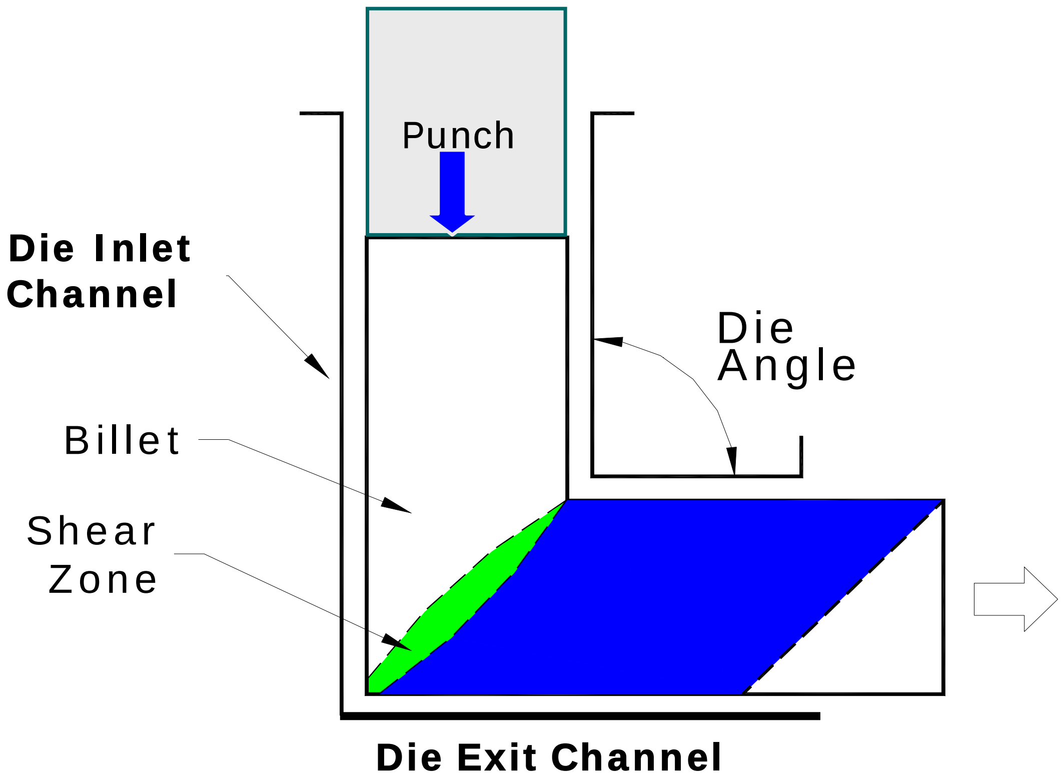
MEEN 489-500 Nanoscale Issues in Manufacturing

Equal Channel Angular Extrusion (ECAE)

Lecture 2 : Bulk Nanostructured Materials

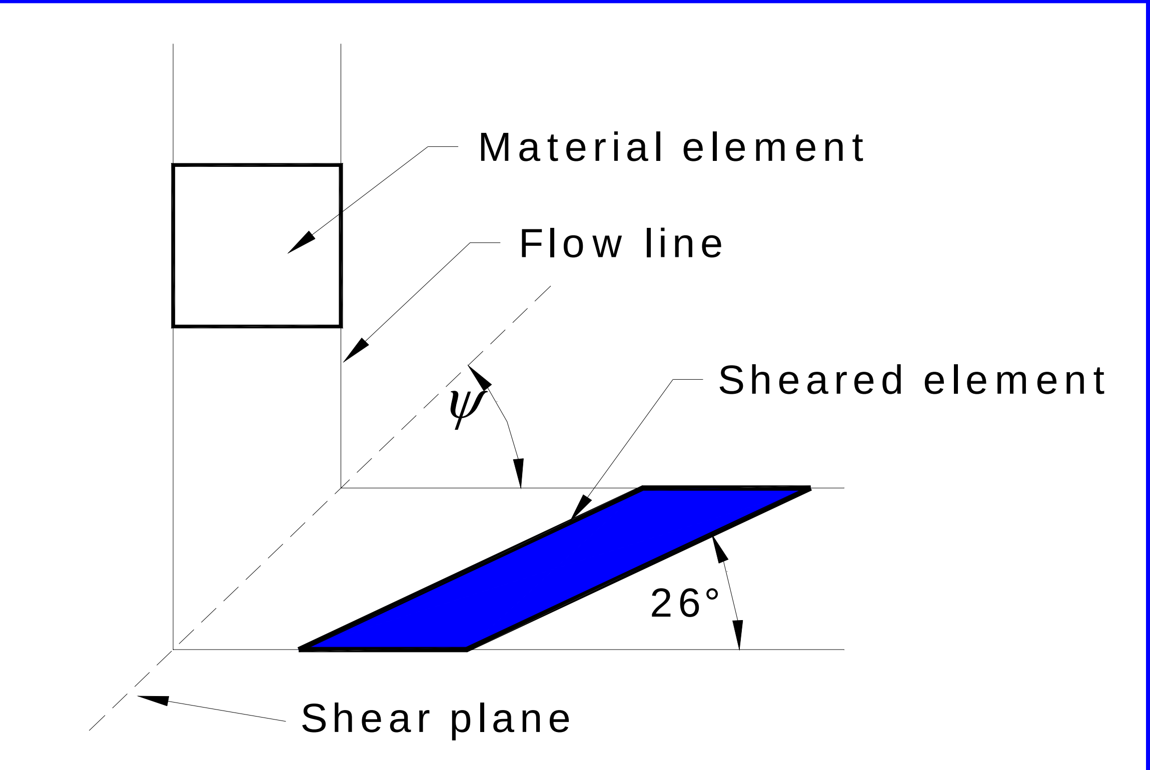
Description of ECAE



Conditions

1. Inlet and outlet channels have nearly the same dimensions
2. Channel intersection is abrupt
3. Lubrication and other means are used to reduce friction

