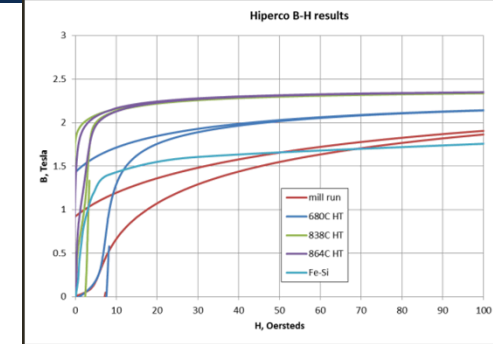
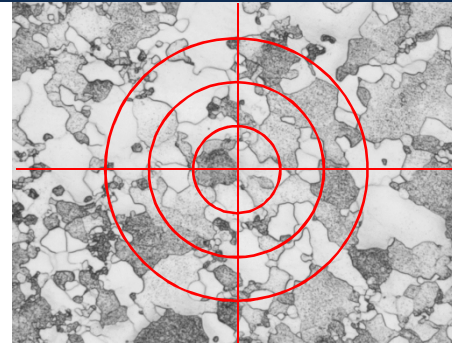
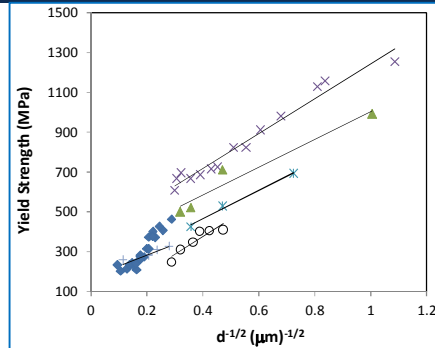
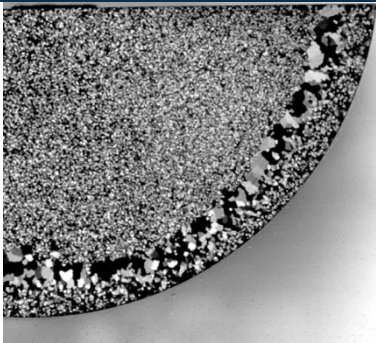


Exceptional service in the national interest



Equal Channel Angular Extrusion (ECAE) of FeCo-2V Soft Magnetic Alloy

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Dr. Ibrahim Karaman, Taymaz Jozaghi

Texas A&M, Dept. of Materials Science and Engineering

October 26, 2016

Other Collaborators

Mike Maguire – Inertia Welding

Mark Reece, Alice Kilgo, Bonnie McKenzie, Joe Michael, Blythe Clark - materials

Rick Kellogg, Sara Szarka, Patrick White – funding, components

Topics

Introduction to Hiperco[®] alloy

Equal Channel Angular Extrusion (ECAE)/Pressing (ECAP)

Microstructure of ECAE Material

Tensile Properties, Hall-Petch Behavior

Magnetic Properties

EBSD/Texture

Summary

Hiperco[®] 50A Soft Magnetic Alloy

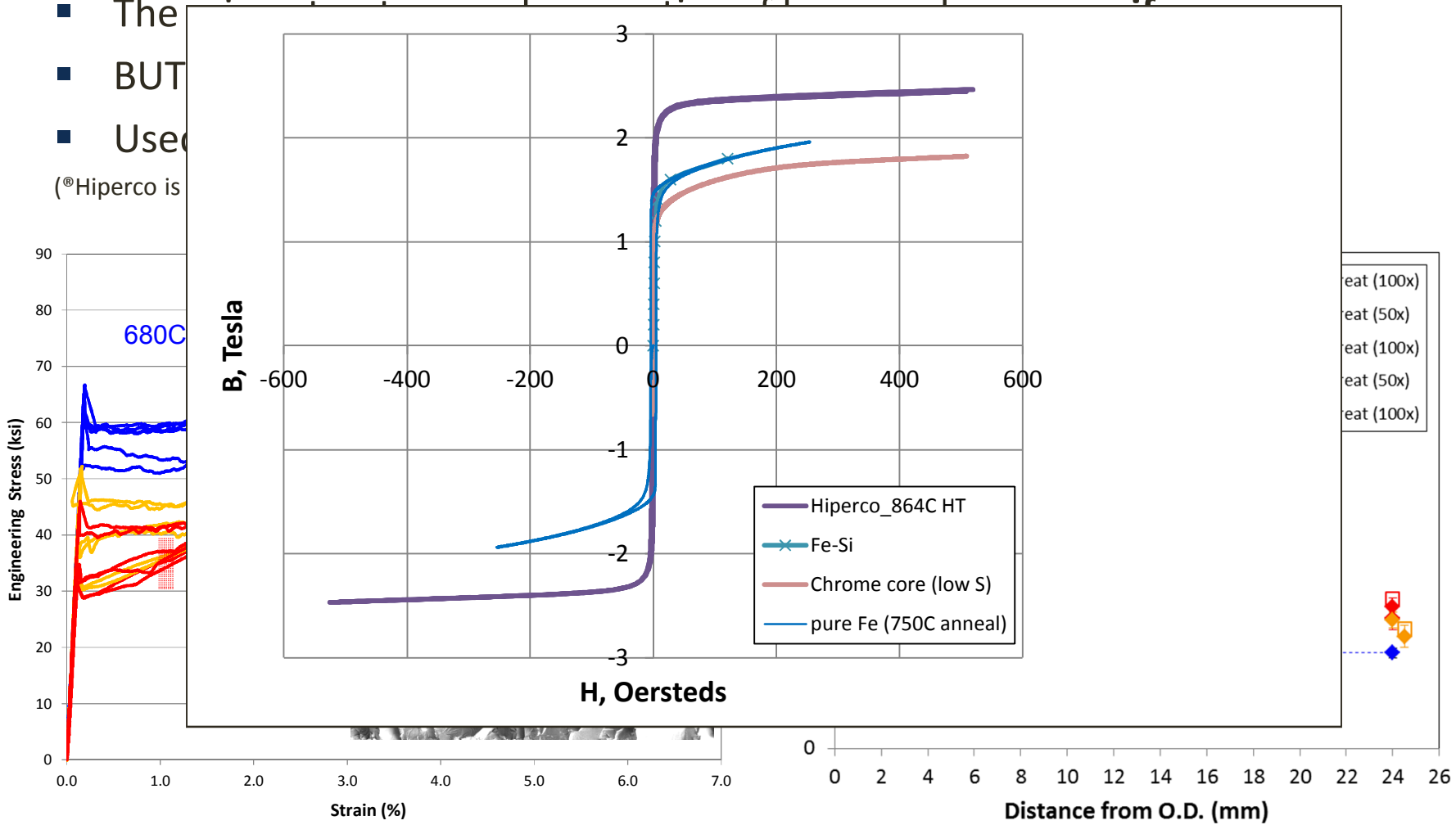
- Hiperco (Fe-Co-2V) undergoes **brittle fracture**, with **low strength** in bar form

