CARNEGIE MELLON UNIVERSITY
DEPARTMENT OF
MATERIALS SCIENCE AND ENGINEERING

Typical Textures, part 1: Thermomechanical Processing (TMP) of Metals

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27-750

Texture, Microstructure & Anisotropy

Last revised: 26th Apr. 2014

Objectives

- Introduce you to experimentally observed textures in a wide range of materials.
- Develop a taxonomy of textures based on deformation type.
- Prepare you for relating observed textures to theoretical (numerical) models of texture development, especially the *Taylor* model.
- See chapter 5 in Kocks, Tomé & Wenk.
- Some slides courtesy of Prof. P. Kalu (FAMU)

Taxonomy

- Deformation history more significant than alloy.
- Crystal structure determines texture through slip (and twinning) characteristics.
- Alloy (and temperature) can affect textures through planarity of slip.
- Annealing (recrystallization) sometimes produces a drastic change in texture.

Why does deformation result in texture development?

- Qualitative discussion:
- Deformation means that a body changes its shape, which is quantified by the plastic strain, ε_p.
- Plastic strain is accommodated in crystalline materials by dislocation motion, or by re-alignment of long chain molecules in polymers.

Dislocation glide ⇒ grain reorientation

- Dislocation motion at low (homologous) temperatures occurs by glide of loops on crystallographic planes in crystallographic directions: *restricted glide*.
- Restricted glide throughout the volume is equivalent to uniform shear.
- In general, shear requires lattice rotation in order to maintain grain alignment: *compatibility*

Re-orientation → Preferred orientation

- Reorientations experienced by grains depend on the type of strain (compression versus rolling, e.g.) and the type of slip (e.g. {111}<110> in fcc).
- In general, some orientations are unstable (*f(g)* decreases) and some are stable (*f(g)* increases) with respect to the deformation imposed, hence *texture development*.

The Taylor model

- The *Taylor* model has one basic assumption: the change in shape (micro-strain) of each grain is identical to the body's change in shape (macro-strain).
- Named for G.I. Taylor, English physicist, mid-20th century; first to provide a quantitative explanation of texture development.

Single slip models ineffective

- Elementary approach to single crystal deformation emphasizes slip on a single deformation system.
- Polycrystal texture development requires *multiple slip systems* (5 or more, as dictated by von Mises).
- *Cannot use simple rules*, e.g. alignment of slip plane with compression plane!

Deformation systems (typical)

- Fcc metals (low temperature):
  {111}<110>
- Bcc metals:
  {110}<111>,
  {112}<111>,
  {123}<111>,
  pencil glide

Hexagonal metals:
{1010}<1210>;
{0001}<1210>;
{1012}<1011>$_{twin}$;
{1011}<1123>;
{2112}<2113>$_{twin}$.

Deformation systems (typical)

Material Class	Primary System	Secondary Systems
Face-centered cubic metals	$\{111\}\langle 1\bar{1}0\rangle$	
Body-centered cubic metals	$\{110\}\langle \bar{1}11\rangle$	$\{123\}\langle 11\bar{1}\rangle$ $\{112\}\langle 11\bar{1}\rangle$
Hexagonal close-packed metals (c/a>1.633) (e.g. Be, Cd, Zn and Mg)	$\{0001\}\langle 11\bar{2}0\rangle$	$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ $\{10\bar{1}1\}\langle 11\bar{2}0\rangle$
Hexagonal close-packed metals (c/a<1.633) (e.g. Zr,Ti and Hf)	$\{10\bar{1}0\}\langle 11\bar{2}0\rangle$	$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ $\{10\bar{1}1\}\langle 11\bar{2}0\rangle$
Diamond cubic (fcc) (e.g. Si, Ge and diamond)	$\{111\}\langle 1\bar{1}0\rangle$	
Rock Salt (fcc) (e.g. MgO, LiF, NaCl)	$\{110\}\langle 1\bar{1}0\rangle$	
CsCl (simple cubic)	$\{110\}\langle 001\rangle$	
Al2O3 (hexagonal)	$\{0001\}\langle 11\bar{2}0\rangle$	$\{11\bar{2}0\}\langle 1\bar{1}01\rangle$ $\{1\bar{1}02\}\langle 1\bar{1}01\rangle$
BeO (hexagonal)	$\{0001\}\langle 11\bar{2}0\rangle$	$\{10\bar{1}0\}\langle 11\bar{2}0\rangle$ $\{10\bar{1}0\}\langle 0001\rangle$

In deformed materials, texture or preferred orientation exists due to the anisotropy of slip. While slip in bcc metals generally occurs in the <111> type direction, it may be restricted to {110} planes or it may involve other planes

(*T. H. Courtney, Mechanical Behavior of Materials, McGraw-Hill, New York, 1990.*)

Strain Measures

- Strain commonly defined as a scalar measure of (plastic, irreversible) deformation: logarithmic strain:=

$$\varepsilon = \ln \{l_{new}/l_{old}\}$$

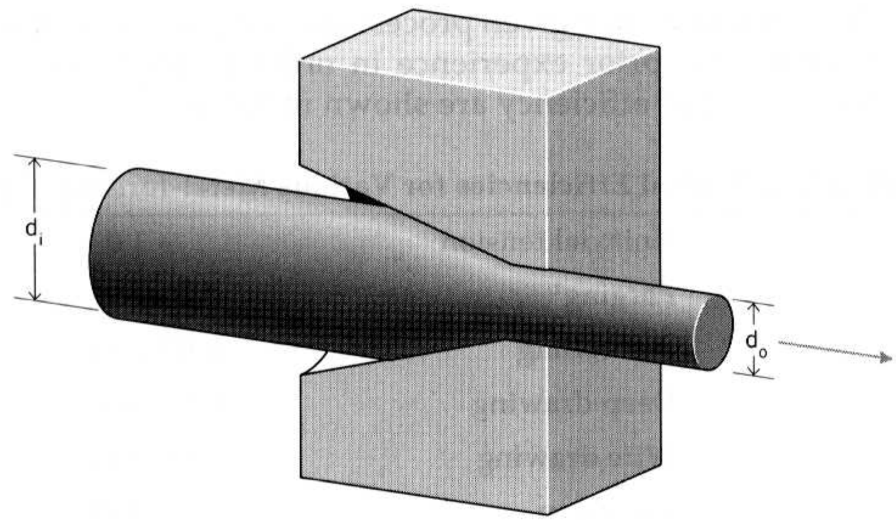
- Rolling strain: typical: reduction in thickness:= $r = 100\% \text{ x } h_{new}/h_{old}$
  better (!) = *von Mises equivalent strain*

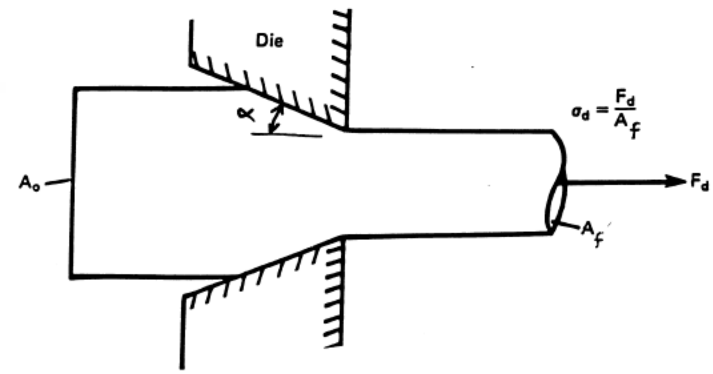
$$\varepsilon_{vM} = 2/\sqrt{3} \ln \{l_{old}/l_{new}\}$$

Deformation Modes:sample symmetry

- Tension, Wire Drawing, Extrusion C_∞
- Compression, Upsetting C_∞
- Torsion, Shear 2
- Plane Strain Compression, Rolling mmm
- Deformation modes of uniaxial type generate fiber textures
- Shear gives monoclinic symmetry
- Plane strain gives orthorhombic symmetry