Description of ECAE

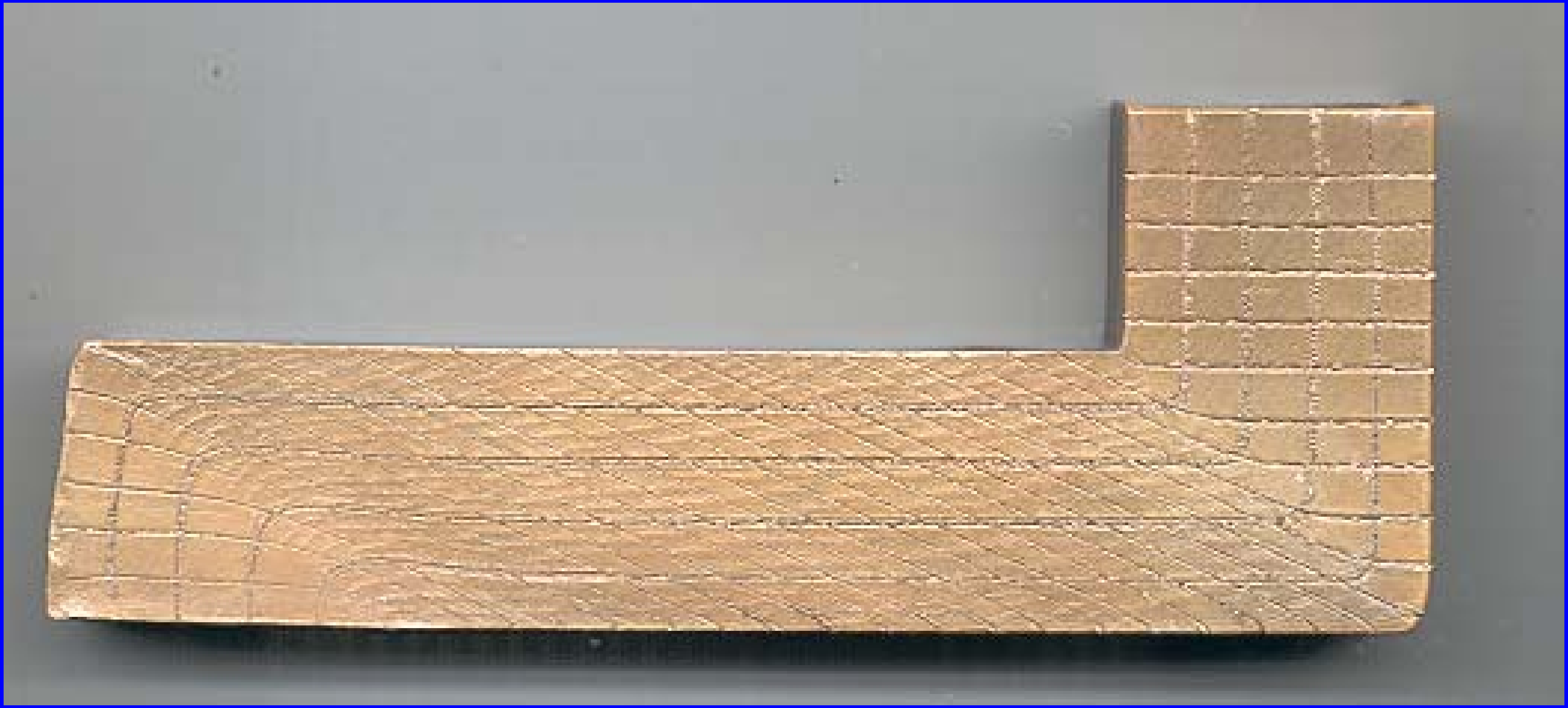


Results

1. Simple shear occurs
2. Effective strain is $(2/\sqrt{3}) \cot \psi$ or 1.16 for $\psi=45°$
3. Effective strain for multiple (N) extrusions is 1.16 N for $\psi=45°$
4. Strain is relatively uniform

ECAE

Example of material element distortion and near surface non-uniform strain in annealed OFHC copper



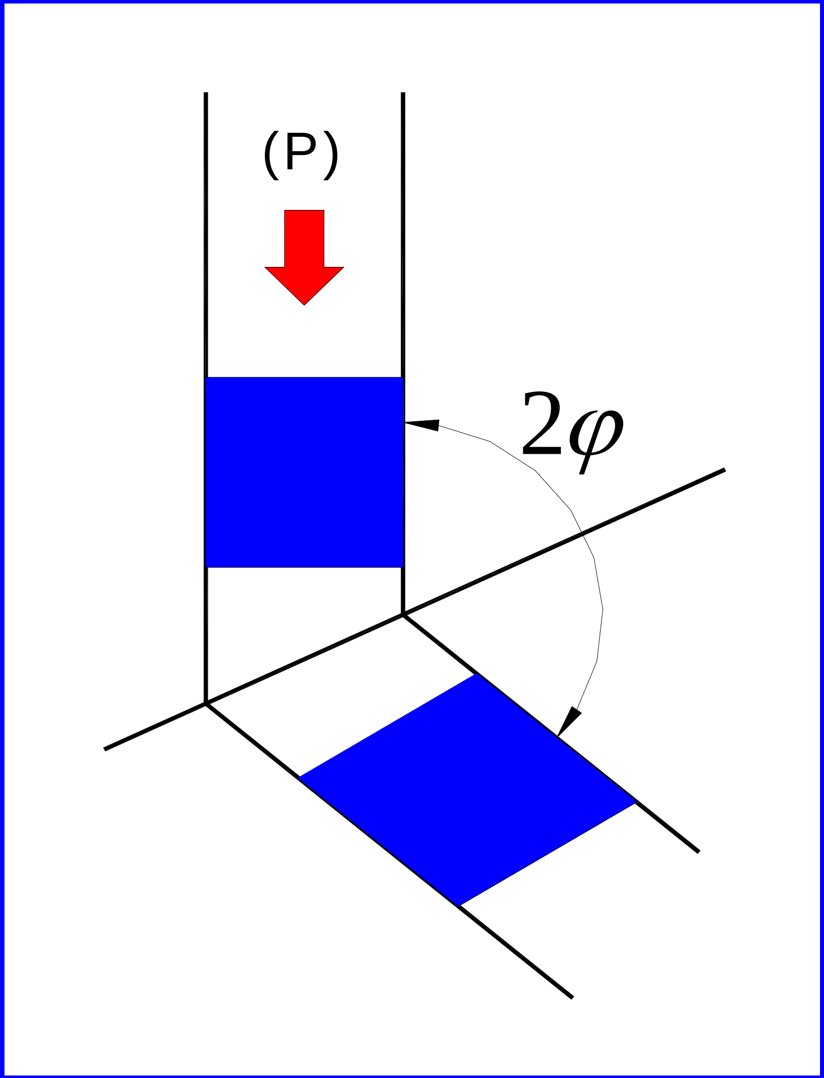
Benefits of ECAE

- ⌘No Change in Workpiece Geometry
- ⌘Uniform Plastic Strain
- ⌘Relatively Low Extrusion Loads
- ⌘Unlimited Strain Space
- ⌘Alternative Product Microstructures
- ⌘Alternative Product Textures
- ⌘Relatively Simple, but Elegant Tooling

Limitations of ECAE

- Material Ductility
- Current methods work only for simple cross-sections
- Some reshaping between extrusions may be necessary
- Surface and end losses

