SAND2017-12555C

Texture Development in soft ferromagnetic Fe-Co-2V processed by Equal Channel Angular Extrusion (ECAE)

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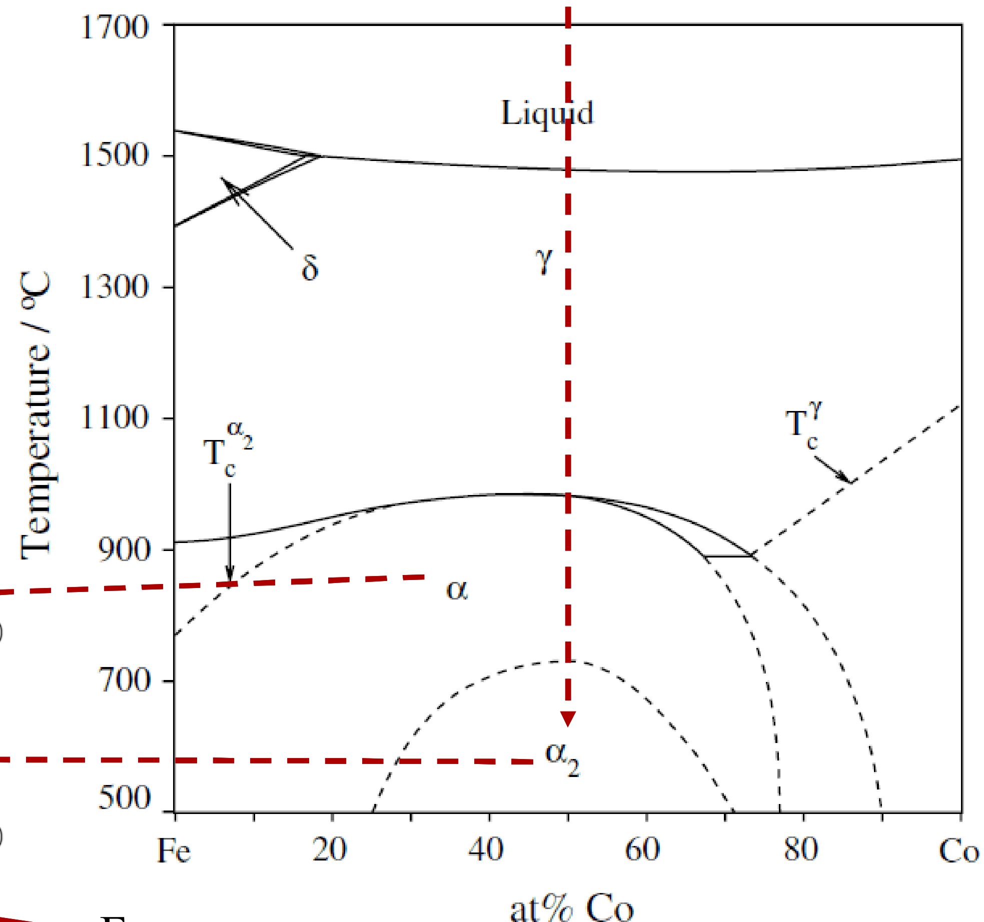
Fe-Co alloy metallurgy

Equiatomic or near-equiatomic Fe-Co alloys that undergo a γ-FCC → α-BCC→ α_2 (B_2) transformations.

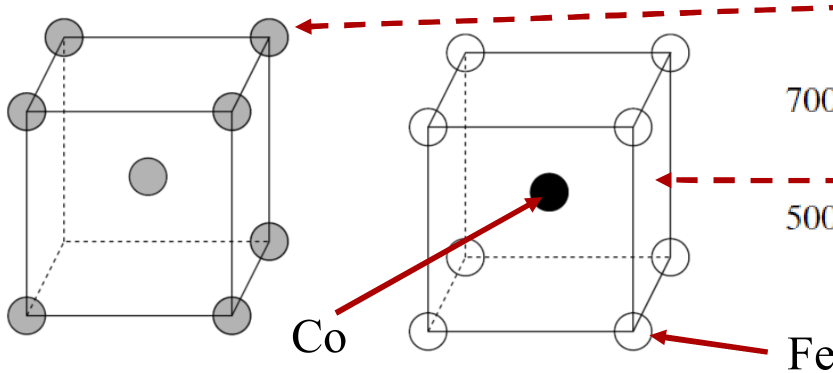
- Poor composition-driven workability, binary Fe-Co difficult to process.
- Commercialized as Fe-Co-2V (Hiperco®) in bar, sheet, strip, coil, and rod forms.

Hiperco® is a tradename of Carpenter Technologies, Reading, PA.



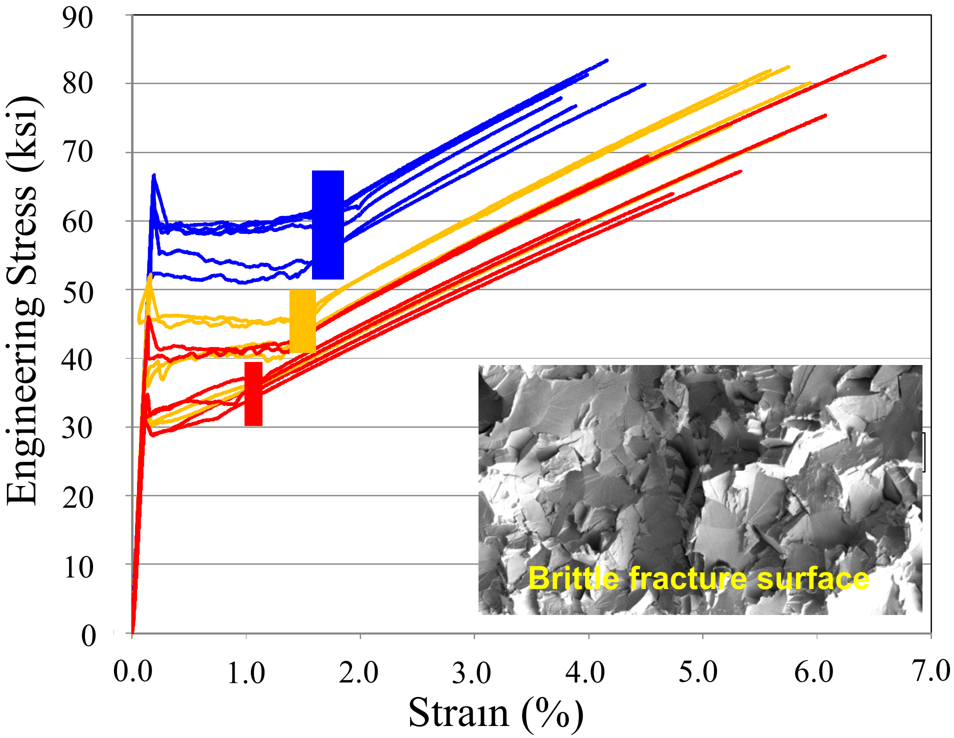
Characteristic properties:

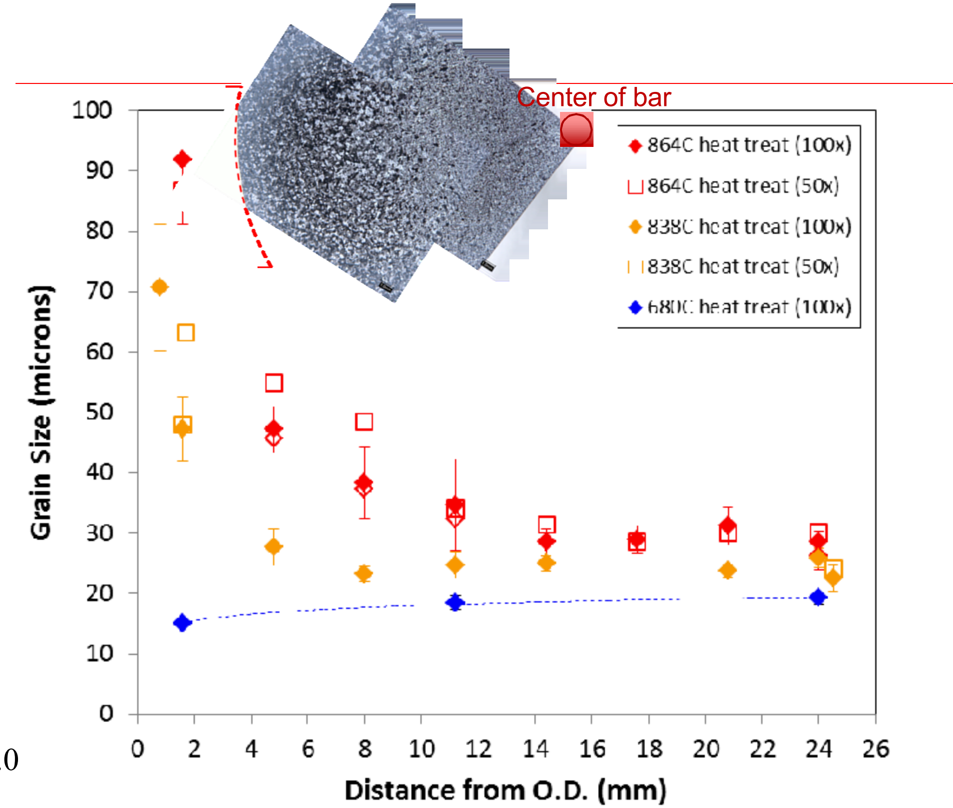
- Highest saturation induction of all engineering soft ferromagnetic alloys
- High curie temperature (> 900 °C)
- High permeability
- Low core loss



Project motivation

- Forged (conventional) Hiperco bar is weak, brittle, and has inhomogeneous microstructures.