Axisymmetric deformation: Extrusion, Drawing



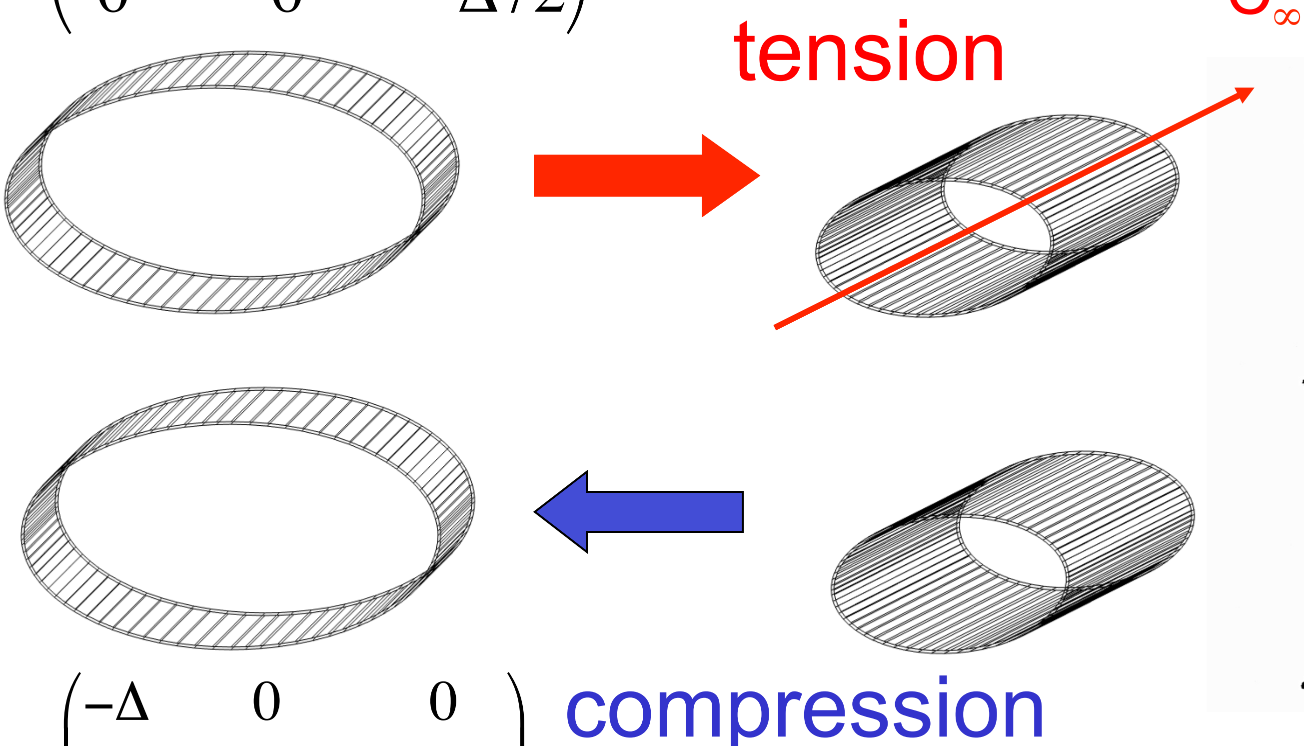


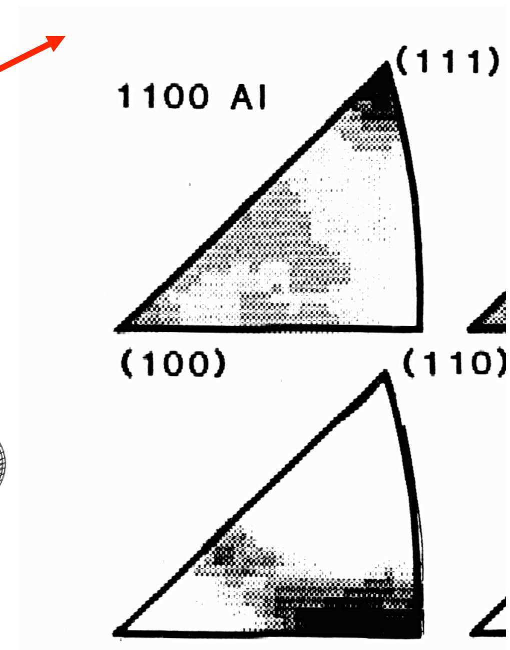
$$\varepsilon = \begin{pmatrix} +\Delta & 0 & 0 \\ 0 & -0.5\Delta & 0 \\ 0 & 0 & -0.5\Delta \end{pmatrix}$$

Uniaxial Strain

$$d\varepsilon = \begin{pmatrix} +\Delta & 0 & 0 \\ 0 & -\Delta/2 & 0 \\ 0 & 0 & -\Delta/2 \end{pmatrix}$$

Inverse Pole Figures (FCC)





$$d\varepsilon = \begin{pmatrix} -\Delta & 0 & 0 \\ 0 & +\Delta/2 & 0 \\ 0 & 0 & +\Delta/2 \end{pmatrix}$$

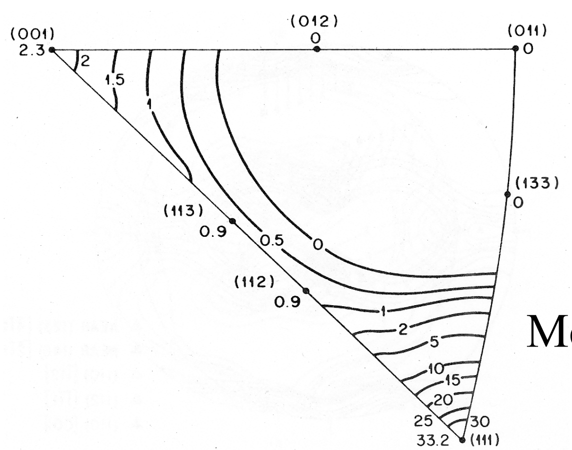
Uniaxial Modes - C_∞

Deformation mode/	fcc/	bcc/	hcp (Ti)
Wire drawing, Round extrusion.	<111> & <100>	<110>	<10-10>
Upsetting, Unixial compression.	<110>	<111> &<100>	<0001>

Note exchange of types between *fcc* & *bcc*

Axisymmetric deformation

- In fcc metals, axisymmetric deformation (e.g. wire drawing) produces fiber texture: <111> + <100> duplex, parallel to the wire.

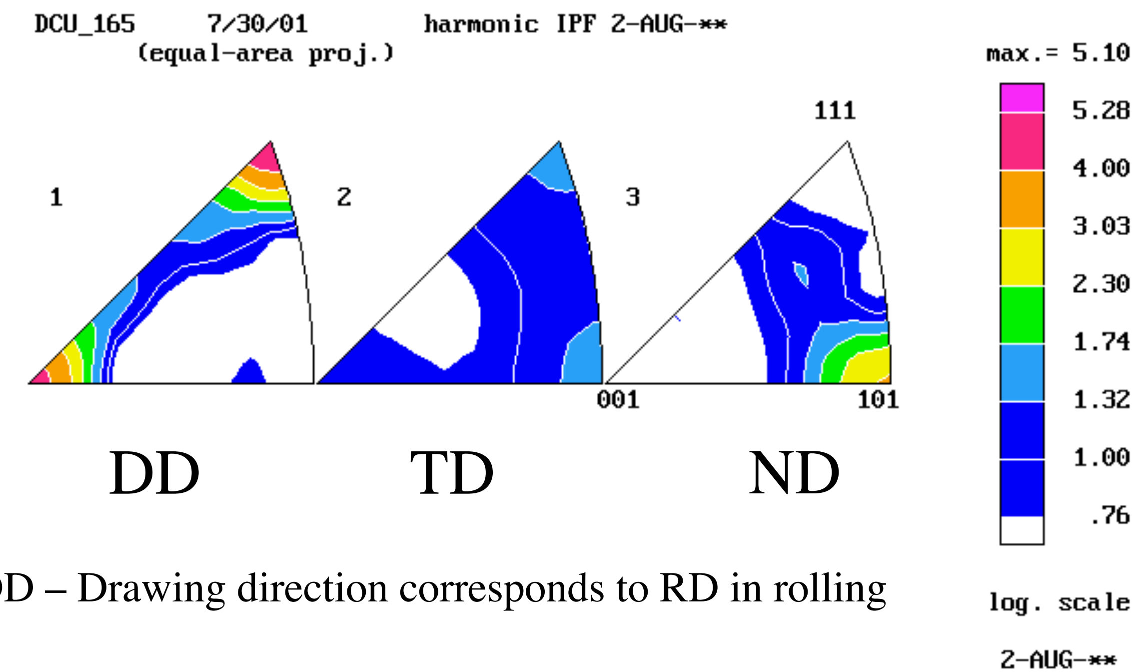


McHargue et al., 1959

Schmid and Wassermann (1963): 60% <111> + 40% <100>
Ahlborn and Wassermann (1963): 66% <111> + 34% <100>
} Electrolytic Copper

Axisymmetric deformation

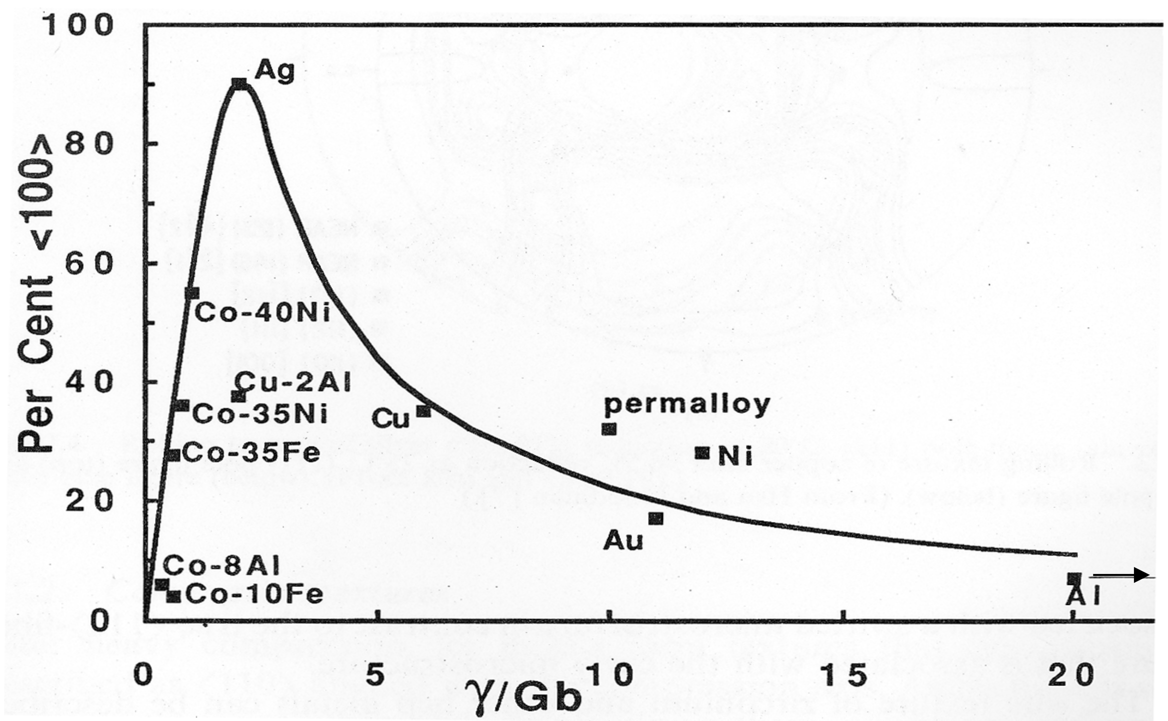
- Axisymmetric deformation ~ higher order symmetry, C_∞
- Texture can be represented by an *inverse pole figure* (IPF).
- In IPF, contour lines show the frequency with which the various directions, <uvw>, in the crystal coincide with the specimen axis under consideration