ECAE Mechanics



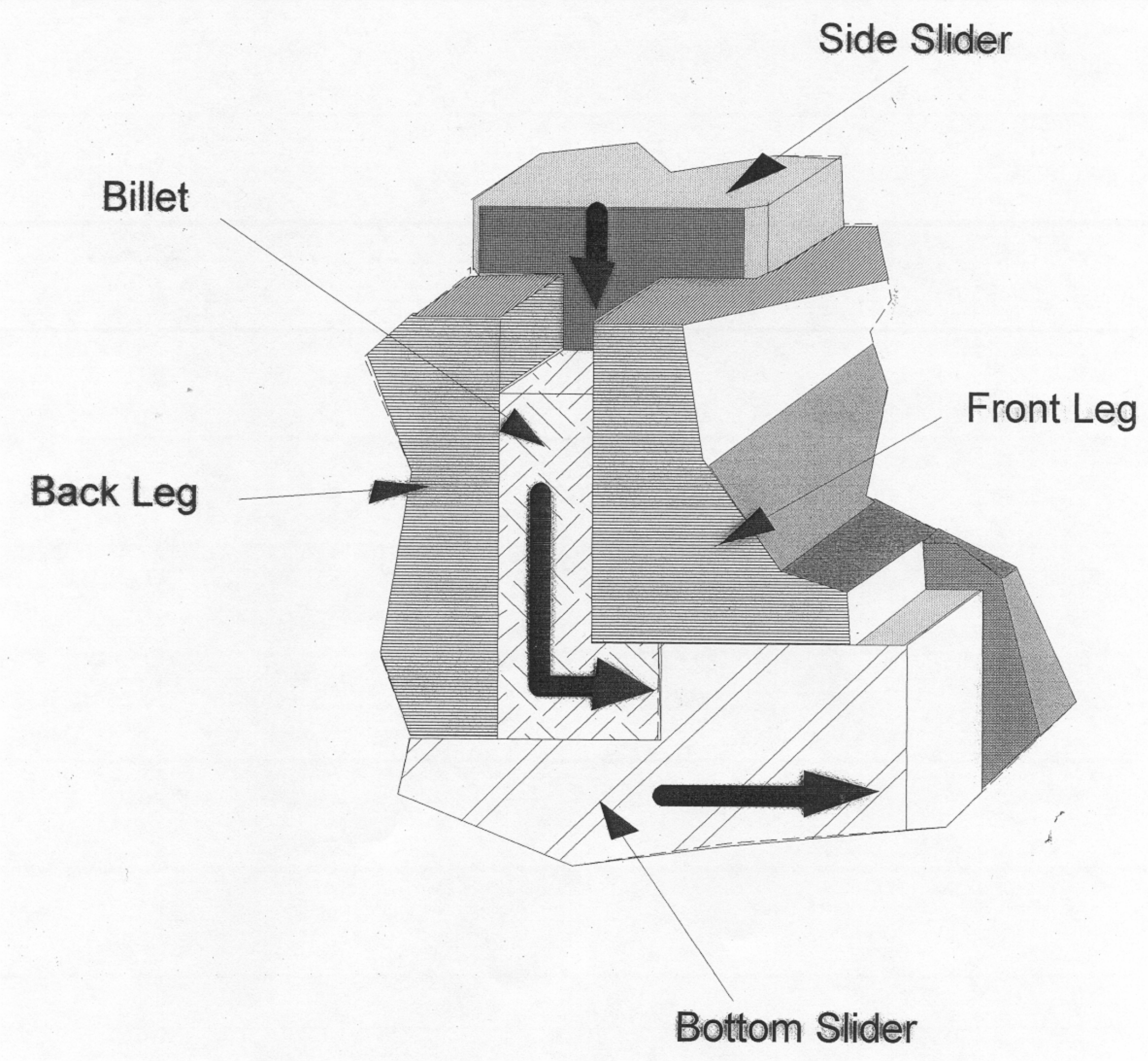
$$\frac{P}{Y} = \frac{2}{\sqrt{3}} \cot \varphi$$