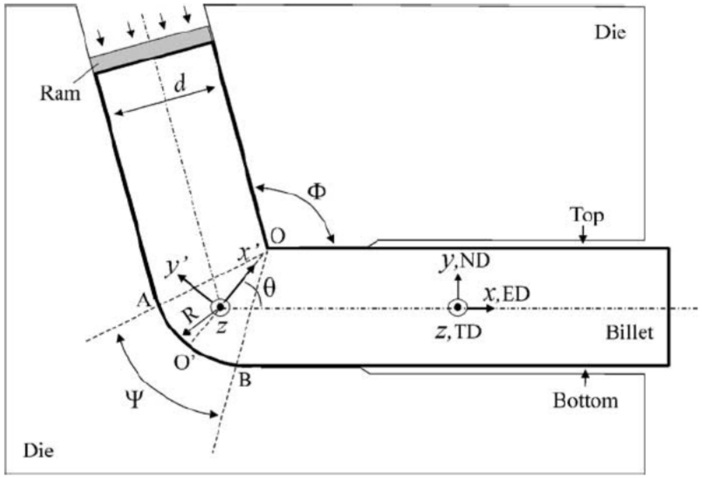


- Goal: achieve uniform microstructures and improved mechanical properties.

- Equal Channel Angular Extrusion

Shear-based deformation processing

Equal Channel Angular Extrusion (ECAE)



V.M Segal, "Engineering and Commercialization of Equal Channel Angular Extrusion (ECAE), *Mat Sci Eng A*, A386, 2004, 269-276.

- **Objective:** explore shear-based ECAE (also known as equal channel angular pressing, ECAP) as bulk processing method for Hiperco bar.

- Large strains ($\varepsilon > 1$) and pressures ($p/2k > 1$) are imposed in each extrusion through simple-shear deformation.

Effective (von Mises) strain:

$$\varepsilon = \frac{2\cot(\frac{\Phi}{2})}{\sqrt{3}}$$

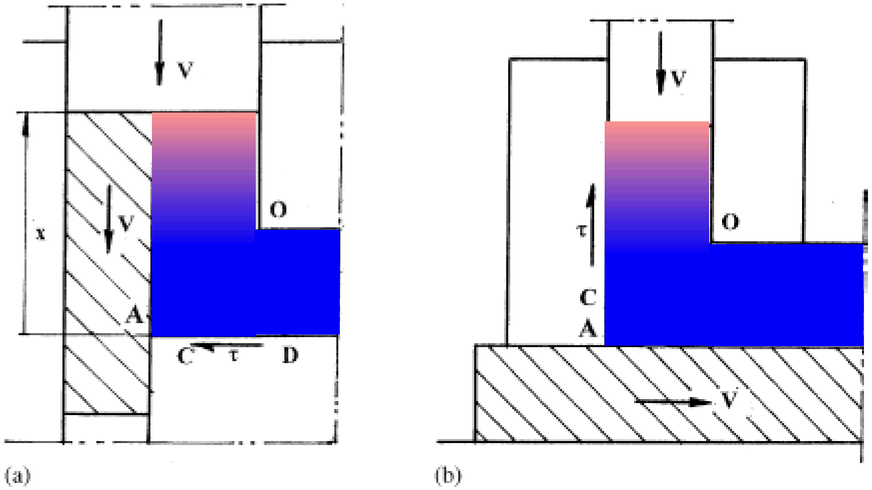
Normalized pressure at shear plane:

$$\frac{p}{2k} = f(\Phi, friction)$$

- Strength and ductility are simultaneously improved through severe microstructure refinement.

Experimental Procedure

Sandia National Laboratories



- Moveable ECAE die walls used to reduce friction during processing – Texas A&M

- V.M Segal, "Engineering and Commercialization of Equal Channel Angular Extrusion (ECAE), *Mat Sci Eng A*, A386, 2004, 269-276.
- V.M. Segal, R.E. Goforth, and K.T. Hartwig, Texas A&M Univ., U.S. Patent No. 5,400,633; 1995.

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

- Multi-pass (4 passes) ECAE routes C and E were explored at 750 → 850°C and quenched – reduce flow stress and suppress ordering transformation.
  - Billets were heated to temperature for 30 min. prior to extrusion.

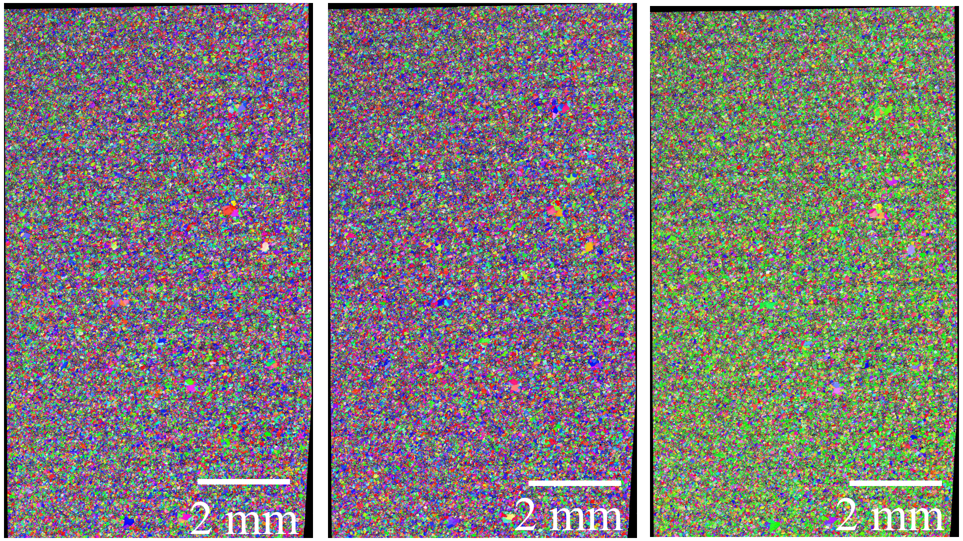
Examined: as-deformed and annealed microstructures and textures