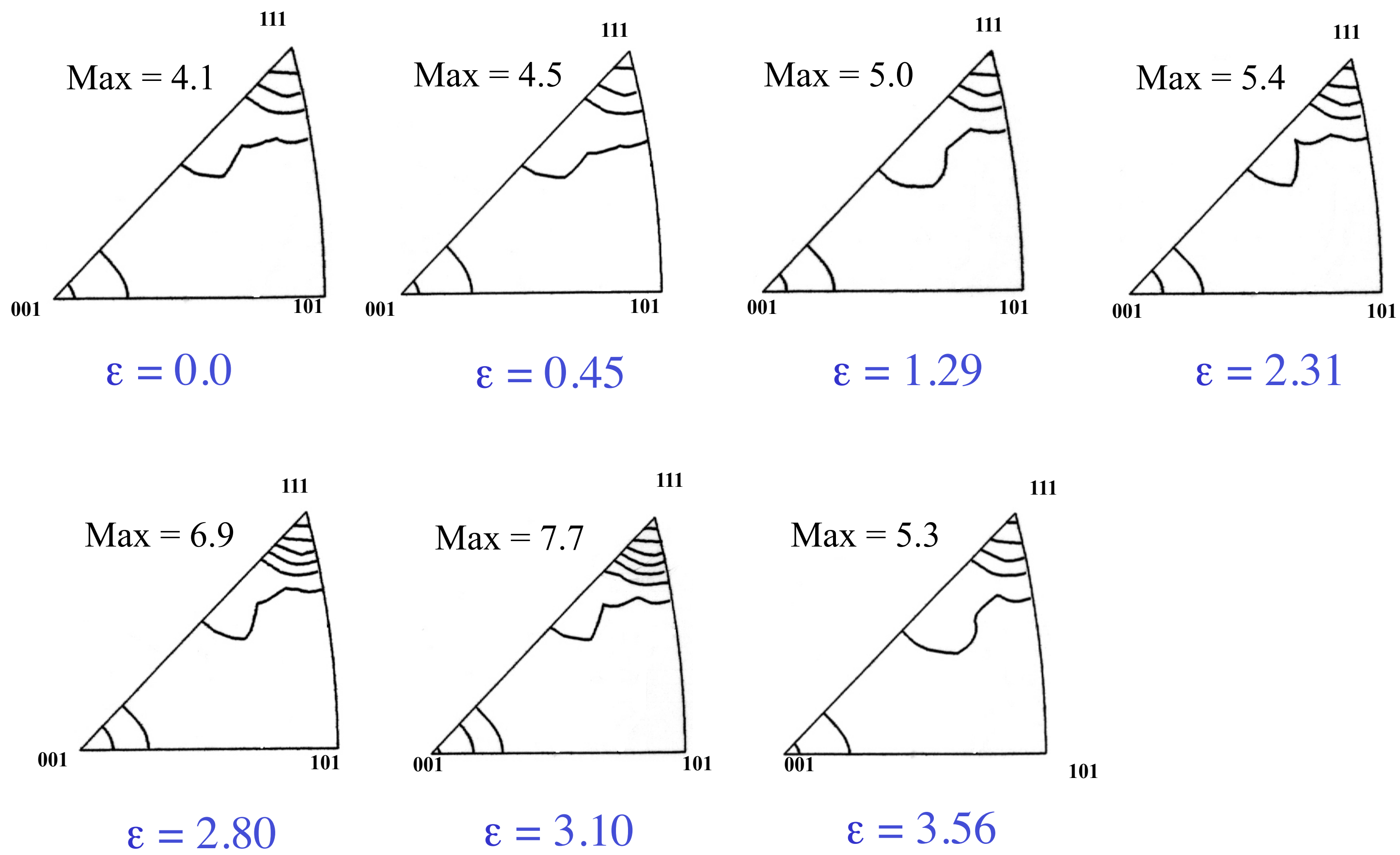
DD – Drawing direction corresponds to RD in rolling

Axisymmetric deformation

- The relative proportions of the two components are determined by the stacking fault energy [English et al., 1965] and vary in a complex manner.