■ The initial yield strength of Hiperco 50A is 100,000 psi

■ BUT

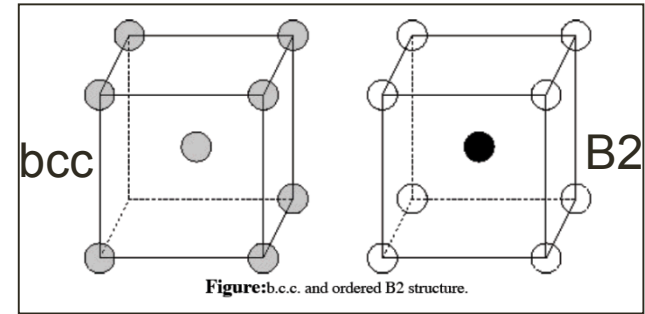
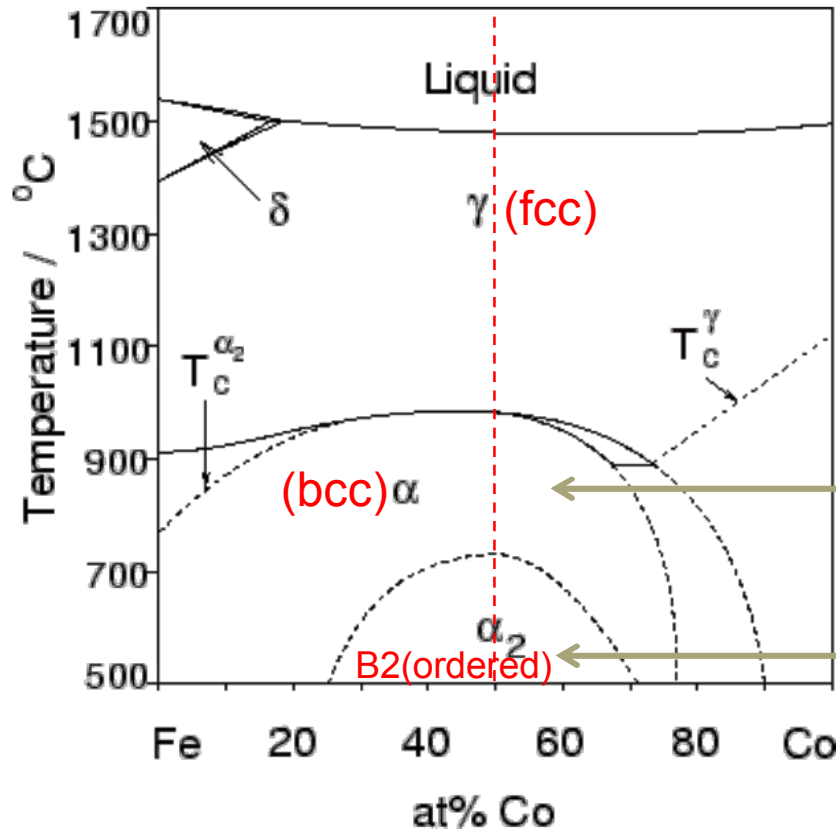
■ Used

(©Hiperco is



Presented at MS&T, 2014

Why does Hiperco[®] have poor mechanical properties?



Crystal structures of Hiperco[®] alloy

bcc: Good mechanical properties, Moderate magnetic properties

B2: Ordered structure has poor mechanical properties, Excellent magnetic properties

Figure: The Fe-Co binary diagram as given in [5]. T_c denotes the Curie temperature.

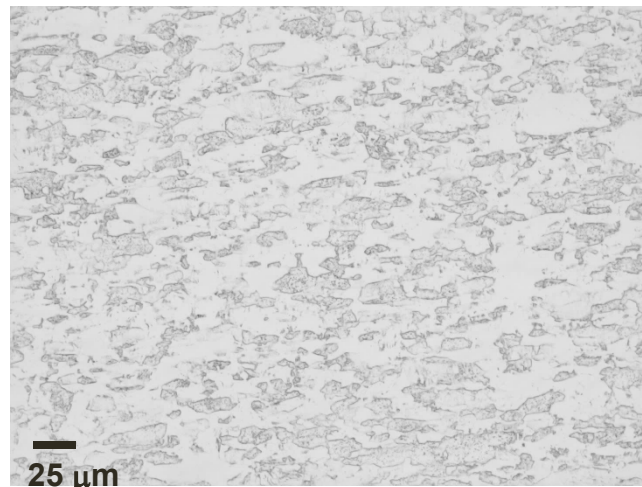
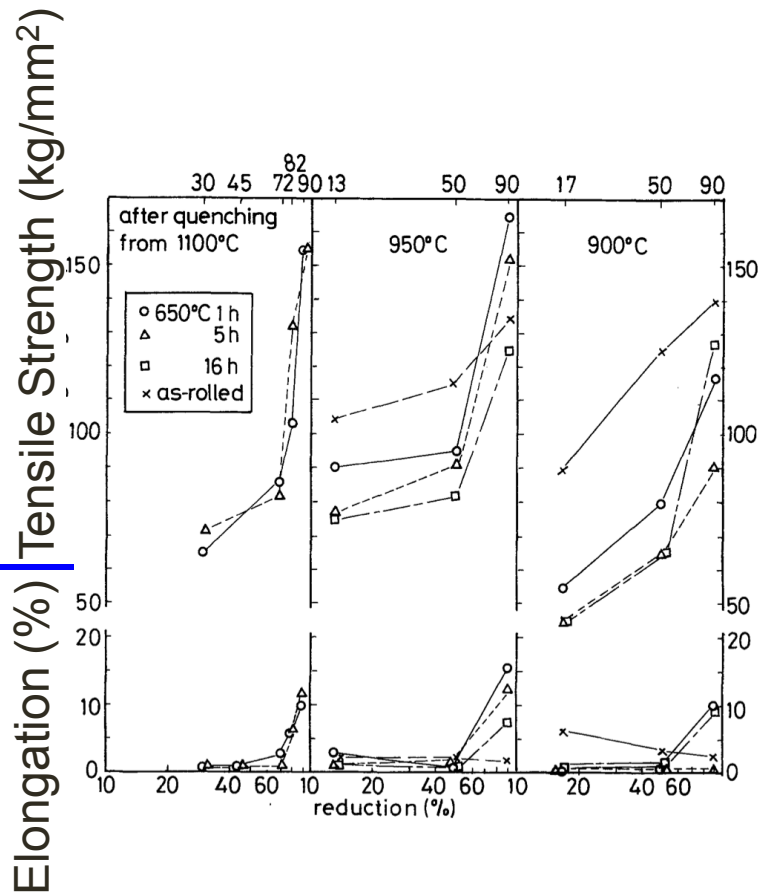
- Ordered FeCo is very brittle and low strength. Addition of 2%V provides some ductility, allowing conventional forming processes and heat treatment
- For best magnetic properties, the alloy is heat treated to **anneal AND order**

Comparison to Sheet Provides Motivation

Forged bar Hiperco[®] is weak, brittle, and inhomogeneous. In contrast, *sheet rolled* Hiperco[®] is stronger and can be more ductile, with adequate magnetic performance.

High levels of cold work (prior to ordering) enhances strength & ductility

Kawahara K., J. Mat. Sci. 18:3437-48 (1983)



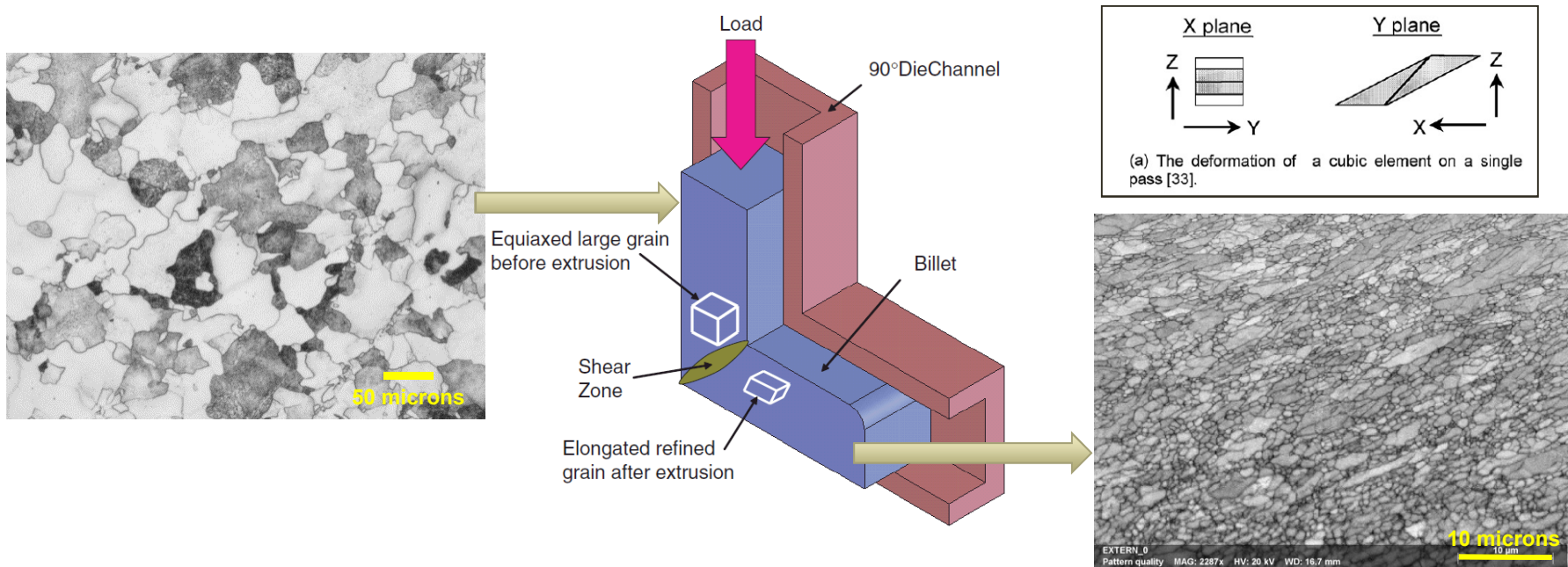
Fine grain microstructure of sheet

Current Research: Equal Channel Angular Extrusion (ECAE), a.k.a. Equal Channel Angular Pressing (ECAP)