- Annealing conditions: 840°C for 2 hours in vacuum, furnace cool at 2.3°C/min

Conventional bar material

Sandia National Laboratories

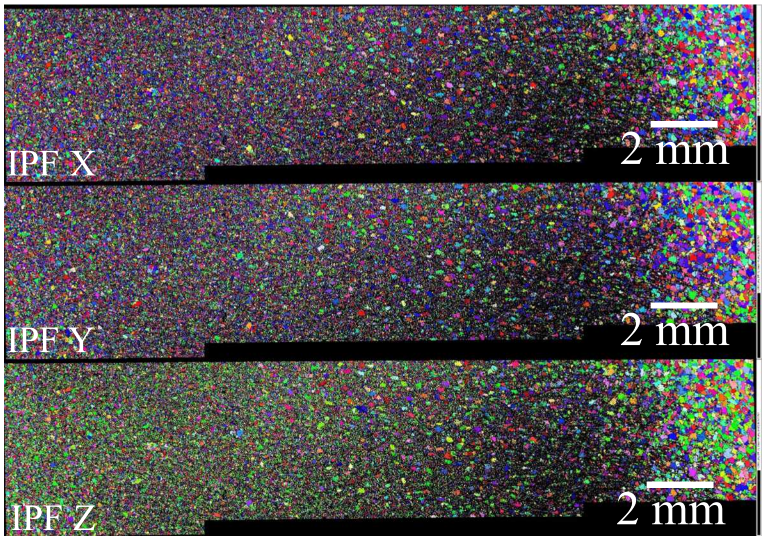
As-received bar stock

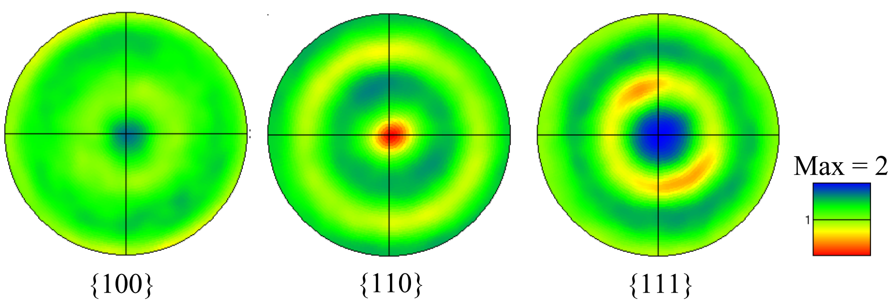


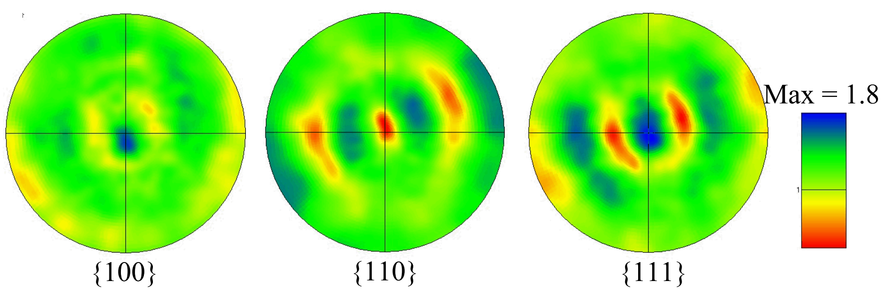
IPF X IPF Y IPF Z

Heat-treated bar stock

Center Outside edge



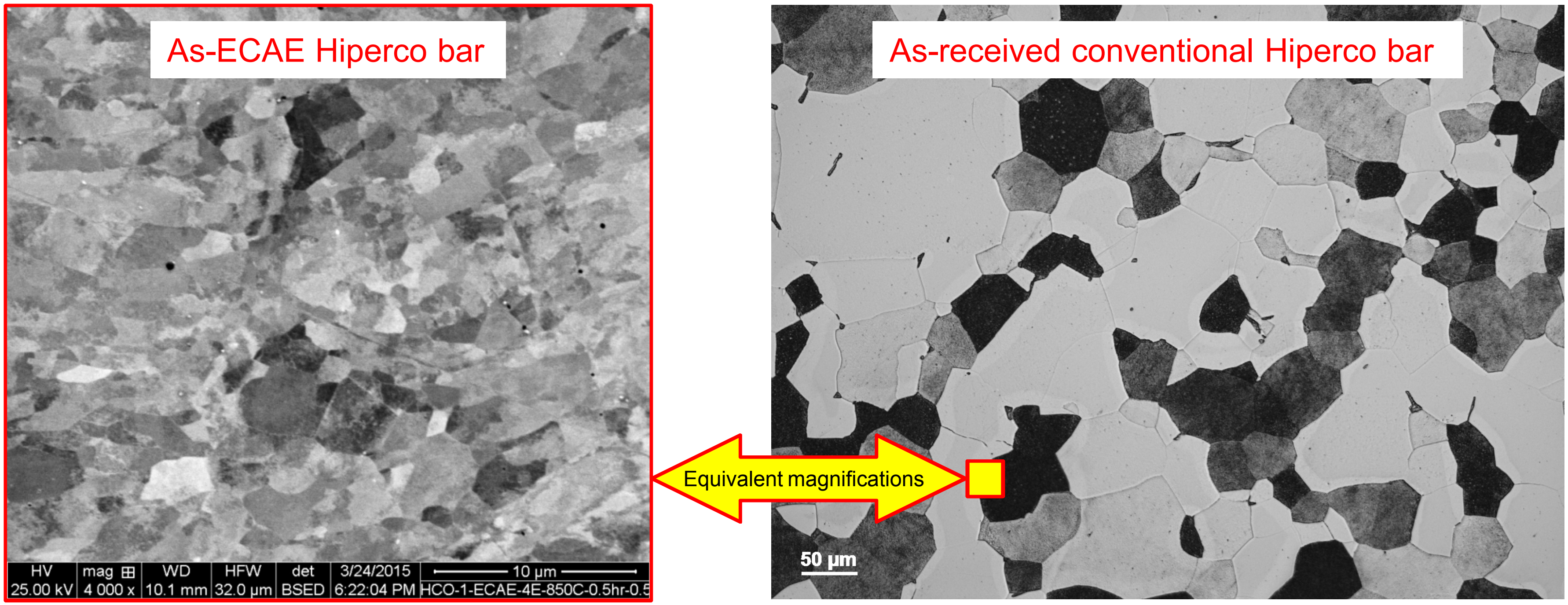




Weak texture with <110> parallel to the bar length.

ECAE bar microstructure?

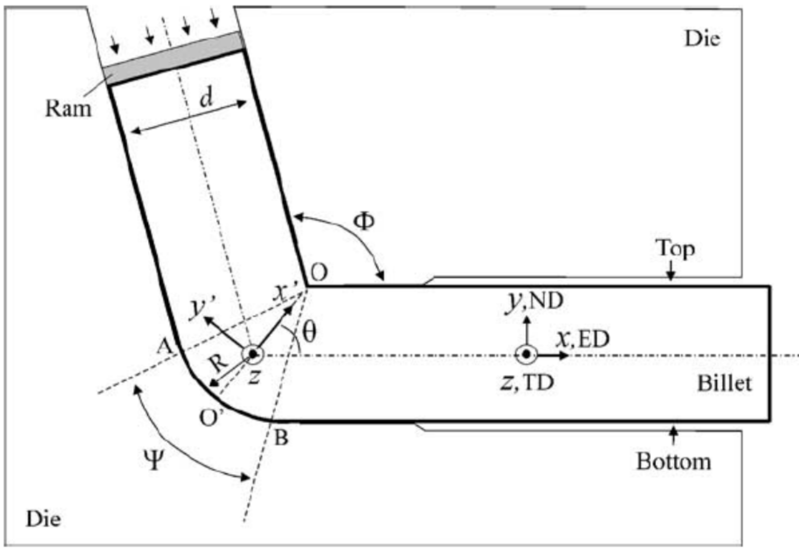
ECAE vs. conventional processing

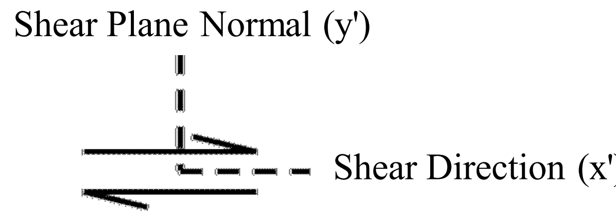


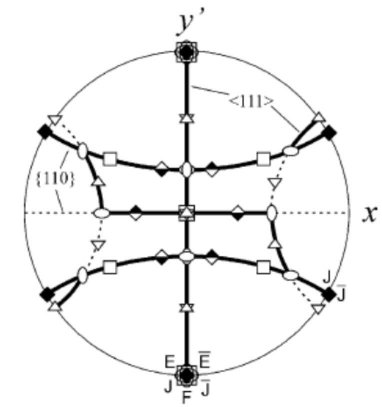
✓ As-ECAE microstructure had a fine, homogeneous grain size of ~ 1.5 micron, while conventional (annealed) bar showed a structure with ~ 50 micron grain size.

Textures?