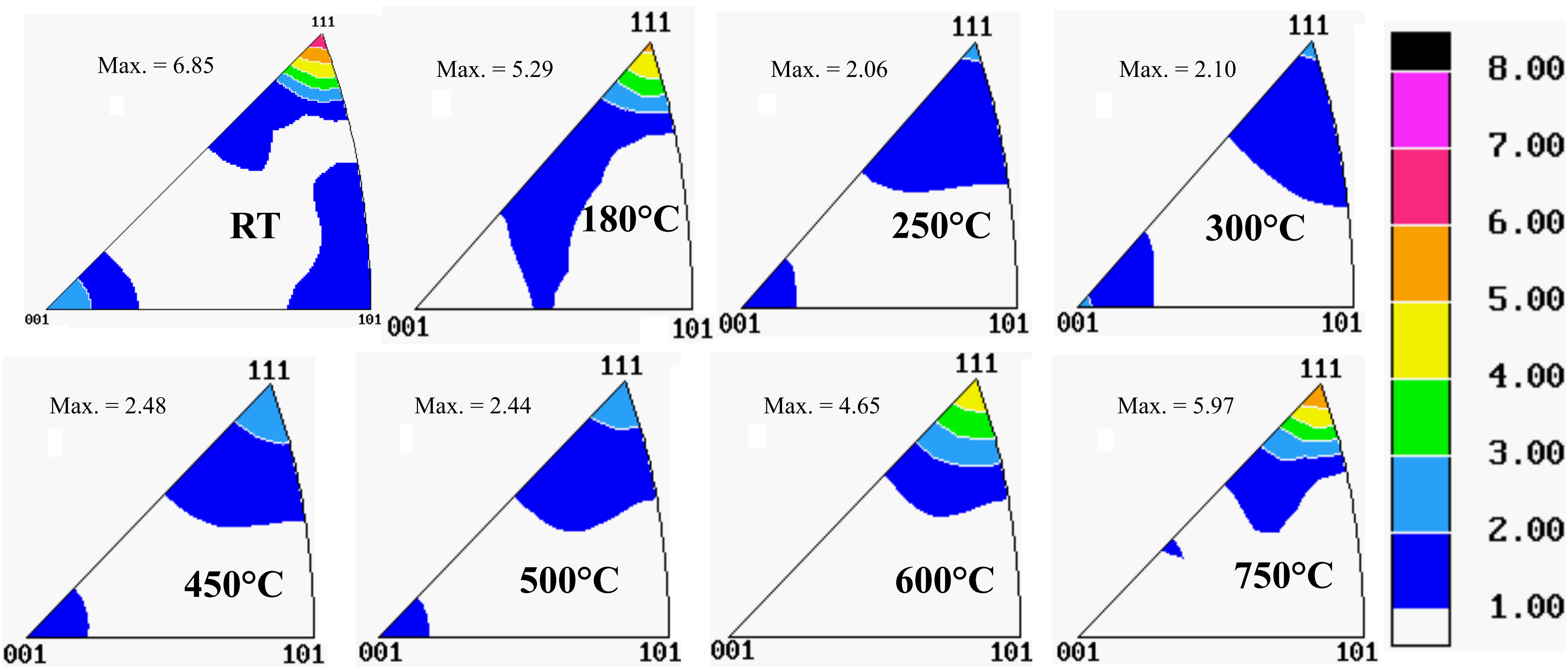
Effect of deformation strain



X-ray IPFs showing the effect of strain on the texture of OFHC copper wire

D. R. Waryoba, Ph. D. Dissertation, FSU, 2003

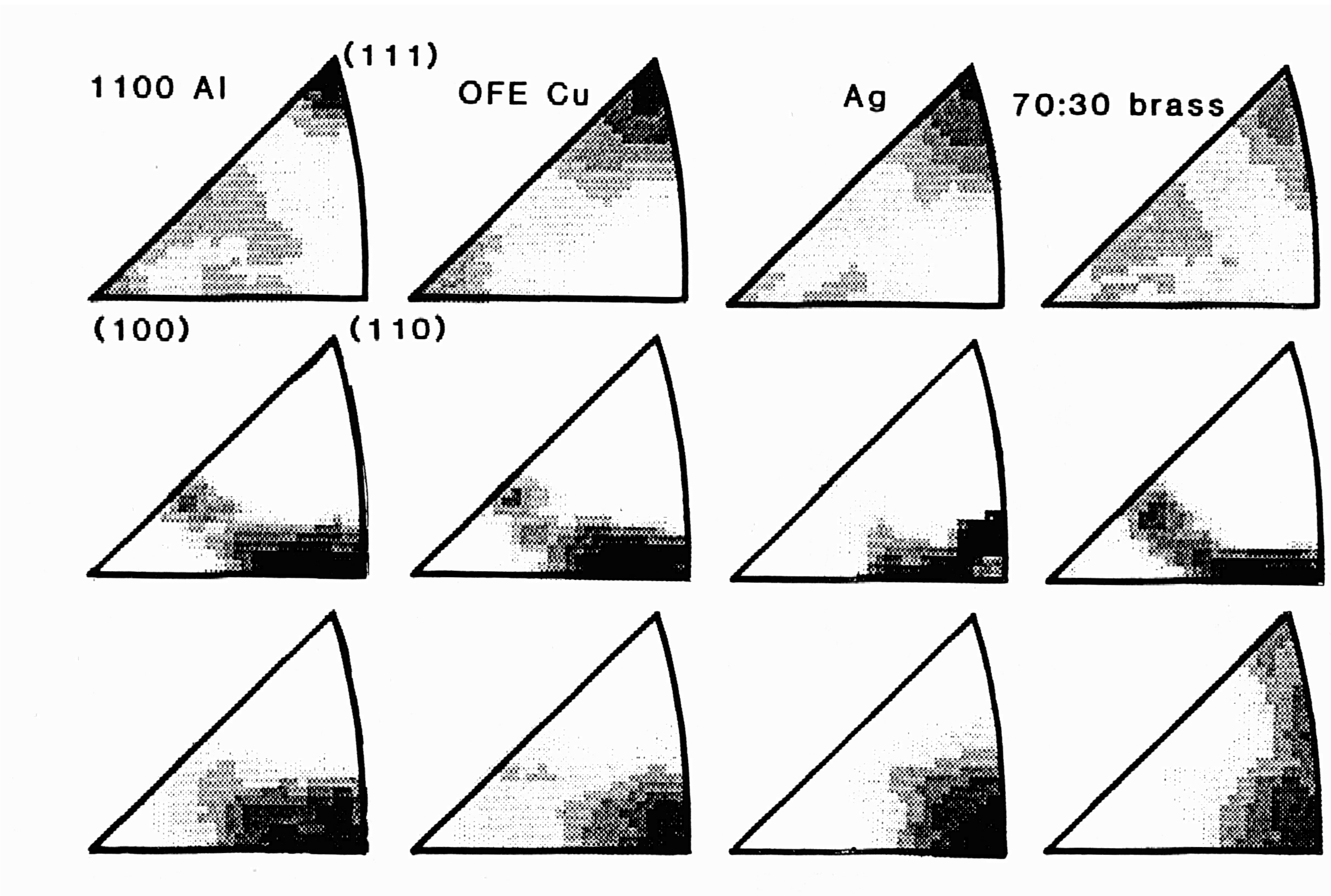
Effect of Temperature



X-ray IPFs showing the effect of annealing temperature on the texture of OFHC copper wire, initially drawn to true strain of 2.31

D. R. Waryoba and P. N. Kalu, TMS 2003,San Diego, CA

Uniaxial Compression: fcc



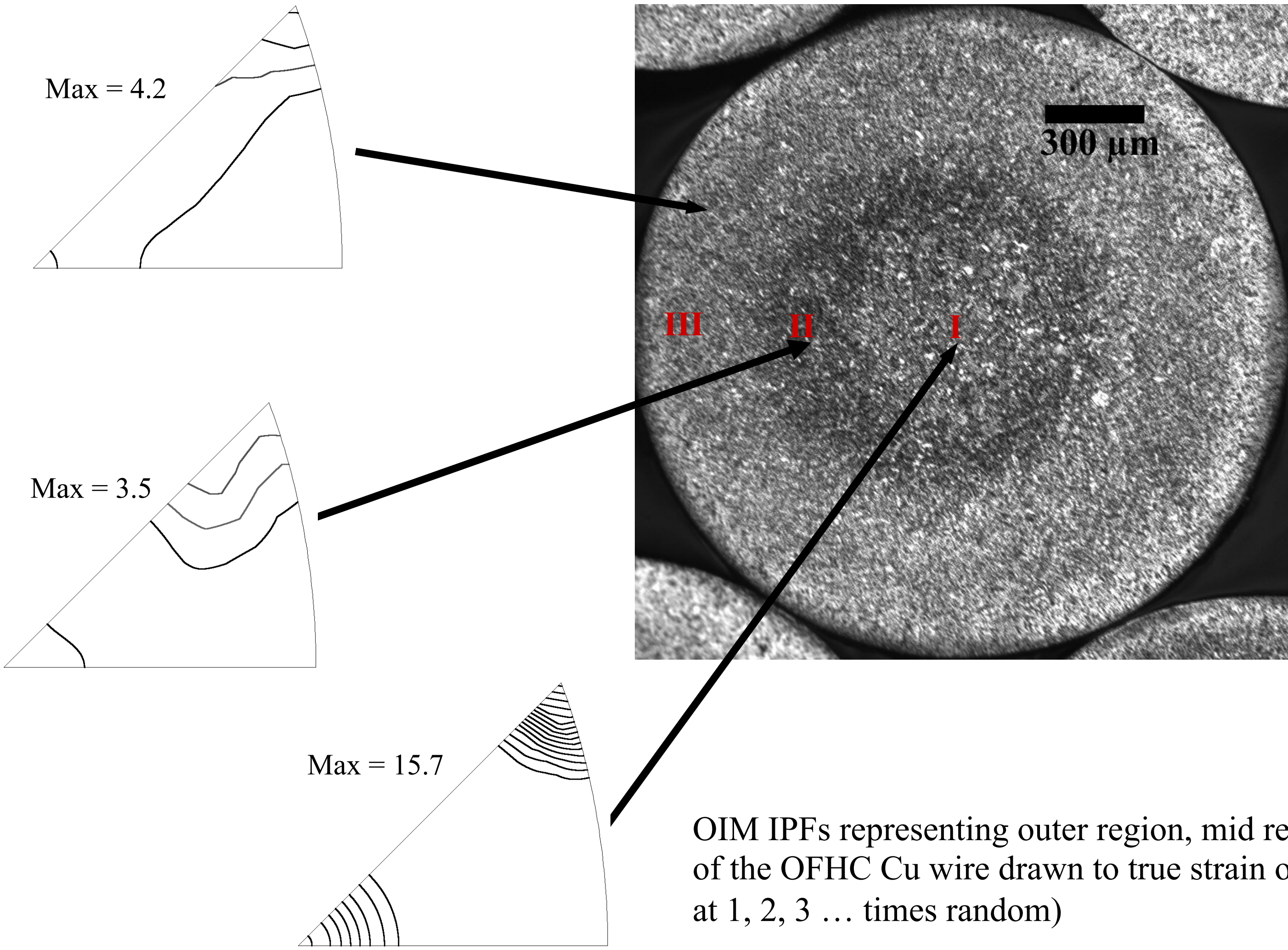
Initial texture

theoretical texture

exptl. texture

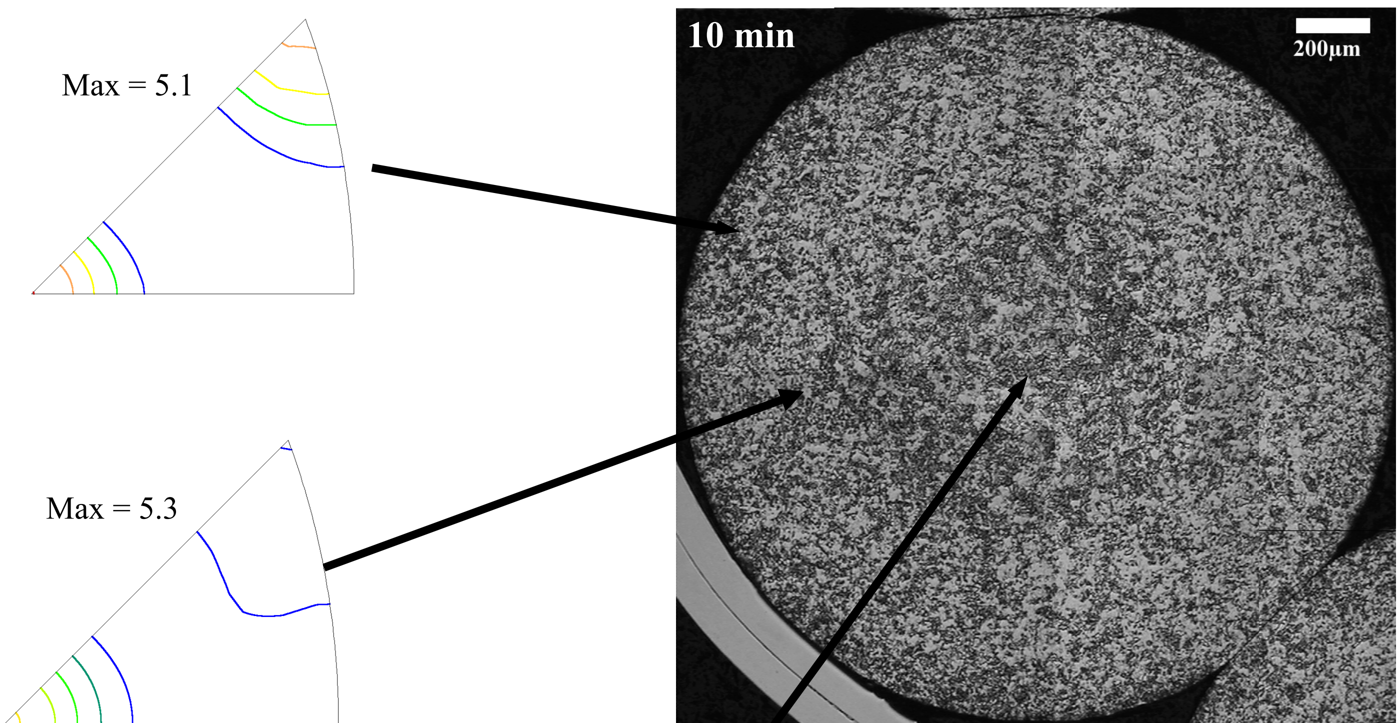
[Kocks Ch. 5: Inverse Pole Figures]

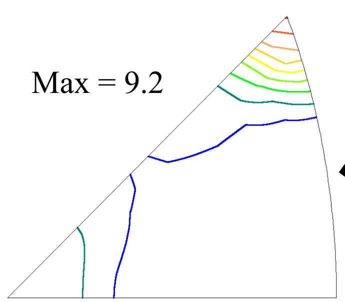
Texture inhomogeneity in Drawn Wires



OIM IPFs representing outer region, mid region, and inner core of the OFHC Cu wire drawn to true strain of 2.31 (contours are at 1, 2, 3 … times random)