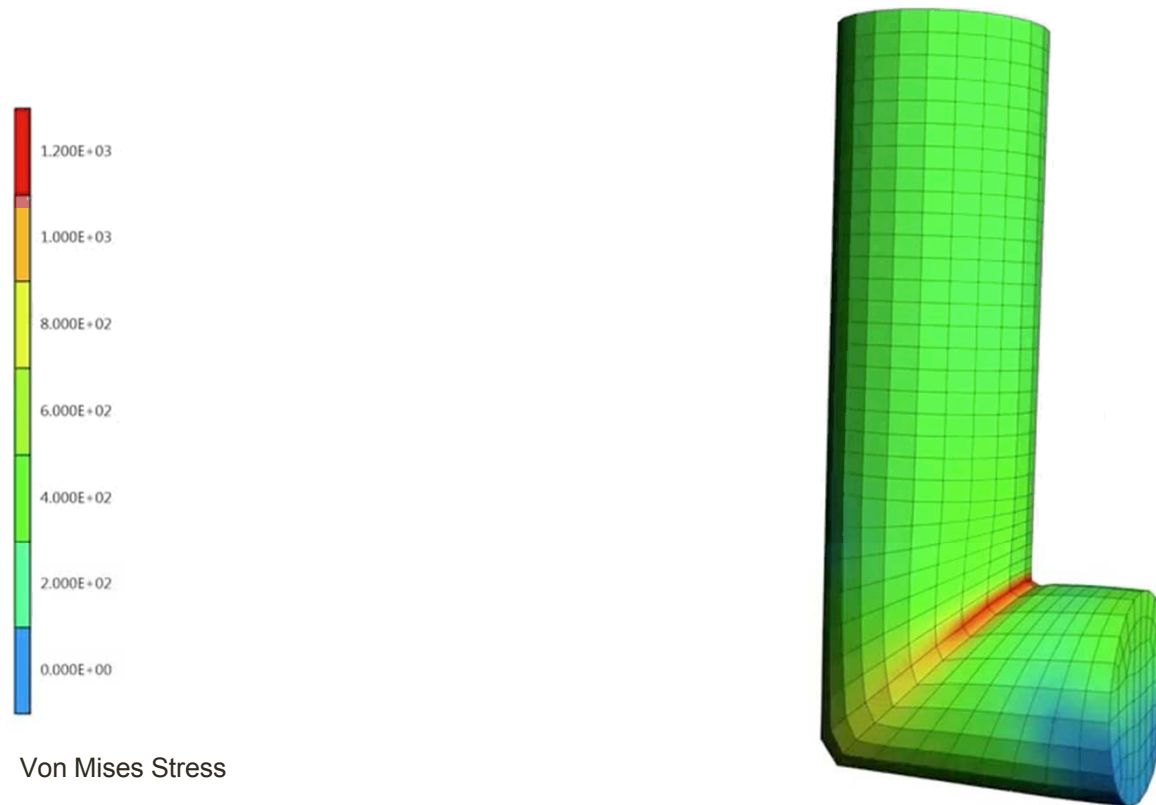
The premise: High-performance magnetic components would benefit greatly from increased mechanical strength and/or ductility in Hiperco®.

The challenge: Is it possible to produce sheet-like mechanical properties in bar? And can the magnetic performance be maintained?

Equal Channel Angular Pressing (ECAP) produces **severe plastic deformation without a change in cross-section**... nanostructured material

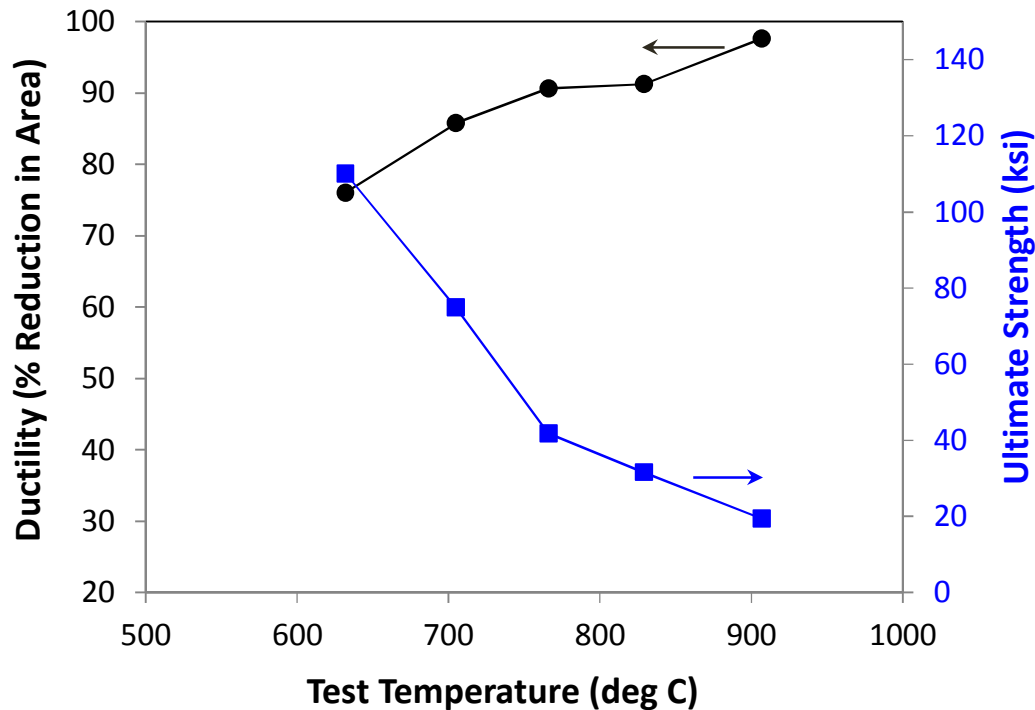


Equal Channel Angular Extrusion/Pressing



A.V. Shutov and R. Kreißig, *Comp. Methods in Applied Mech. and Eng.*, 197(21-24), pp 2015-29, 2008.
A.V. Shutov et al., *Materialwissenschaft und Werkstofftechnik*, 43(7), pp 617-25, 2012.