Simple shear textures in BCC





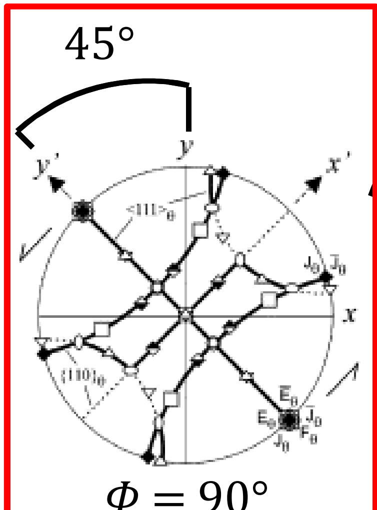


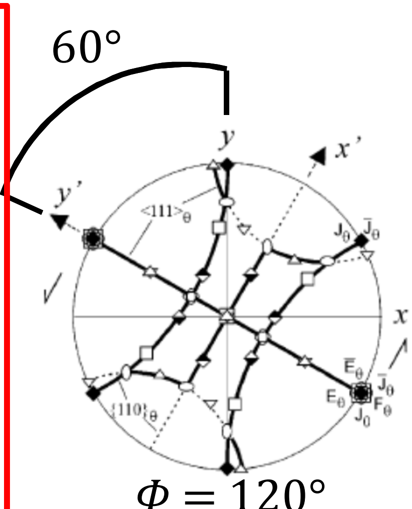
{110} pole figure

<111> - fiber

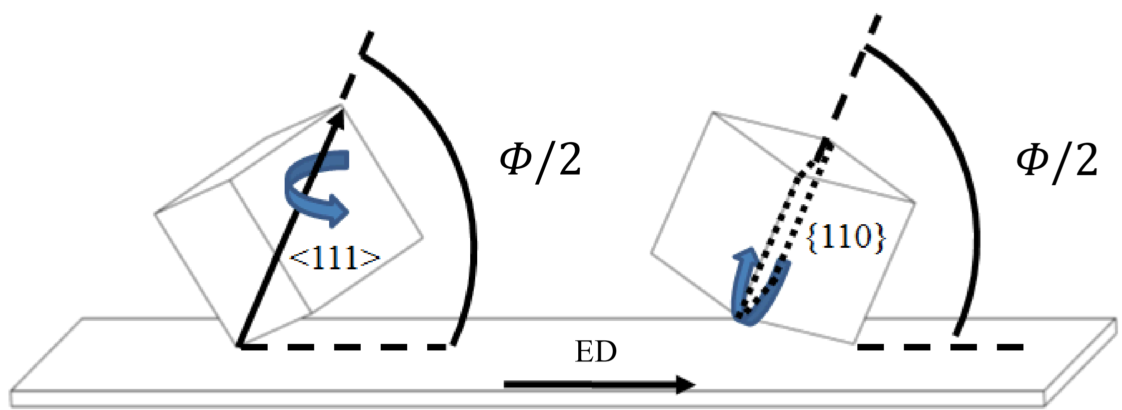
{110} - fiber

S. Li, I. J. Beyerlein, and M. A. M. Bourke: Mater. Sci. Eng., A, 2005, vol. 394, pp. 66–77.

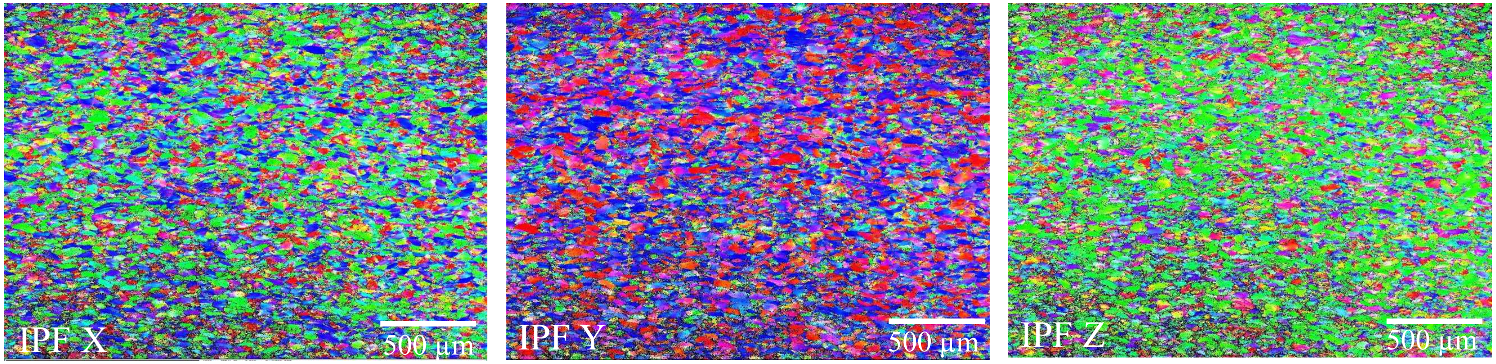


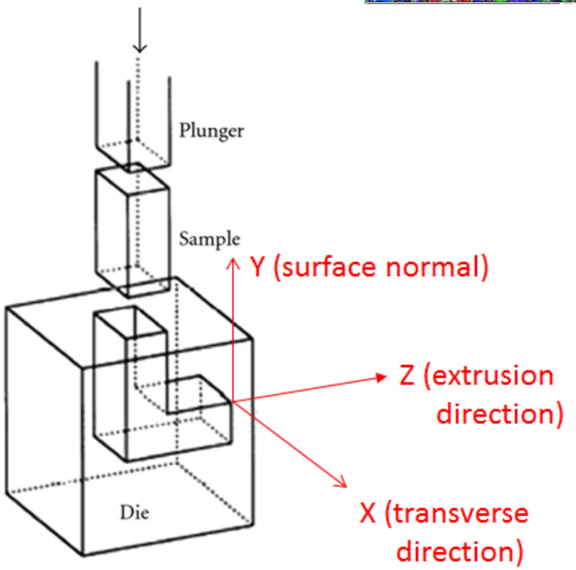


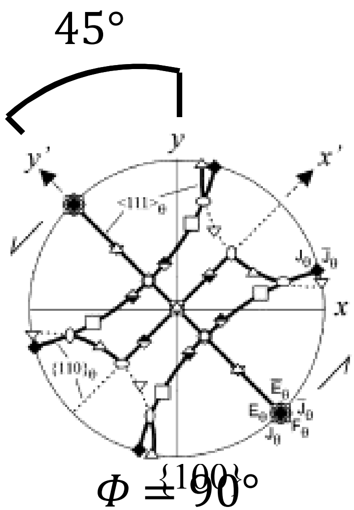
Idealized Simple Shear Texture

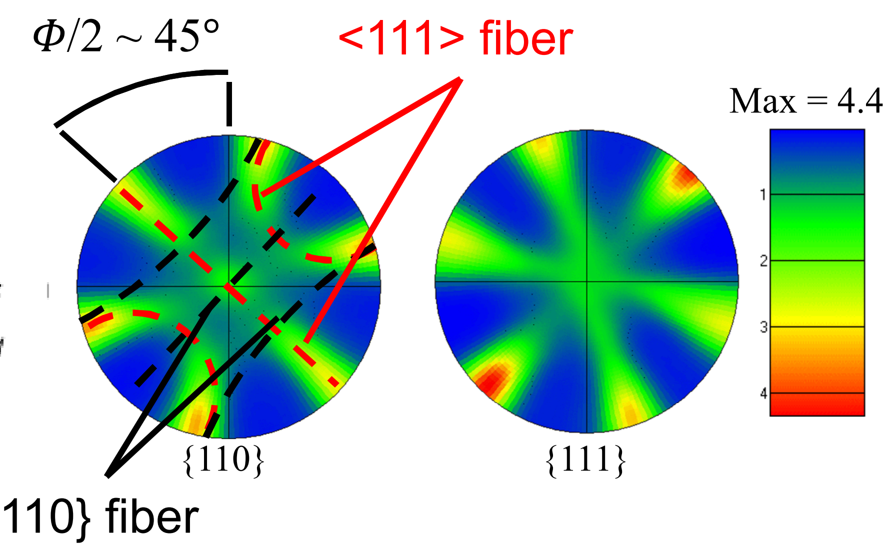


As-deformed ECAE Hiperco structure and texture



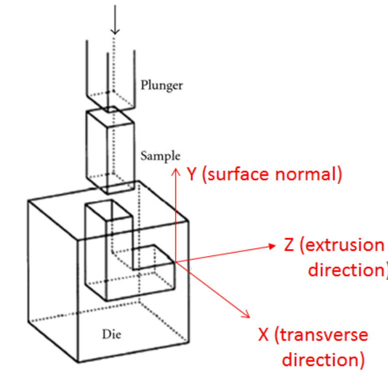




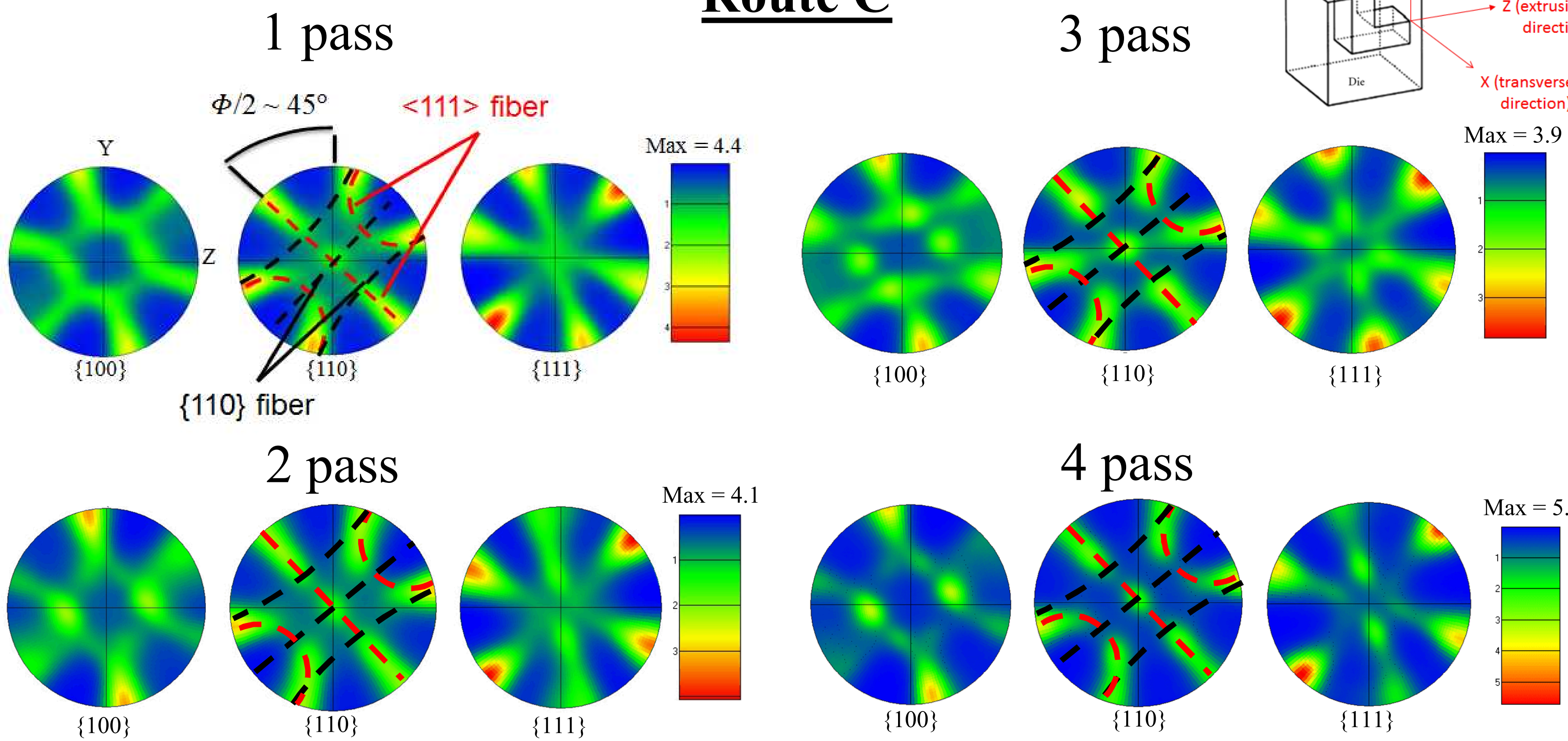


ECAE single pass

Multi-pass as-deformed textures



Route C

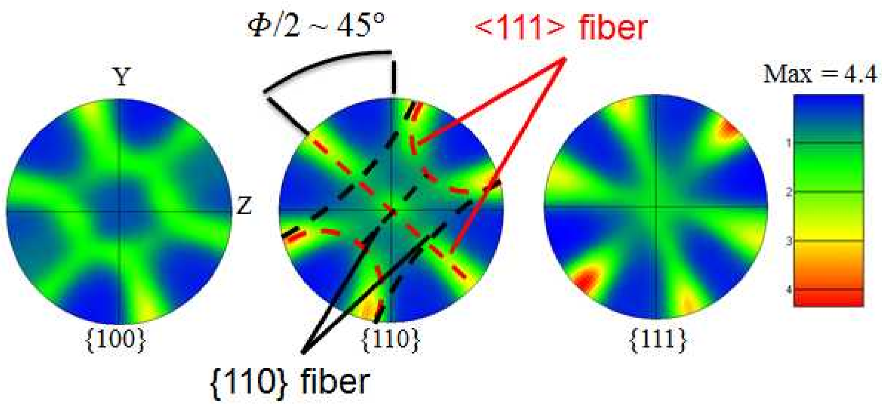


- ➤ Consistent shear texture of a single ECAE pass