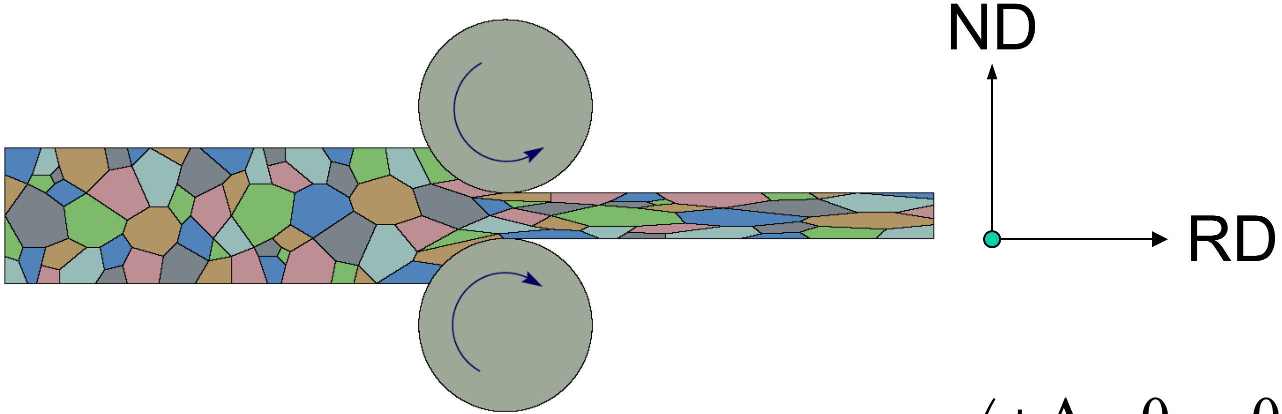
Texture inhomogeneity in Drawn Wires





OIM IPFs representing outer region, mid region, and inner core of the OFHC Cu wire drawn to true strain of 2.31 and annealed at 250°C for 10 min (contours are at 1, 2, 3 … times random)

Rolling = Plane Strain

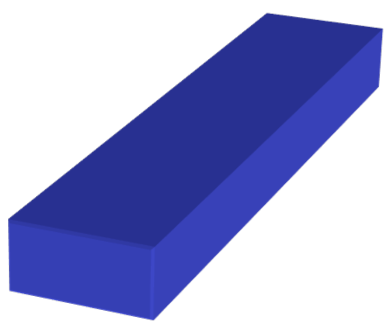


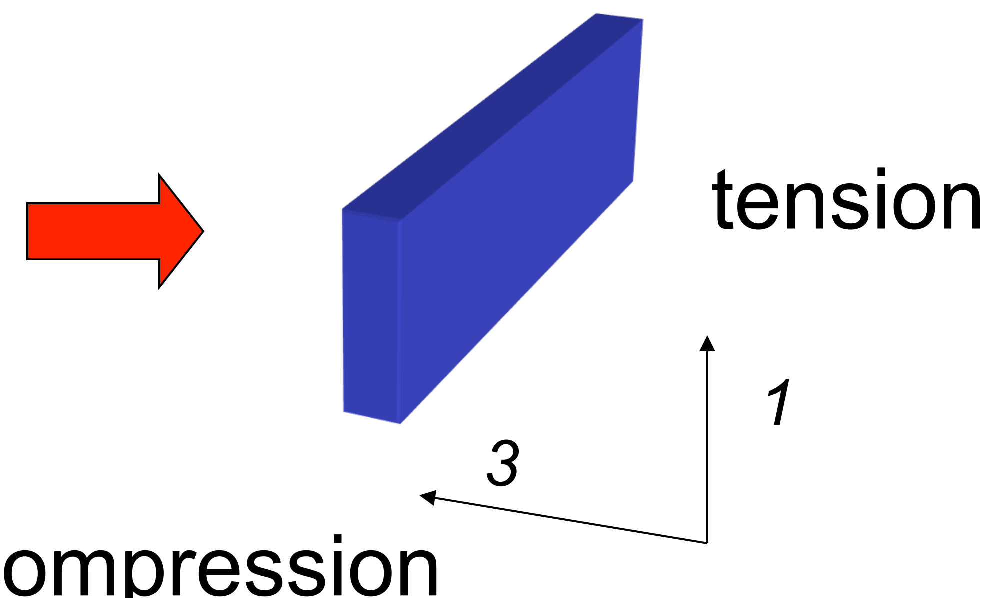
$$\varepsilon = \begin{pmatrix} +\Delta & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\Delta \end{pmatrix}$$

Rolling ~ plane strain deformation means extension or compression in a pair of directions with zero strain in the third direction: a *multiaxial strain*.

Plane strain (rolling)

Plane strain means extension/compression in a pair of directions with zero strain in the third direction: a *multiaxial strain*.



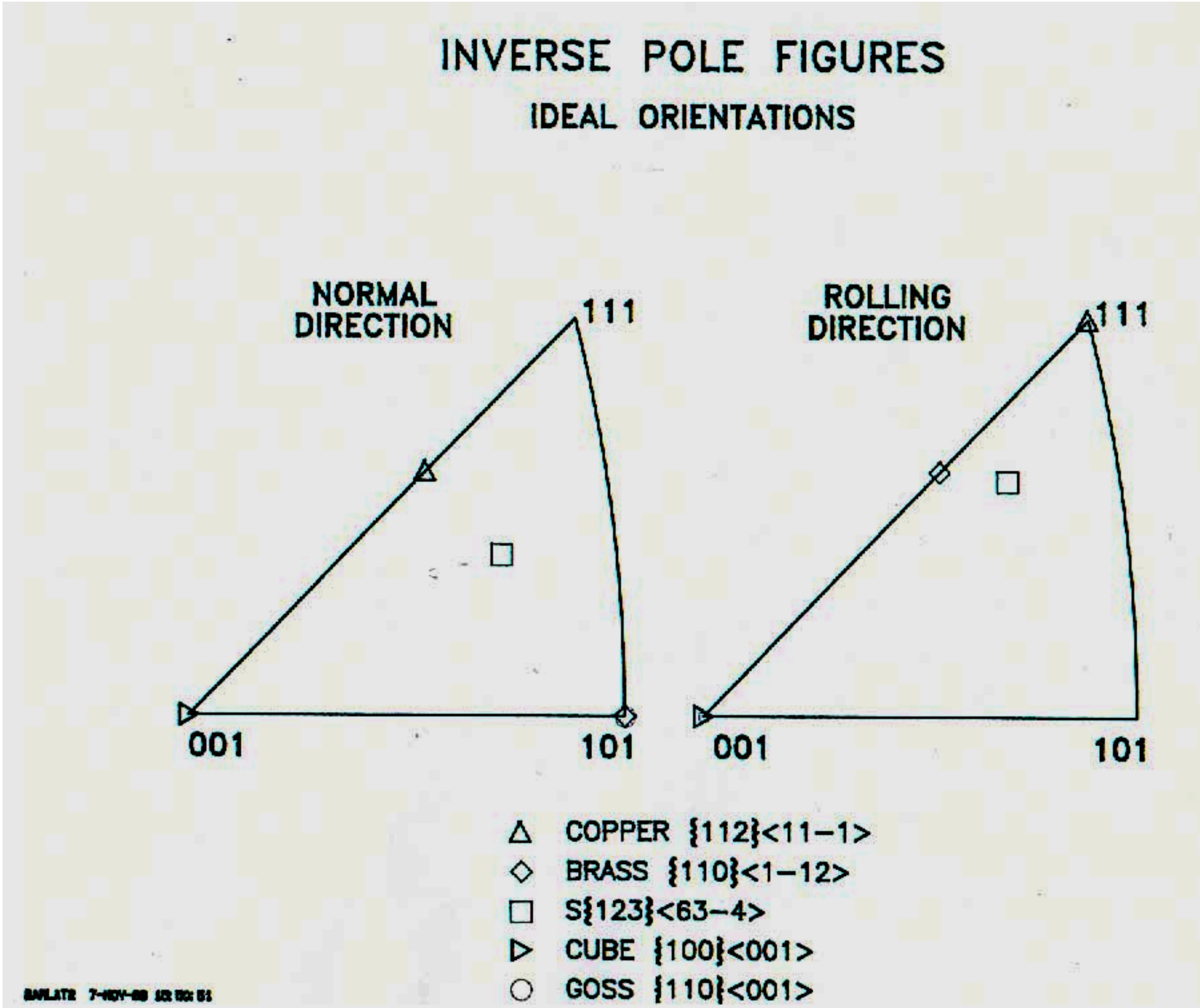


$$d\varepsilon = \begin{pmatrix} +\Delta & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\Delta \end{pmatrix}$$