$$\varepsilon_{total} = \frac{2}{\sqrt{3}} N \cot \varphi$$

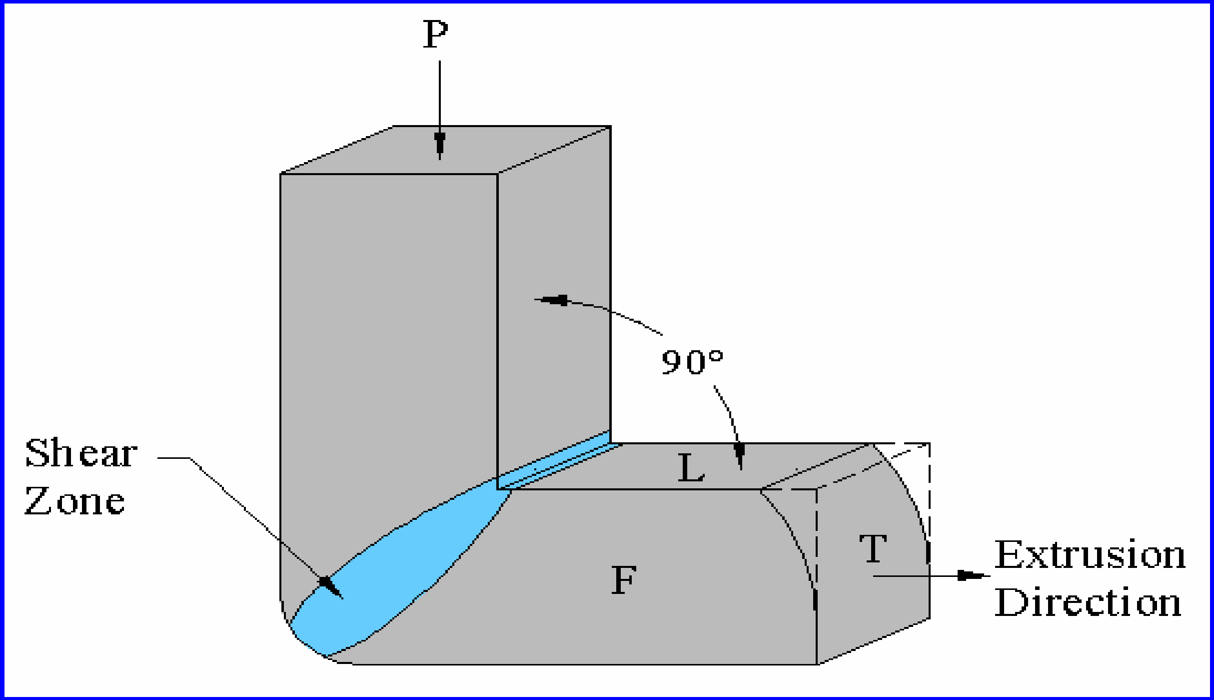
Y: Flow stress

N: Number of passes

ECAE Process



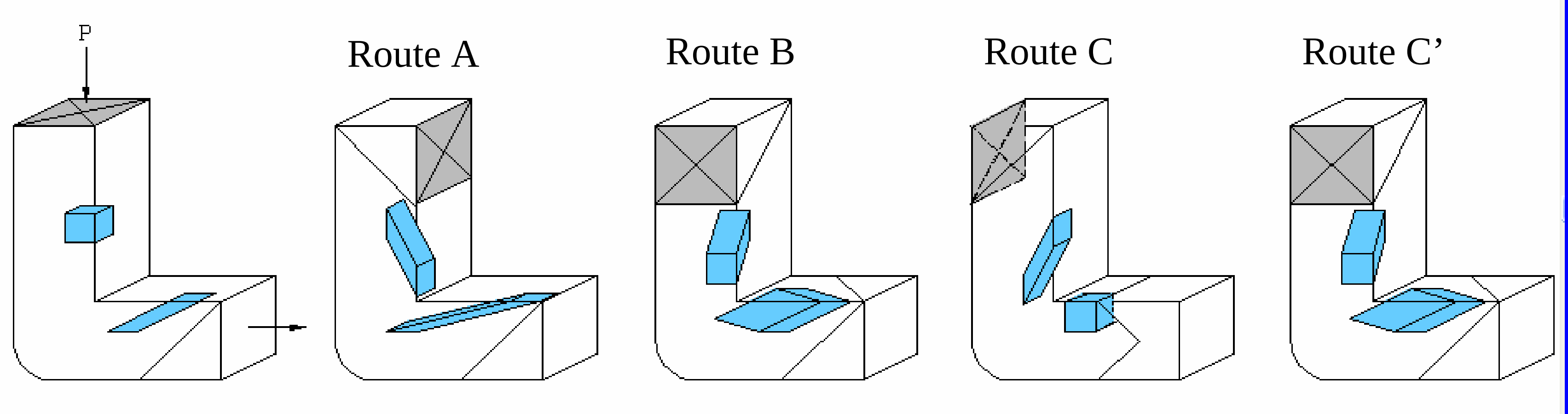
Definitions



ECAE Route Description

First Pass (N=1)

Second Pass (N=2)

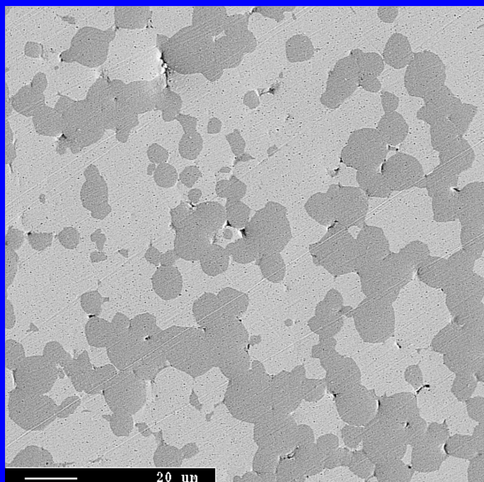


Route name	Min. # of passes	Billet rotations about the extrusion axis				Material Yield*	Effect on microstructure
		1 ➔	2 ➔	3 ➔	4 ➔ N		
A	1	0°	0°	0°	etc.	0.58	elongation (lamellar)
B (B_A)	2	+90°	-90°	+90°	etc.	0.67	elongation (filamentary)
C	2	180°	180°	180°	etc.	0.83	back/forth shearing
C' (B_C)	4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

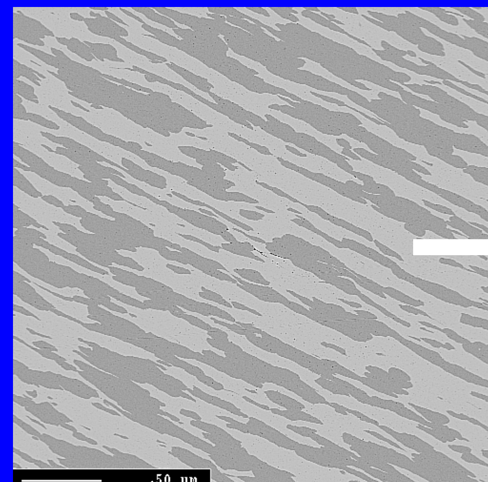
* Theoretical yield of fully deformed material after N=4 in billet with length/width ratio of 6

Effect of ECAE routes on morphology

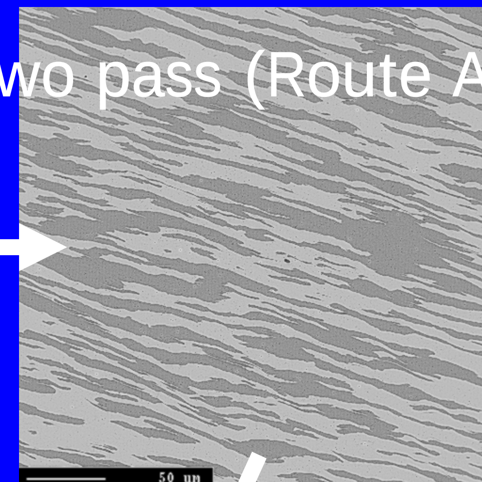
Microstructure of AgCu powder blend through ECAE passes



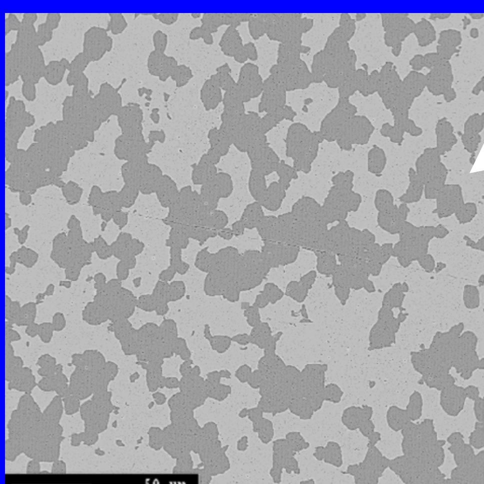
Compressed prior to ECAE



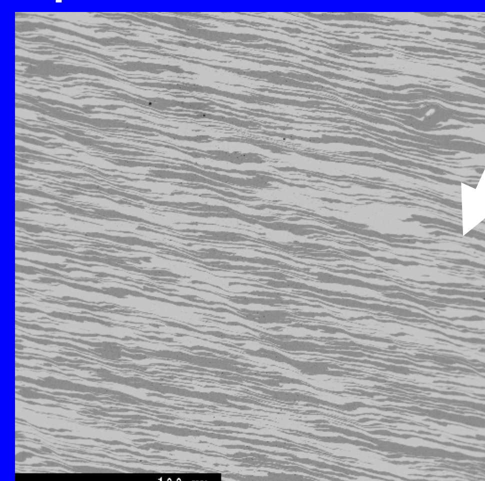
One pass



Two pass (Route A)



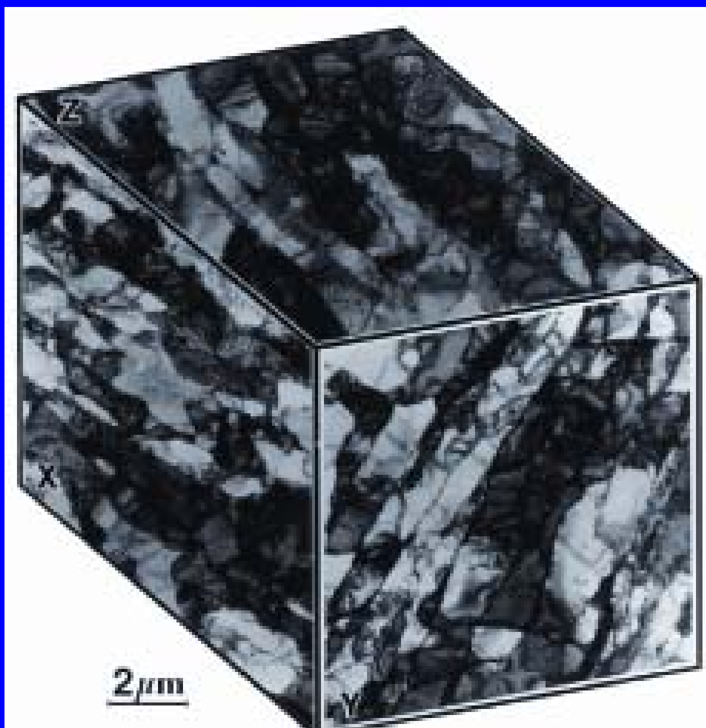
Two pass (Route C)