- ➤ How does this compare with other multi-pass ECAE studies?

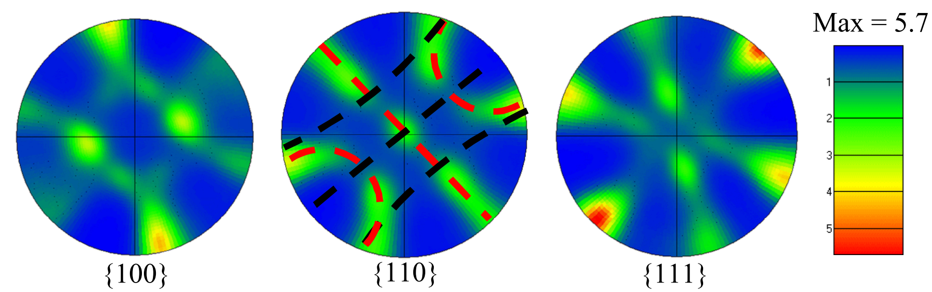
Comparison with other ECAE Route C textures

Route C

1 pass



4 pass

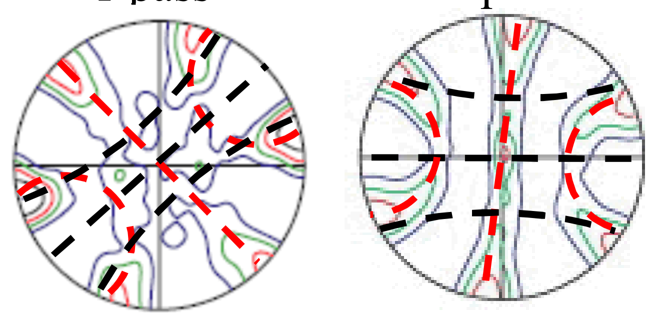


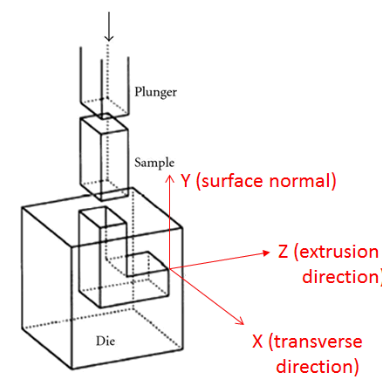
(110) Pole figures
IF steel, Route C

S. Li, et al., "Effect of processing route on microstructure and texture development in equal channel angular extrusion of interstitial-free steel, *Acta Mater.*, 54, 2006, 1087-1100

1 pass

4 pass

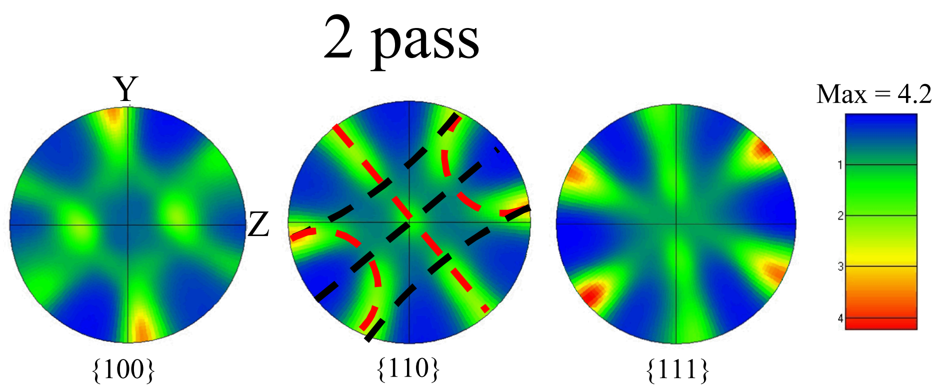


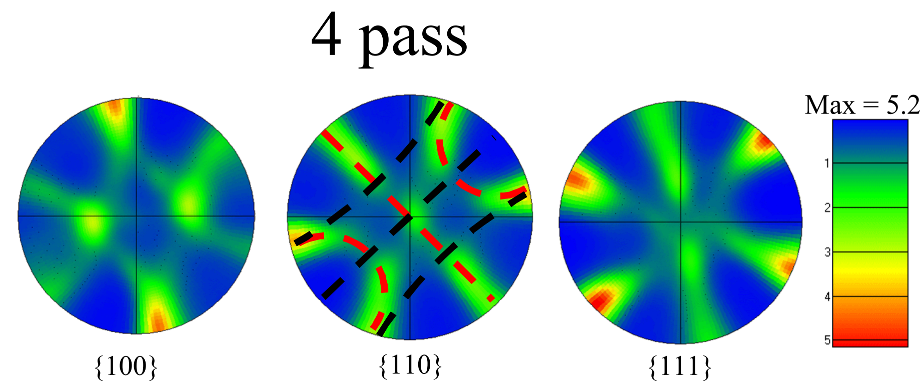


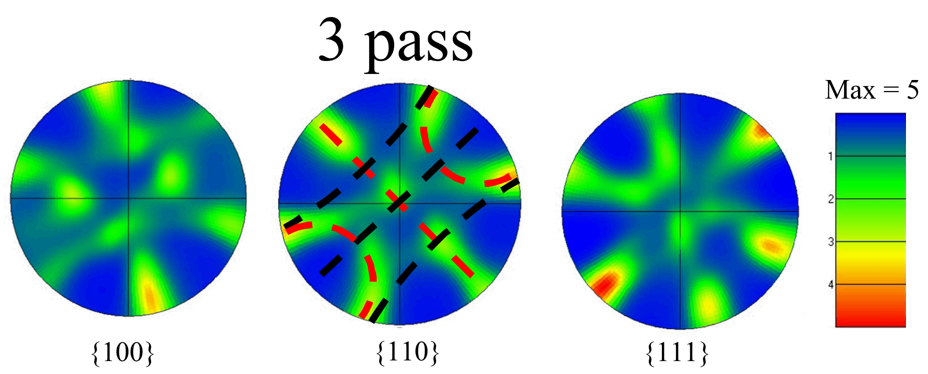
- ➢ High temperature processing annealed out previous pass effects
- ➢ Texture entering die did not influence its development in subsequent ECAE passes