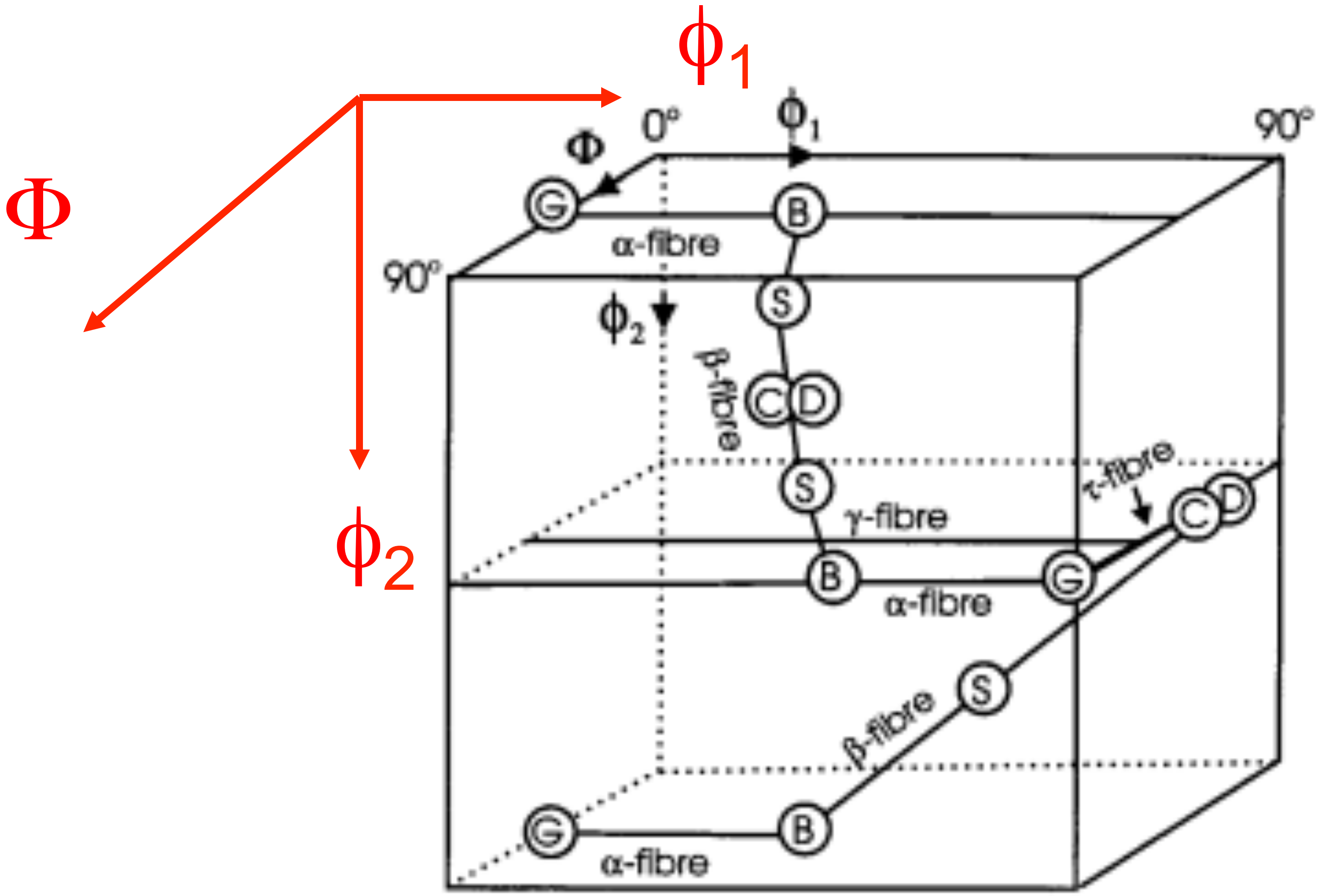
Typical rolling texture in FCC Materials

Type	Component	{hkl}<uvw>	Euler Angles (Bunge)		
			φ_1	θ	φ_2
Deformation	Bs	{011}<211>	35	45	0
	S	{123}<634>	55	35	65
	Cu	{112}<111>	90	30	45
	$Shear_1$	{001}<110>	0	0	45
	$Shear_2$	{111}<110>	0	55	45
	$Shear_3$	{112}<110>	0	35	45
Recrystallization	Goss	{011}<001>	0	45	0
	Cube	{001}<100>	0	0	0
	RC_{RD1}	{013}<100>	0	20	0
	RC_{RD2}	{023}<100>	0	35	0
	RC_{ND1}	{001}<310>	20	0	0
	RC_{ND2}	{001}<320>	35	0	0
	P	{011}<122>	70	45	0
	Q	{013}<231>	55	20	0
	R	{124}<211>	55	75	25

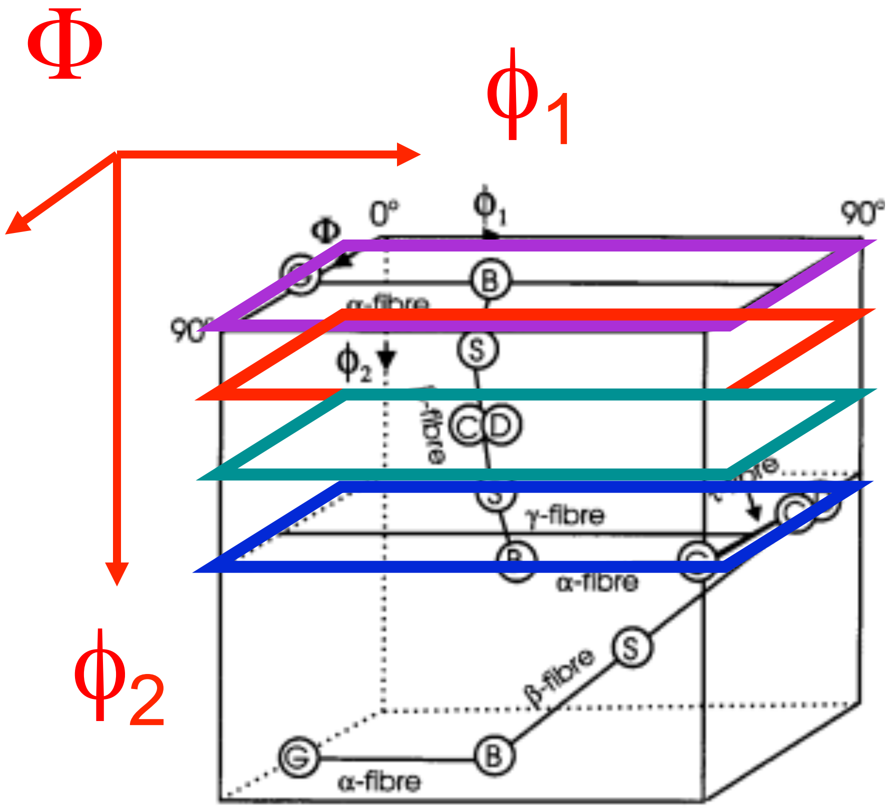
fcc/	bcc/	hcp (Ti)
Shear:		
A:{111}<uvw>	E:{110}<001>	??
B:{hkl}<110>	D:{112}<110>	
C: {001}<110>		
Rolling: Partial Fibers:		
beta, alpha	gamma, alpha	{0001}

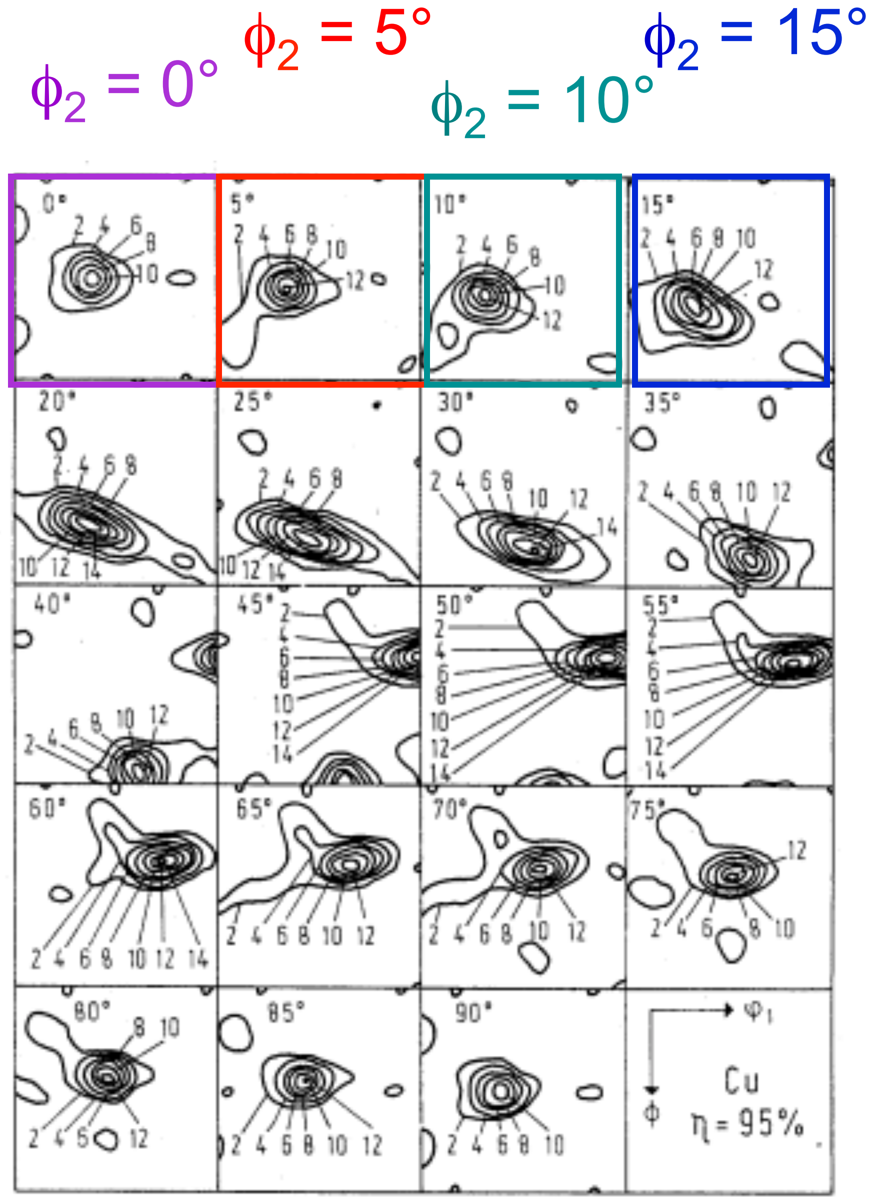

INVERSE POLE FIGURES
IDEAL ORIENTATIONS
NORMAL DIRECTION
111
001
101
ROLLING DIRECTION
111
001
101
COPPER {112}<11-1>
BRASS {110}<1-12>
S{123}<63-4>
CUBE {100}<001>
GOSS {110}<001>