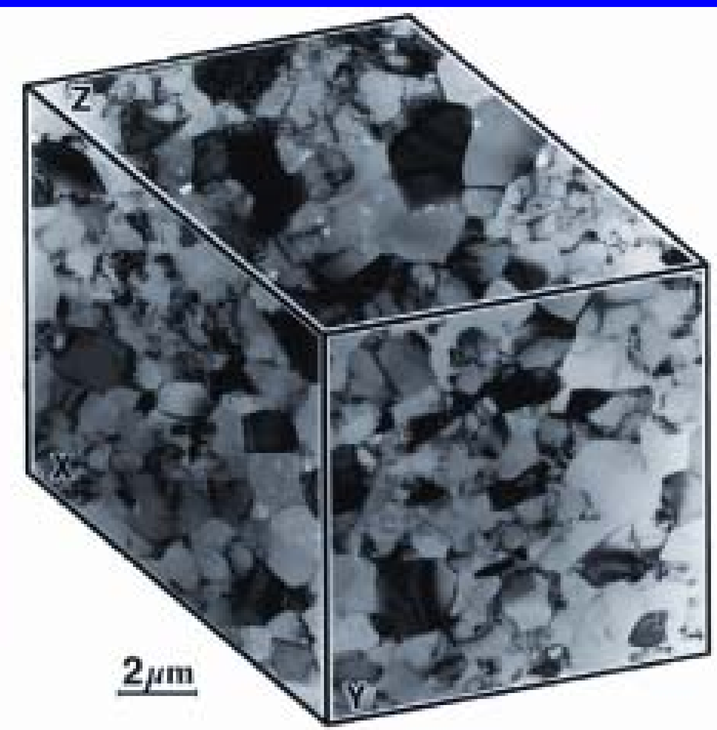
Four pass (Route A)