High-Temperature Ductility Enables ECAE

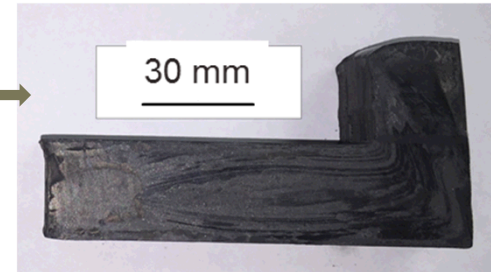


- High temperature tensile testing shows Hipercoco[®] has appreciable ductility at high temperatures ($\geq \sim 750^{\circ}\text{C}$)
- Encouraging enough to proceed with ECAE trials *at high temperature*
- Collaboration with Texas A&M ECAE laboratory

11+ ECAE trials completed at Texas A&M

HCO-1	4E 850C (WQ)	Microstructure, tensile, magnetic
HCO-2	1E 750C	Extrusion didn't finish
HCO-3	1E 850C / 2&3E 750C	Significant cracking and shear bands
HCO-4	1E 950C	Significant surface cracking
HCO-5	4E 850C / 5&6E 750C (WQ)	Microstructure, tensile
HCO-6	2C 850C / 3&4C 750C (WQ)	Microstructure, tensile
HCO-7	2C 850C / 3&4C 750C / 5C 700C	Significant shear bands and load increase, indicates transformation to B2 structure
HCO-8	2C 850C / 3&4C 750C (AC)	Same as HCO-6 except air cooled Tensile tests complete
HCO-9	1&2C-850C / 3&4C-750C (WQ)	Same as HCO6
HCO-10	1&2C-850C / 3&4C-750C (WQ)	Same as HCO6
HCO-11	1&2C-850C / 3&4C-750C (AC)	Same as HCO8

(All trials: 30 min heating prior to extrusion, Extrusion rate 0.5 in. per sec.)



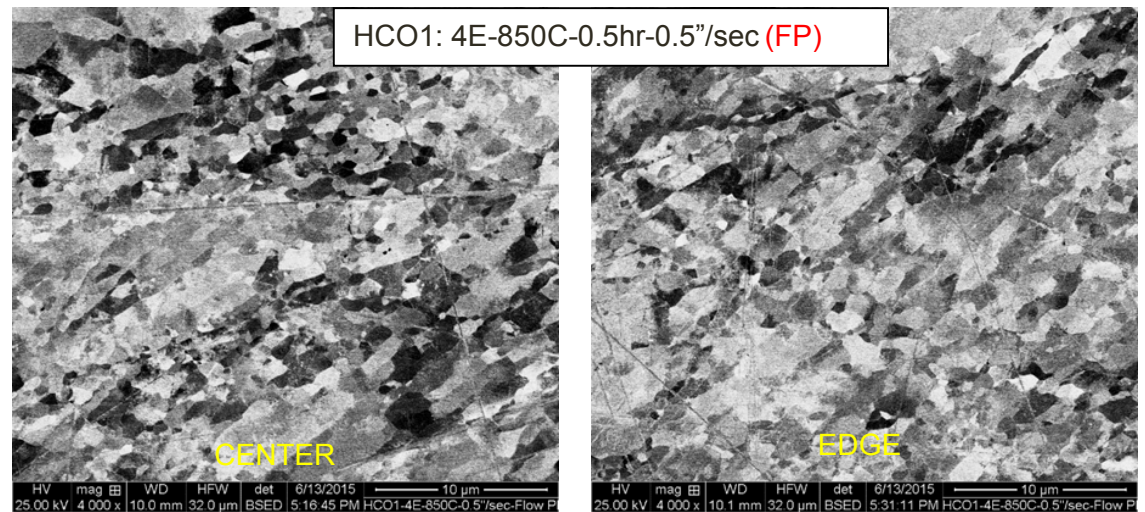
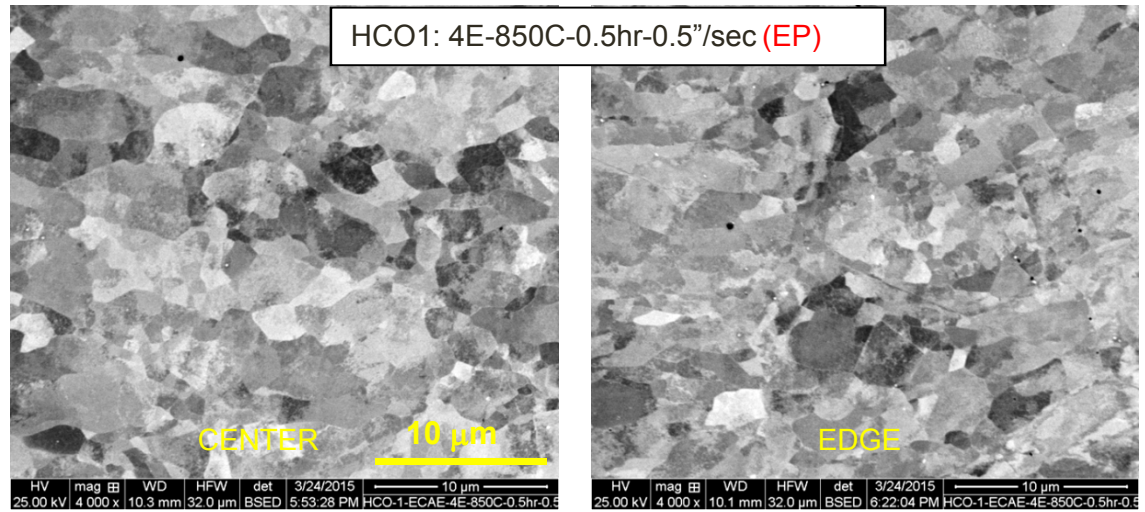
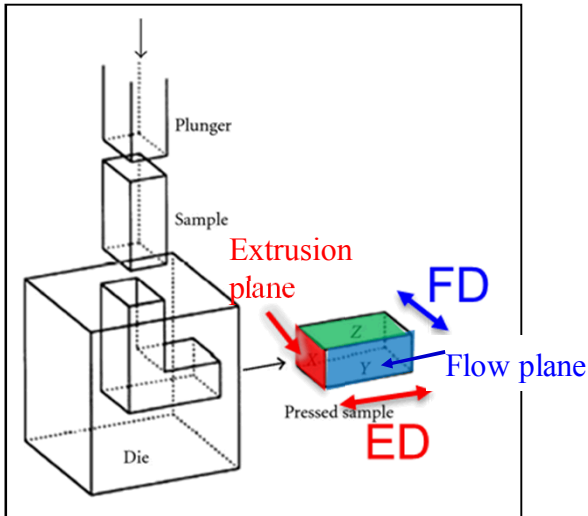
Results show ECAE at 850 → 750°C range can successfully produce material for testing

The sample is axially rotated between ECAE passes.

