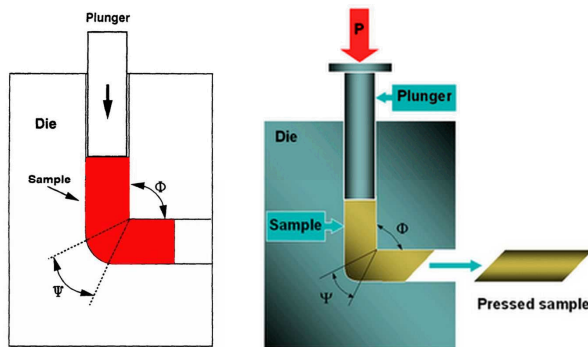
Search ID: pha0045

"To be honest, I would have never invented the wheel if not for Urg's ground breaking theoretical work with the circle."

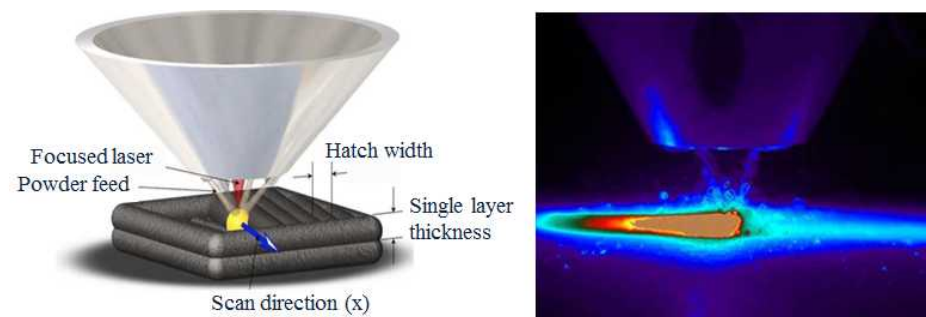
# What is advanced manufacturing?

*The utilization of new, innovative technologies or techniques that improve the production and performance of products.*

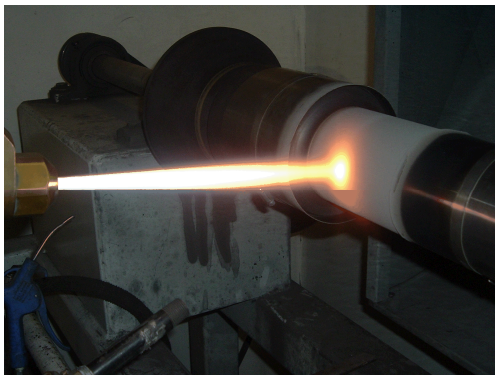
## Deformation-based



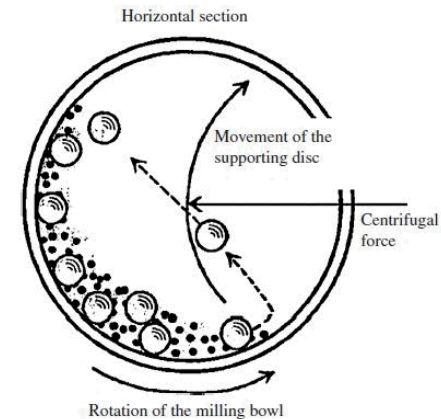
## Solidification-based



## Coatings-based



## Powder-based

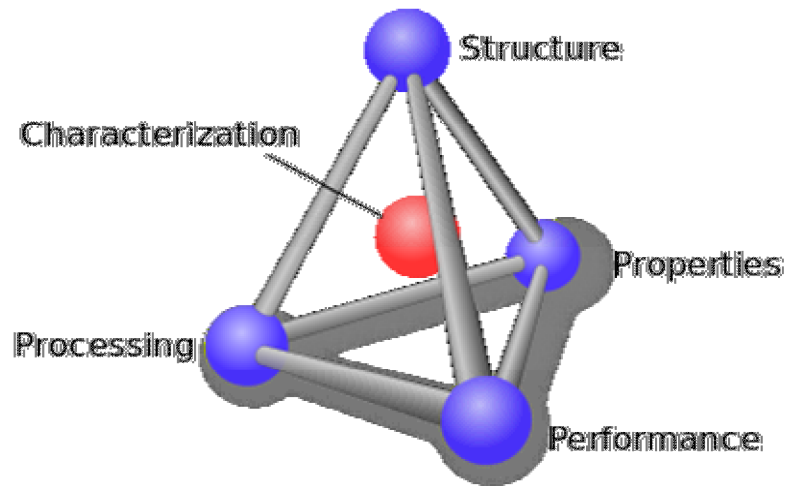


# Outline

## Processing-microstructure-properties relationships:

1. Shear-based deformation processing of Fe-Si (electrical steel) sheet *via* large strain extrusion machining (LSEM)
2. Laser Engineered Net Shaping (LENS<sup>TM</sup>) of Fe-Co-1.5V (Hiperc<sup>o</sup><sup>®</sup>-like composition)

Hiperc<sup>o</sup><sup>®</sup> is a tradename of Carpenter Technology Corp., Reading, PA.



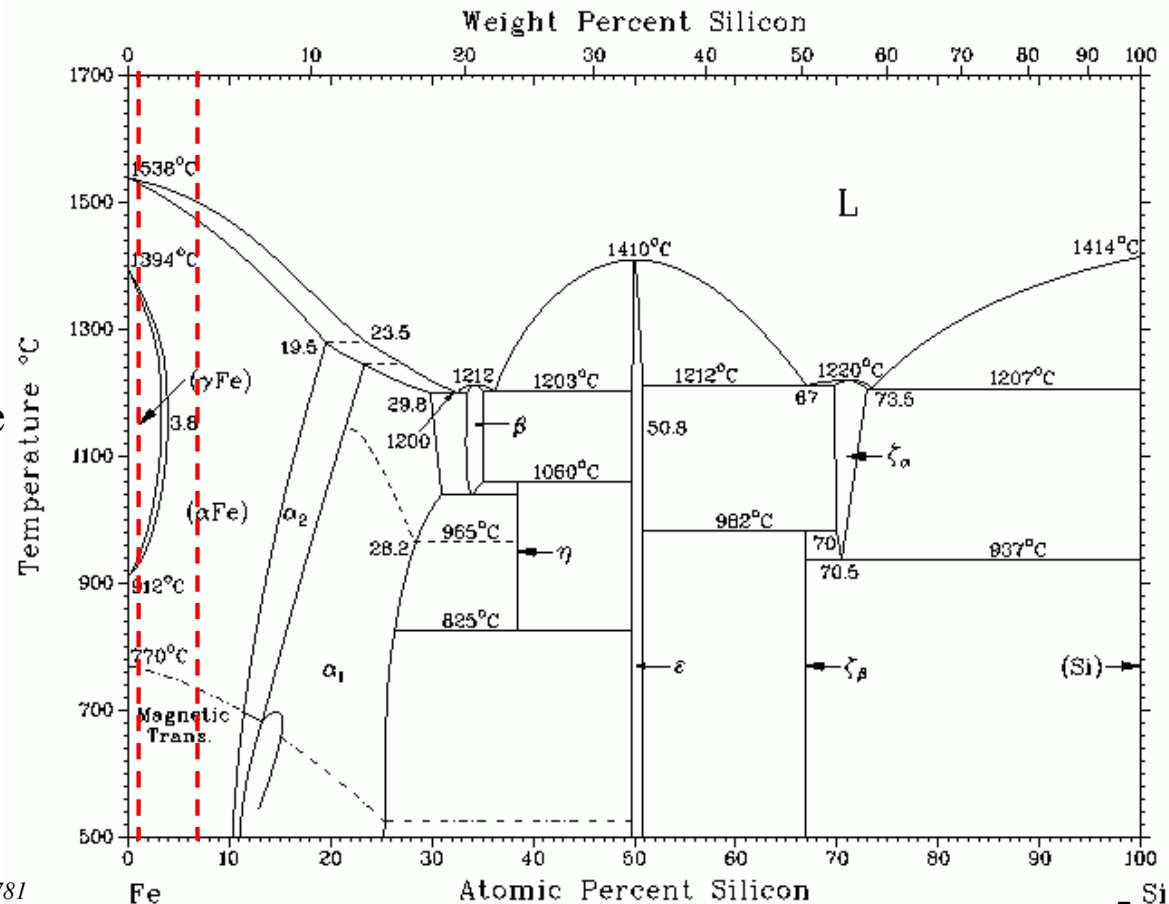
# Electrical Steel (Fe-Si) Metallurgy

Silicon containing  $\alpha$  (BCC) iron alloy (0.5 – 3.5 wt%Si – commercial range)

- Traditionally unworkable with increasing Si content (> 3.5 wt%Si)
- Optimum magnetic properties at 6.5 wt%Si – workability issues (atomic ordering)

With added silicon;

- Stabilize  $\alpha$  phase
- Increase electrical resistivity (reduce Eddy current losses)
- Increase magnetic softness (decrease coercivity)
- Low carbon content to minimize  $\gamma+\alpha$  region



# Rolled Electrical Steel Sheet

Tw

Ing

1)

2)

3)

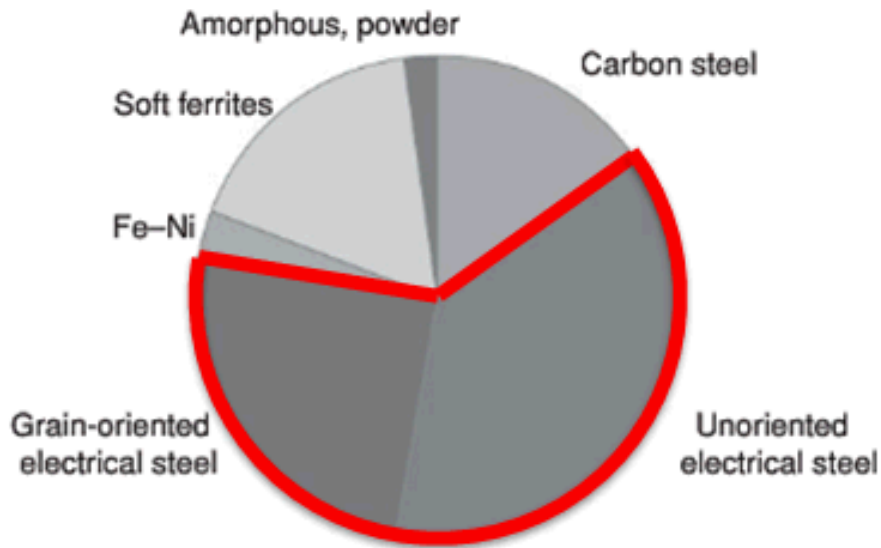
Isot

tran



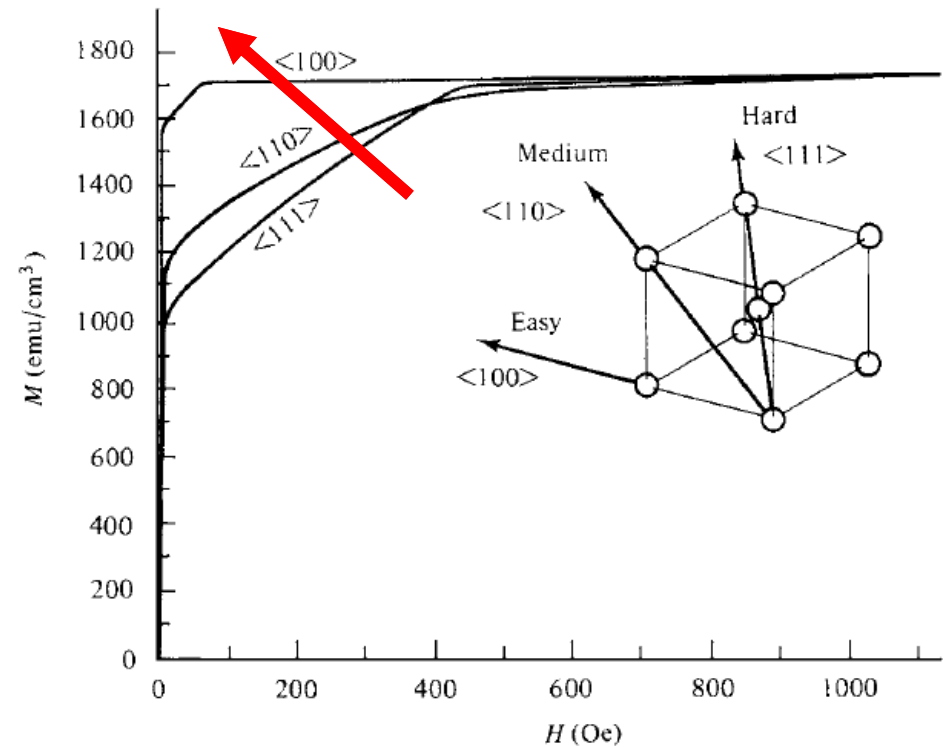
# Why Electrical Steel?

Magnetically soft iron alloys –  
global breakdown



\$10 billion/year, ~ 60% from  
Electrical Steel (Fe-Si alloys)

## Crystal Magnetic Anisotropy



*Magnetism and Magnetic Materials, J. M. D. Coey, 2009*  
*Introduction to Magnetic Materials, B.D. Cullity, C.D. Graham*

# Commercial processing limitations

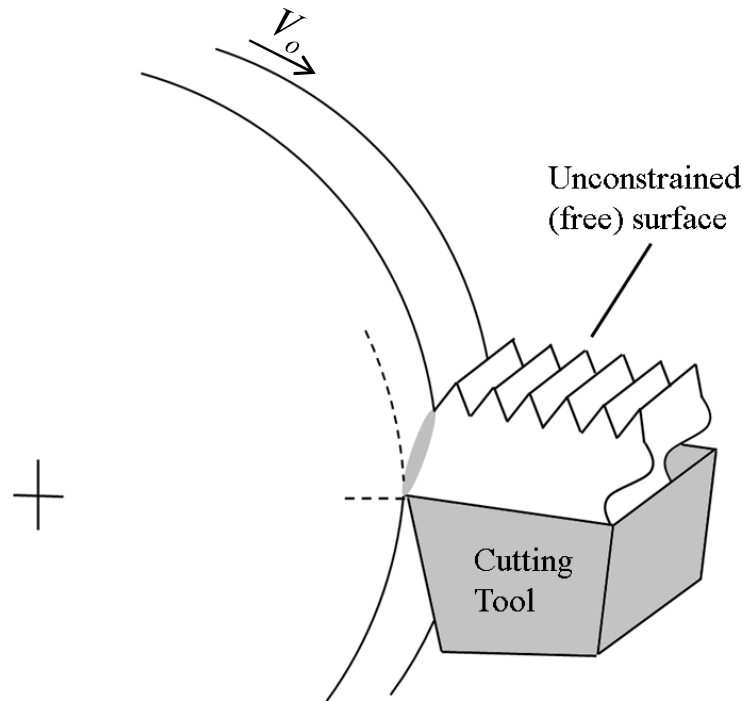
1. Multi-step nature (both hot and cold)
  - Energy intensive and costly
2. Limited control over properties (texture, Si composition)
  - Only NGO or GO up to 3.5wt%Si

Desires:

1. Single-step process
2. Wider range of textures in sheet of high Si content ( $> 3.5\text{wt}\% \text{Si}$ )

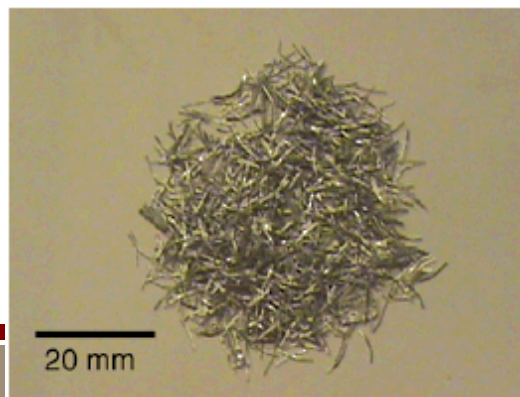
**Sheet processing method: hybrid machining**

# Machining

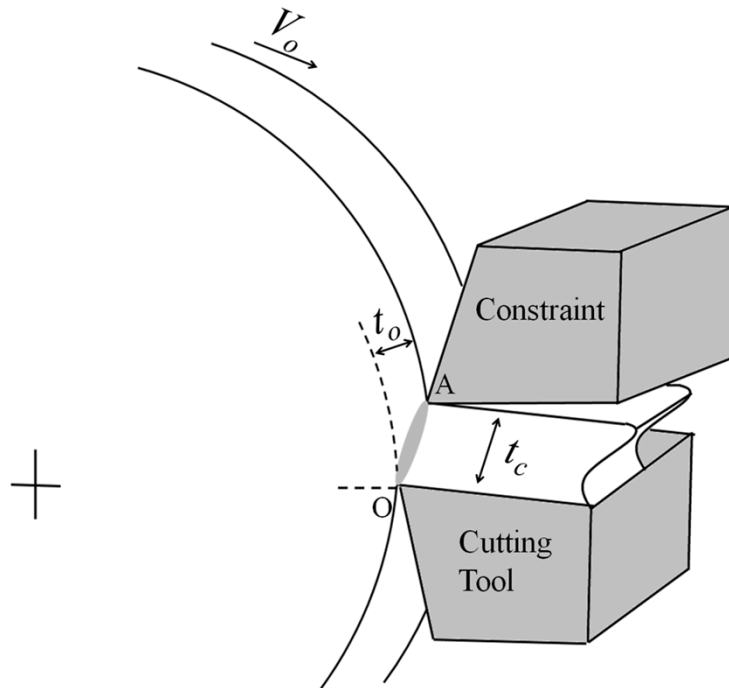


- Single step, large strain ( $\bar{\epsilon} > 1$ ) deformation
- High strain rates ( $\dot{\epsilon} > 10^3 \text{ s}^{-1}$ ) – high deformation temperatures

Scrap (waste) material



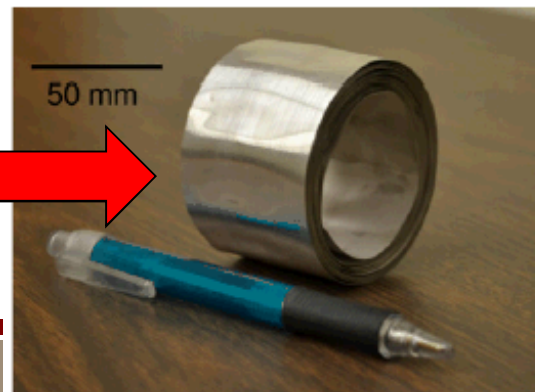
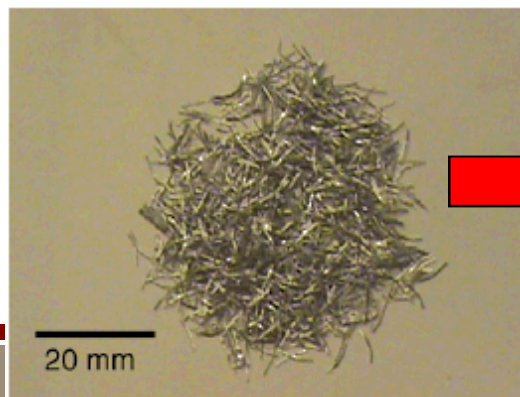
# Large strain extrusion machining



- Single step, large strain ( $\bar{\epsilon} > 1$ ) deformation
- High strain rates ( $\dot{\epsilon} > 10^3 \text{ s}^{-1}$ ) – high deformation temperatures
- Large hydrostatic pressures
- Wide range of control over deformation