Microstructure after ECAE

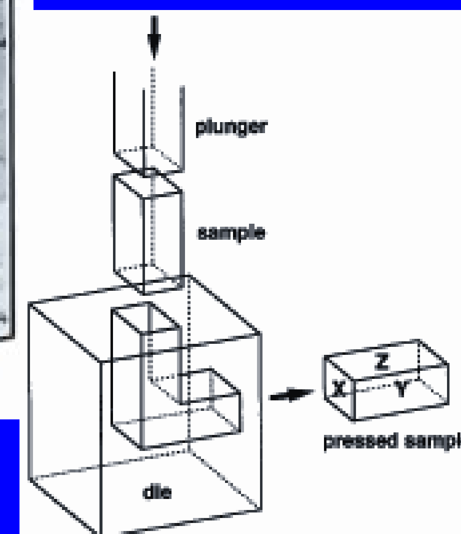
Al



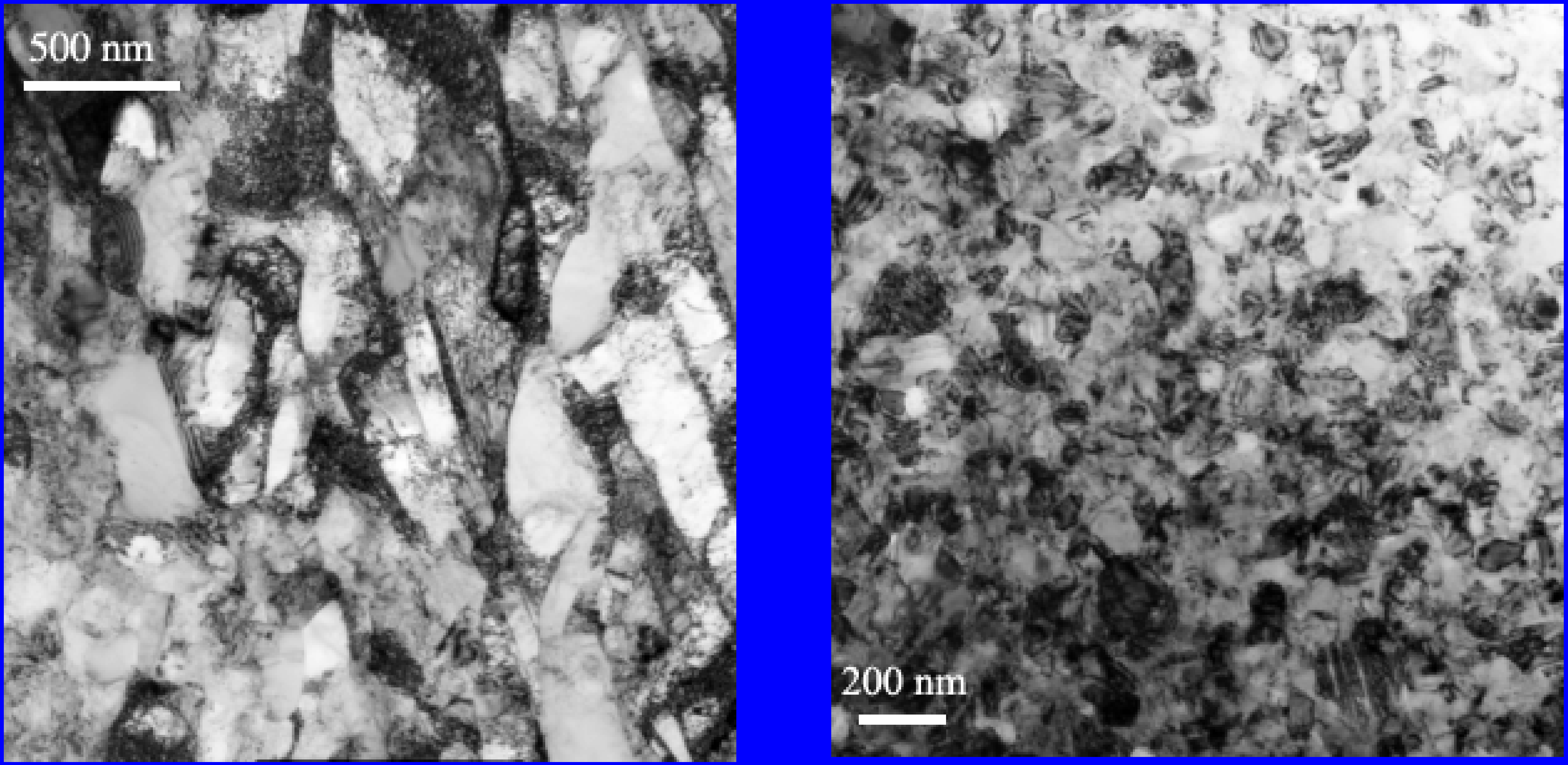
1 A



4 C'



Microstructure after ECAE



Cu

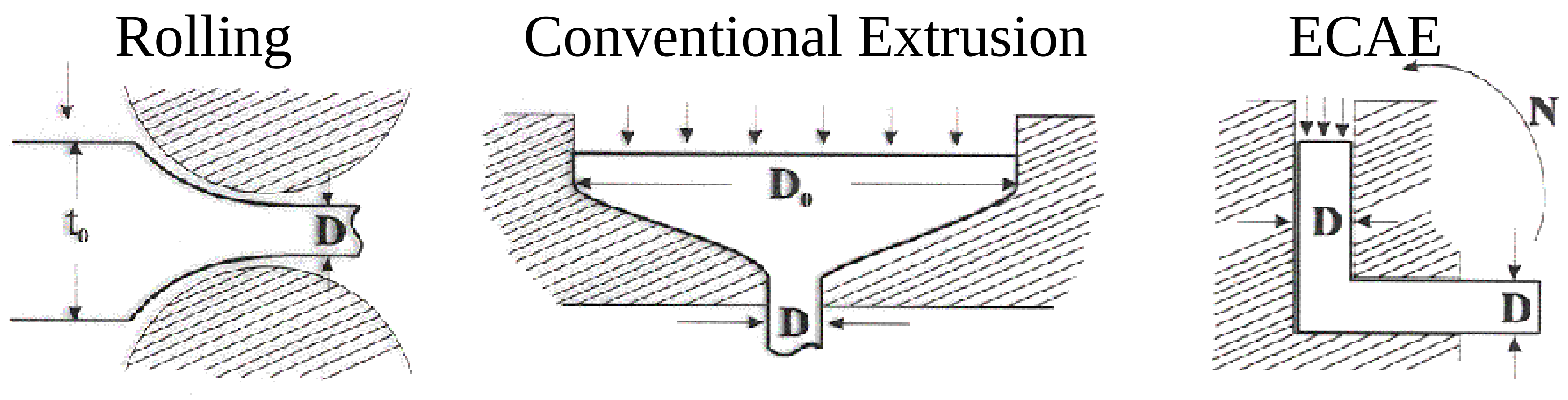
ECAE Die Angle Effects

Full Die Angle	Punch Pressure / Flow Stress	Strain Intensity	Equivalent Reduction Ratio	Equivalent Area Reduction	Conventional Extrusion / ECAE Pressure Ratio	Conventional Extrusion / ECAE Load Ratio
(2ψ)	(p/σ_0)	(ε_i)	$(A_0/A_f)_e$	$(AR)_e$	(p_{CE}/p_{ECAE})	(p_{CE}/p_{ECAE})
150	0.27	0.31	1.37	30	1.80	2.50
120	0.58	0.68	1.95	49	2.20	4.30
90	1.16	1.17	3.20	69	2.50	8.00

Results of Multiple Extrusions Through a 90° Die

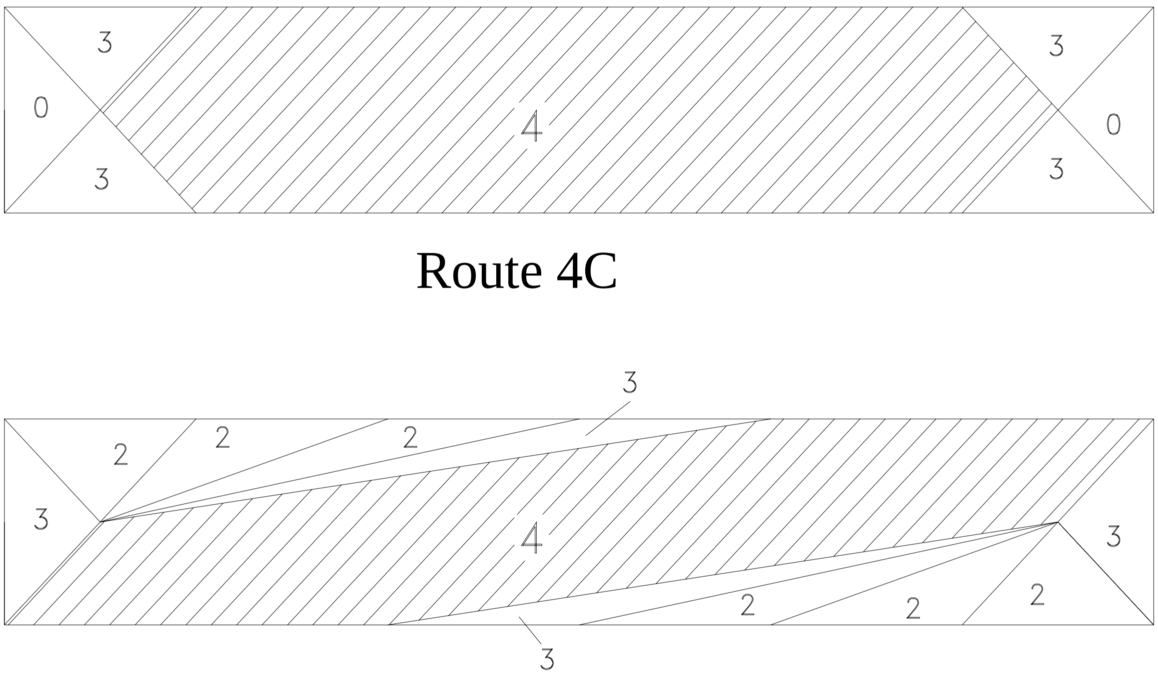
Number of Passes	Total Strain Intensity	Equivalent Reduction Ratio	Equivalent Area Reduction	Angle of Element Inclination	Element Aspect Ratio	Element Surface Area Ratio
			(%)	(deg.)		
0	0	0	0	0	1	1.0
1	1.15	3.2	69	22	5	1.4
2	2.31	10.2	90	13	17	2.0
4	4.62	105	99	7	65	3.4
8	9.24	10100	99.99	3	257	6.0

Comparison Between Conventional, Rolling, Conventional Extrusion and Multipass ECAE



Equivalent Reduction Ratio (A_0/A_1)	Original Plate Thickness (t_0)	Original Billet Diameter (D_0)	Number of ECAE Passes (N)
3.2	3.2 x D	1.8 x D	1
105	105 x D	10.2 x D	4
10100	10100 x D	100 x D	8