Cartesian Euler Space



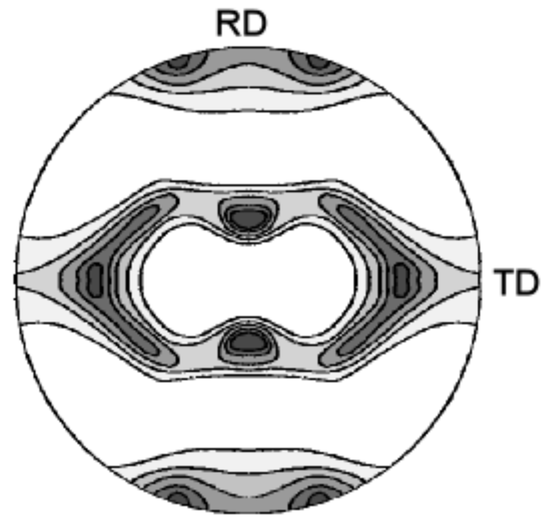
Sections

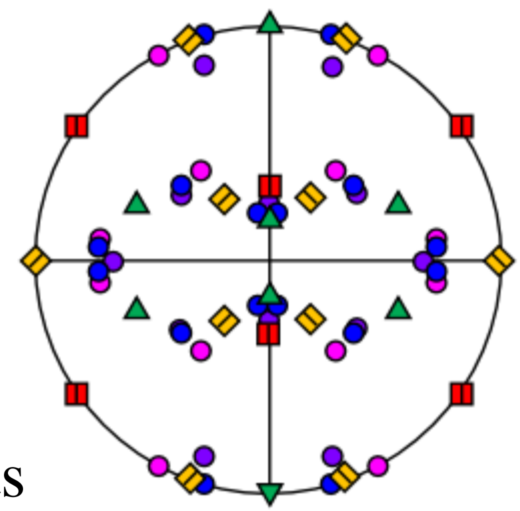

Φ
φ1
φ2
0°
90°
Φ
φ1
φ2
α-fibre
γ-fibre
β-fibre


φ2 = 0°
φ2 = 5°
φ2 = 10°
φ2 = 15°
Cu
η = 95%

PF Representation

Name	Indices	Bunge (φ_1,Φ,φ_2)
▲ copper	{112}<11$\bar{1}$>	90°, 35°, 45°
● S1	{124}<21$\bar{1}$>	59°, 29°, 63°
● S2	{123}<41$\bar{2}$>	47°, 37°, 63°
● S3*	{123}<63$\bar{4}$>	59°, 37°, 63°
◆ brass	{110}<$\bar{1}$12>	35°, 45°, 0°
Taylor	{4 4 11}<11 11 $\bar{8}$>	7°, 71°, 70°
■ Goss	{110}<001>	0°, 45°, 0°



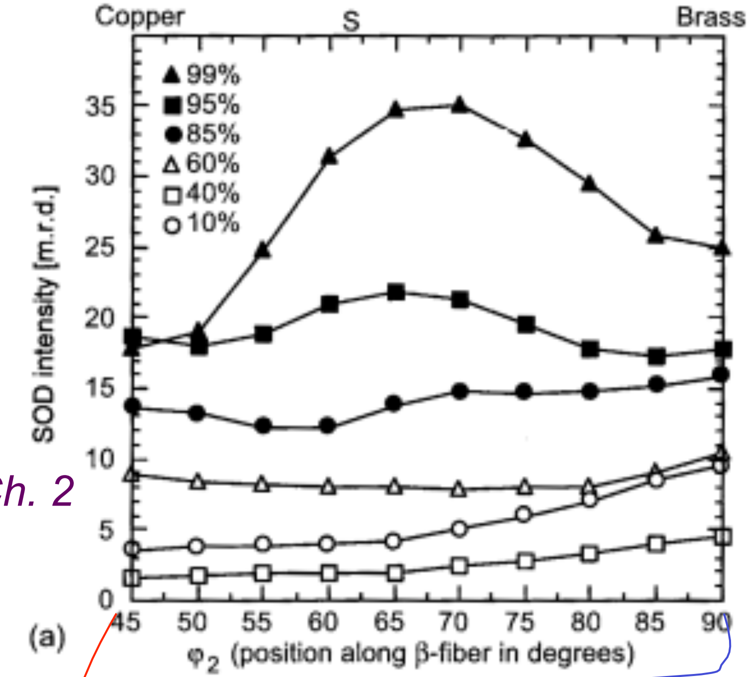


Note how very different components tend to overlap in a pole figure.

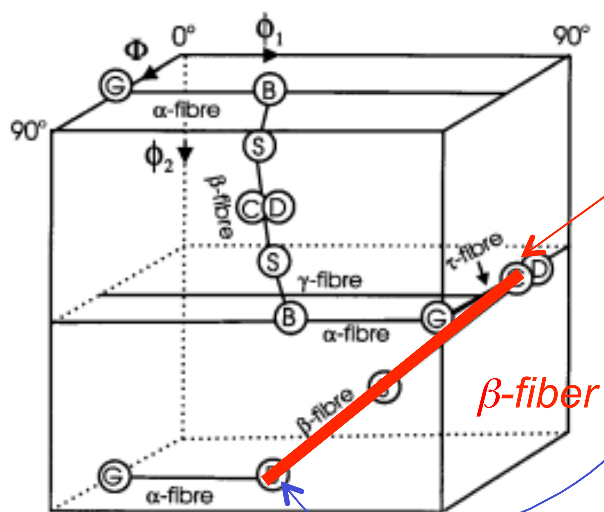
Fiber Plots:

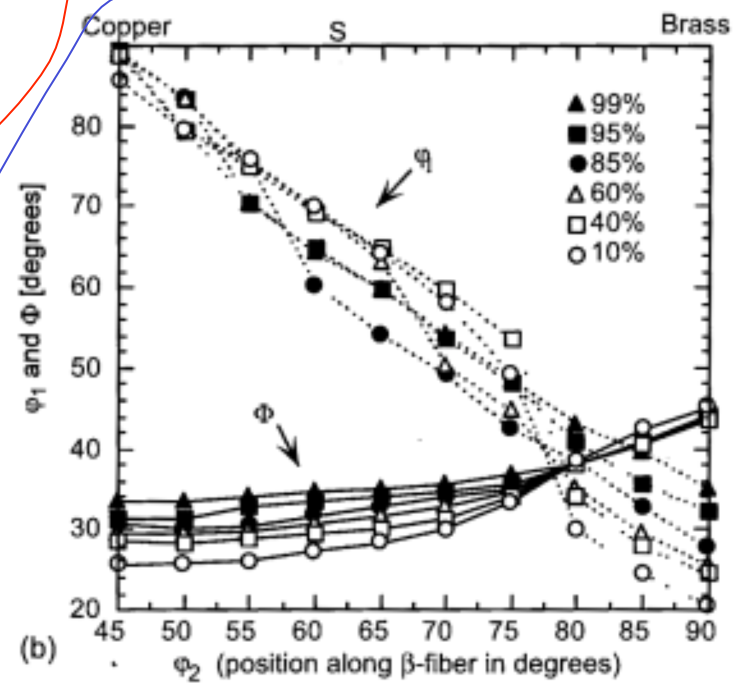
various rolling reductions:
(a) intensity versus position along the fiber
(b) angular position of intensity maximum versus position along the fiber

Kocks, Ch. 2



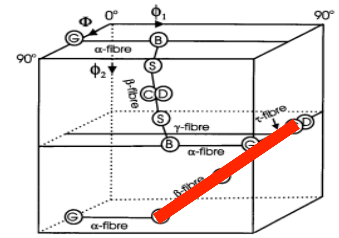
(a)



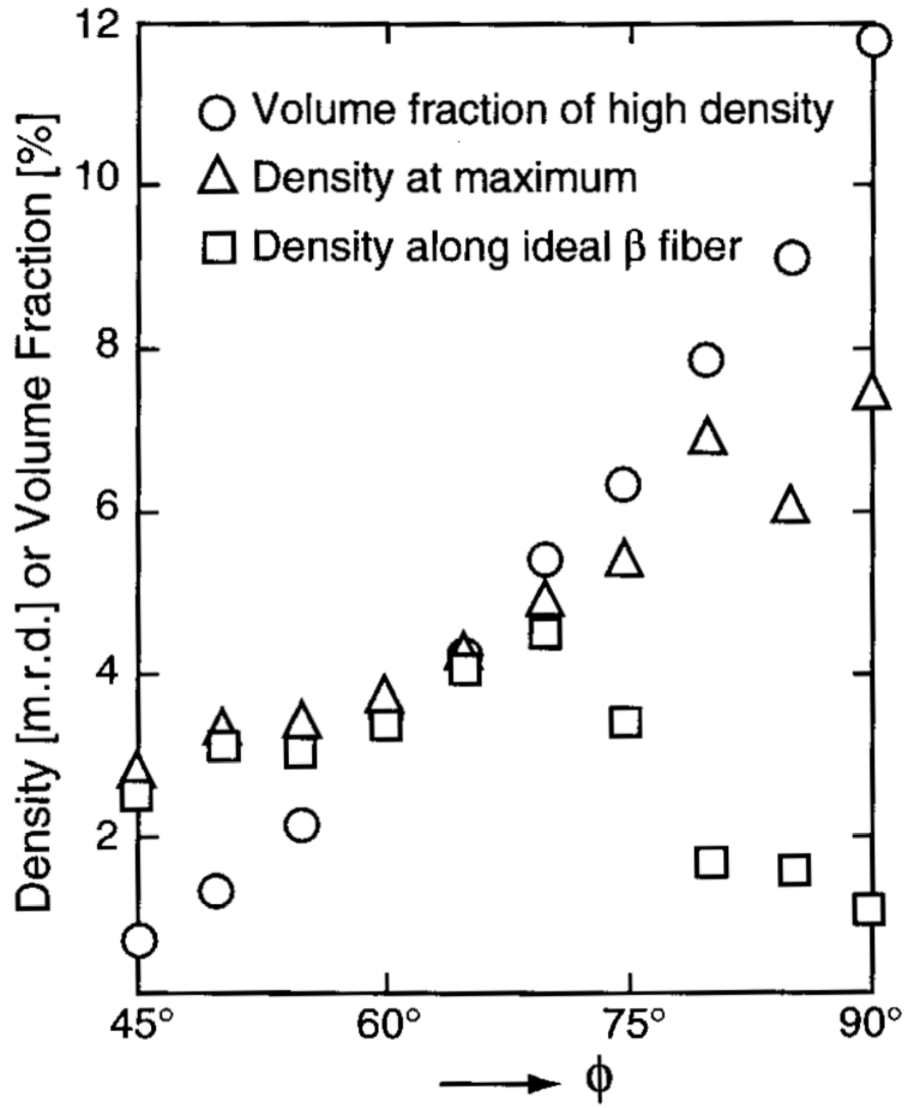


(b)