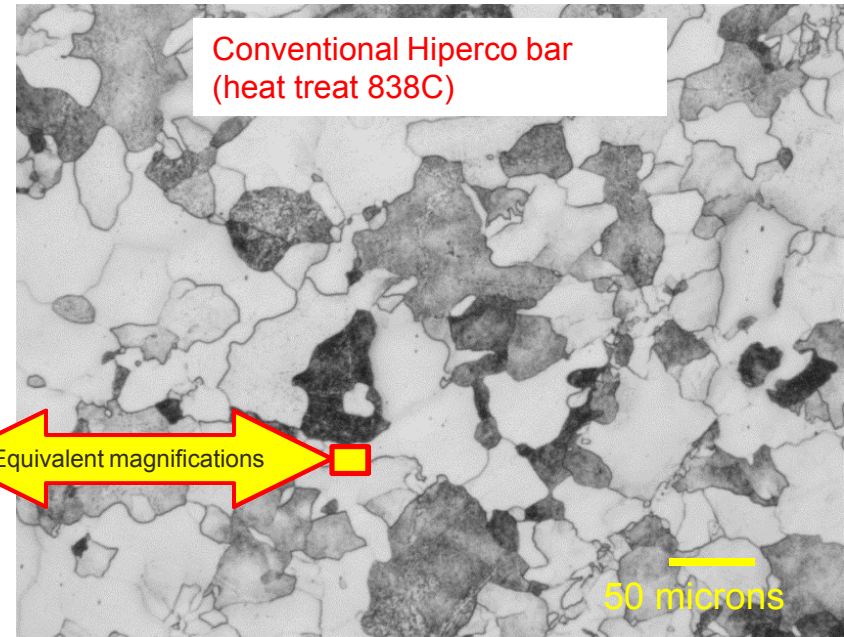
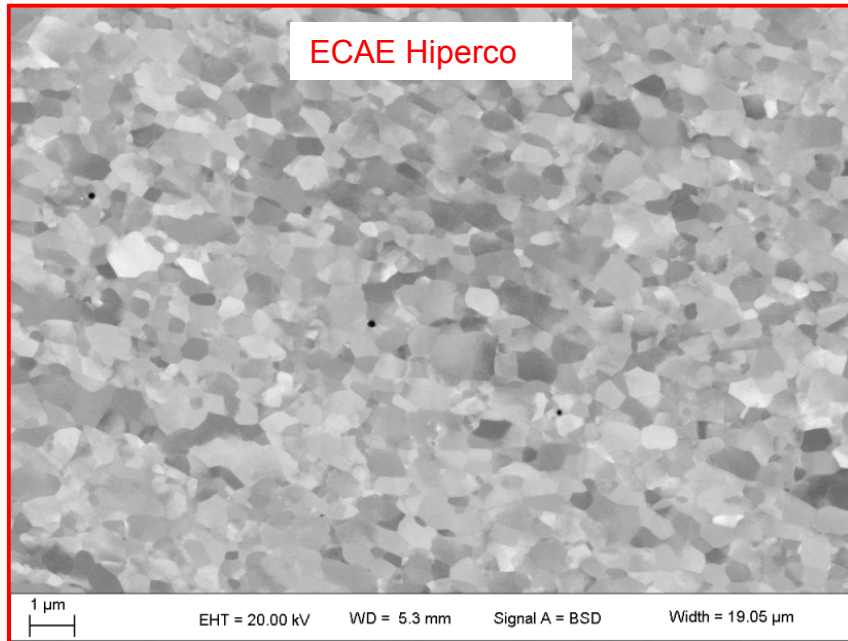
Route name	Min. # of passes	Billet rotations about the extrusion axis				Material Yield*	Effect on microstructure
		1 →	2 →	3 →	4 → N		
A	1	0°	0°	0°	etc.	0.58	elongation (lamellar)
B (B _A)	2	+90°	-90°	+90°	etc.	0.67	elongation (filamentary)
C	2	180°	180°	180°	etc.	0.83	back/forth shearing
C' (B _C)	4	+90°	+90°	+90°	etc.	0.67	back/forth cross-shearing
E	4	180°	90°	180°	etc.	0.78	back/forth cross-shearing

ECAE Hiperco: Fine Grain Size, Relatively Uniform

- Significant grain refinement achieved, 1-3 micron g.s.
- Uniform microstructure from center to edge of billet
- Note, this Hiperco has 600 ppm Nb (meant to promote grain refinement)



Compared to Typical (Forged) Bar



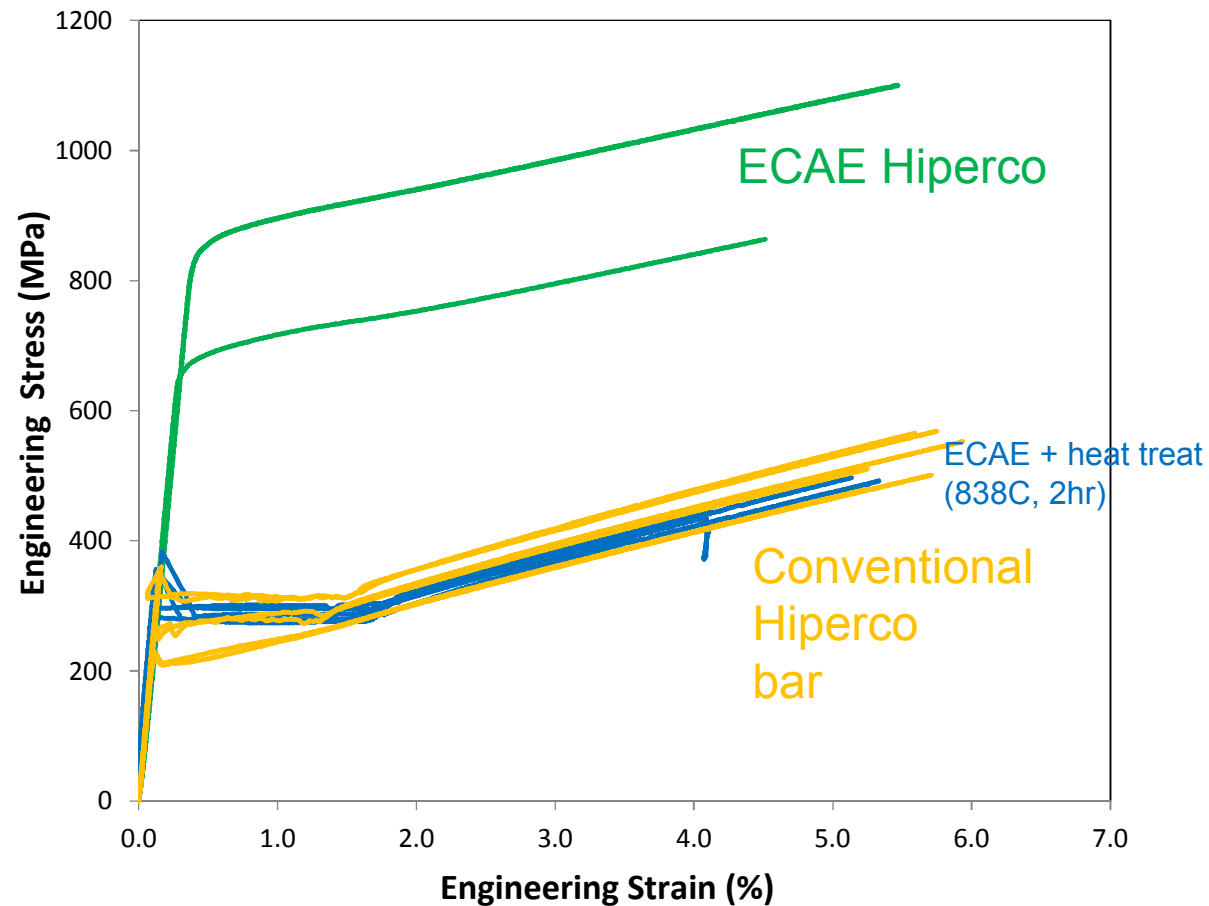
As-ECAE material vs. conventional bar (heat treated)

- Entire ECAE image (same magnification) would fit inside the small red box
- ECAE approx. 1.5 micron grain size, conventional bar ~ 25-50 micron grain size
- Current work: determine crystallographic texture with EBSD