Scrap (waste) material

LSEM

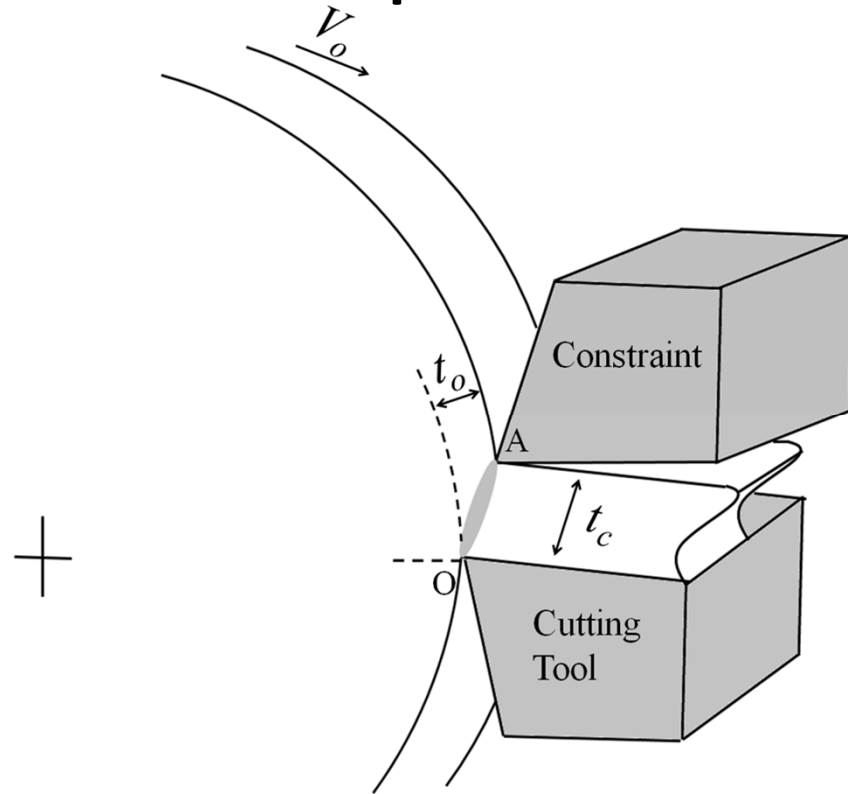


# Large strain extrusion machining

## Large Strain Extrusion Machining (LSEM)



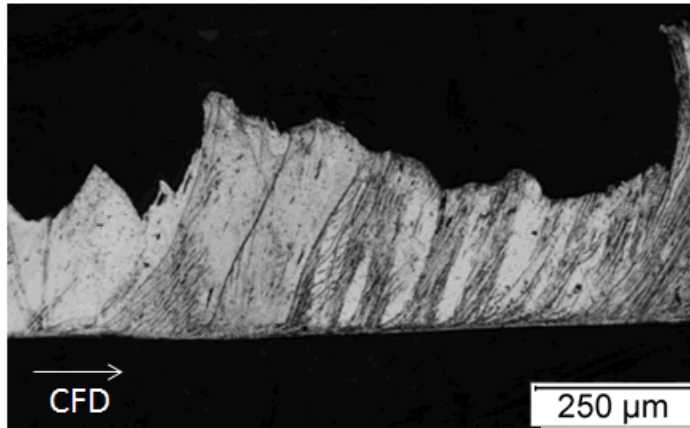
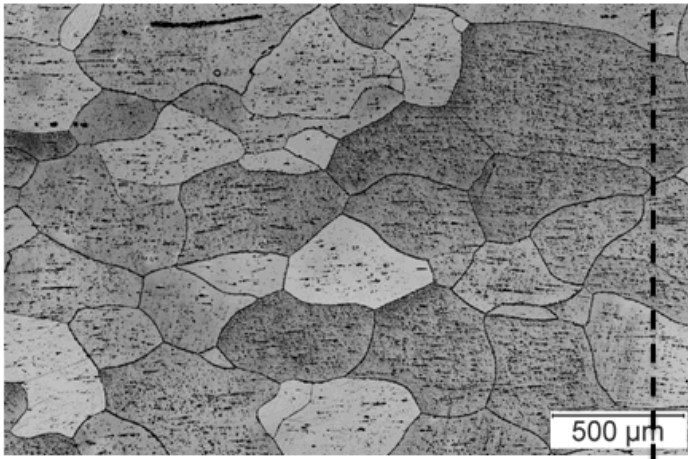
# LSEM experimental procedure



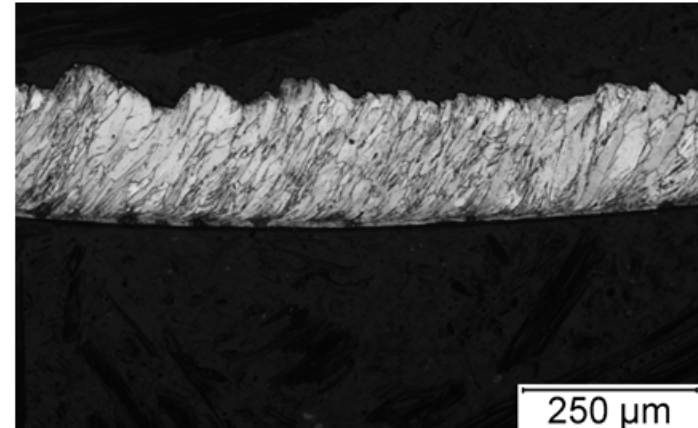
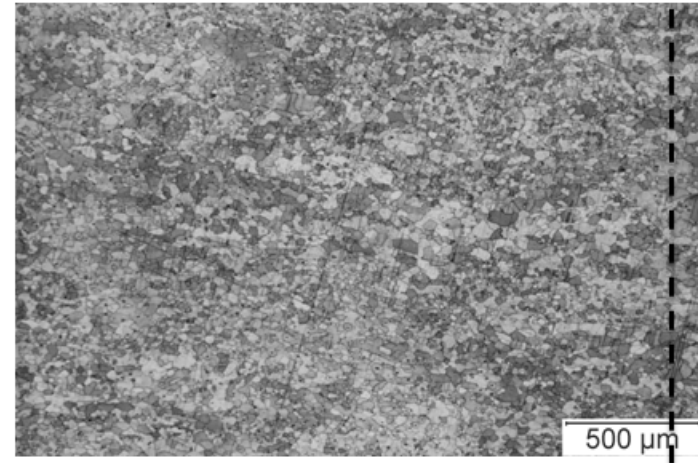
- Two high silicon Fe-Si alloys: 4wt%Si and 6.5wt%Si
- Varied LSEM deformation parameters – effects on microstructure, crystallographic texture and magnetic properties
- Microstructure – optical microscopy
- Texture – electron backscatter diffraction (EBSD)
- Properties – permeameter (Magnet-Physics, Inc.)

# 4wt%Si Workpiece

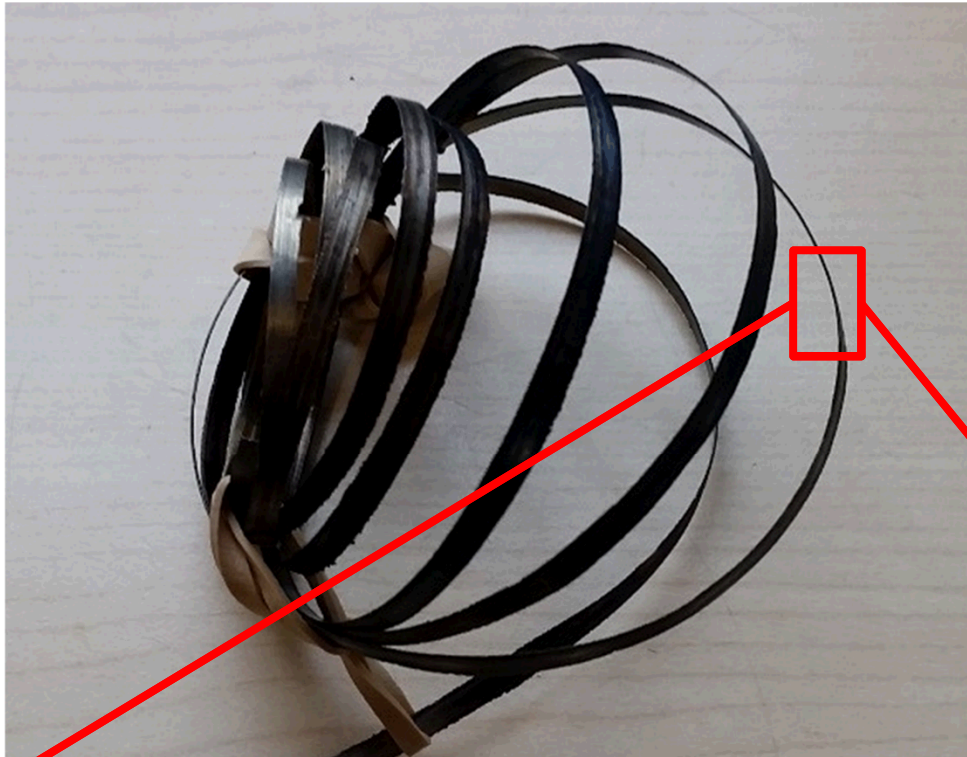
- Hot rolled plate – Scientific Alloys, Inc.
- Equiaxed grain size,  $d \sim 500 \mu\text{m}$
- Composition (wt%): 3.83Si-0.32Mn-0.028C-0.018P-0.015S-0.006Al, bal. Fe



- Warm rolled and annealed at  $700^\circ\text{C}$  for 30 min
- Equiaxed grain size,  $d \sim 20 \mu\text{m}$



# LSEM – Continuous 4wt%Si strip

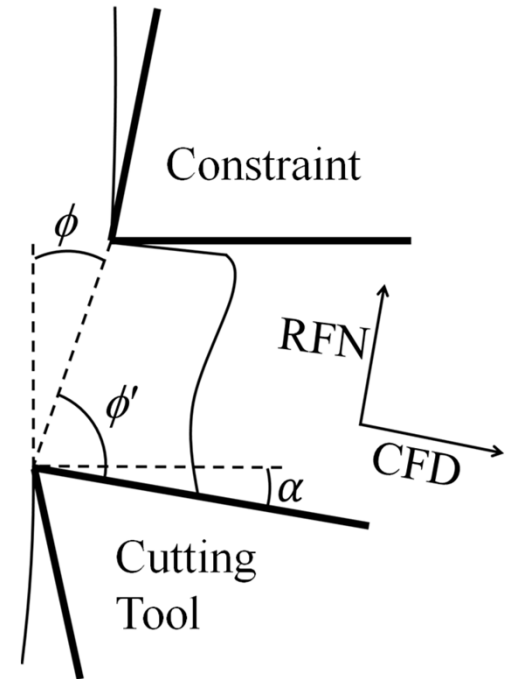
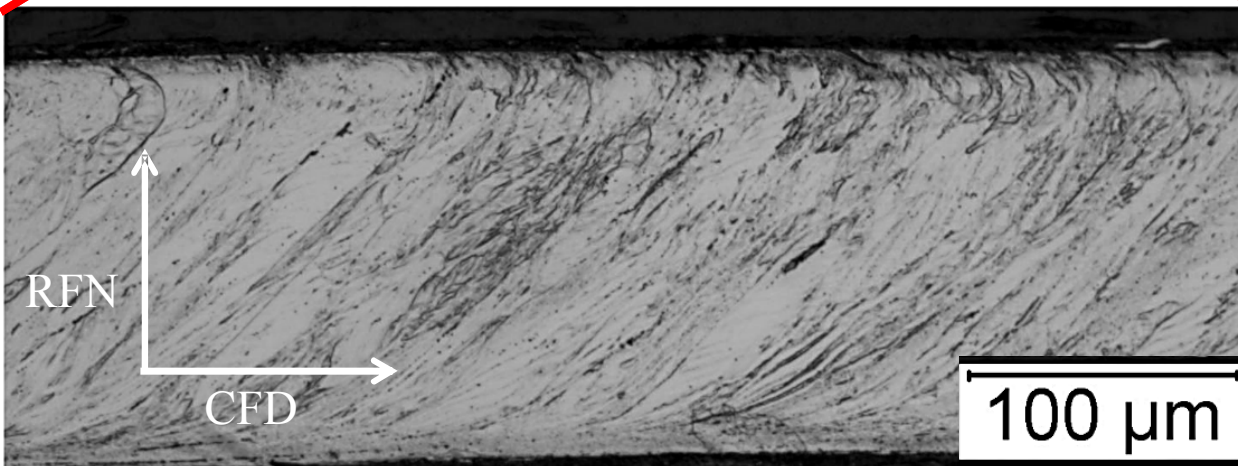


1.5 m long strip

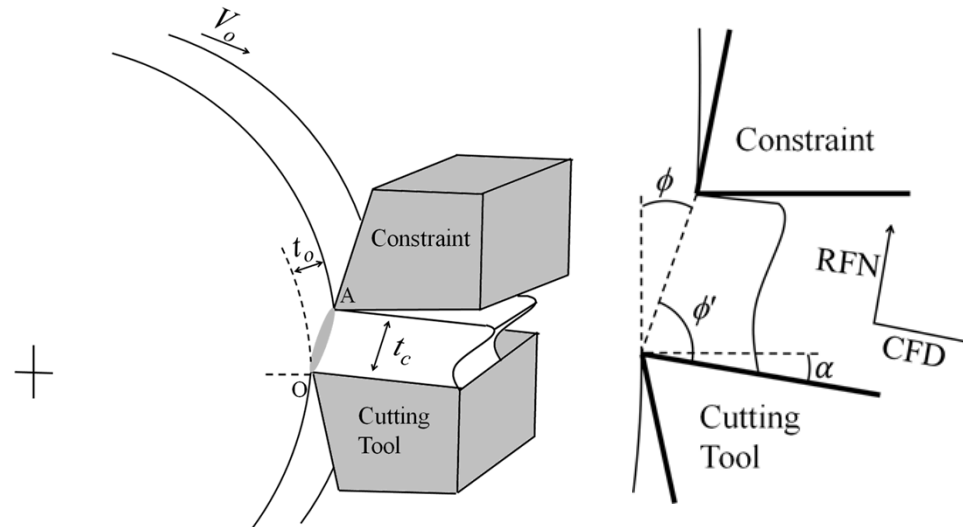
$$t_c = 450 \mu\text{m}$$

$$T_o = 25 \text{ }^\circ\text{C}$$

$$V_o = 1 \text{ m/s}$$



# LSEM mechanics



**Chip Thickness Ratio:**  $\lambda = \frac{t_c}{t_o}$

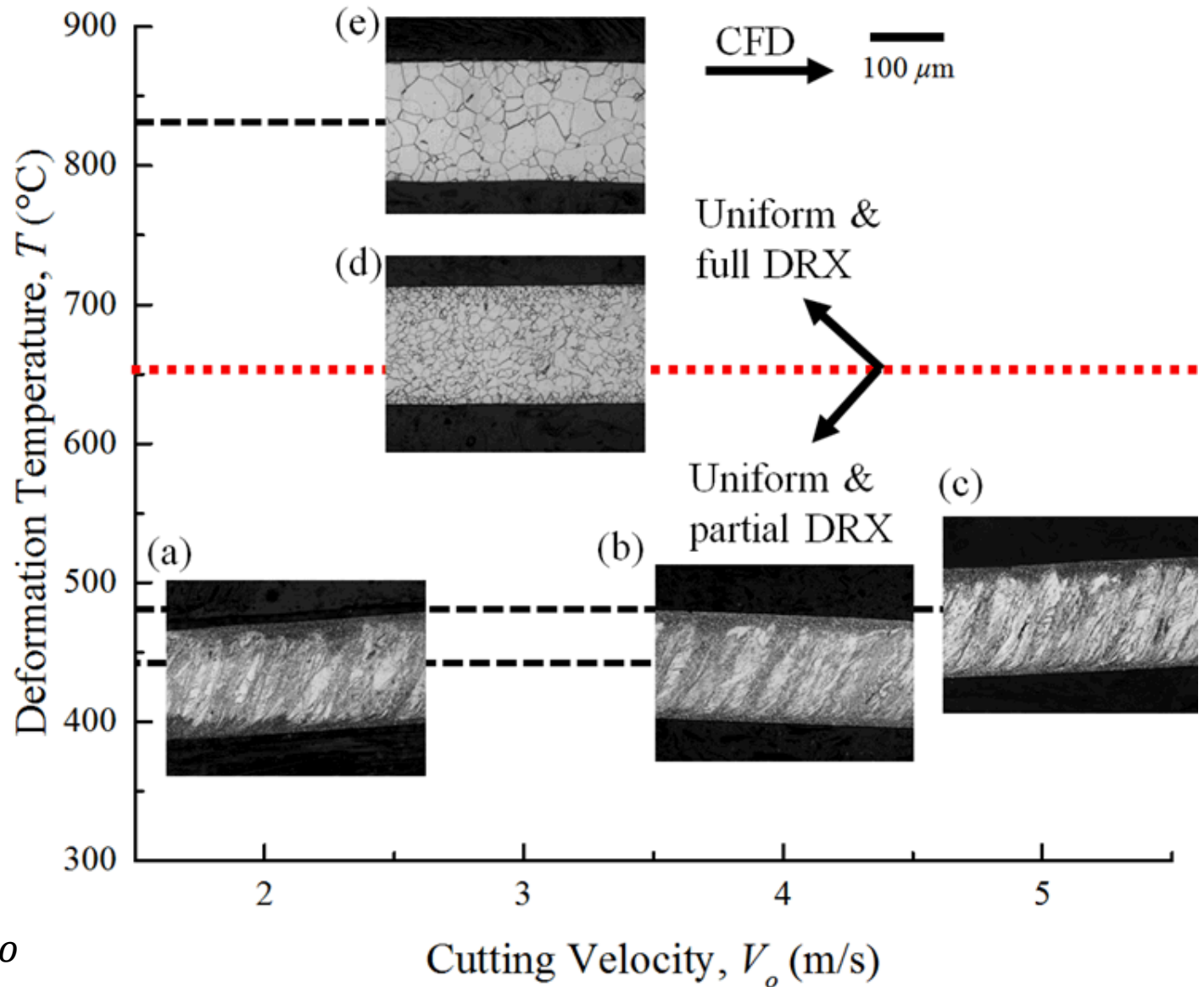
**Effective (von Mises) Strain:**  $\bar{\epsilon} = \frac{1}{\sqrt{3}} \left( \frac{\lambda}{\cos \alpha} + \frac{1}{\cos \alpha} - 2 \tan \alpha \right)$

**Hydrostatic Pressure (normalized):**  $\frac{p}{k} = 1 + 2\theta$  where  $\theta = 2 \tan^{-1} \left( \frac{\frac{1}{\lambda} - \sin \alpha}{2} * \cos \alpha \right)$

**Deformation Temperature:**  $T = u_s \frac{(1-\Gamma)}{\rho c} + T_0$ ; where  $u_s = \frac{2}{3} \left( \frac{F_c}{t_o t_w} \right)$  ( $T = 400^\circ\text{C} - 850^\circ\text{C}$ )

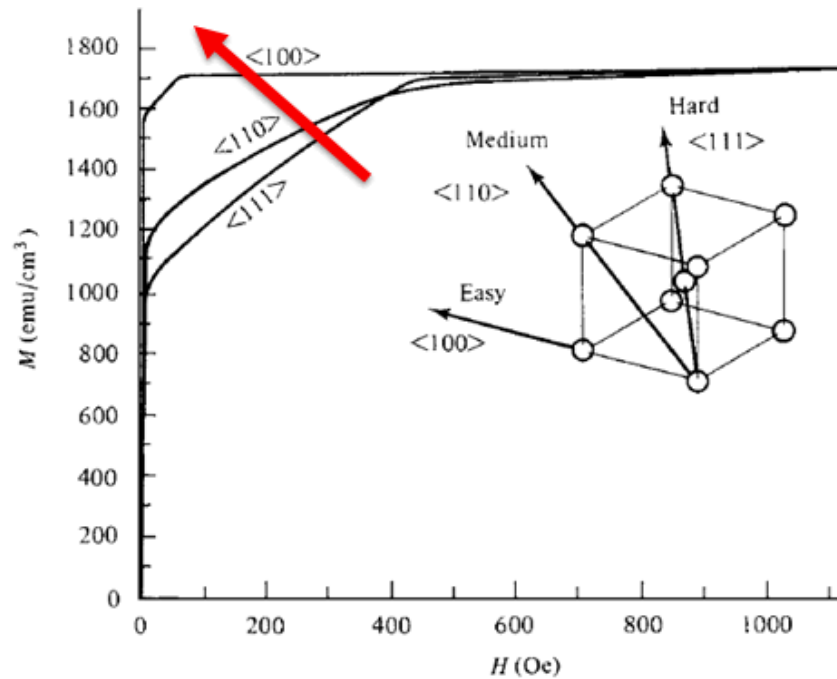
**Shear Plane Angle:**  $\phi' = (90^\circ + \alpha - \phi)$  where  $\phi = \tan^{-1} \left( \frac{\cos \alpha}{\lambda - \sin \alpha} \right)$