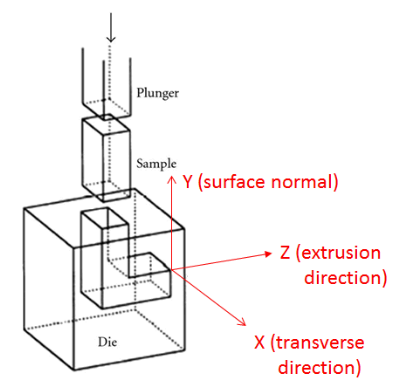
What about ECAE route E?

Route E



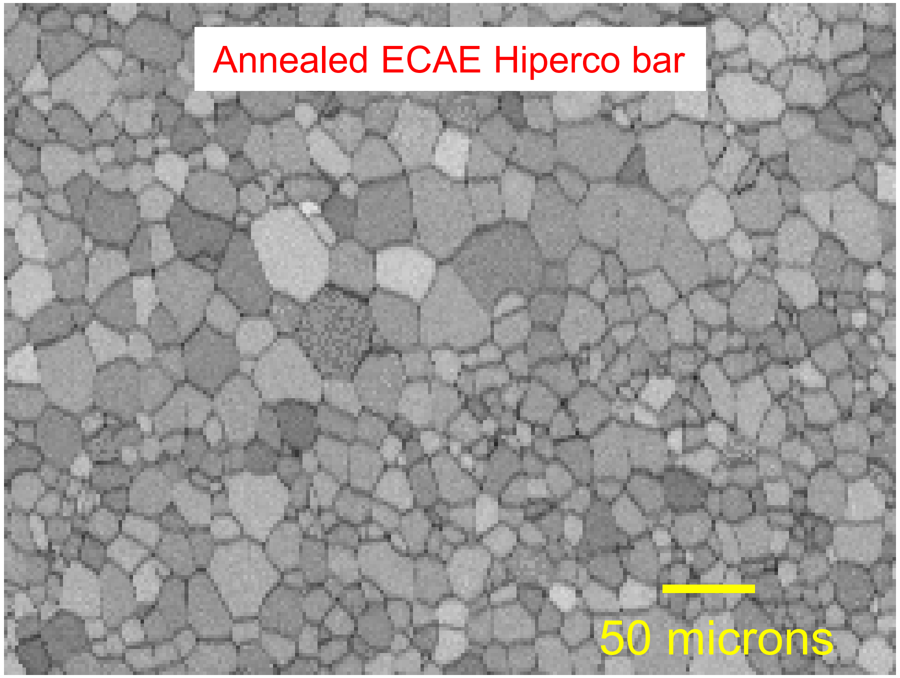


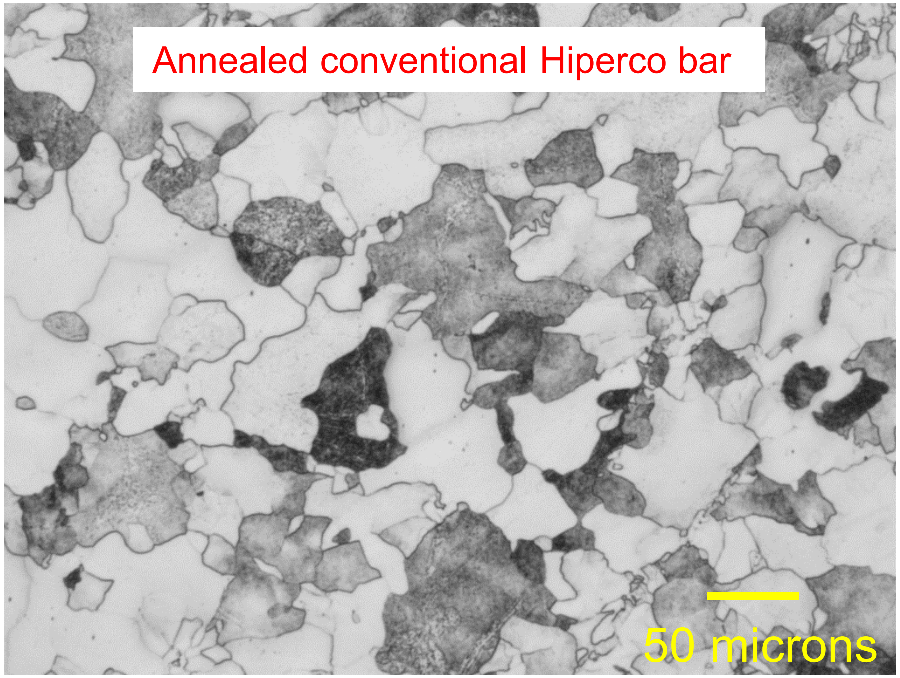




Similar texture results to route E from the high temperature processing

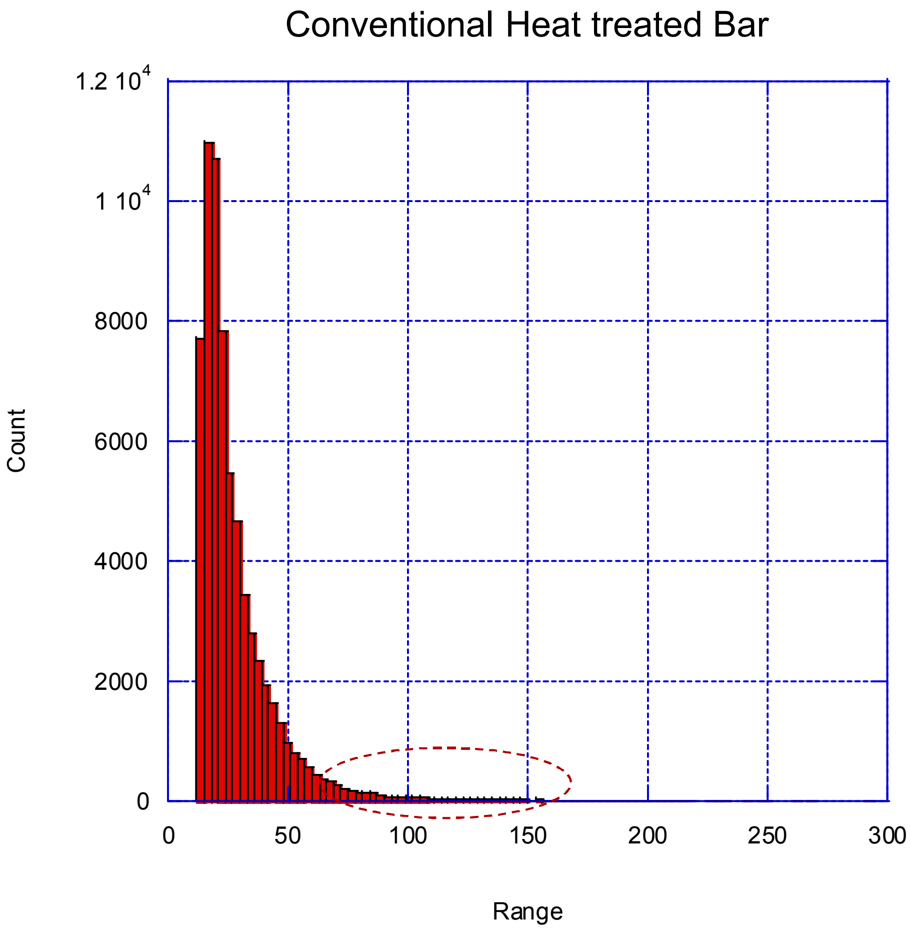
ECAE vs. conventional processing