Limitations of ECAE



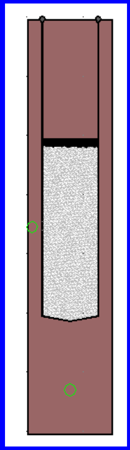
Route 4C

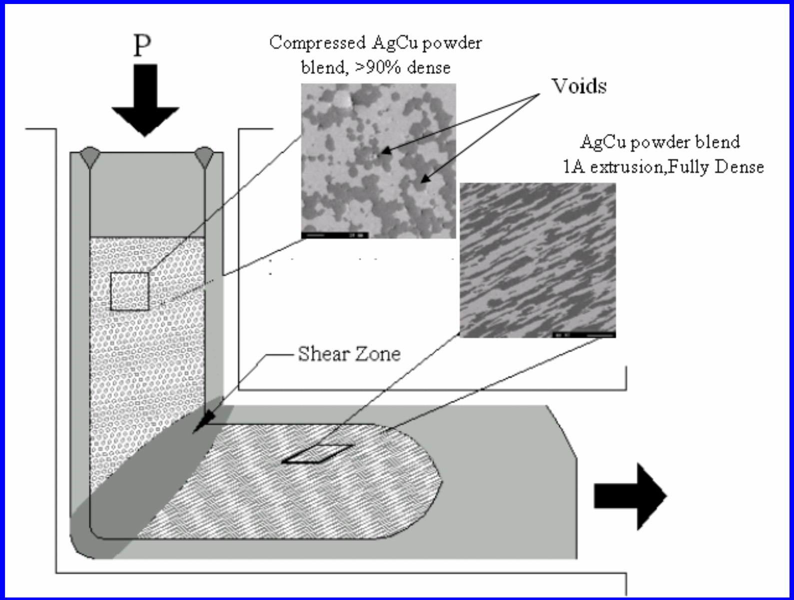
Route 4A

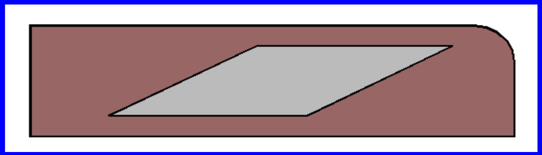
Reality Check

- Process Attributes
  - Elegant Idea
  - Simple Workpiece Geometry
  - Basic Press Needed
  - Large Strain in Bulk Product
  - Uniform Strain
  - Different Microstructures
  - Different Textures
  - Large Application Space
- Negative Aspects
  - Undeformed End Zones
  - New Approach to Deformation Processing
- Unknowns
  - Scale-Up
  - Continuous Processing
  - Complex Cross-sectional Shapes
  - Unknown Method Performance (Dead Zones, Inadequate Ductility...)

Consolidation of powder by ECAE







Can/Powder Description

- **Inert Can Material**
- **Sufficient hydrostatic pressure**
- **0.75 x 0.75 x 3.5 inch**
- **0.50Æ x 1.5 inch Long Cavity**
- **Loose Powder with ~0.35 Void Fraction**
- **Vacuum Bake/Outgas**
- **e-beam Weld Seal**
- **Instrumented with Thermocouples**

Deformation Conditions

- **90º Die Angle**
- **Isothermal Tool**
- **Constant Punch Speed**
- **Hydrostatic Pressure**
- **Simple Shear Uniformly Deforms Can and Encapsulate**
- **Heat of Deformation**
- **Collect Measurements**
  - **Load-Stroke**
  - **Time-Temperature**

Extruded Billet Characteristics

- **Near Full Density**
- **Shorter Billet (Cavity Length Decreases by ~1/3)**
- **Cavity Geometry Changes Shape (Depends on Number of Passes and Route)**

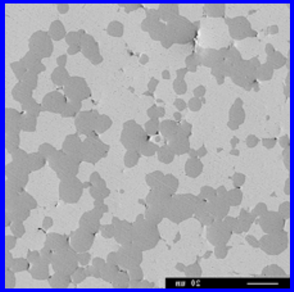
Potential Benefits of Powder Consolidation by ECAE

- ⌘ Small heated cross-section relative to conventional area reduction extrusion (better heat transfer conditions)
- ⌘ Large product cross-sections may be possible (conservation of cross-section during extrusion)
- ⌘ High length/diameter ratio product may be possible
- ⌘ Combined compaction and shear
- ⌘ Consolidation to near full density after a single extrusion
- ⌘ Consolidation to full density at lower temperature than needed for HIPing
- ⌘ Lower punch loads than for area reduction extrusion

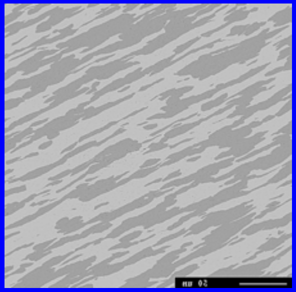
Theoretical Change in Particle Surface Area for Different ECAE Routes

Route Name	Percent increase in cubic element surface area for different numbers of passes (N values)				
	0	**1**	**2**	**4**	**8**
A	0	41	103	235	502
B	0	41	67	158	345
C	0	41	0	41	0

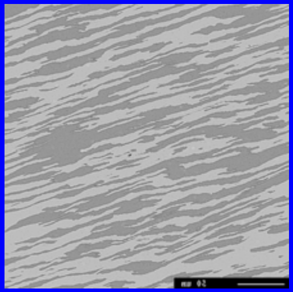
N=0



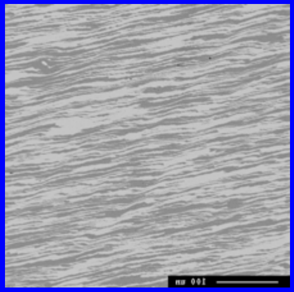
N=1 (Route A)



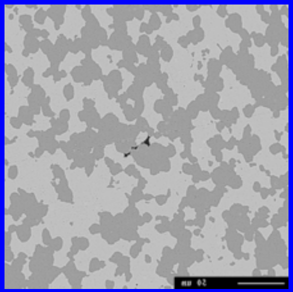
N=2 (Route A)



N=4 (Route A)



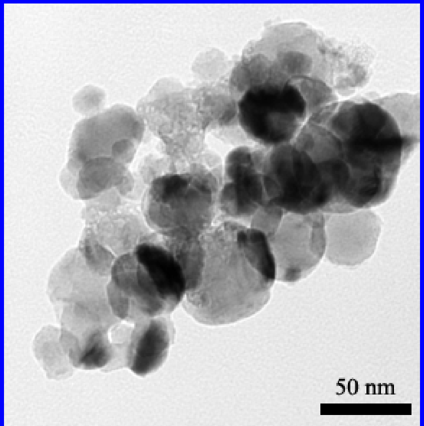
N=2 (Route C)