# LSEM structures



$$T = u_s \frac{(1-\Gamma)}{\rho c} + T_o$$

# Texture



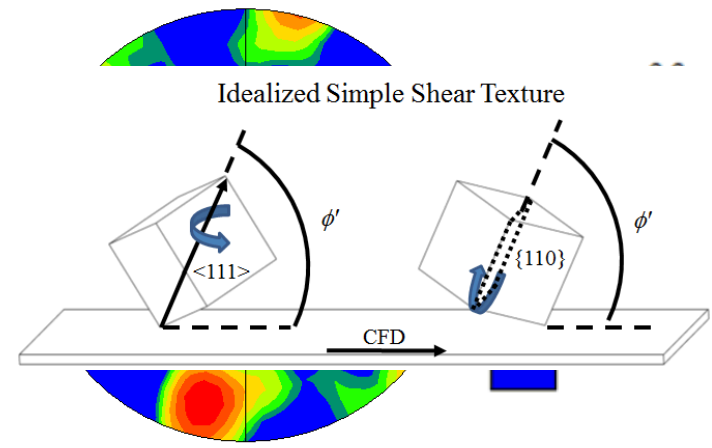
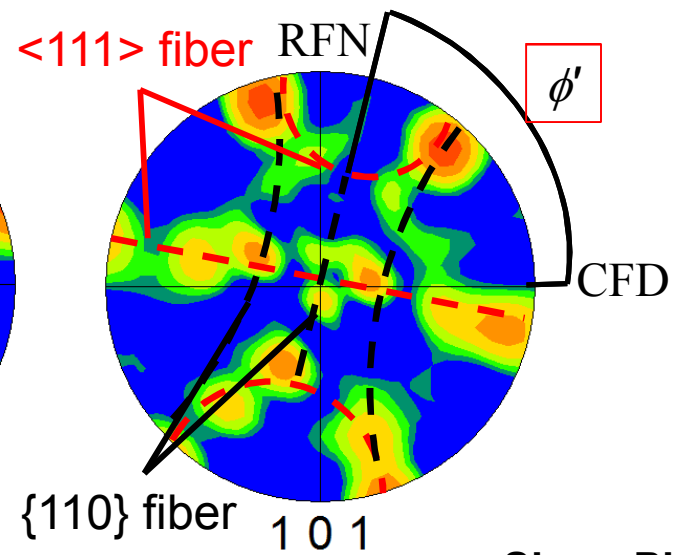
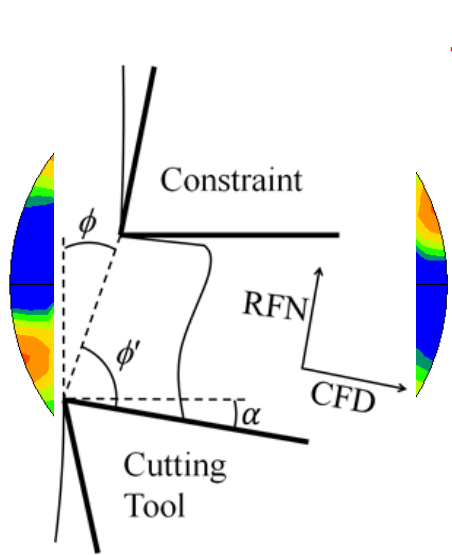
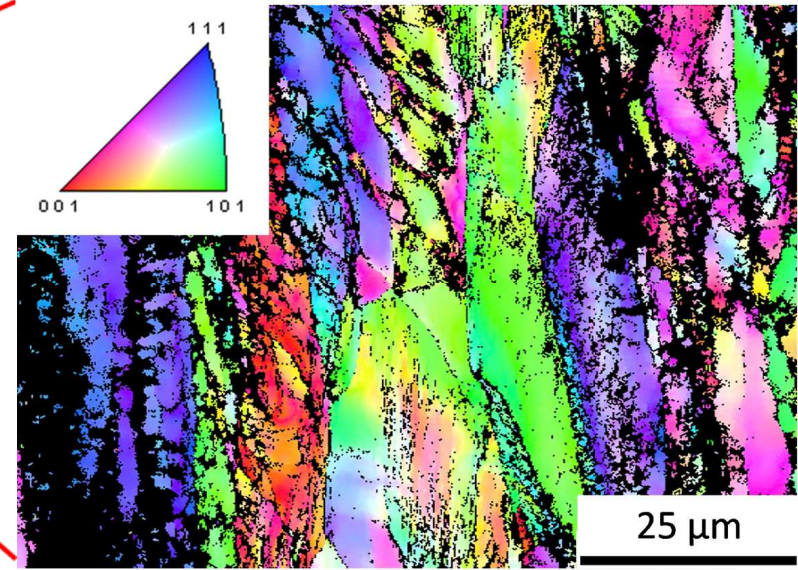
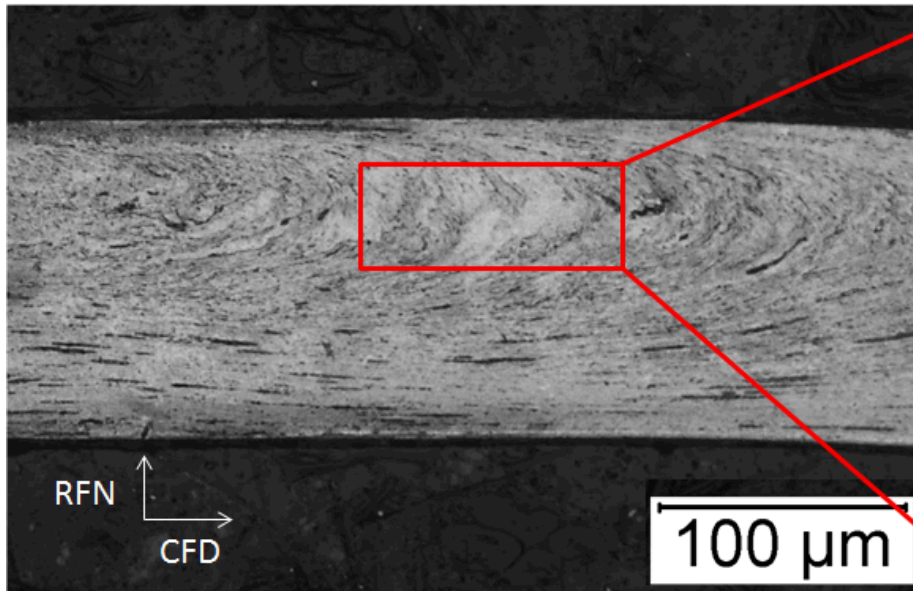
LSEM texture?

Grain-oriented  
Fe-Si (Goss)

Non grain-oriented  
Fe-Si



# Cold work texture

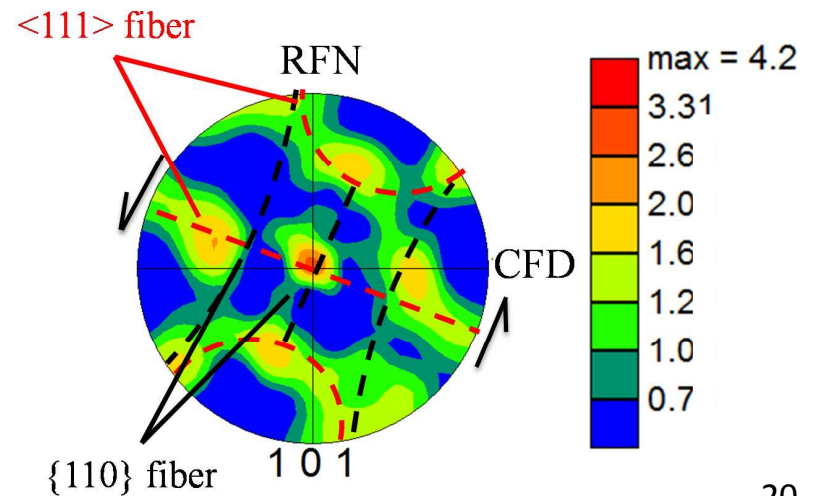
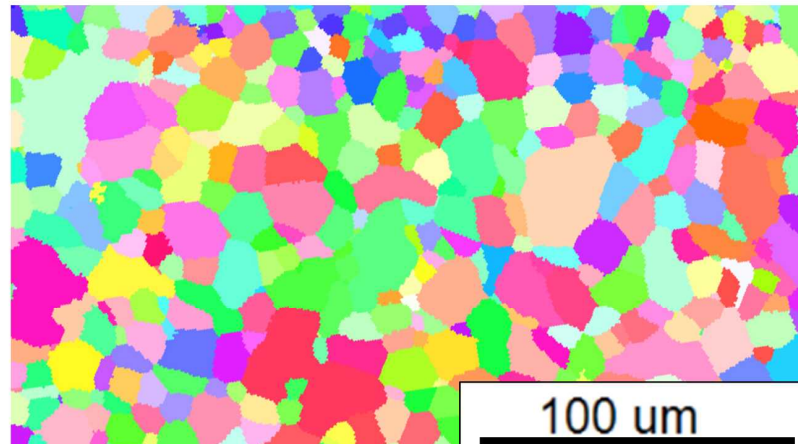
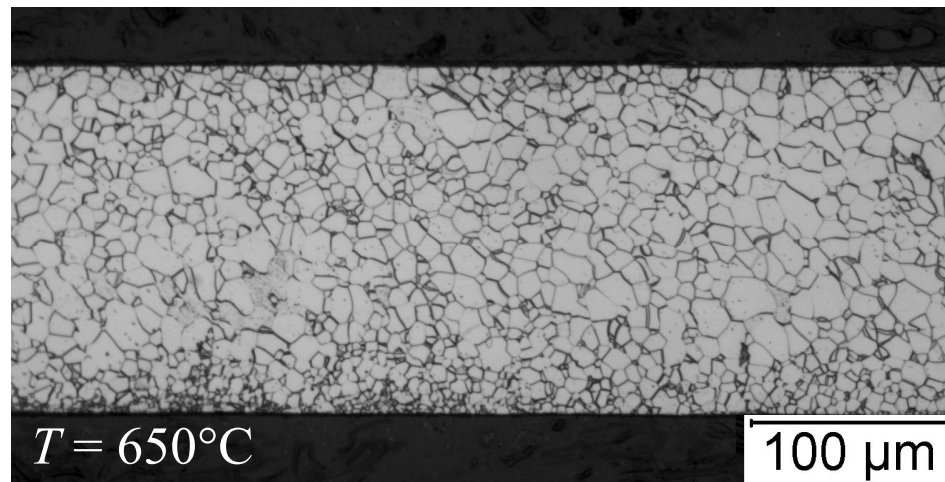


Shear Plane Angle:  $\phi' = (90^\circ + \alpha - \phi)$

# Hot work texture

Full dynamic recrystallization (*in situ*)

Simple shear cold-work texture character retained

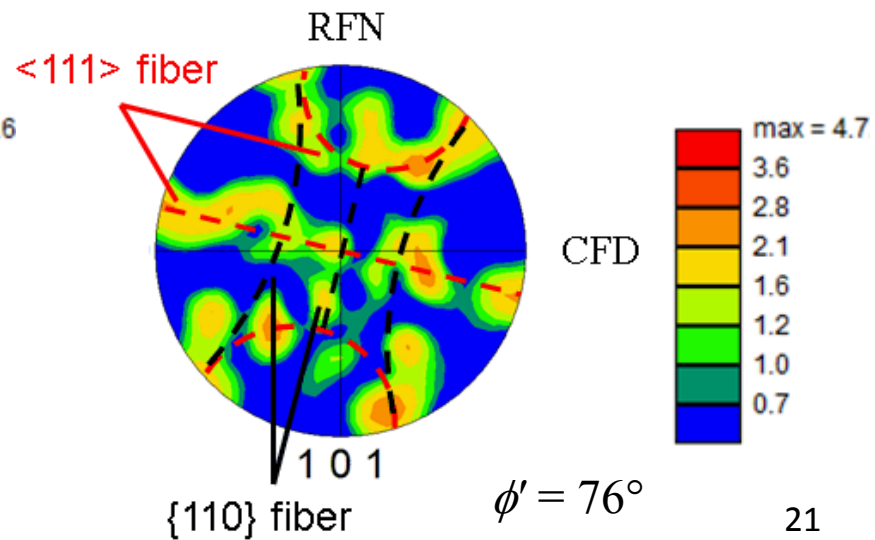
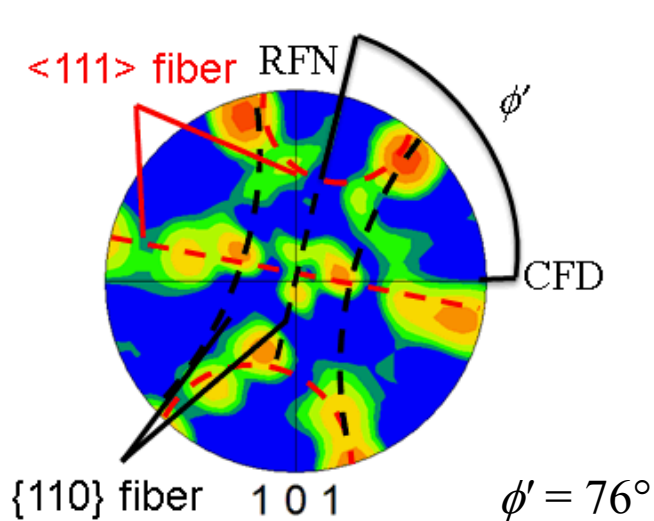
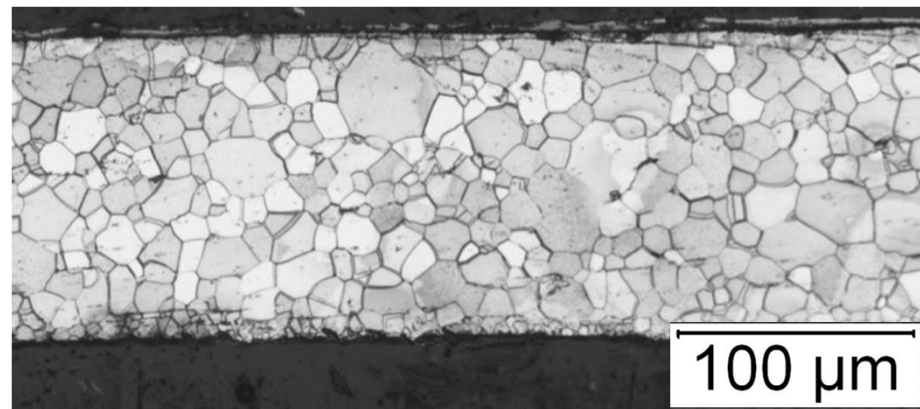
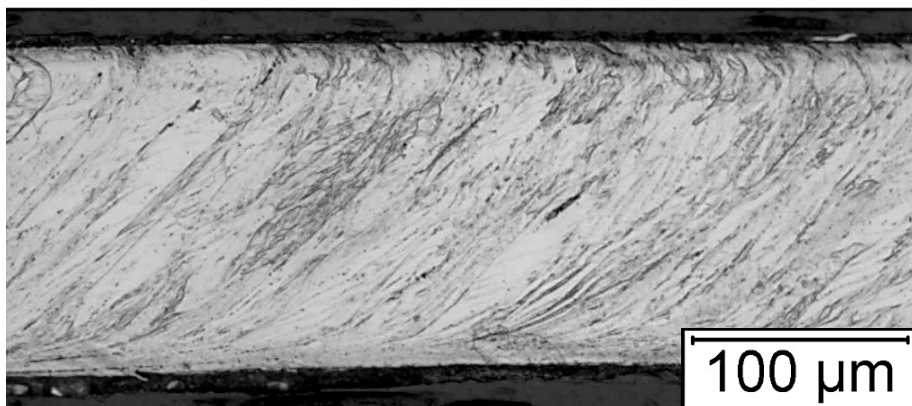


# Static recrystallization texture

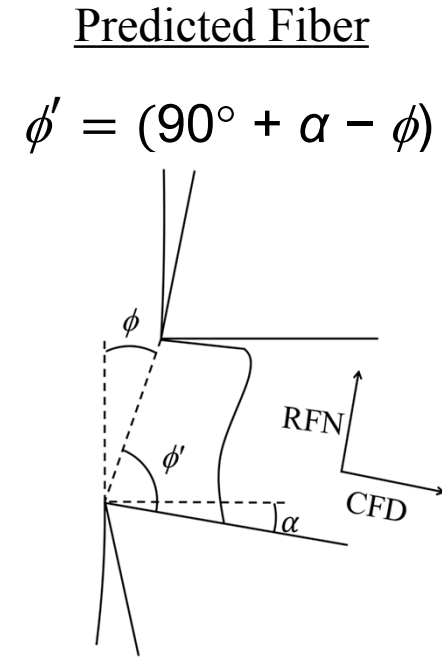
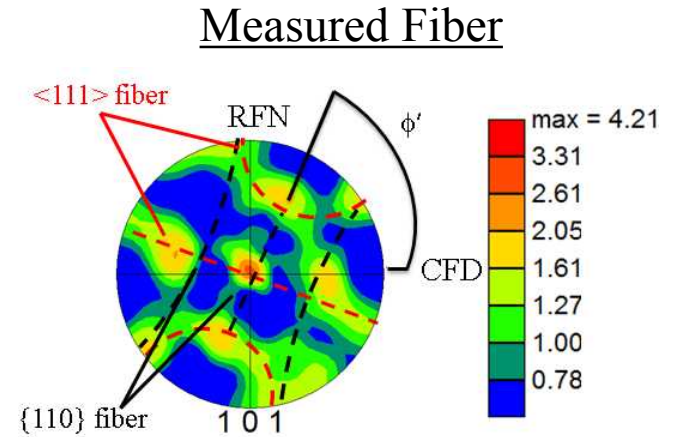
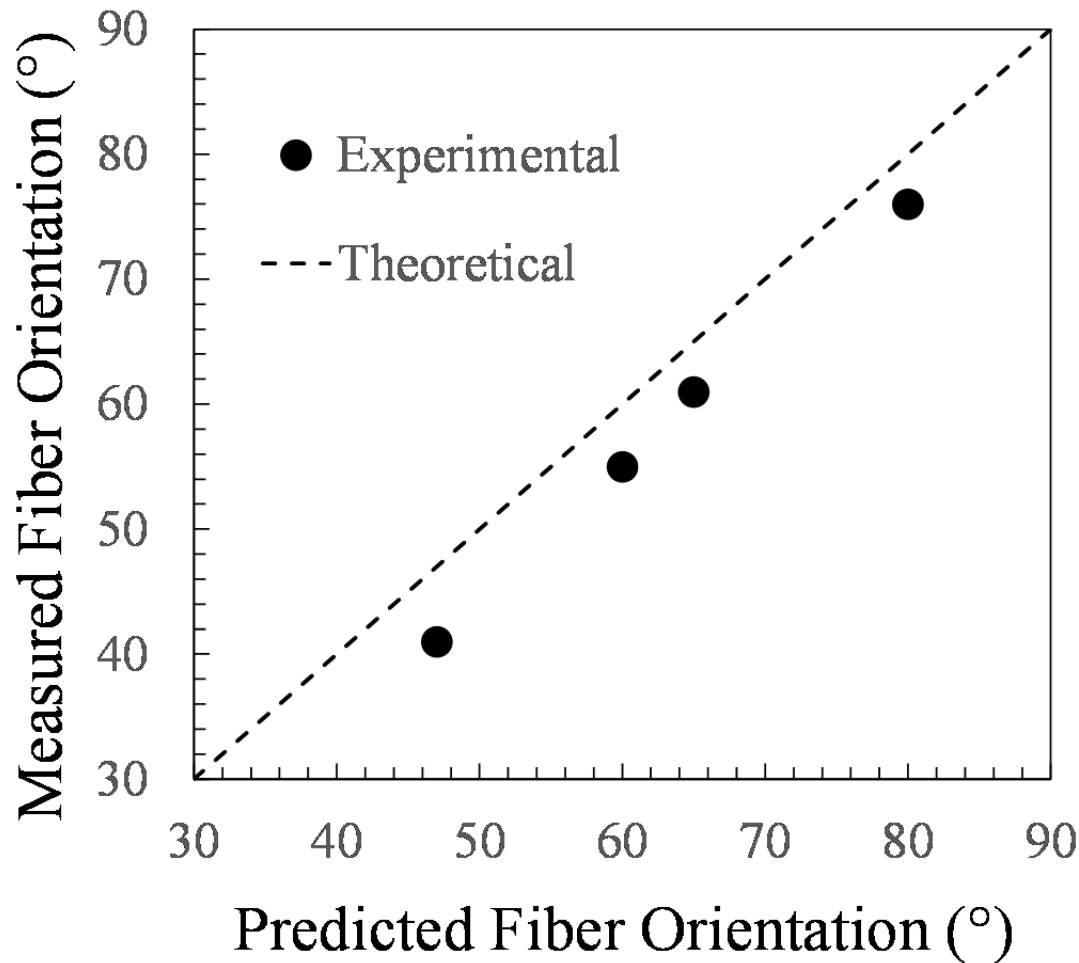
*Simple shear cold-work texture character retained*

As-deformed,  $T = 370^\circ\text{C}$

$700^\circ\text{C}$ , 30 min.