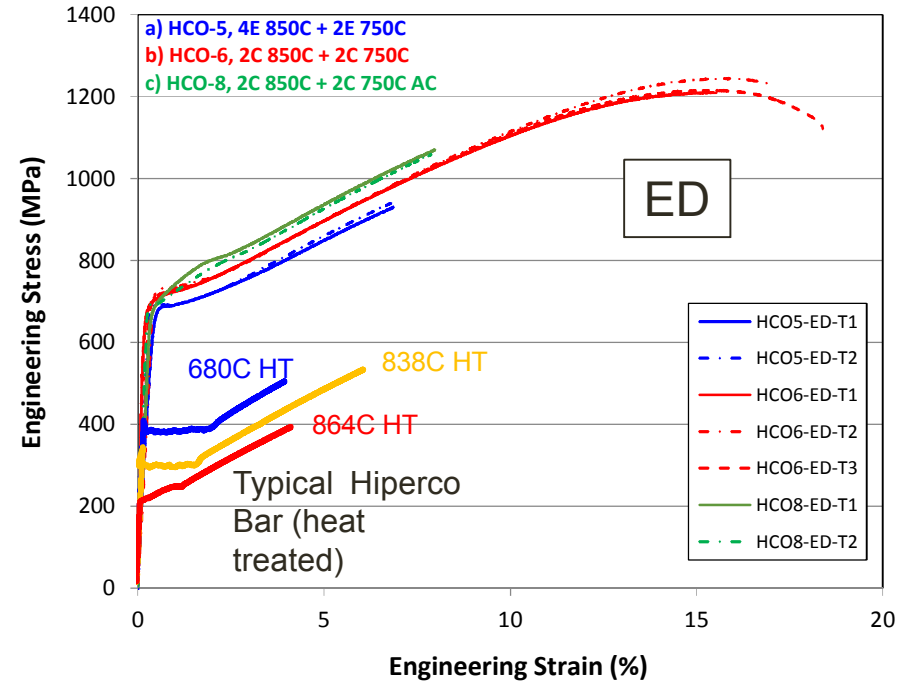
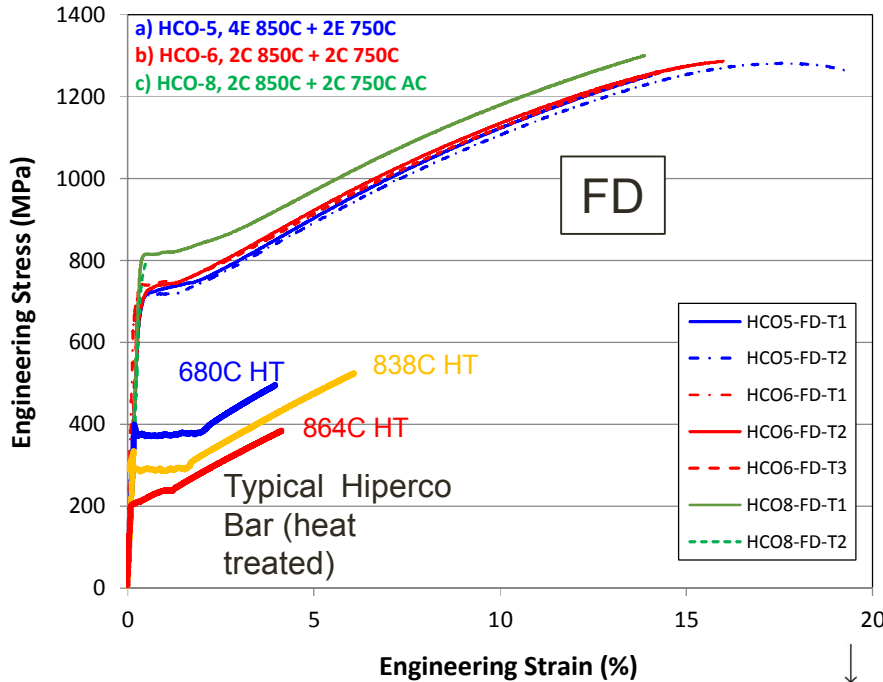
High Strength Achieved

HCO-1, 4 passes, Route E, 850C

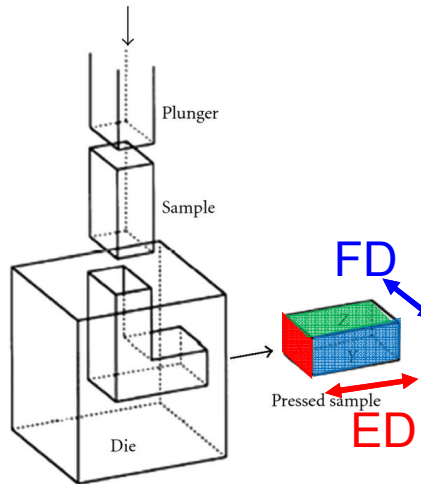
- 2 to 3 fold increase in strength in the as-ECAE condition
- Ductility is comparable to conventional Hipercó[®] bar
- Heat treatment (to gain magnetic performance) results in low strength comparable to conventional bar 😞



High Strength AND High Ductility

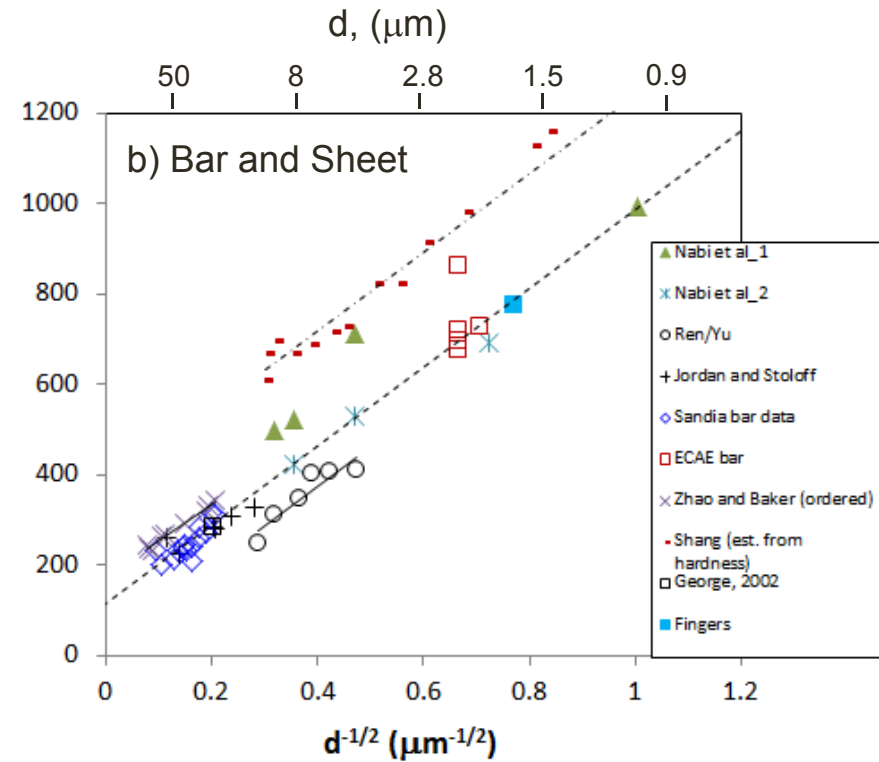
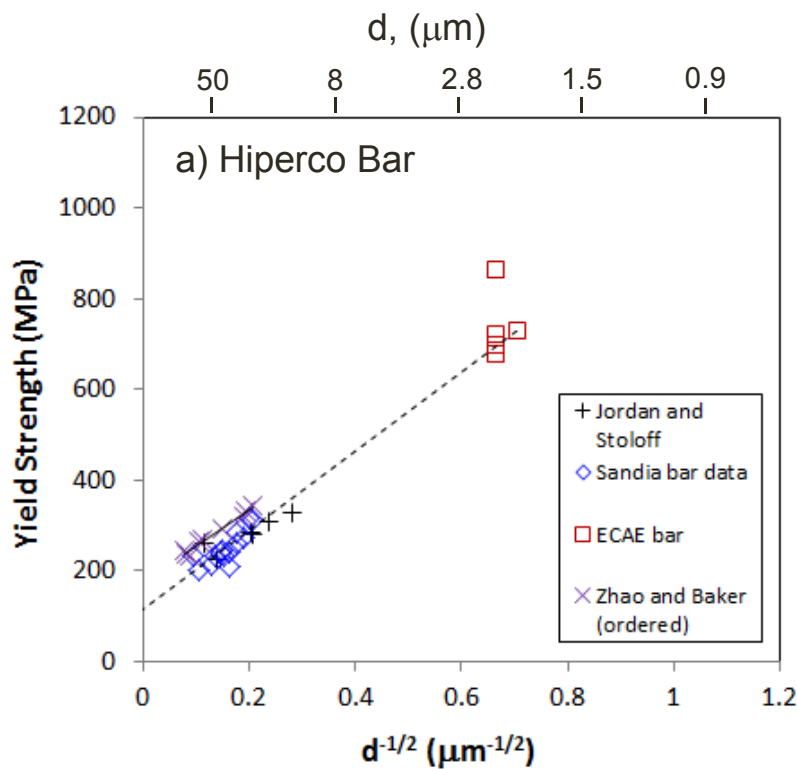


- **ECAE 750C: 2-3x stronger AND 2-5x ductility. Good properties even in transverse**
- **Route C: Appears more isotropic, in fewer processing steps**
- Note: a few samples failed in the grips with low ductility



- HCO-8 Route C with air cool after ECAE. Attempt to produce ordered B2 crystal structure *without separate heat treatment*
- **Current work: characterize for magnetic performance**