Flow Plane of CuAg Composite

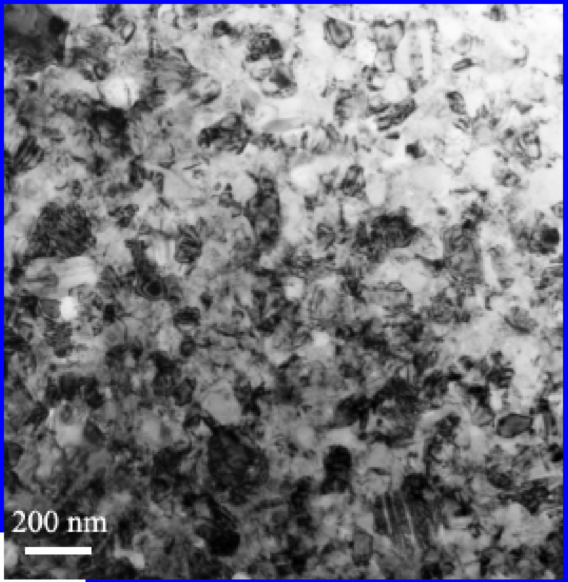
Powder Consolidation

⌘ Nanopowder consolidation using ECAE

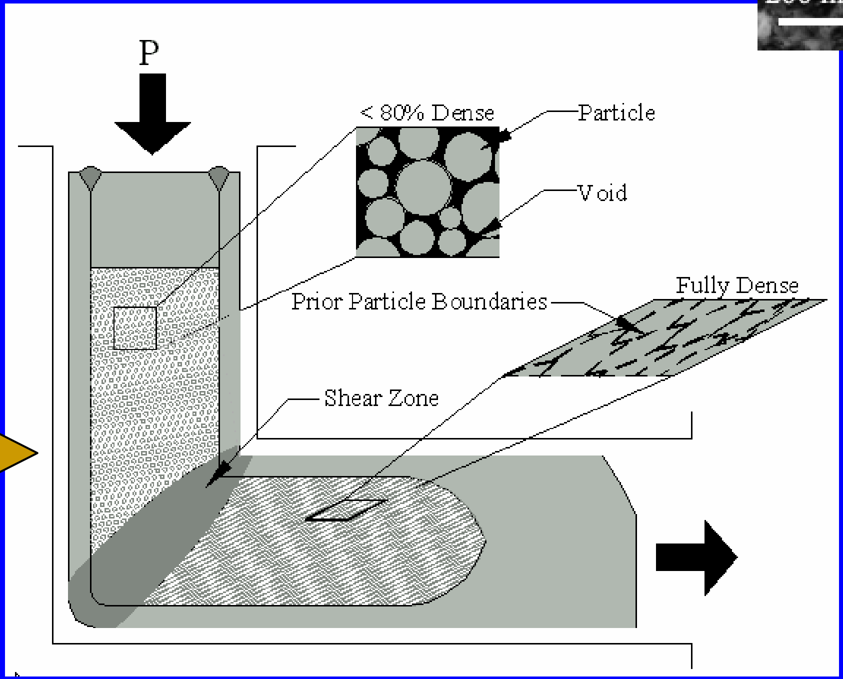


Nanopowders (Cu-50 nm, SS-100 nm, Cu-130 nm)

Nanopowder fabrication Methodology: Electro-Explosion of Wires



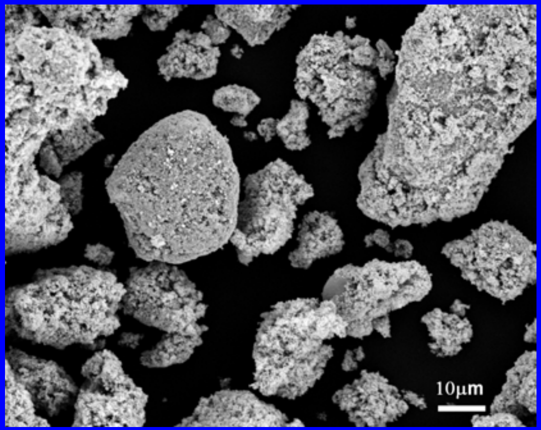
Consolidated 130 nm Cu powder

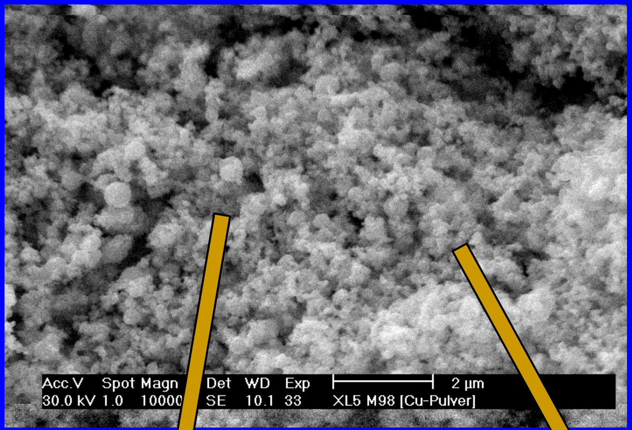


Consolidation in a can

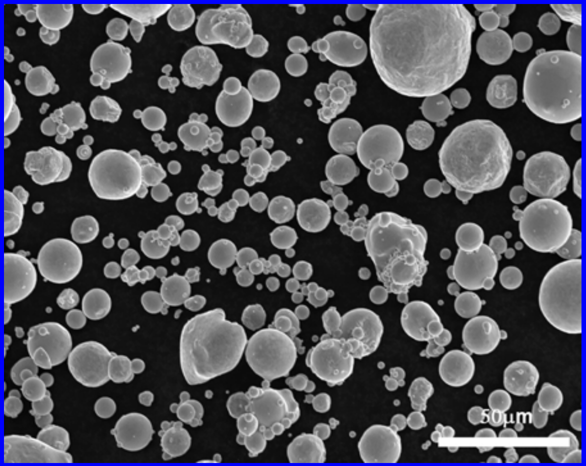
Agglomeration Phenomena

Electroexploded Nanopowder ($O_2 \approx 0.1$ wt%) (FNAA)

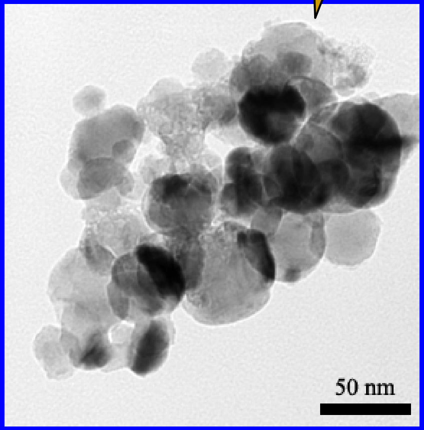




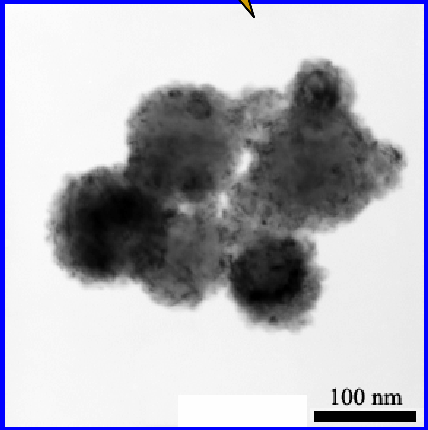
Agglomerates



Micropowder (DOE Ames)
99.99 wt% Cu, -325 mesh
Ave. Grain Size: 4.2 microns (X-Ray analysis)



Average size 67 nm (X-Ray analysis)



Average size 130 nm (X-Ray analysis)