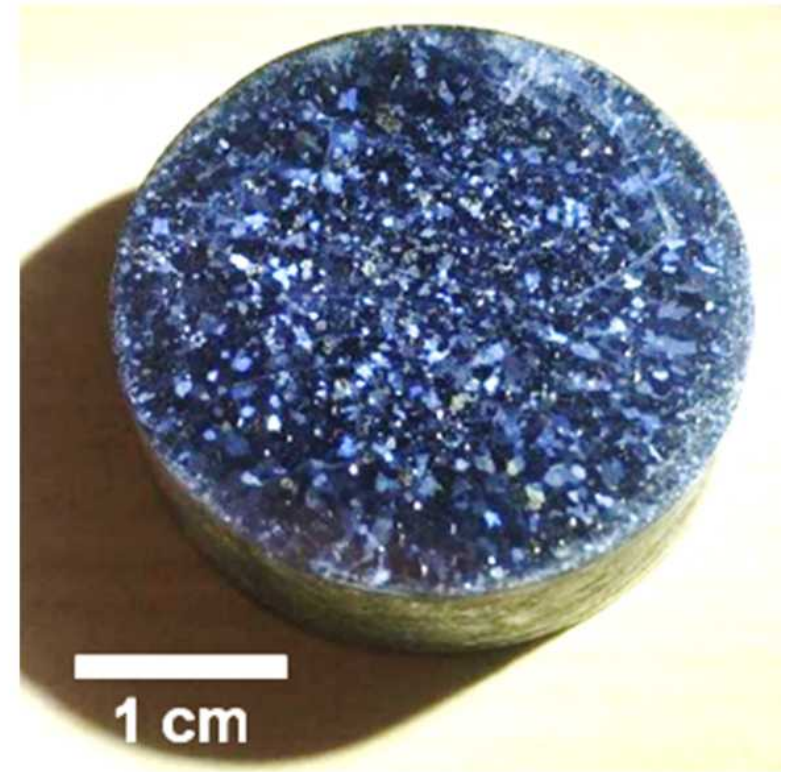


# Bulk recrystallization textures



# 6.5wt%Si workpiece

- Unable to get commercially
- Cast in-house using 2 kg vacuum induction furnace
  - Backfilled with Ar-5% $H_2$  atmosphere
- Cylindrical copper mold set atop a copper chill plate
  - Ingot: 1.2" diameter x 4" long
- Charge materials:
  - Electrolytic iron/Interstitial free (IF) steel
  - Semiconductor silicon



Cast Fe-6.5wt%Si ingot

- Equiaxed grain size,  $d \sim 500 \mu\text{m}$
- No significant microshrinkage porosity or macrosegregation

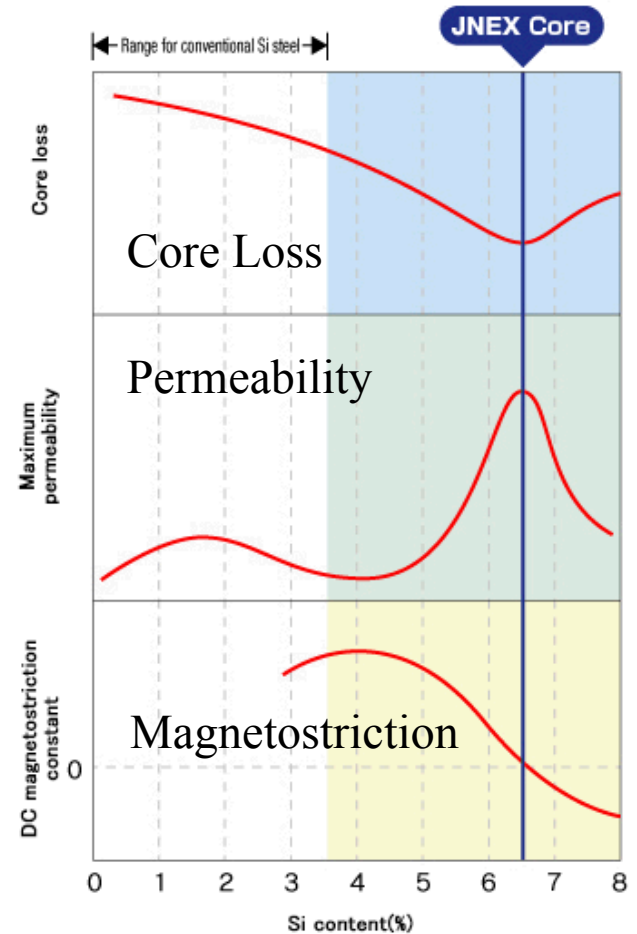
# Fe-6.5%Si

- Magnetic properties optimized at 6.5 wt%Si
- Cannot roll – low alloy workability
- > 7 patents for other processing routes
- Most successful – CVD siliconizing (expensive, limited by diffusion)



Attempting to cold roll Fe-6.5wt%Si....

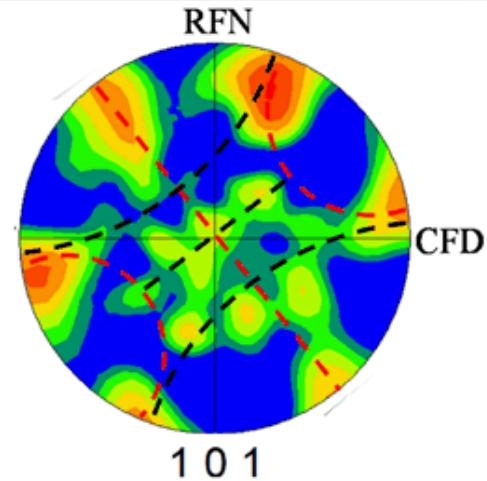
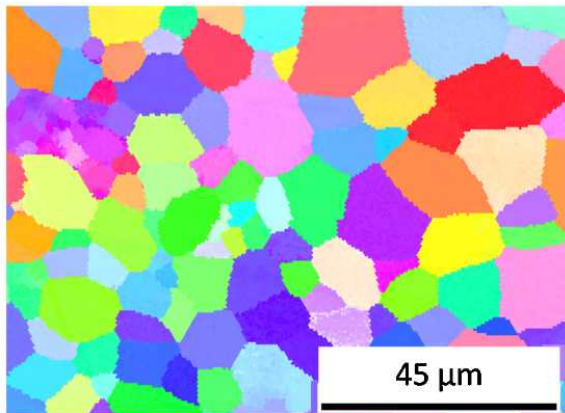
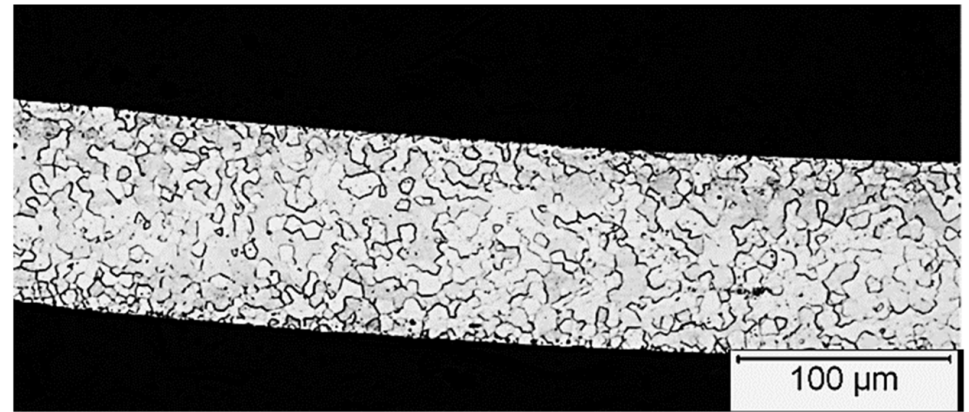
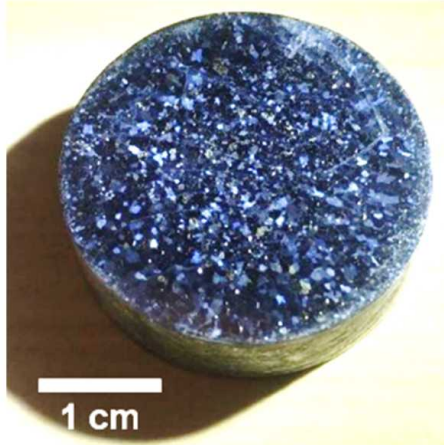
JFE-steel Corp.



# Fe-6.5%Si strip by LSEM

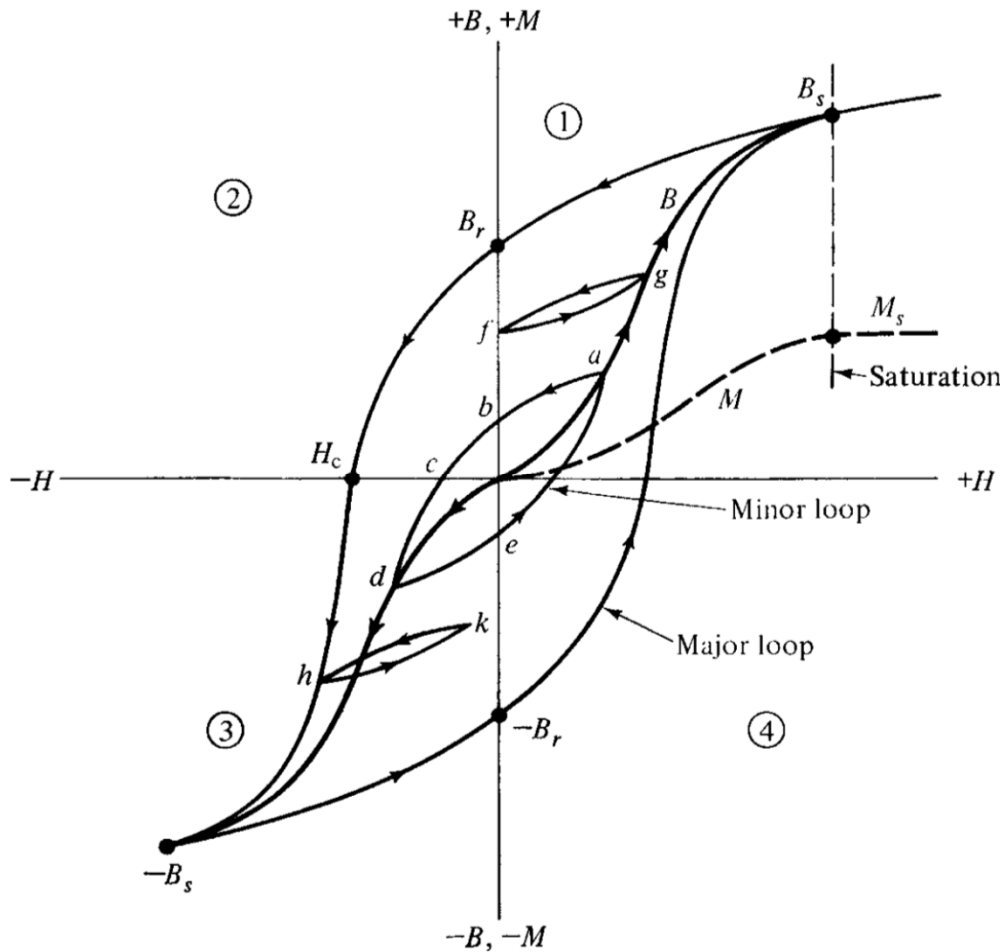
- Continuous strip at the ideal silicon composition
- Directly from as-cast ingot – **dynamic recrystallization**
- Shear texture again retained
- US patent application 62209719

$$\lambda = 1, T_o = 500 \text{ } ^\circ\text{C}$$



# Magnetic properties characterization

## Quasi-static Hysteresis Loop



### Key Properties:

$B_s$  – saturation induction

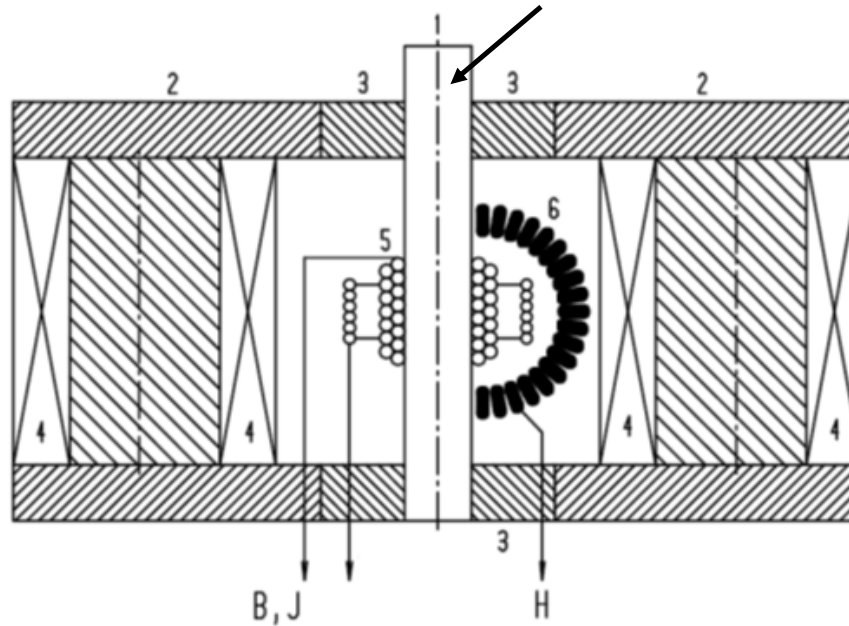
$H_c$  – coercivity

$\mu = B/H$  – permeability (slope of virgin magnetization curve) – here, focus on  $\mu_{max}$

# Magnetic properties measurement method

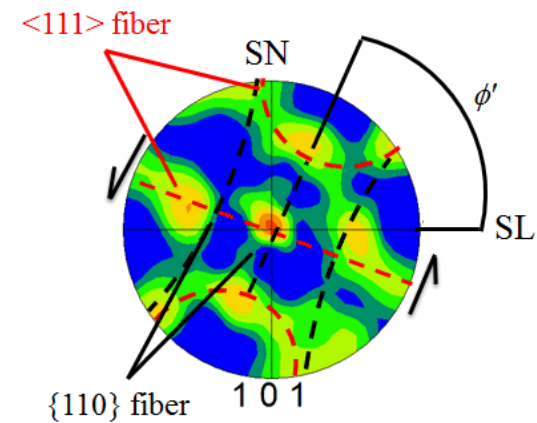
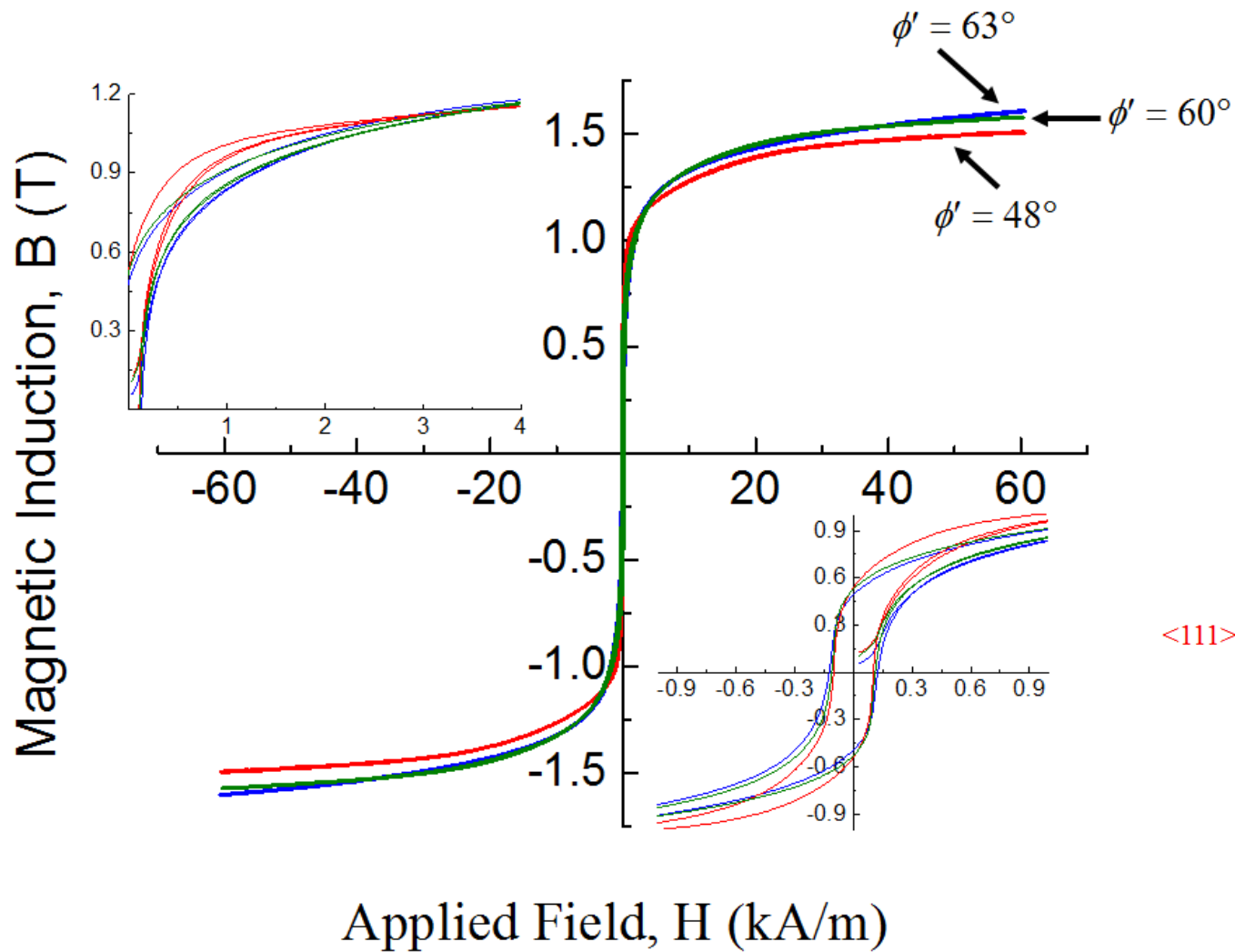
Magnet-Physics, Inc. (Fishers, IN)  
Remagraph C-500 (Type B Permeameter)  
ASTM A773/A773M-14 & IEC 60404-4

Sample, thickness cross-section

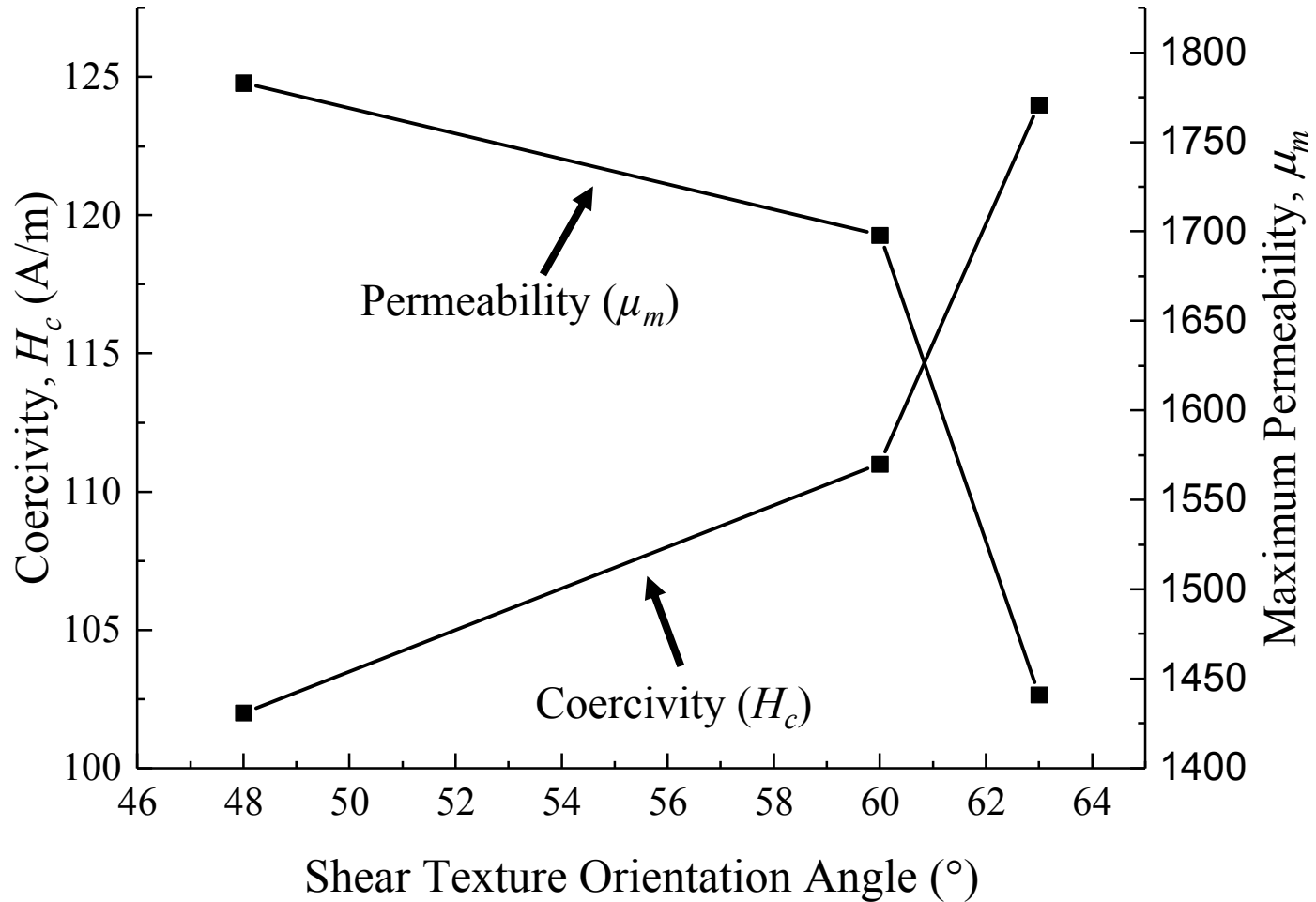


$H$  – measured from sample surface using C-shaped coil  
 $J$  – measured using J-compensated windings, ( $B = \mu_0 H + J$ )