Strength follows Hall-Petch Relationship



- Highest strength FeCo-2V ever produced in *BAR* form (*As-ECAE condition*)
- Strength comparable to fine-grain, cold-worked sheet

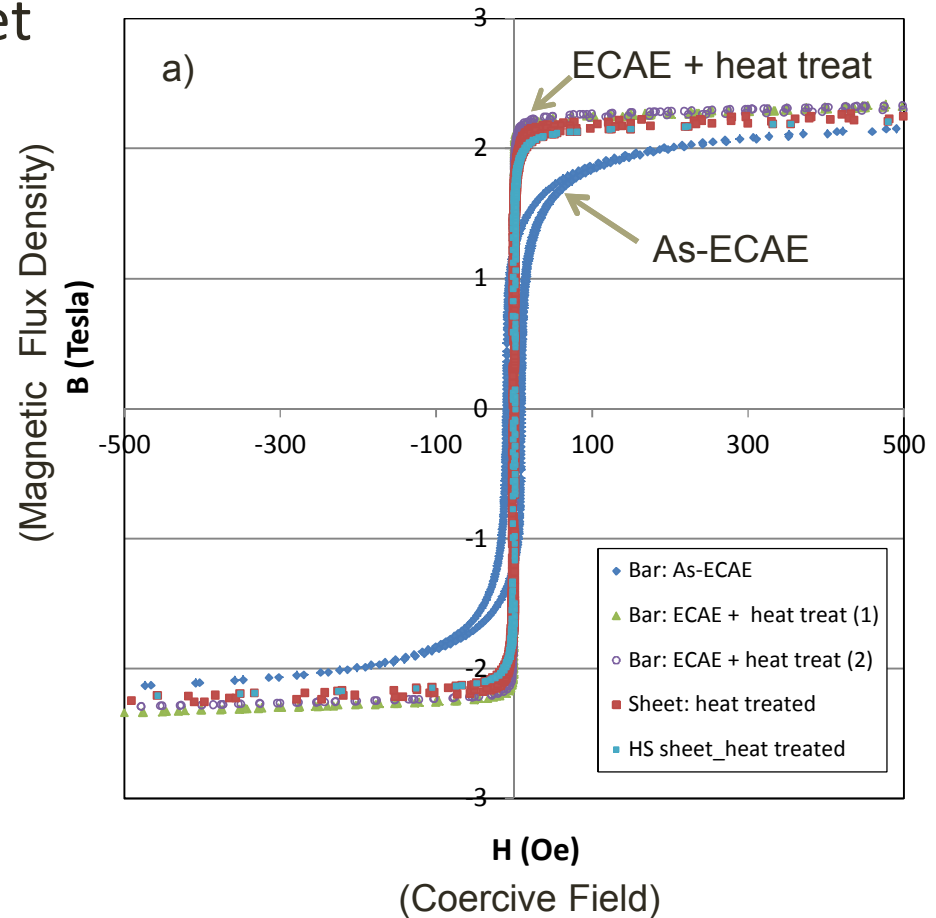
Follows Hall-Petch relationship: $\sigma_y = \sigma_o + kd^{-1/2}$

σ_y : yield strength, σ_o : intrinsic (friction) stress,

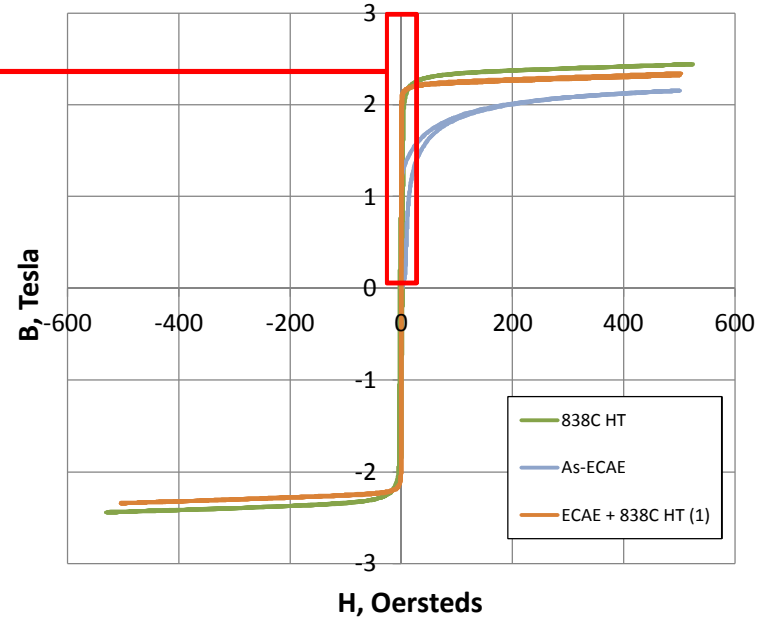
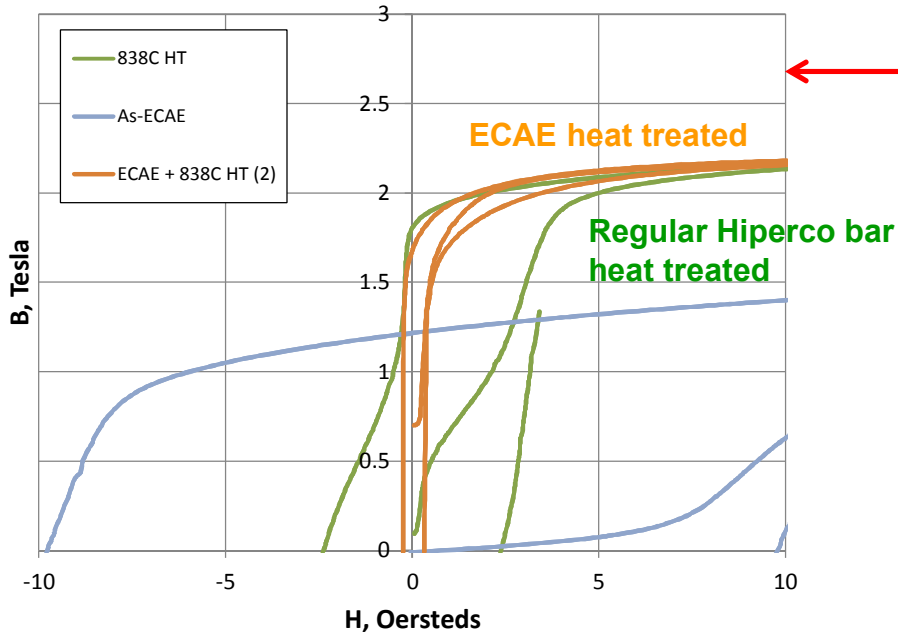
k : constant (Hall-Petch coefficient), d : grain size

Magnetic Performance of ECAE Material

- Magnetic B-H test rings machined from ECAE material and tested according to ASTM A773
- Compared to Hiperco[®] sheet
 - Heat treatment after ECAE results in very good magnetic response. **Could be due to crystallographic texture effects after heat treatment...current investigation**
 - Unfortunately, mechanical properties are sacrificed in the fully heat treated condition



Excellent Magnetic Performance of ECAE Material in Heat Treated Condition



- Very low coercivity (H_c) for ECAE + heat treatment
- Unfortunately, mechanical properties are sacrificed in the fully heat treated condition

Material	Bmax (Tesla)	Br (Tesla)	Hc (Oersteds)	μ_{max}
As-ECAE Hipercro	2.15	1.21	9.78	723
Heat treated ECAE Hipercro	2.34	1.82	0.30	~37000
Conventional bar_838C HT	2.47	1.92	2.35	28283
Hipercro Sheet_838C HT	2.14	1.45	0.70	

Summary:

- ECAE can be successful in the 850 to 750°C range. Finish at 750C, best results.
- Significant microstructural refinement is achieved
- Full heat treatment (for magnetic properties) reduces strength and ductility to conventional bar levels
- ECAE at 850C followed by 750C: High strength AND high ductility. Why?? Suggests that 750C limits recrystallization in favor of deformation (cold work)...points toward a dislocation substructure being important for ductility.
- Magnetic behavior is “moderate” in the as-ECAE condition, very good in the heat treated condition. Possible texture effects?