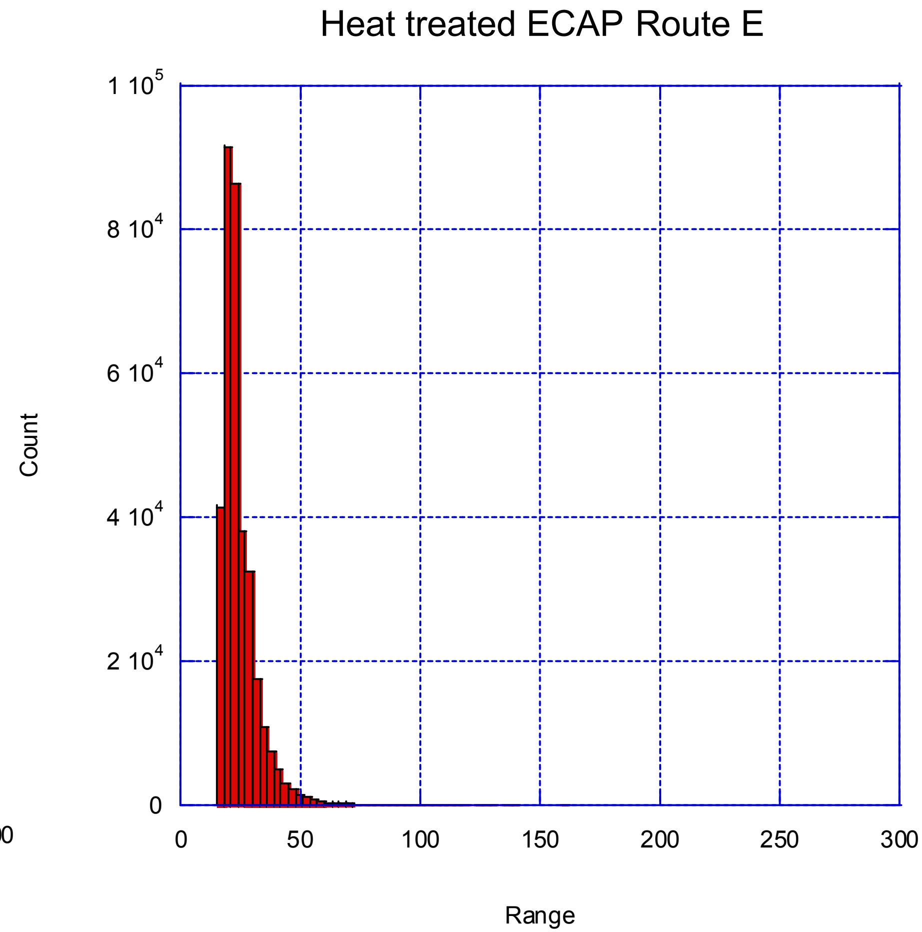




- Annealed Hiperco bar had finer grain size than conventional bar.

Annealed ECAE vs. annealed bar

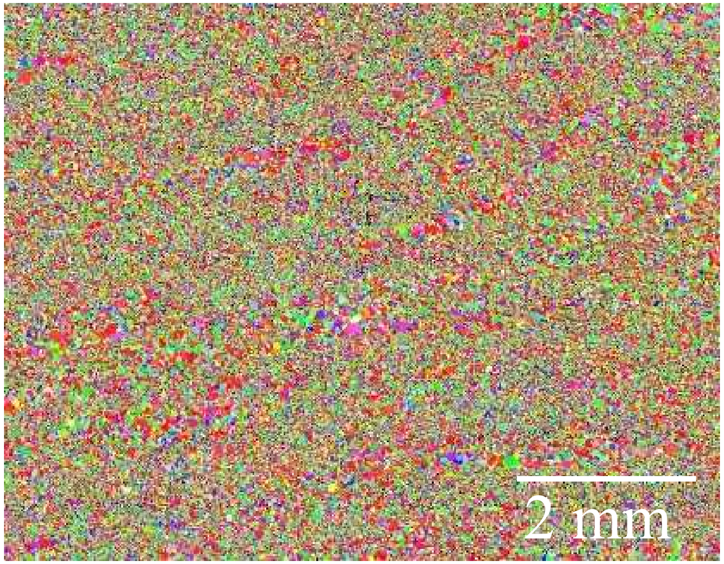


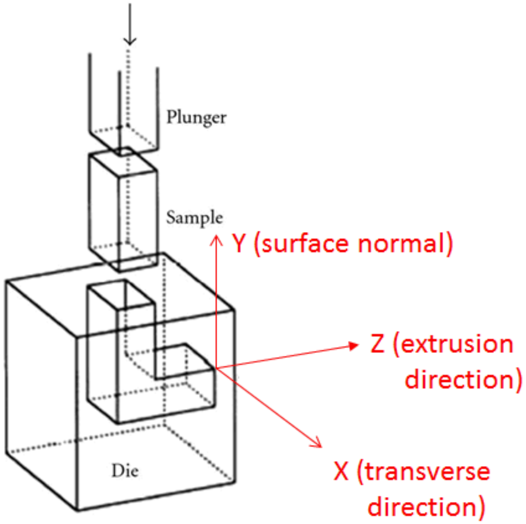


✓ More homogeneous microstructure for ECAP vs. conventional bar!

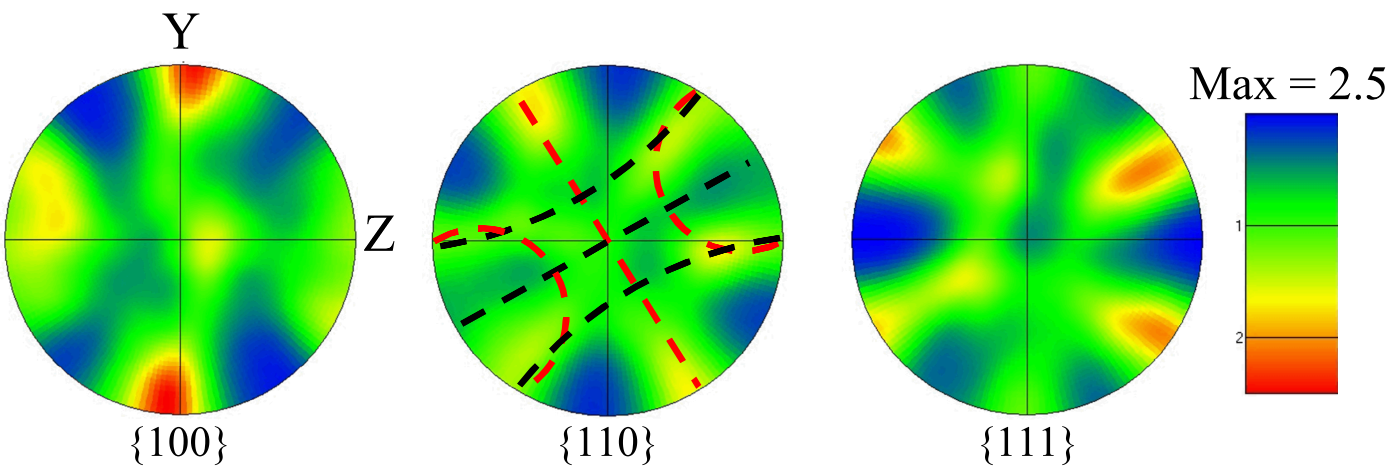
Textures?