# Properties of shear-textured Fe-4wt%Si



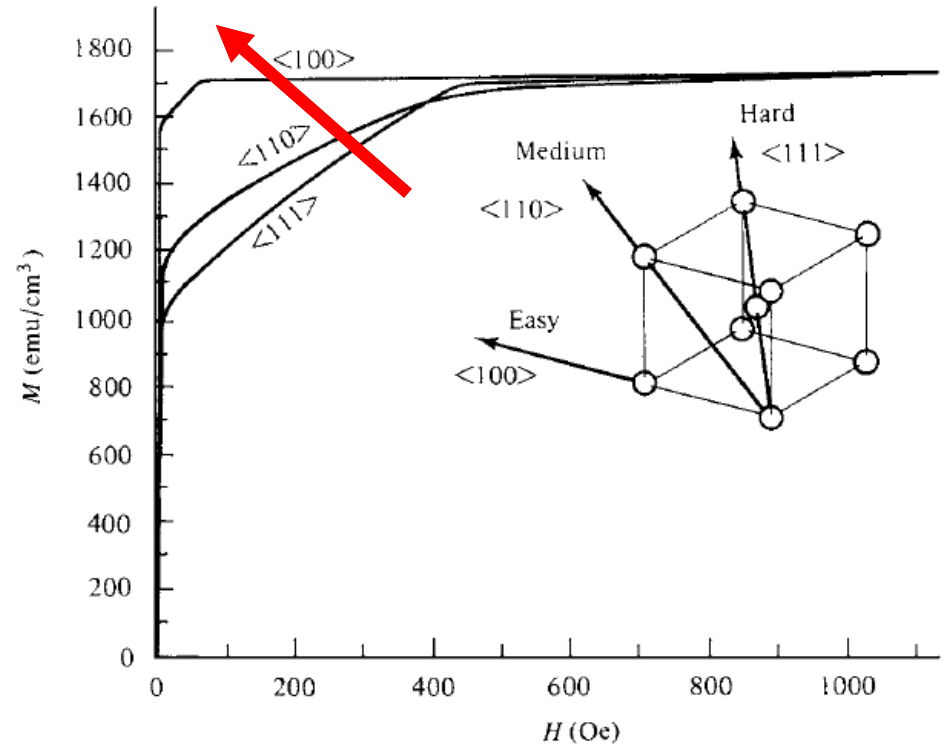
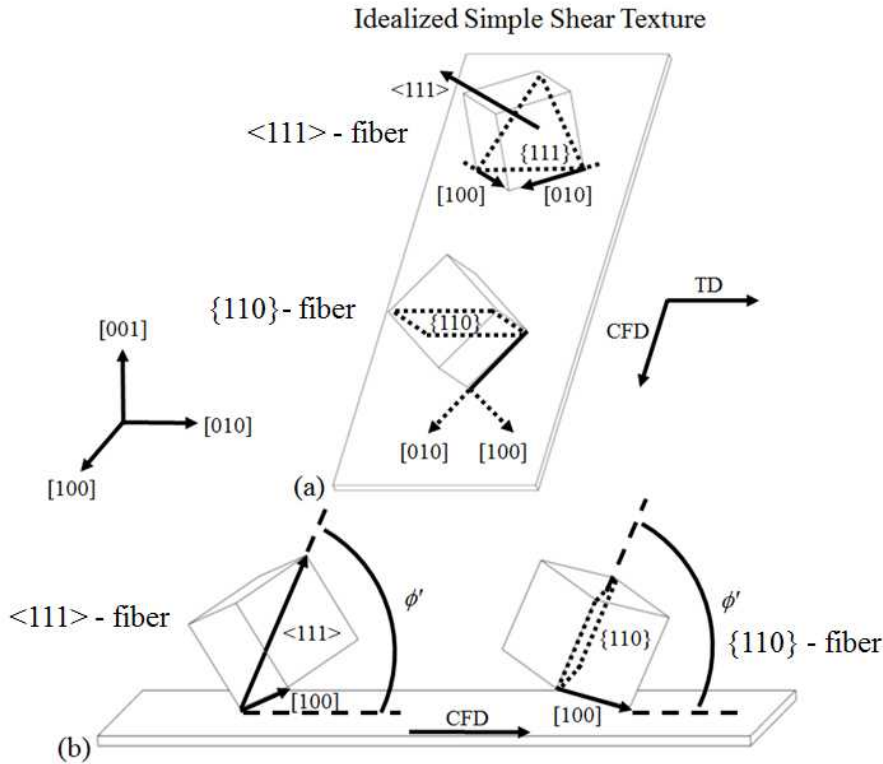
# Texture effects on 4wt%Si permeability



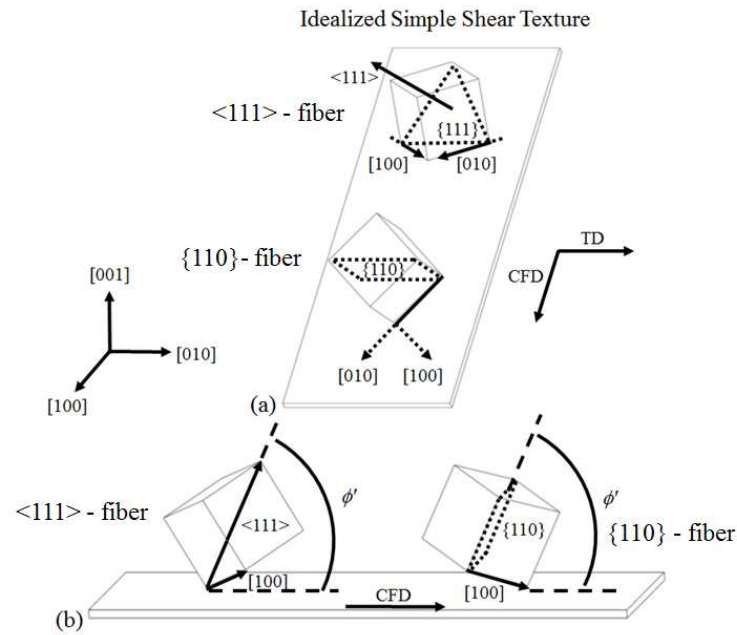
Orientation of the shear texture had minor effects on the properties – related to the crystal anisotropy?

# Textures are important for magnetic properties!

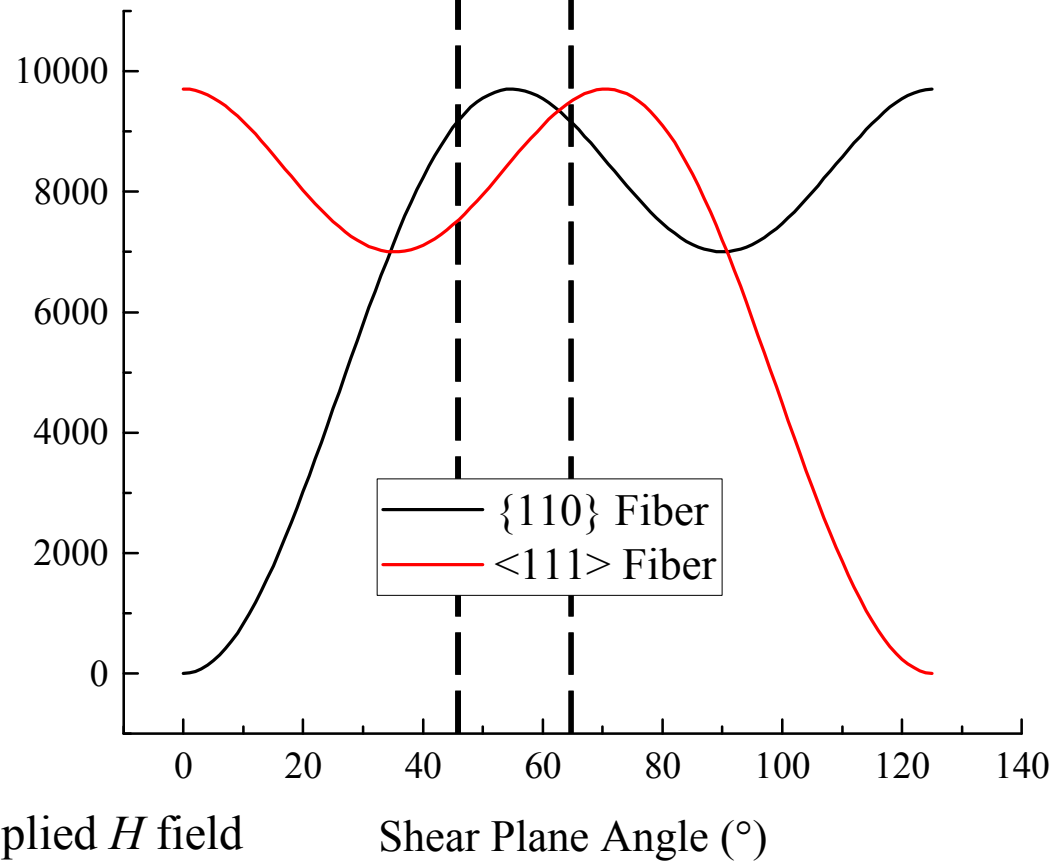
## Crystal Magnetic Anisotropy



# Crystal anisotropy energy



Crystal Anisotropy Energy ( $\text{J/m}^3$ )

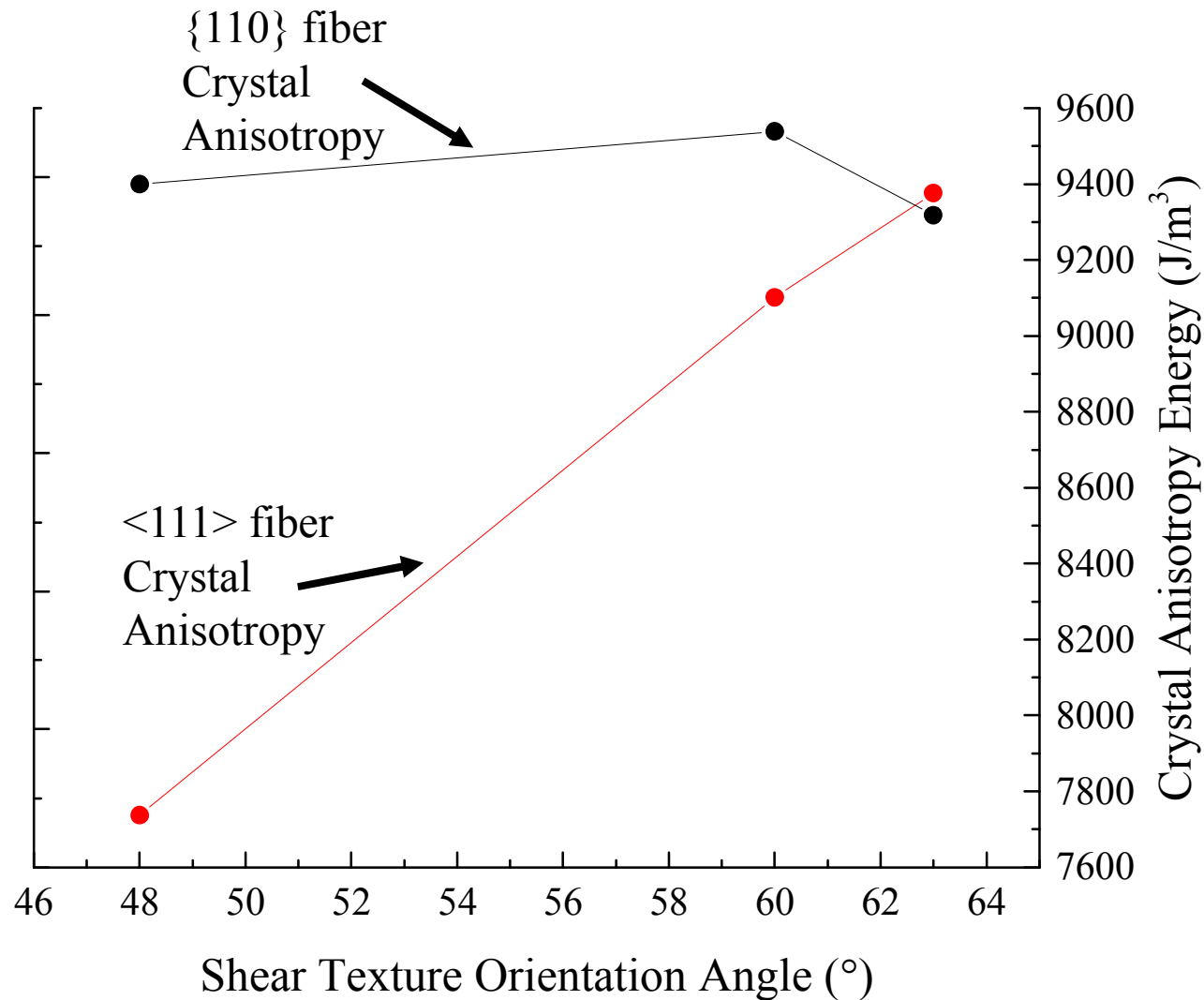


## Crystal Anisotropy Energy:

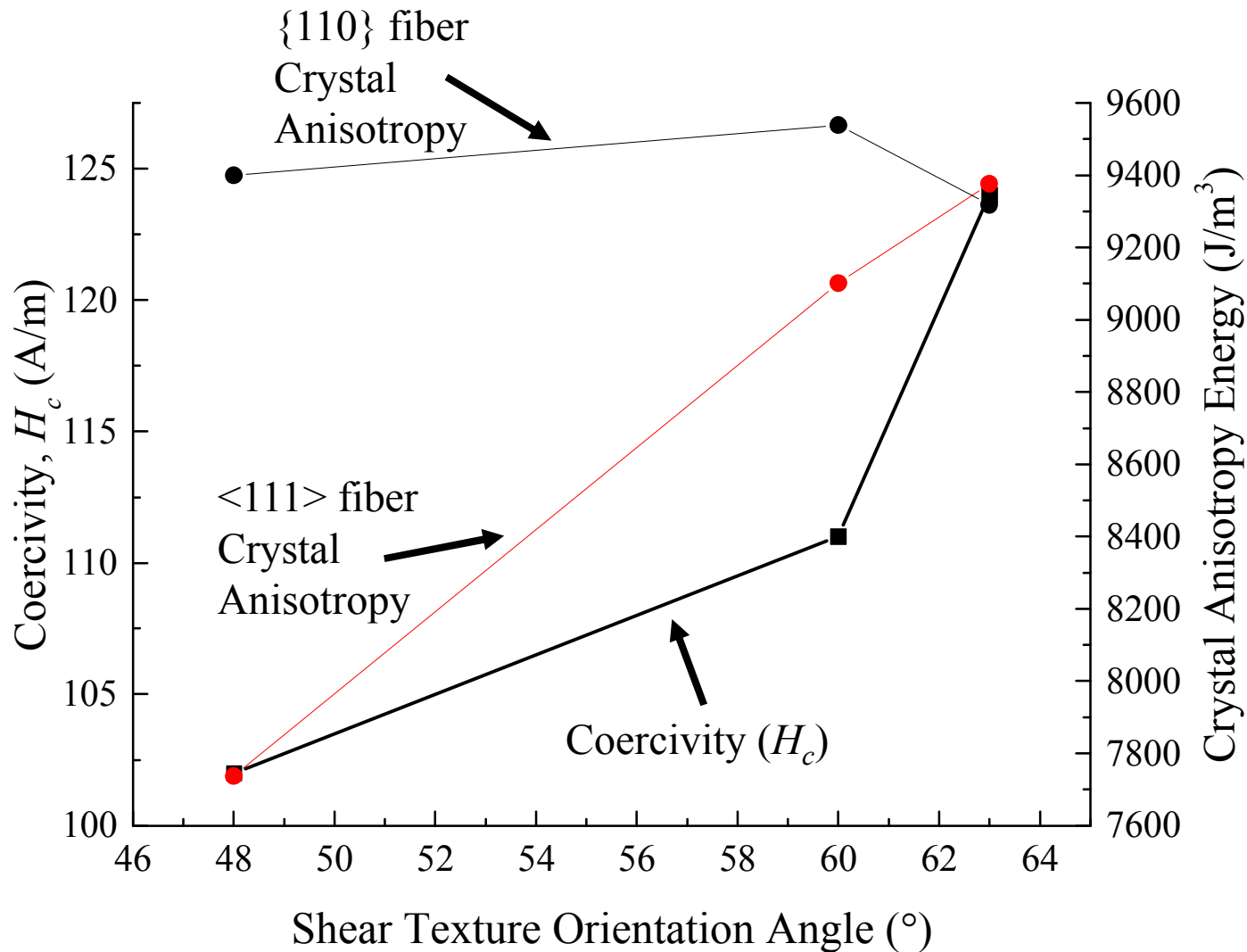
- Intrinsic energy (force) opposing the applied  $H$  field
- Results from anisotropy of BCC lattice structure
- Estimated using first few terms of infinite series:

$$E = K_0 + K_1(\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + K_2(\alpha_1^2 \alpha_2^2 \alpha_3^2) + \dots$$