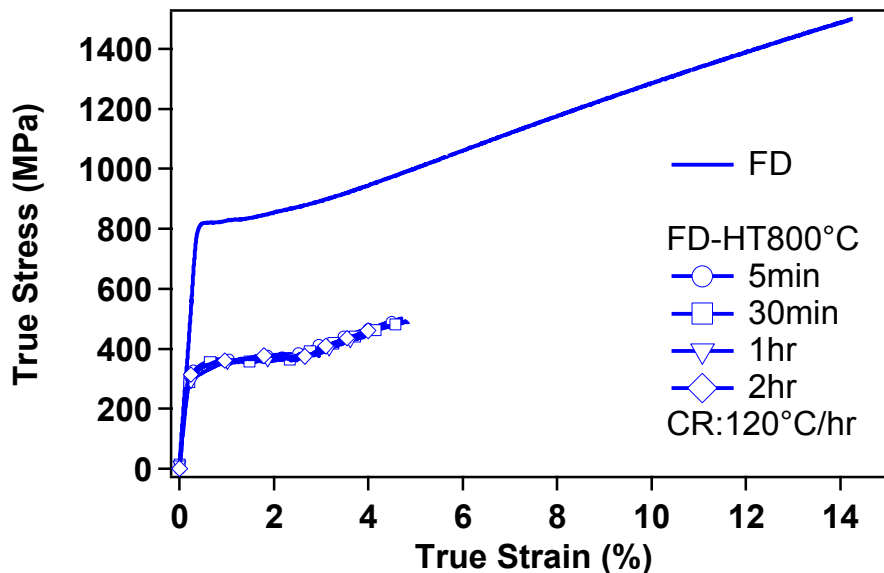
Current and Future Work:

- ❑ Explore lower temperature/shorter time heat treatments
- ❑ Ongoing EBSD and crystallographic texture analyses
- ❑ Explore other bar diameters for ECAE. Longer billet lengths, larger diameters
- ❑ Address the issue of surface cracking. Clad with steel sheet or spray Cu?
- ❑ Measure “order parameter” (degree of order) in Hiperco®

- Extra slides

Ongoing Efforts

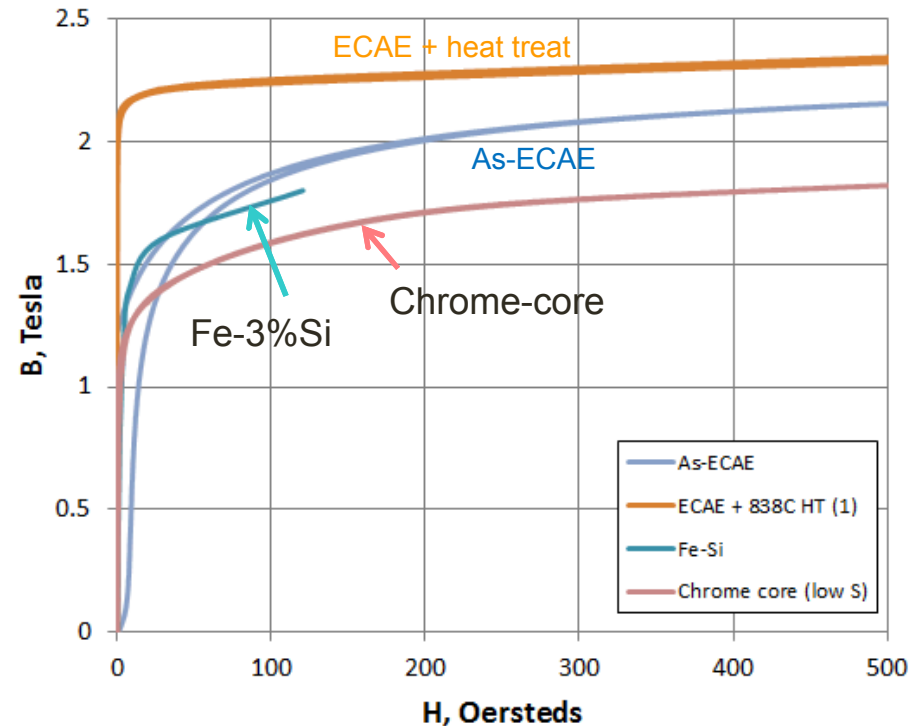
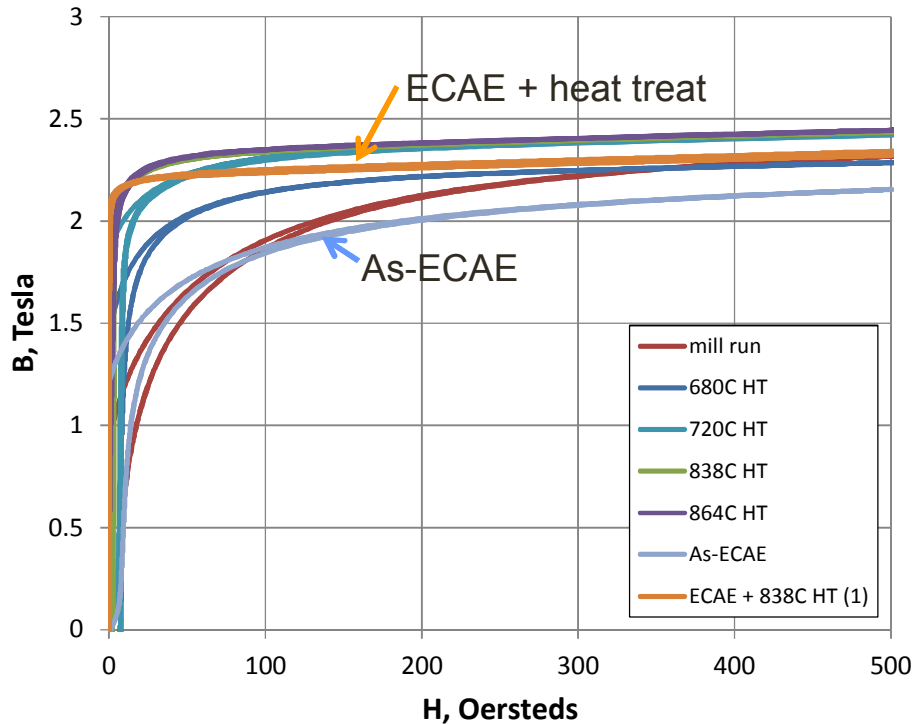
- Investigate alternative heat treatments after ECAE. Will *short times at lower temperatures* give good magnetic performance AND good mechanical response?
- Magnetic measurements on air-cooled material
- Characterization of grain size and crystallographic texture
- Repeat tensile testing on recent extrusions -- show repeatability



Even only 5 minutes at 800C is enough to eliminate ECAE structure and reduce mechanical properties

Currently investigating lower temperature heat treatments

Magnetic Performance, other materials



Compared to conventional Hipercoco bar

- As extruded condition comparable to “mill run” Hipercoco
- In heat treated condition, magnetic saturation is slightly lower, permeability slightly higher than conventional bar

Compared to other soft magnetic alloys

- Competes well with other alloys, even in the as-ECAE condition

Other Previous Research

- Zhao and Baker (1994) (Conventional) “Extrusion Processing of FeCo”, *J. Materials Science*
 - 750C, 1000C extrusion temperatures
 - Fe-30Co, Fe-50Co, Fe-70Co
 - 20-100 μm grain size range
- Kawahara et al. (1980s): studied the effects of cold-work on sheet material
 - High strength and higher ductility are possible with high amounts of cold-work $\geq \sim 80\%$
 - Attributed to local concentration disordered (LCD) zones
- Many researchers (1960s-2000s)
 - Hall-Petch behavior in sheet and bar FeCo-V material
 - Various researchers attribute improved ductility to 2nd phase particles, very fine grain size, partial recrystallization with subgrains to prevent dislocation pileups and crack propagation (slide partitioning/slip dispersion) (George et al, 2002, Stoloff et al, 1964-1970, Pitt and Rawlings, 1983, Thornburg, 1969)