Annealing textures for route E



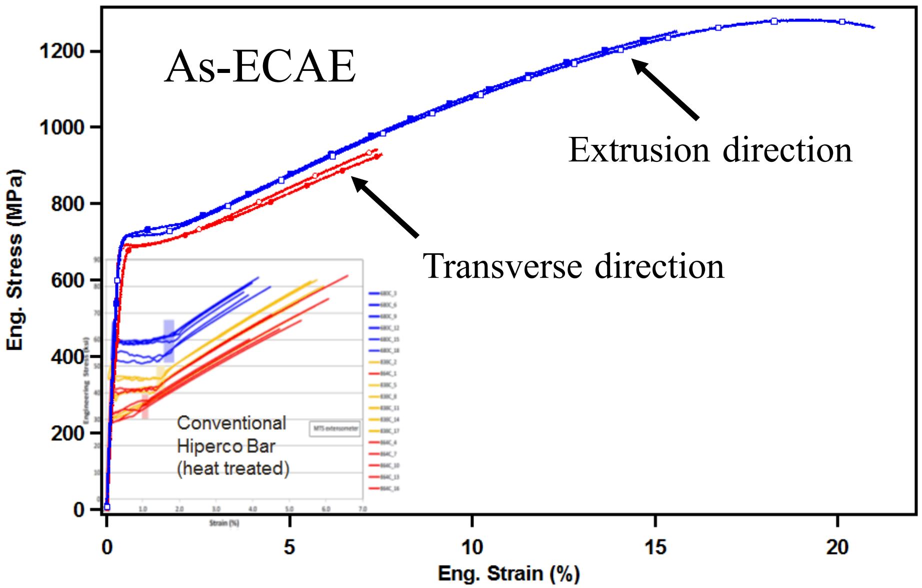


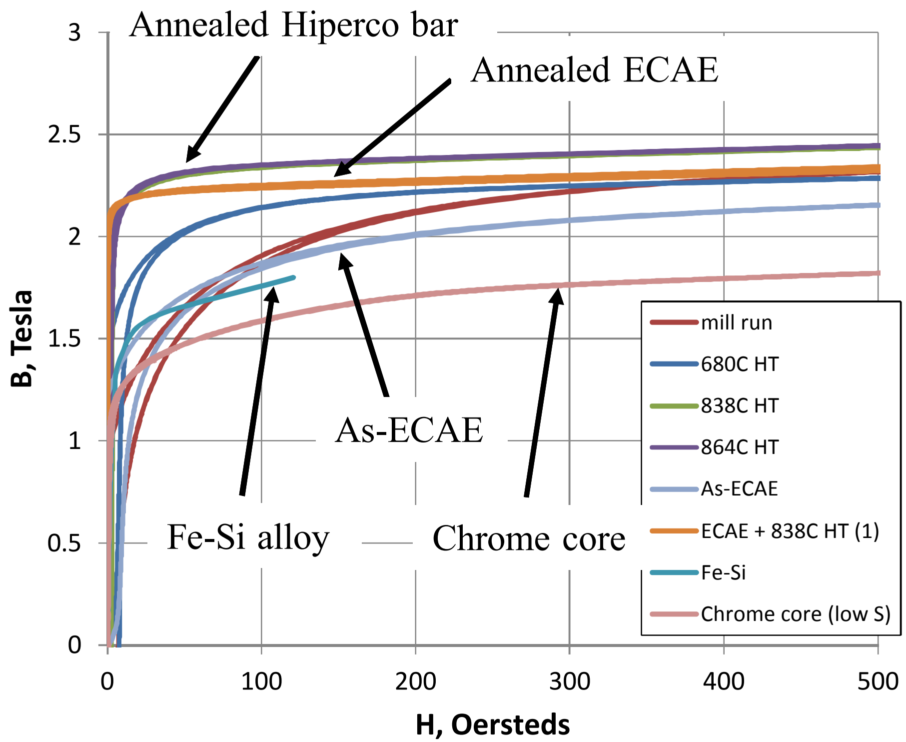
Annealed at 838°C for 2 hours in 10^{-5} Torr, 2.3°C/min.



Weak simple-shear texture

Properties characterization





- As-ECAE material is 2-3x stronger AND 2-5x more ductile than conventional bar
- The result of combined fine grain size and reduced ordering

- Slightly lower saturation induction than conventional bar, however slightly higher permeability and lower coercivity.
- Properties as-good or better than other alloys, even in as-ECAE condition

Conclusions

1. ECAE successfully produced Hiperco bar with more ideal, homogeneous refined microstructure.

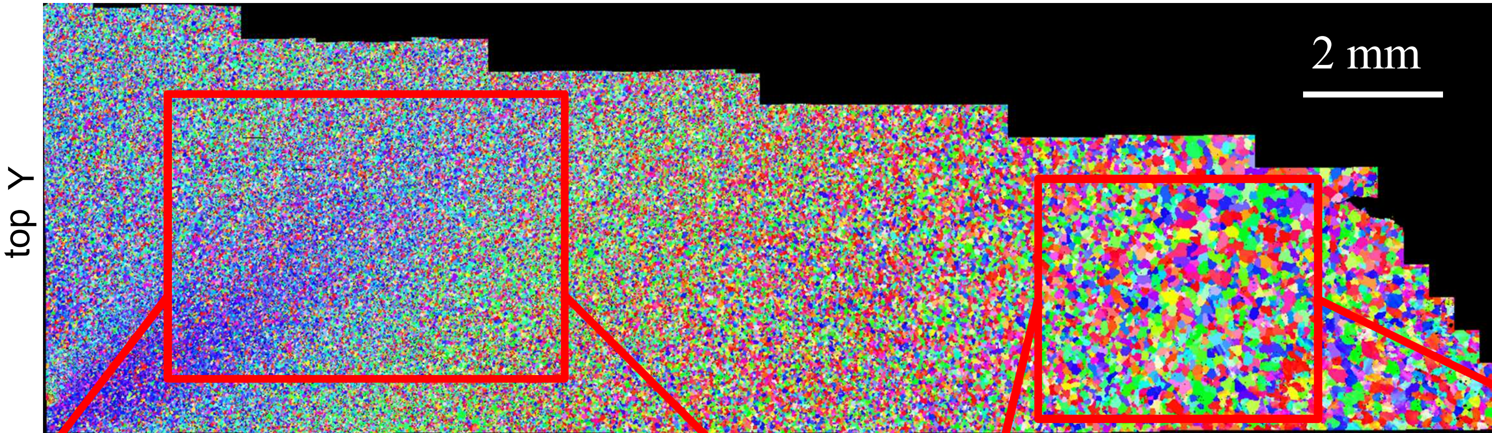
2. Shear-type as-deformed textures developed for all conditions at an orientation expected from a single ECAE pass. High temperatures during processing are believed to have annealed out deformation and promote a single-pass texture.

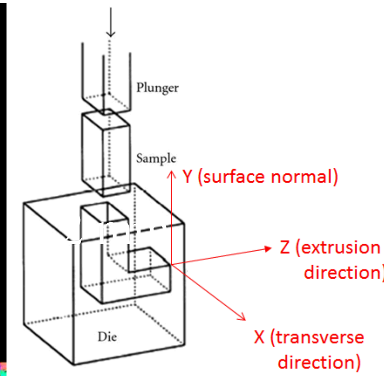
3. Following recrystallization annealing, textures were mostly shear-type but significantly weaker relative to the as-deformed.

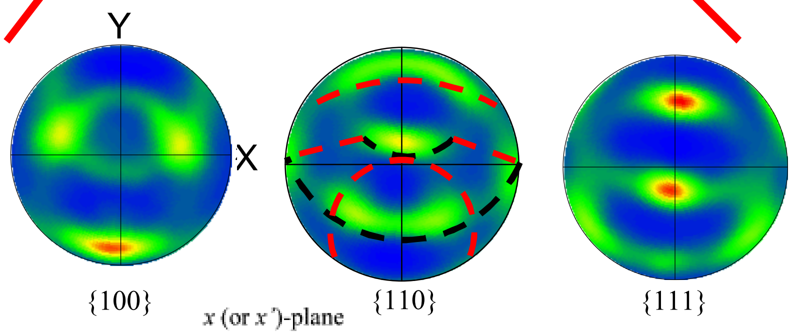
4. Mechanical properties of as-deformed bar showed greater strength AND ductility compared to conventional Hiperco bar.

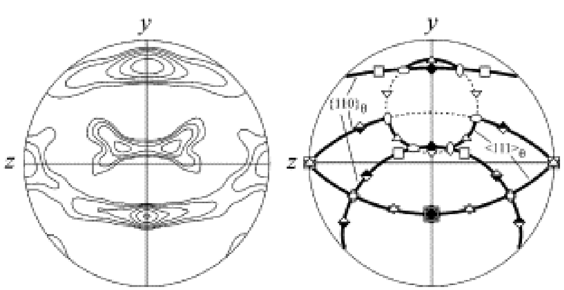
5. Magnetic properties were as-good or better than other conventionally processed alloys. Following annealing, ECAE Hiperco possessed superior permeability and coercivity compared to conventional bar, but a slightly lower saturation induction.

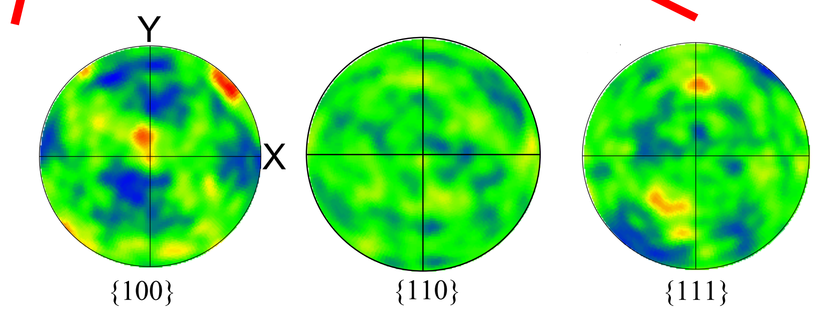
Annealing textures for route C











No significant texture in coarse grain region

Fine grain region shows shear-type texture