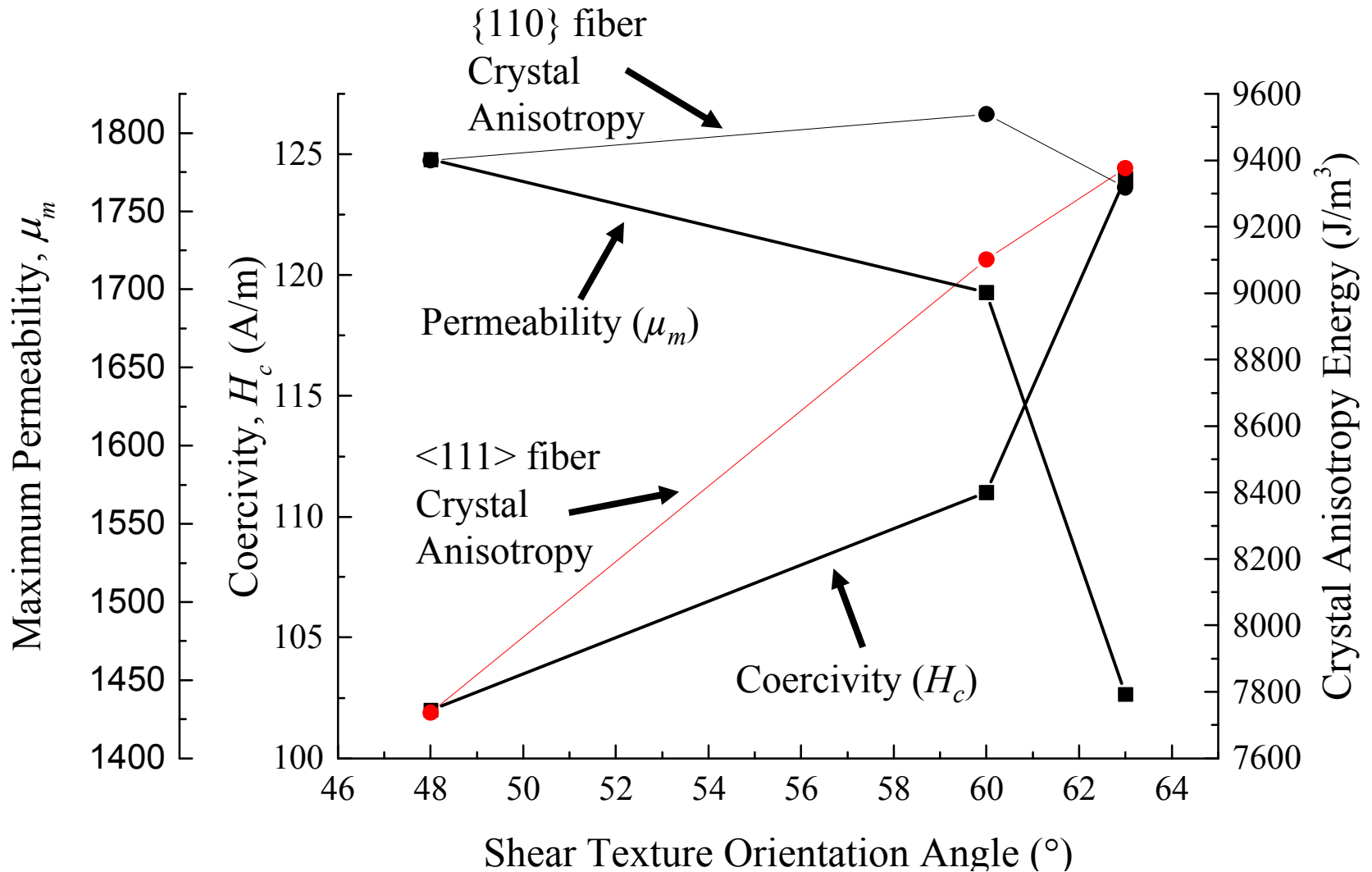
# Texture effects on 4wt%Si properties



# Texture effects on 4wt%Si properties



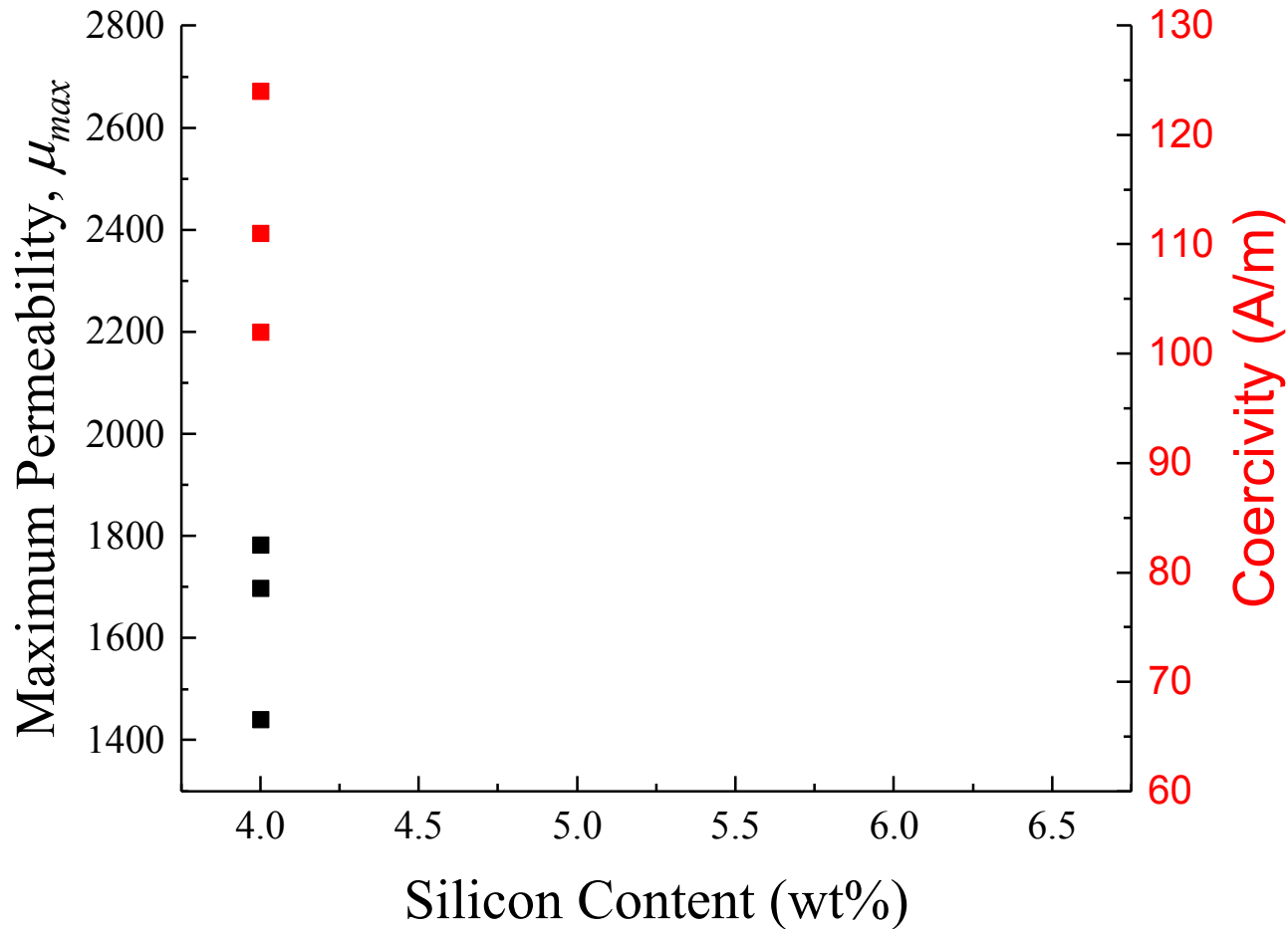
# Texture effects on 4wt%Si properties



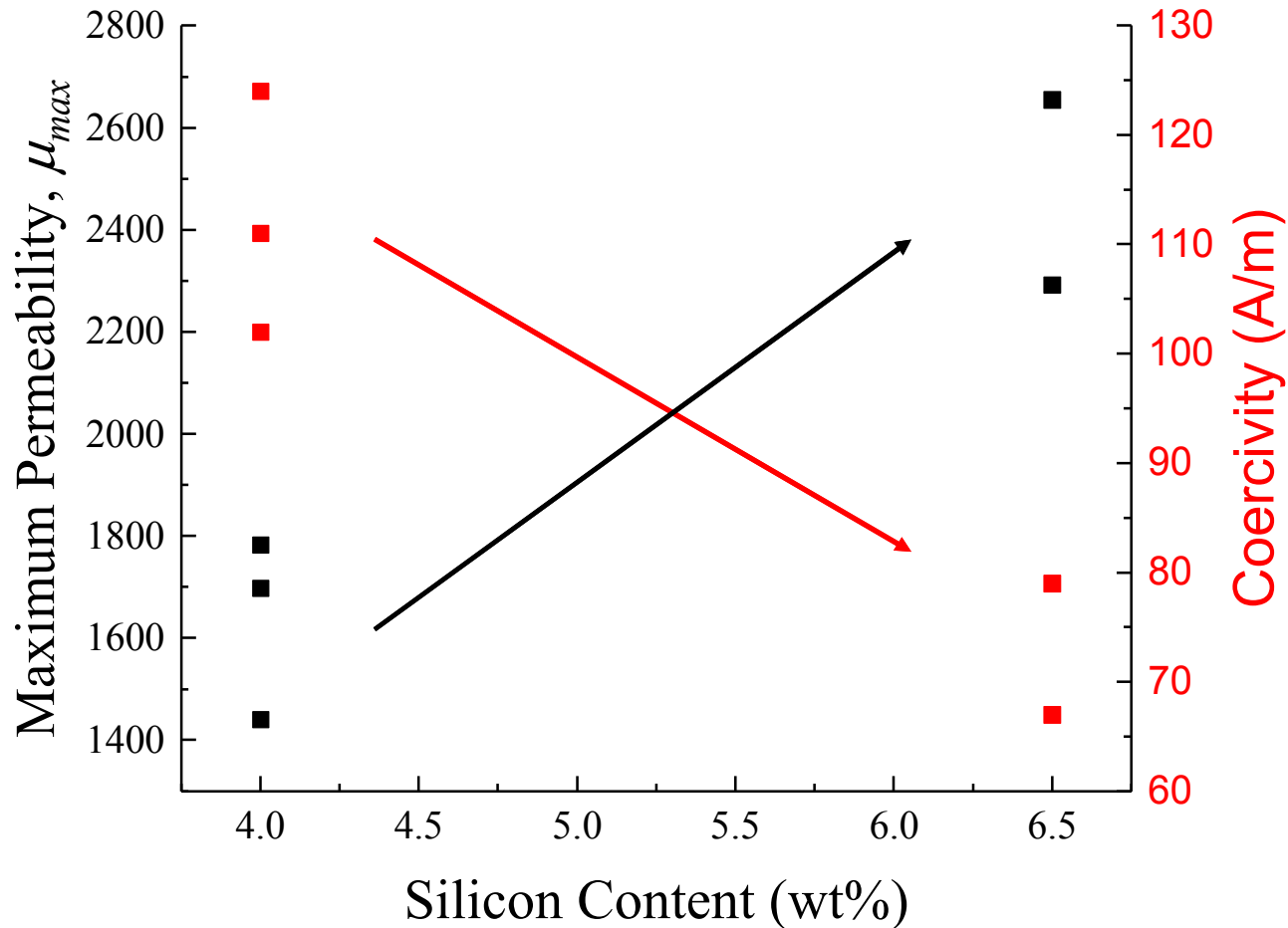
Coercivity decreases and permeability increases with *decreasing* shear plane angle due to a *minimization of crystal anisotropy energy* for the <111> fiber.

**Composition?**

# Composition effects on properties



# Composition effects on properties



- Increased permeability and decreased coercivity with increasing silicon content.

# LSEM Conclusions

1. Continuous sheets were processed with a range of microstructures from Fe-Si, up to 6.5wt%Si, *via* simple shear deformation.
2. A range of shear textures were developed in a predictable manner, which were retained upon annealing.
3. The trend in coercivity and magnetic permeability was found to be related to the  $\langle 111 \rangle$  fiber crystal anisotropy energy.
4. Increased silicon content of the Fe-6.5wt%Si alloy improves properties.

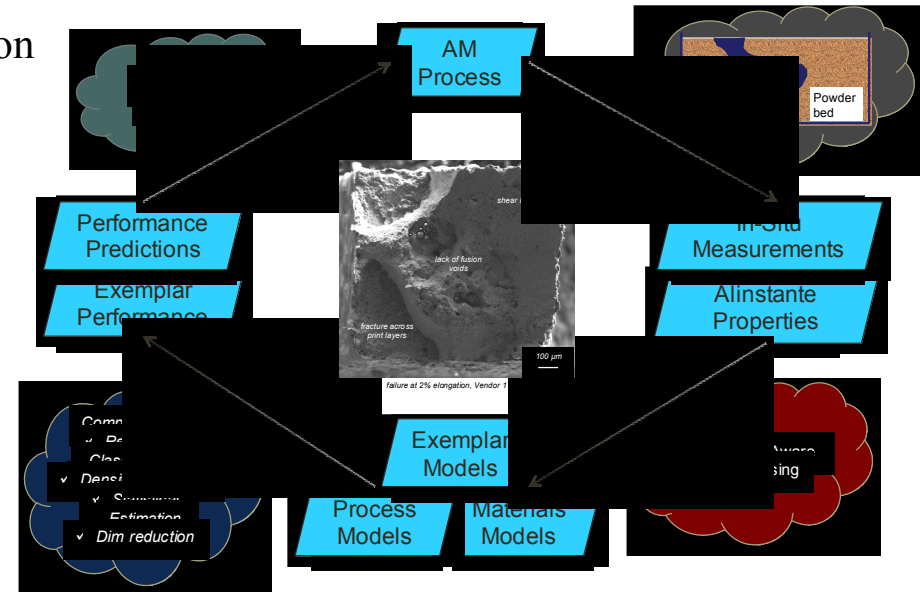
# Sandia AM Born Qualified overview

**Goal:** Combine promise of **additive manufacturing** with **deep materials & process understanding** to revolutionize design, manufacturing, & qualification paradigms

➤ Materials, designs, and ultimately components are “*Born Qualified/Certified*”

**Why Additive Manufacturing (AM) as driver for design, manufacturing, and qualification revolution?**

- Disruptive technology that allows simultaneous creation of optimized part geometries and materials-by-design
- AM is ideal for low volume, high value, high consequence, complex parts
- Inherently flexible and agile
- Ability to create near-net shape parts



This contribution explores AM on soft ferromagnetic alloys

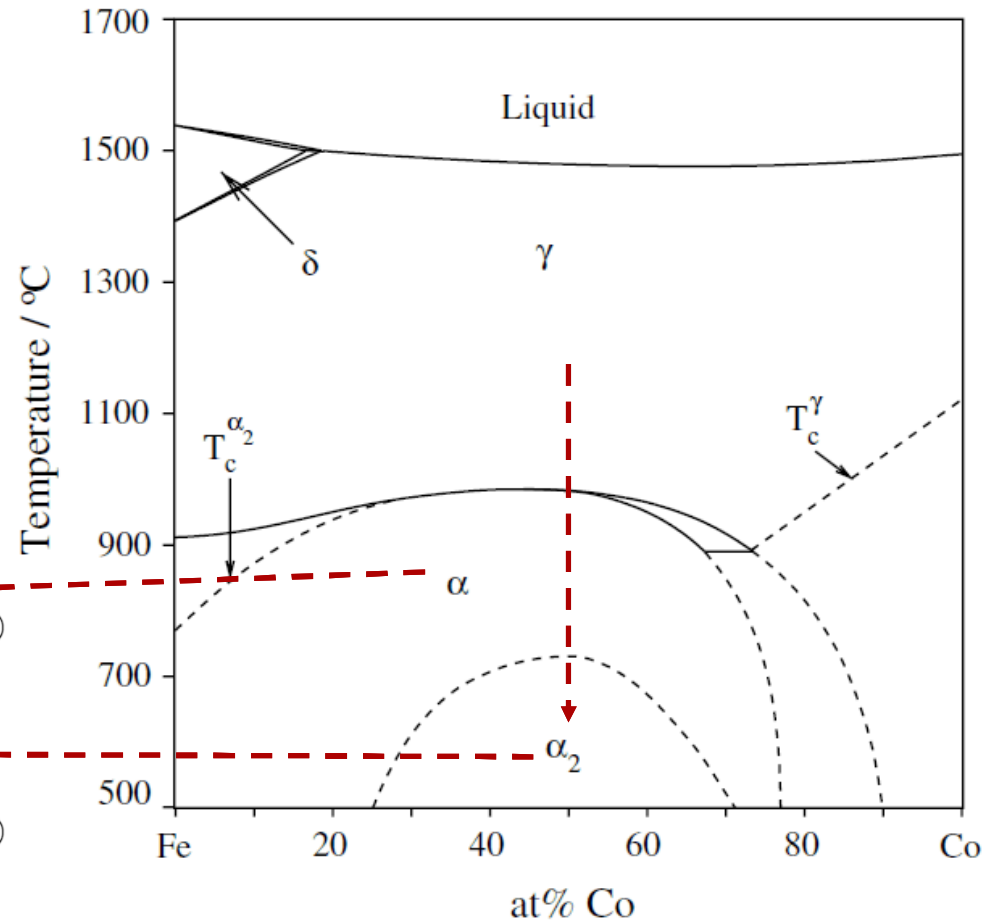
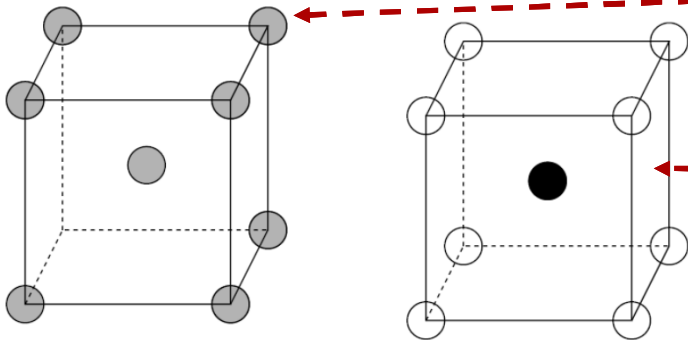
# Fe-Co alloy metallurgy

Equiatomic or near-equiatomic binary alloys of Fe and Co with FCC→BCC and order-disorder transformation of BCC→L2<sub>0</sub> (B<sub>2</sub>)

- Poor composition-driven workability
- Commercialized as Fe-Co-2V (Hiperco<sup>®</sup>) in bar, sheet, strip, coil, and rod forms

Characteristic properties:

- Highest saturation induction of soft ferromagnetic alloys
- High curie temperature
- High permeability
- Low core loss



# Commercial processing limitations

## Similar issues to the Fe-Si sheet processing:

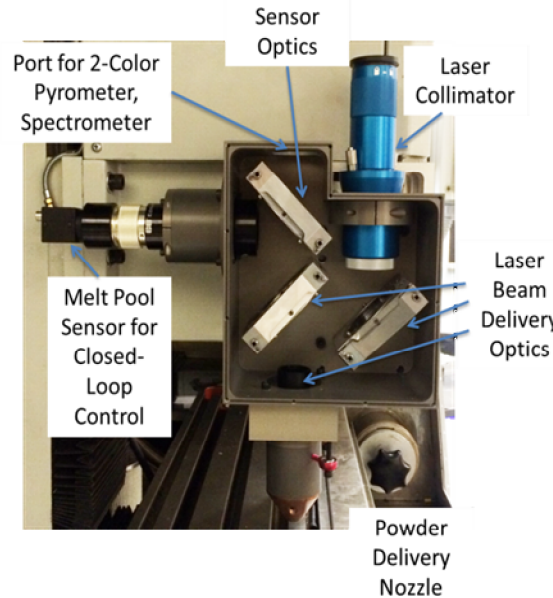
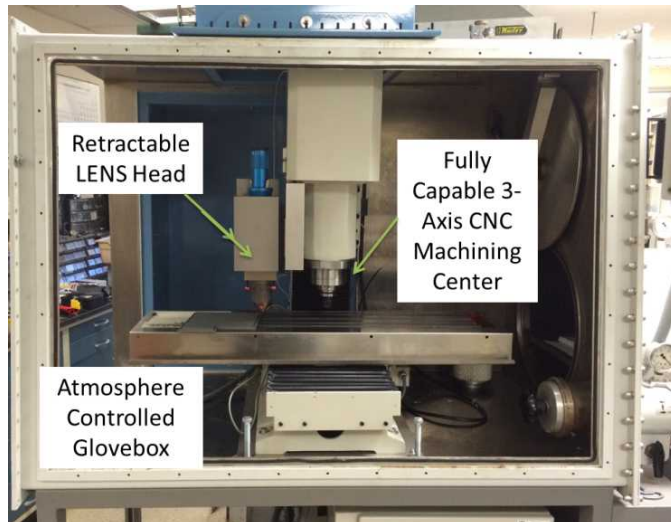
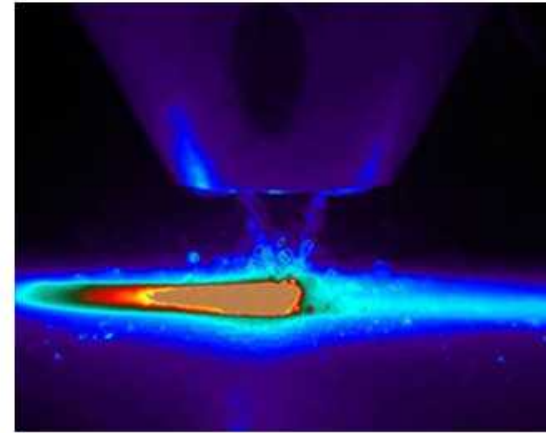
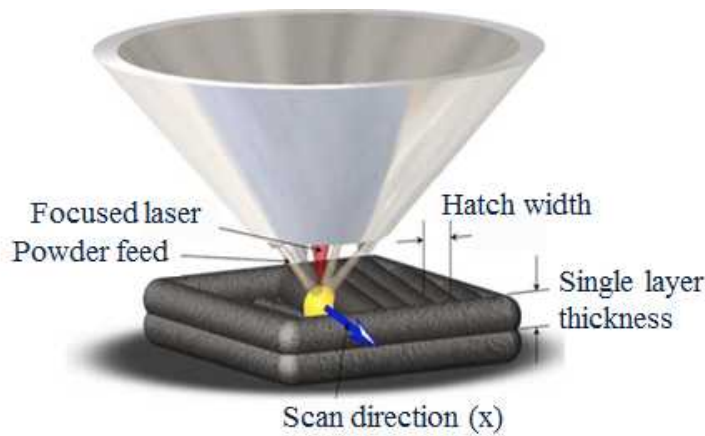
1. Multi-step nature (both hot and cold) for bar, sheet, strip and rod forms
  - Energy intensive and costly
2. Cannot produce ideal binary Fe-Co composition
  - Fe-Co-X alloys are required, producing suboptimal properties

## Desires:

1. Achieve ideal binary composition in near-net shape (reduce manufacturing steps)
2. Test the hypothesis that AM can be used to control the degree of atomic ordering in bulk shapes

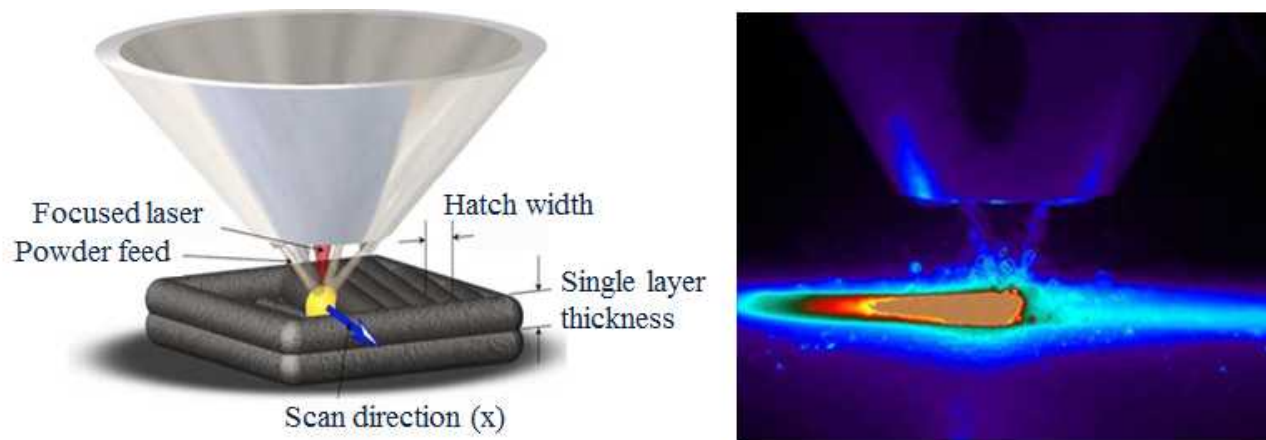
**Metals additive manufacturing (AM) – Laser  
Engineered Net Shaping (LENS)**

# Sandia LENS capability



- Laboratory-scale LENS in Tormach CNC 770 frame.
- YLS-2000 Laser from IPG Photonics with 2 kW maximum output at 1064 nm.
- Control the powder feed through feed wheel and carrier gas (independently) to fluidize the powder.

# LENS experimental procedure



- Goal: Demonstrate LENS with Fe-Co and Fe-Si pre-alloyed powders (Sandvik)
- Varied LENS process conditions – effects on order-disorder transformation in Fe-Co-1.5V alloy
- Microstructure and texture – electron backscatter diffraction (EBSD)
- Magnetic properties – B-H rings on SMT-700 system following ASTM-A773 (Magnetic Instrumentation, KJS Associates, IN)

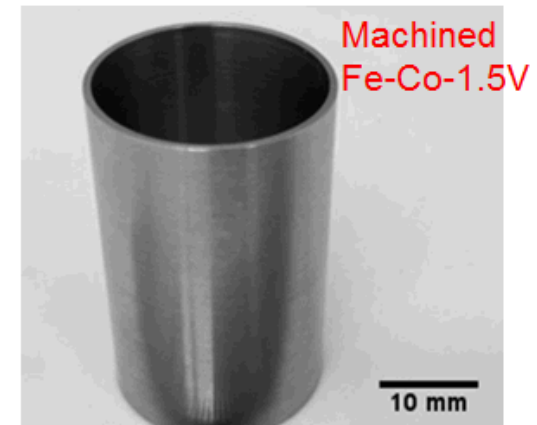
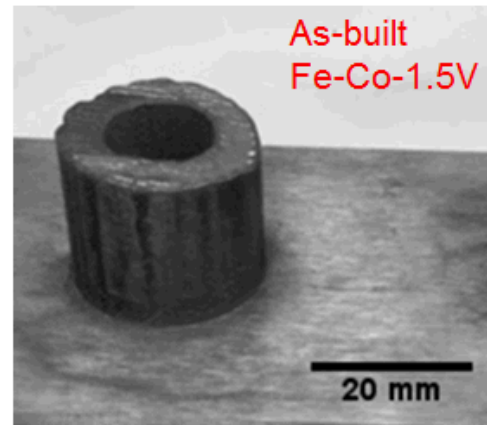
# LENS of soft ferromagnetic alloys

## Conditions

Laser power = 150-450 W

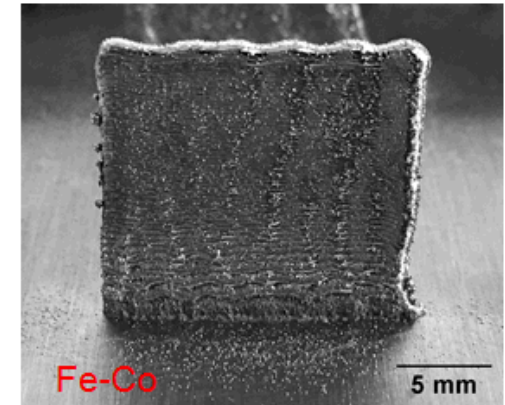
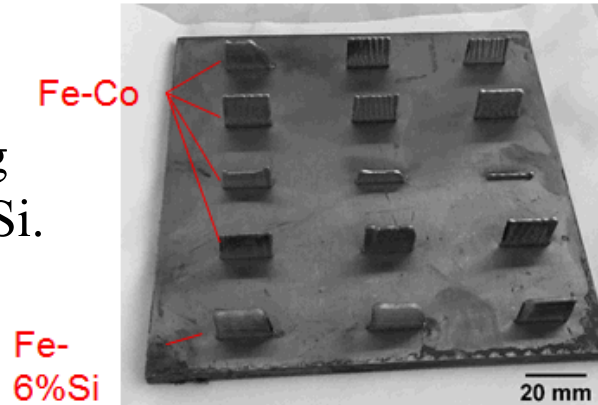
Build speed = 150-600 mm/min

Interlayer interval time = 0.3-10 s



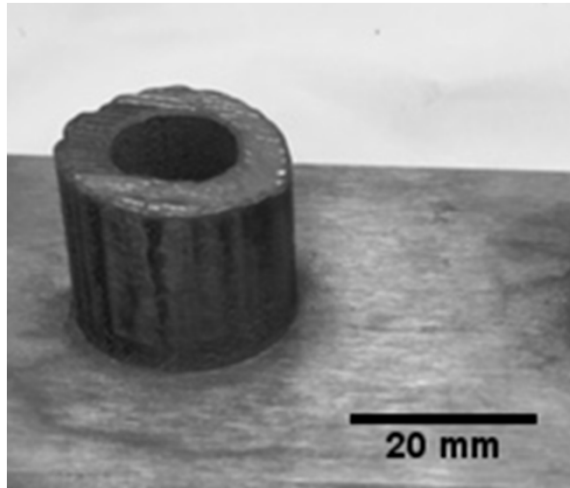
## Feature Result

Fe-Co and Fe-Si alloys were processed *via* LENS – including Fe-Co-1.5V, Fe-Co, and Fe-6%Si.

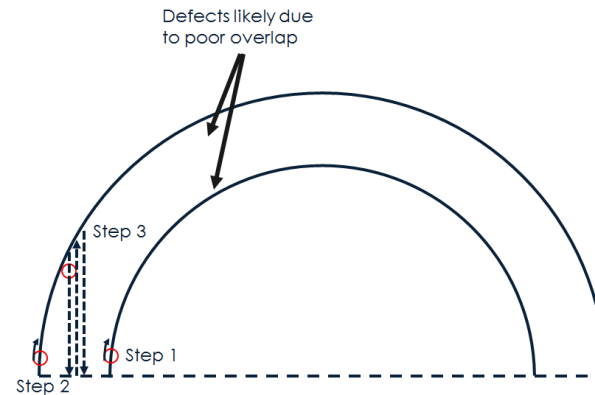


# Build strategy matters!

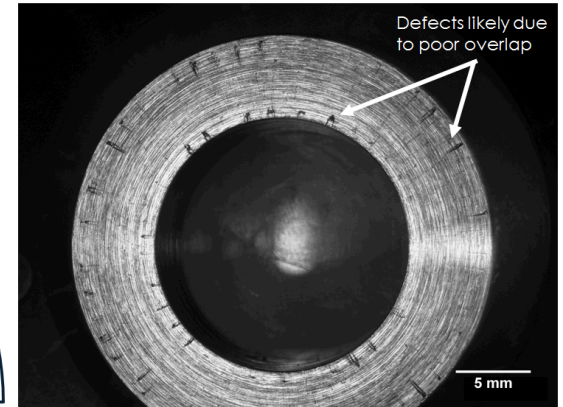
Defects from cross-hatch pattern.



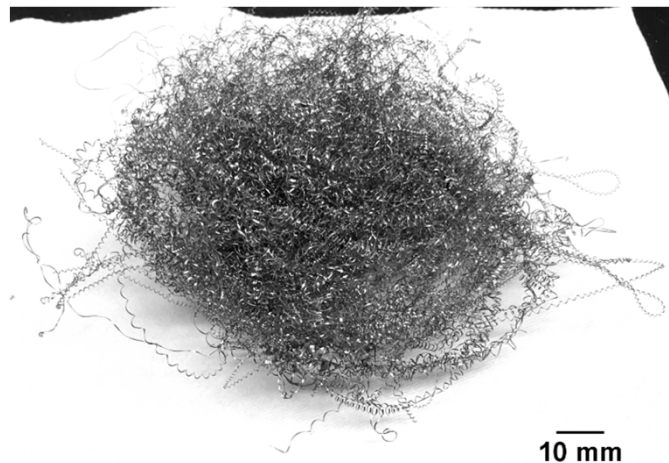
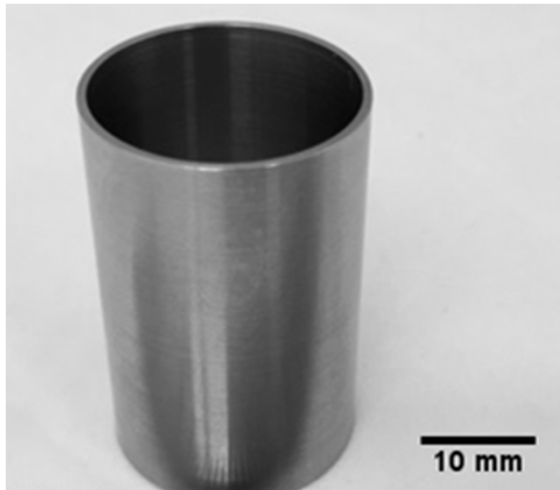
(a)



(b)



**BUT** with a concentric pattern, **no defects** and long continuous chips during machining, often a feature in cutting ductile metals (e.g., Al, Cu, Fe, etc.).



“...ductile metals tend to form long, continuous ribbon-shaped coils... such long continuous chips tend to form tangled nests...”

pg. 479 in 2<sup>nd</sup> edition of Metal Cutting Principles by Milton Shaw

# Measuring atomic ordering

- Laser power, build speed, and time between subsequent layers (interlayer interval time) were varied.

## Processing parameters were selected to:

1. Vary the degree of retained heat within LENS thin walls.
2. Impose near order of magnitude variation in specific energy and predicted cooling rate.

**Bloemburgen Model:**  $\frac{dT}{dt} \cong \frac{\alpha Q v_b^{1/2}}{d^2 (2\rho c k d)^{1/2}}$

**Rosenthal Model:**  $\frac{dT}{dt} \cong \frac{\kappa v_b}{\alpha Q} (T_m - T_o)^2$

## Characterization of ordering:

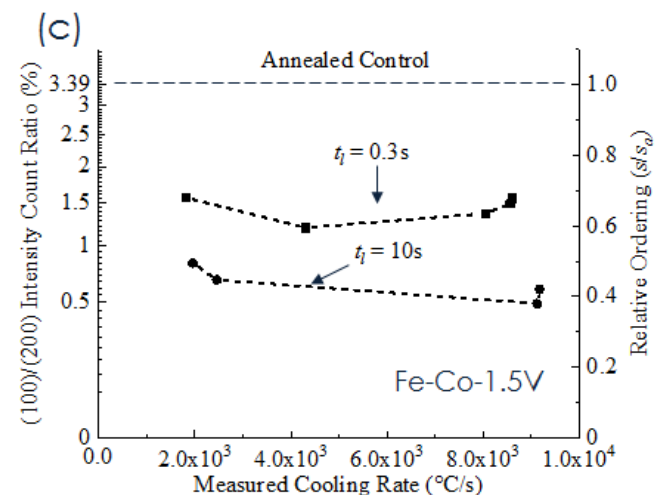
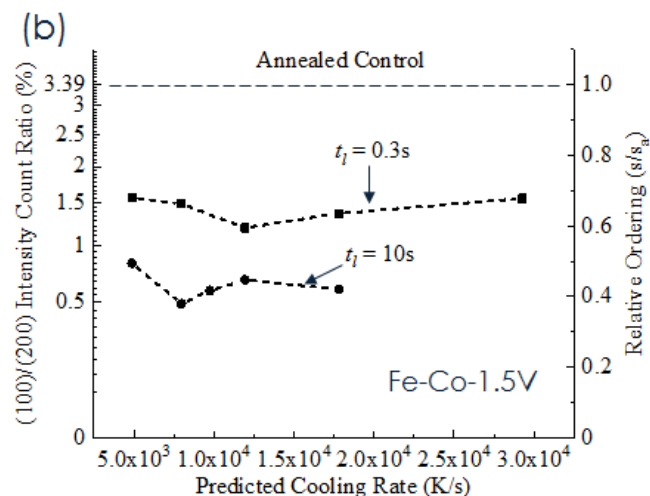
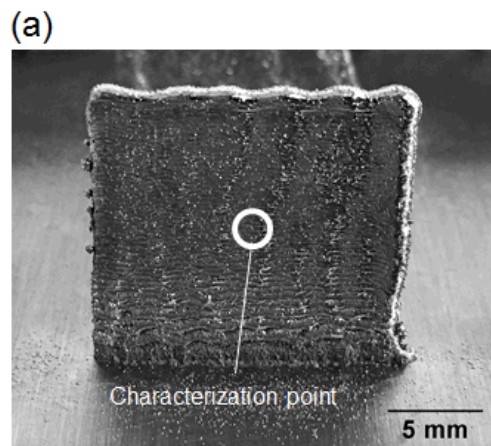
- Used Cobalt X-ray radiation to characterize samples.
- Tracked (100) superlattice peak count intensity relative to (200).
- Ratios were normalized to an annealed condition for **relative** ordering.

**Relative Ordering Parameter**  $\frac{s}{s_a} = \sqrt{\frac{I_{100}}{I_{200}}}$   
 $\frac{s}{s_a} = \sqrt{\left(\frac{I_{100}}{I_{200}}\right)_a}$

Processing Parameters			Output Parameters*		
Laser Power (W)	Build Speed (mm/min)	Interlayer Interval Time (s)	Specific Energy (J/mm <sup>2</sup> )	Rosenthal Model Predicted Cooling Rate (K/s)	Bloemburgen Model Predicted Cooling Rate (K/s)
150	150	0.3	75	1.1 E4	4.9 E3
150	400	0.3	28	2.8 E4	8.0 E3
300	225	0.3	100	8.0 E3	1.2 E4
300	500	0.3	45	1.8 E4	1.8 E4
450	600	0.3	56	1.4 E4	2.9 E4
150	150	10	75	1.1 E4	4.9 E3
150	400	10	28	2.8 E4	8.0 E3
300	150	10	150	5.3 E3	9.8 E3
300	225	10	100	8.0 E3	1.2 E3
300	500	10	45	1.8 E4	1.8 E4

\*Near order of magnitude change in output parameters

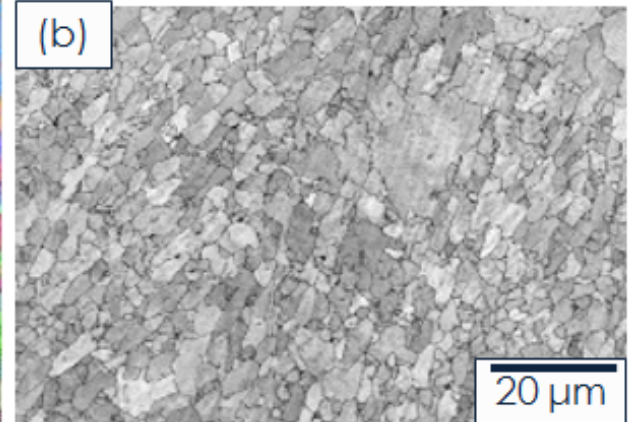
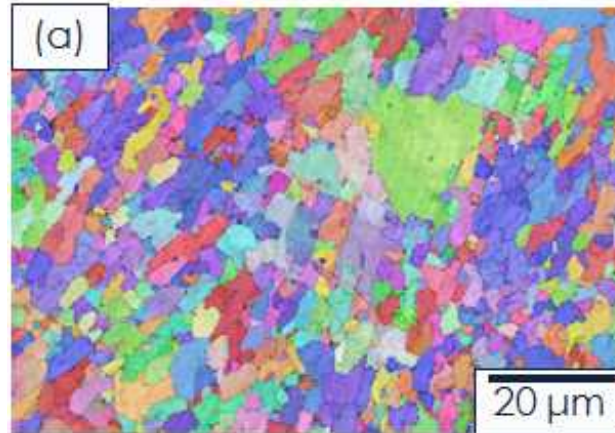
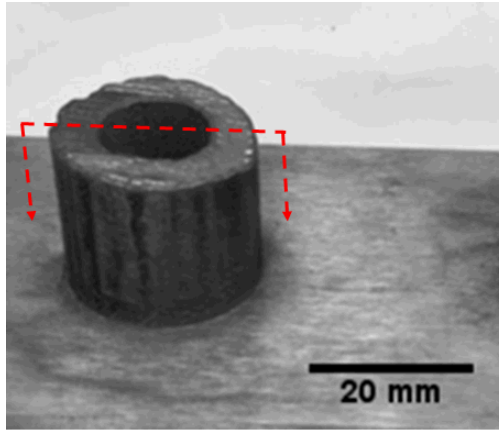
# Reduced ordering *via* LENS!



Laser Power (W)	Build Speed (mm/min)	Interlayer Interval Time (s)	I <sub>100</sub> (counts)	I <sub>200</sub> (counts)	I <sub>100</sub> /I <sub>200</sub> (%)	Relative Ordering (s/s <sub>a</sub> )
Annealed Control			684	20183	3.39	1
150	150	0.3	481	30722	1.57	0.68
150	400	0.3	547	39194	1.49	0.66
300	225	0.3	394	32866	1.2	0.59
300	500	0.3	462	33807	1.37	0.64
450	600	0.3	409	26280	1.56	0.68
150	150	10	173	20945	0.83	0.5
150	400	10	160	32949	0.49	0.38
300	150	10	73	12478	0.59	0.42
300	225	10	72	10570	0.68	0.45
300	500	10	181	29976	0.60	0.42

- **Hypothesis validated:** AM samples were less ordered (s) than annealed condition (s<sub>a</sub>).
- Laser power and speed negligibly influenced ordering.
- Walls with less interlayer interval time were more ordered – **more retained heat**.
- Supported by thermal measurements – **sharper gradients for lower interlayer interval times and less ordering**

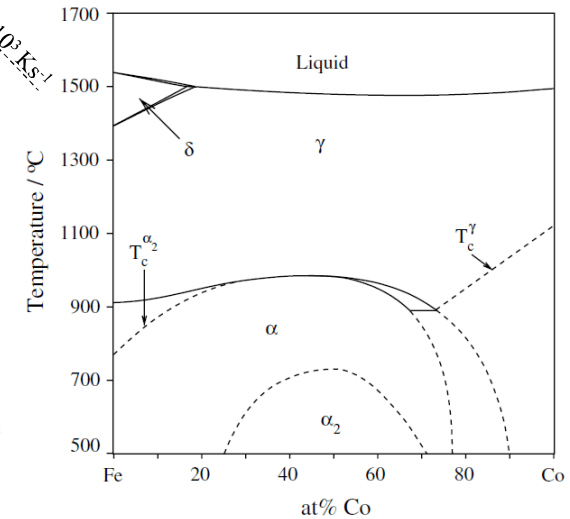
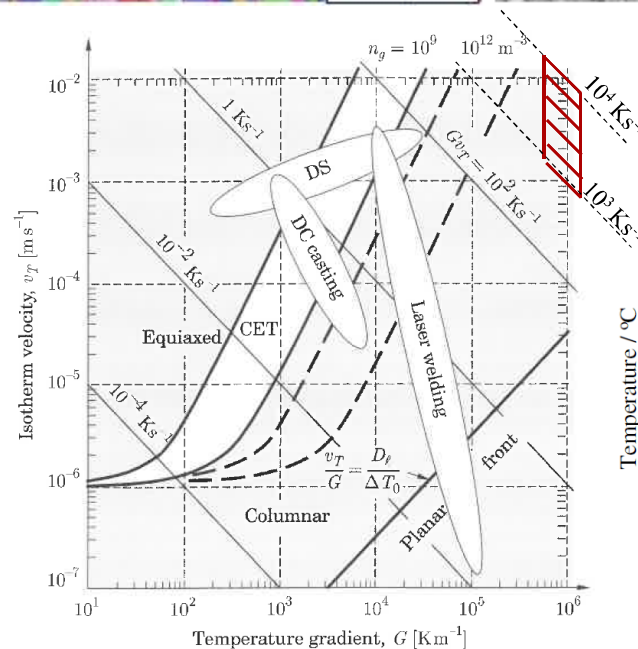
# As-built microstructure



- Unique, fine equiaxed ( $d = 2\text{-}2.5$  micron) as-built structure with almost no texture in LENS cylinders – **why?**
- Thermal measurements suggest columnar structures to be expected

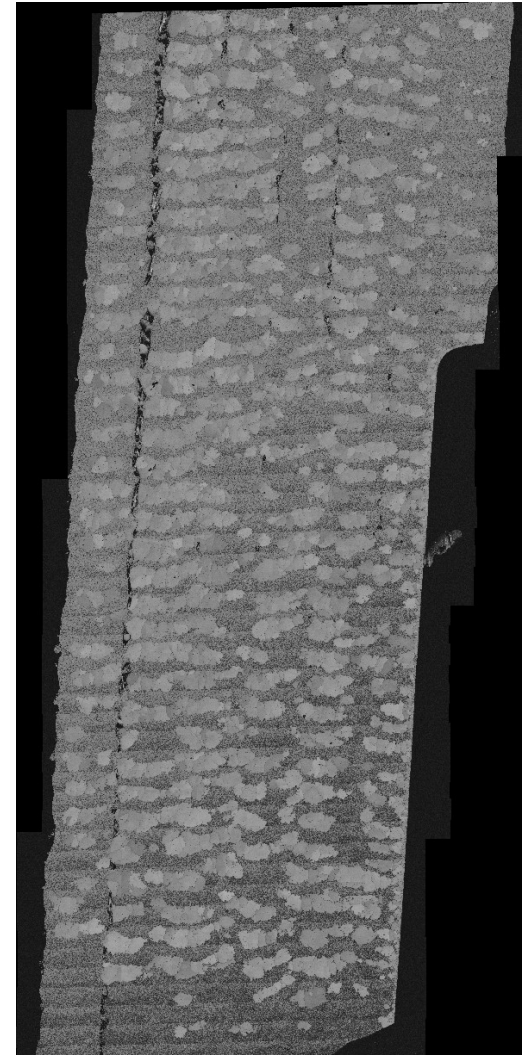
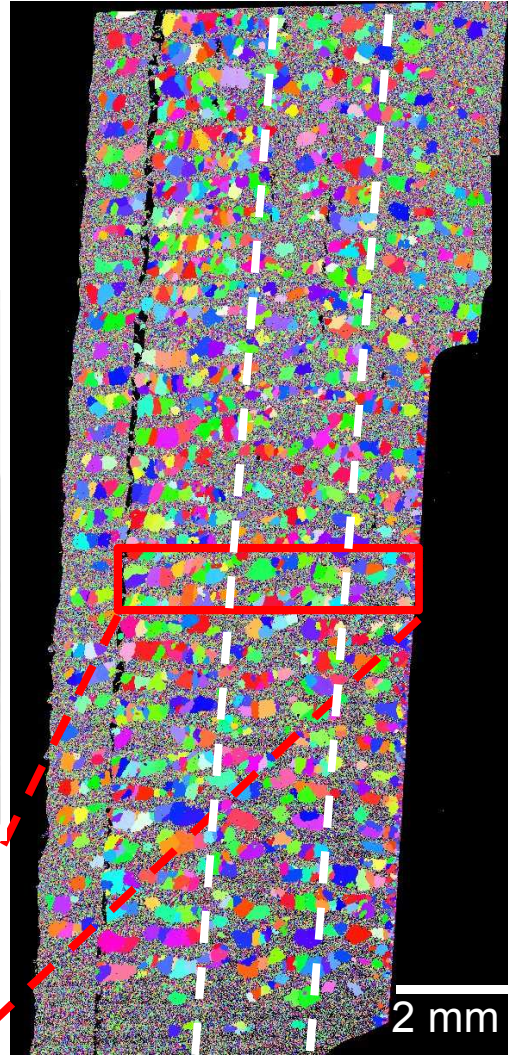
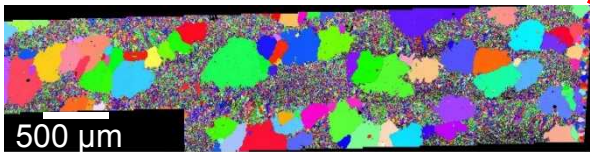
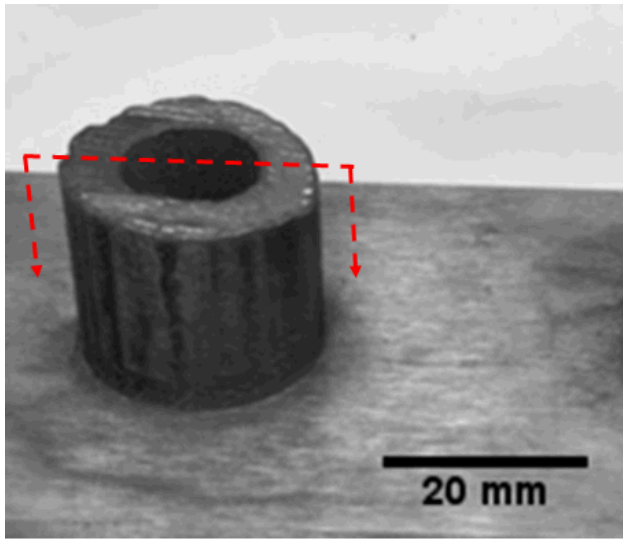
Currently investigating, some ideas:

1. layer-by-layer annealing
2. oxide inclusions and other inoculants
3. cyclic solid-state phase transformation



# Annealed microstructure

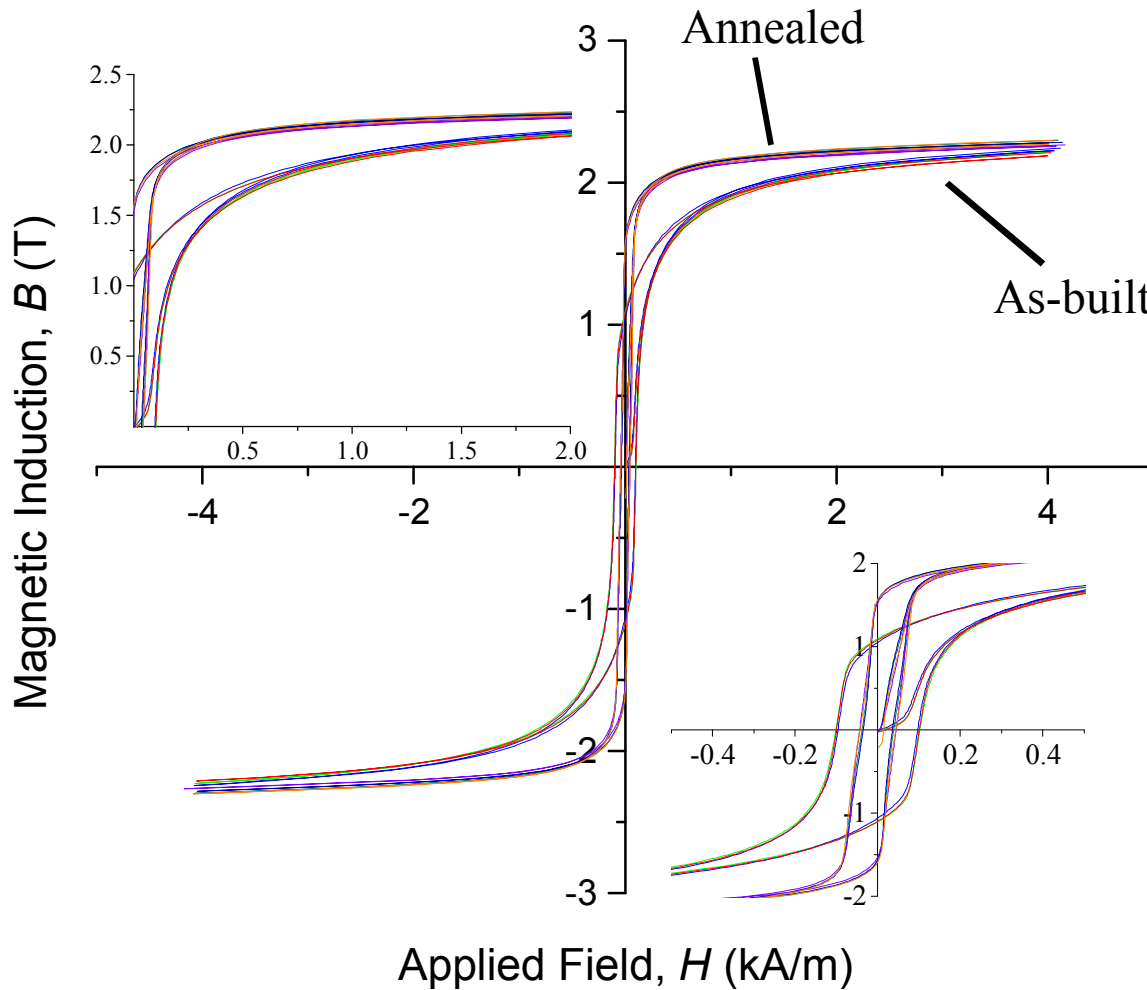
Annealed at 838°C for 2 hours  
under high vacuum ( $< 1 \text{ E-5 torr}$ ),  
2.3°C/min furnace cooling.



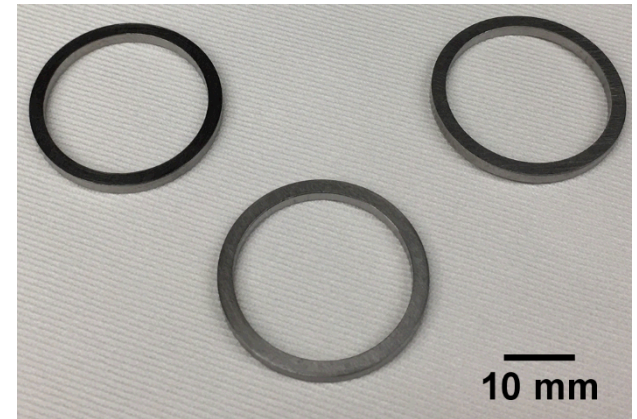
- Unique bimodal equiaxed grain structure with large grains dispersed in a fine grain matrix – *why?*
- large grains,  $d \sim 200 - 600$  micron – *good for magnetic*
- fine grain matrix,  $d \sim 2-2.5$  micron – *good for mechanical*

***Magnetic Properties?***

# Quasi-static hysteresis loops



- As-built condition exhibited a more 'sheared' hysteresis loop – magnetically harder
- Properties were consistent for given condition
- Weak texture promotes isotropy



Fe-Co-1.5V B-H rings for magnetic properties characterization

# Properties are within reported values

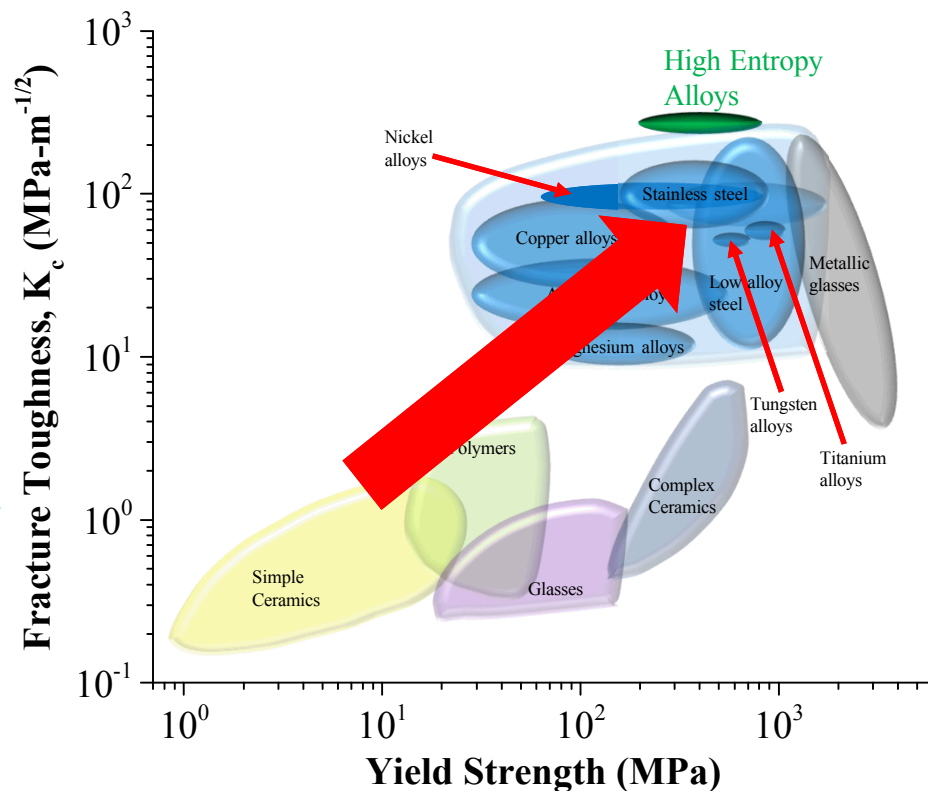
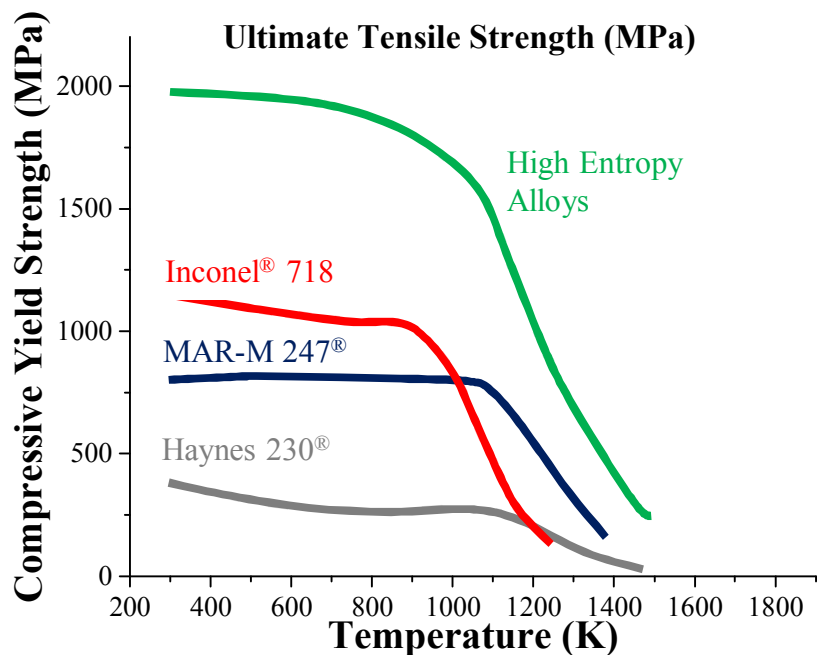
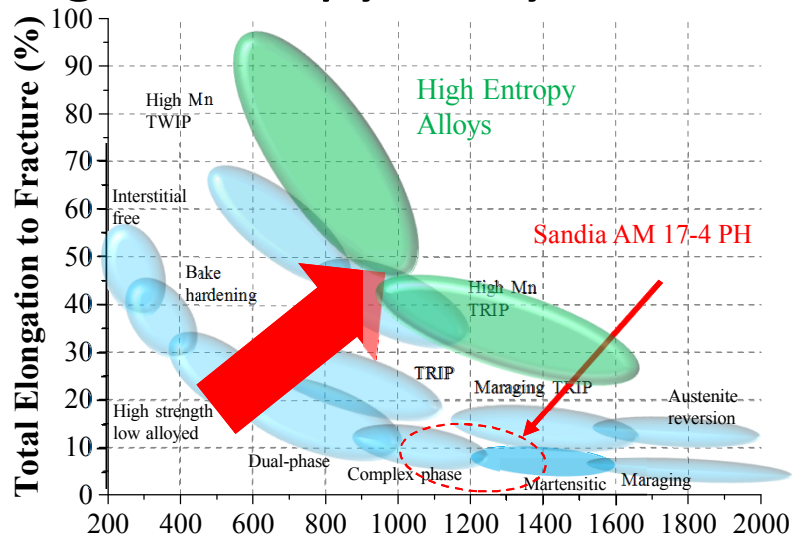
Condition	Specimen	Maximum Induction, $B_{max}$ (T)	Coercivity, $H_c$ (A/m)	Maximum Permeability, $\mu_m$
<b>As-built Fe-Co-1.5V</b>	1	2.23	1013.46	511
	2	2.24	965.58	532
	3	2.21	1005.48	512
<b>Average</b>	--	$2.23 \pm 0.012$	$995 \pm 21$	$518 \pm 10$
<b>Annealed Fe-Co-1.5V</b>	1	2.30	383.04	1639
	2	2.28	351.12	1733
	3	2.26	438.9	1571
	4	2.30	430.92	1517
<b>Average</b>	--	$2.29 \pm 0.017$	$401 \pm 36$	$1615 \pm 81$
<b>Conventionally processed Fe-Co alloys</b>				
<b>Fe-Co</b>	--	2.4	150 90-200	5000-8000
<b>Fe-Co-2V</b>	--	2.3	95-160 393	4000-8000
<b>Fe-Co-2V (as-rolled, 90%)</b>	--	2.2	2900	--

# LENS Conclusions

1. LENS successfully demonstrated on Fe-Co and Fe-Si soft ferromagnetic alloys at more ideal compositions.
2. X-ray measurements suggest reduced atomic ordering in as-built LENS thin walls compared to an annealed condition.
3. Interlayer interval time had noteworthy effects on ordering due to more time at temperature, preliminary thermal gradient measurements agree.
4. Unique fine equiaxed grain structure, which evolved abnormally during recrystallization annealing.
5. Magnetic properties were within conventional processing extremes – **compromise between magnetic and mechanical performance looks promising.**

# Another interesting AM project

## High Entropy Alloys



**Goal:** demonstrate these alloys as a materials-based solution to *achieve the promise of metals AM, i.e. insertion into high consequence applications.*

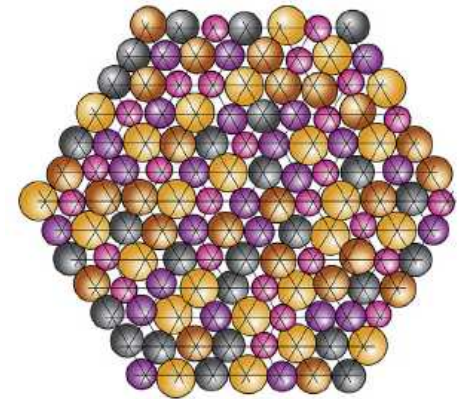
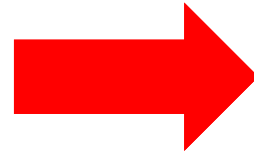
# Why explore High Entropy Alloys?

**High Entropy Alloys:** primarily solid solutions containing 5+ alloying constituents, where the solutions have high configurational entropy ( $\Delta S_{conf} > 1.4R$ , approx. 12 J/mol-K) .

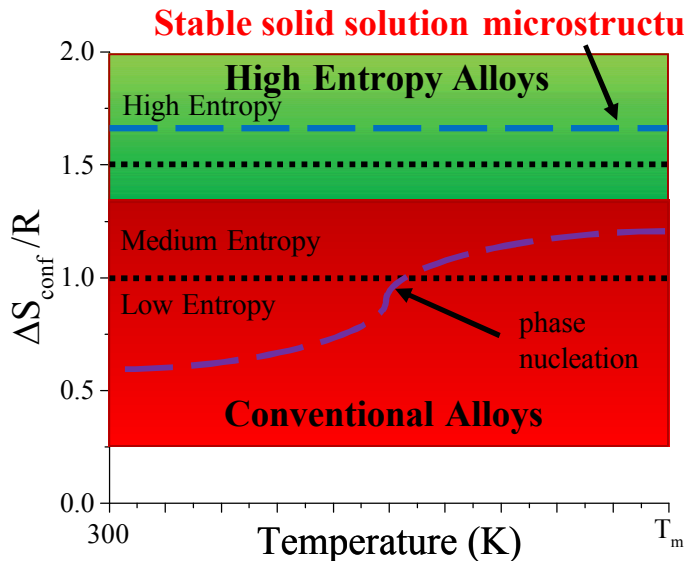
High configurational entropy is believed to thermodynamically suppresses phase separation, a primary route for degradation of mechanical properties.

## Competition between Gibbs energy for solid solution and intermetallic formation

$$\Delta G^{SS} < \Delta G^{IM} \rightarrow \Delta S^{SS} > \frac{\Delta H^{IM} - \Delta H^{SS}}{T}$$



Disordered solid solution



Thermodynamically stable and **predictable** solid solution microstructure, independent of processing!

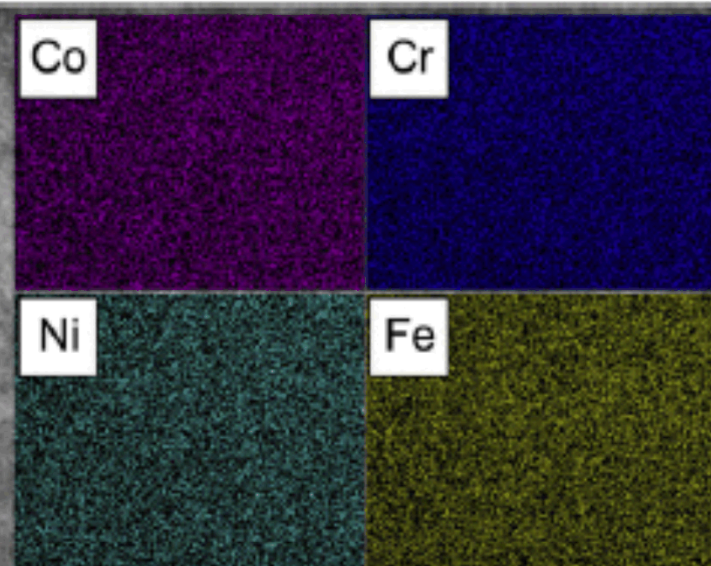
Ideal for layer-by-layer melting/re-melting of AM...

***This hypothesis remains controversial and highly-debated, and why the proposed work has high scientific impact potential.***

# Can High Entropy Alloys be a materials-based solution to metals AM?

- Due to unique
- Recent investments

Example AM CoCrFeNi HE alloy microstructure



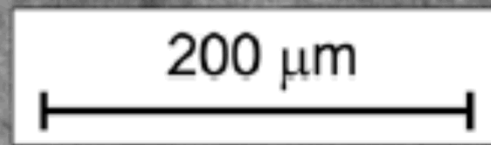
re  
detailed  
ing.  
d a  
ing

*Table I – comparison method,*

Conventional  
Laser AM  
Conventional  
E-beam /

Solid solution microstructure with homogeneous distribution of elements

re (%)  
%  
%  
%



**Punch-line:** HE alloys have consistent mechanical properties insensitive to processing method and melt/re-solidification of AM!

# Summary

Two advanced manufacturing processes were used to produce soft ferromagnetic alloys. Workability issues were overcome in both cases **for fundamentally different reasons**.

LSEM: favorable deformation mechanics suppress flow localization and cracking

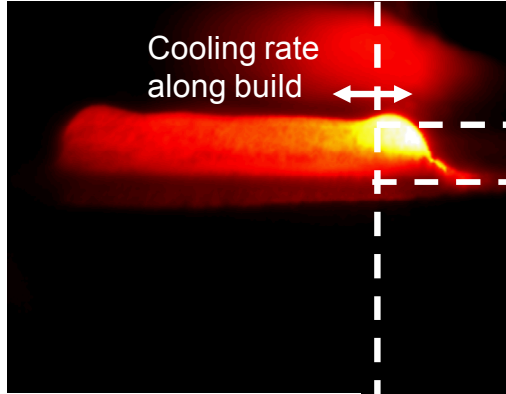
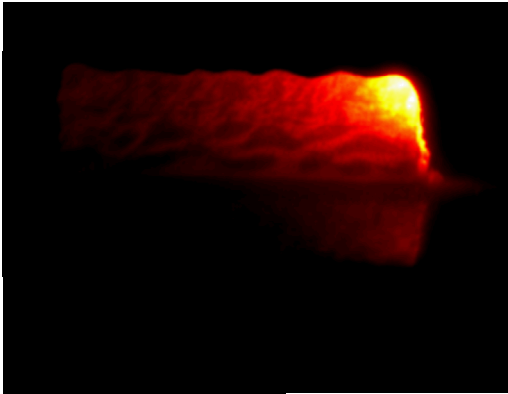
LENS AM: localized solidification-based approach avoids issues in conventional thermomechanical (deformation-based) processing

# Thermal measurements produce more questions...

- No trends between cooling rate (both FLIR and 2-color pyrometer) and relative ordering.
- Builds with lower interlayer interval time developed sharper thermal gradient for a given laser power and build speed.

Power: 150W  
Build speed: 150 mm/min  
Interlayer interval time: 10s

Power: 450W  
Build speed: 600 mm/min  
Interlayer interval time: 10s



$$\frac{dT}{dt} \approx v_b \times \frac{dT}{dx}$$

$$\frac{dT}{dt} = \text{cooling rate}$$

$$v_b = \text{build velocity}$$

$$\frac{dT}{dx} = \text{thermal gradient (horizontal or vertical)}$$