Volume fraction vs. density (intensity)

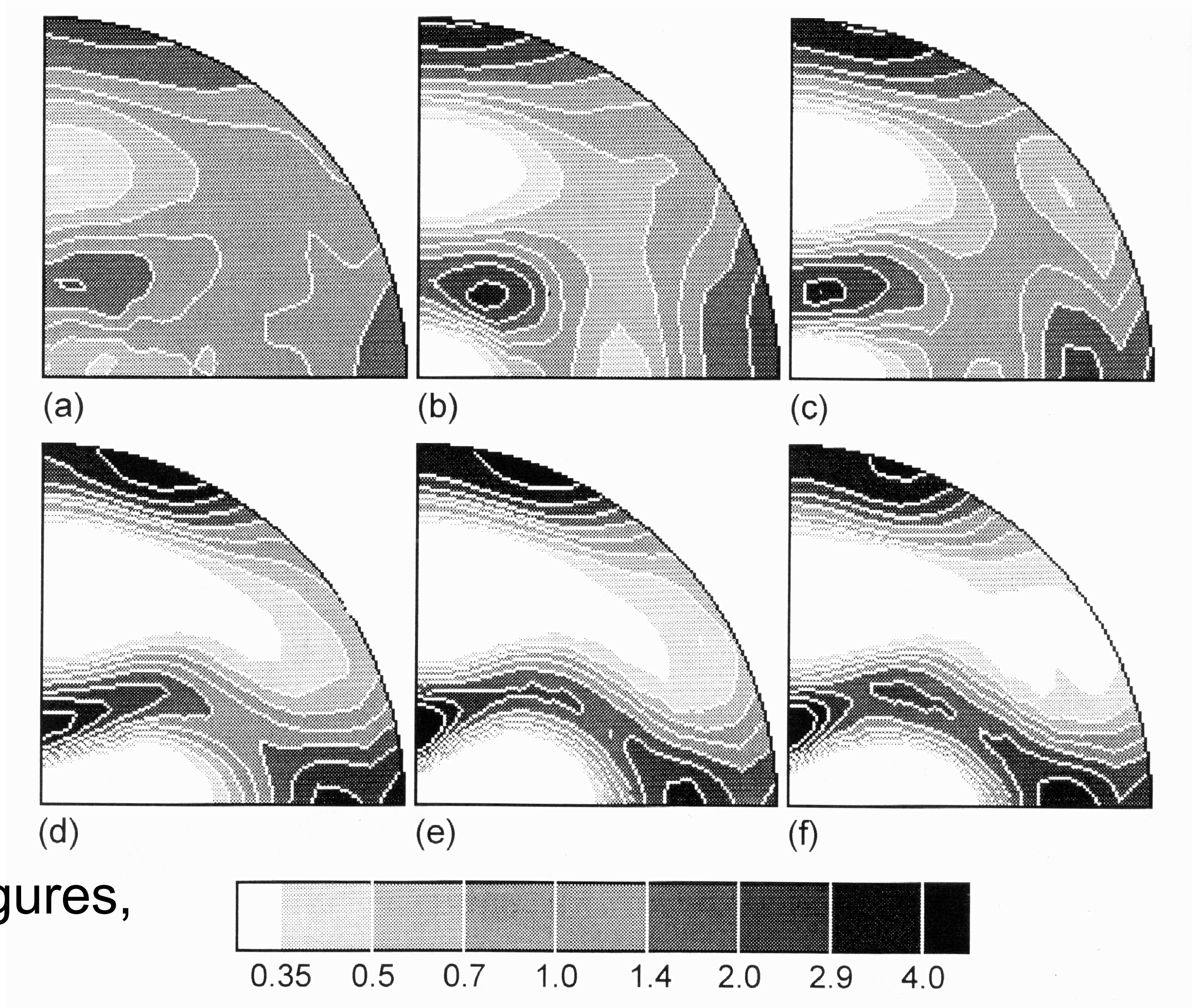


- Volume fraction associated with region around the fiber in a given section.
- V_f increases faster than density with increasing Φ.
- Location of max. density not at nominal location.



Kocks, Ch. 2

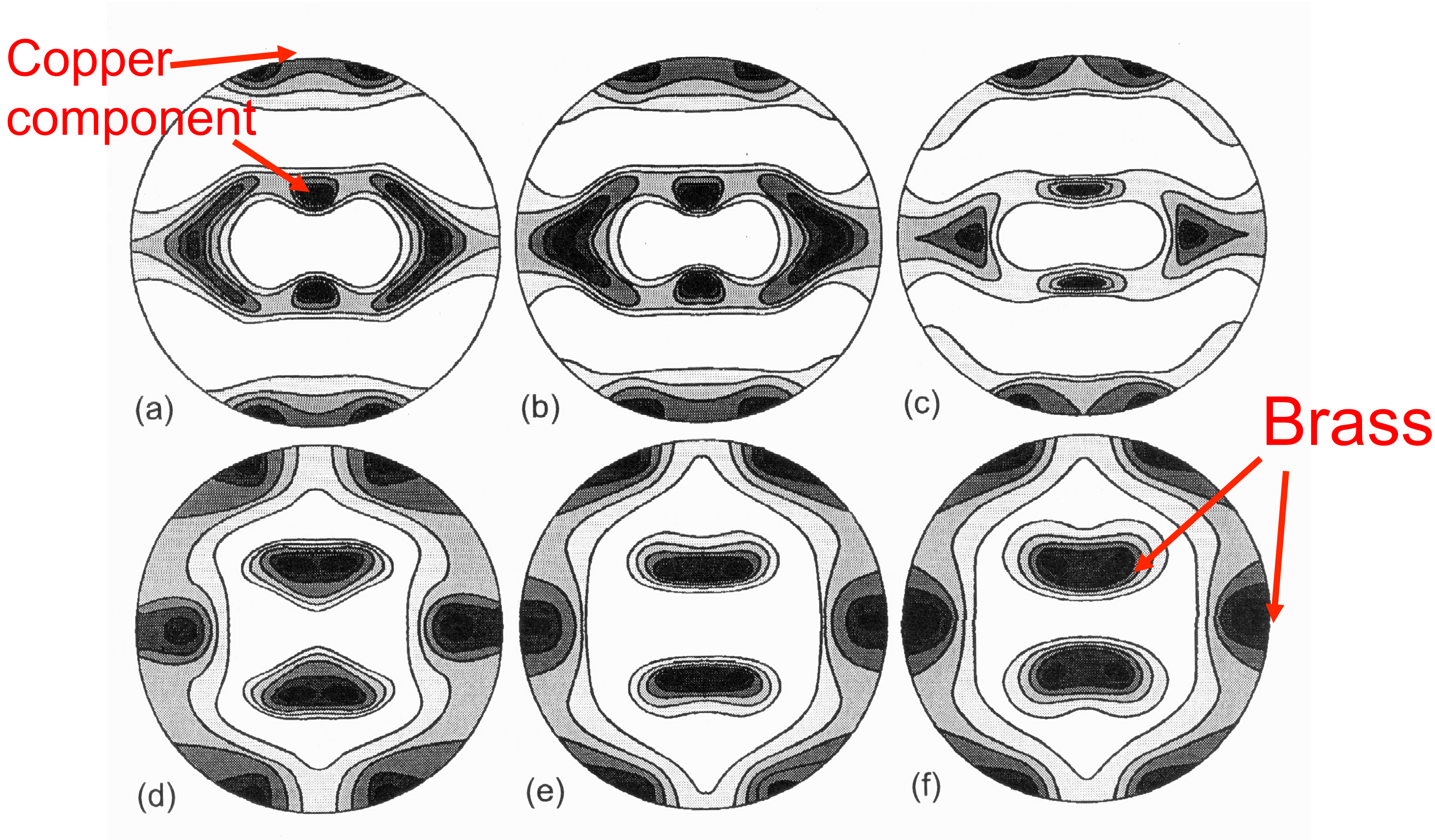
Rolling fcc Cu: Effect of Strain



{111} Pole Figures, RD vertical

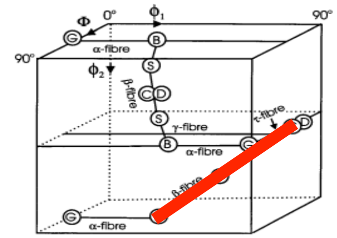
von Mises strains= initial, 0.5, 1.0, 2.0, 2.7, 3.5

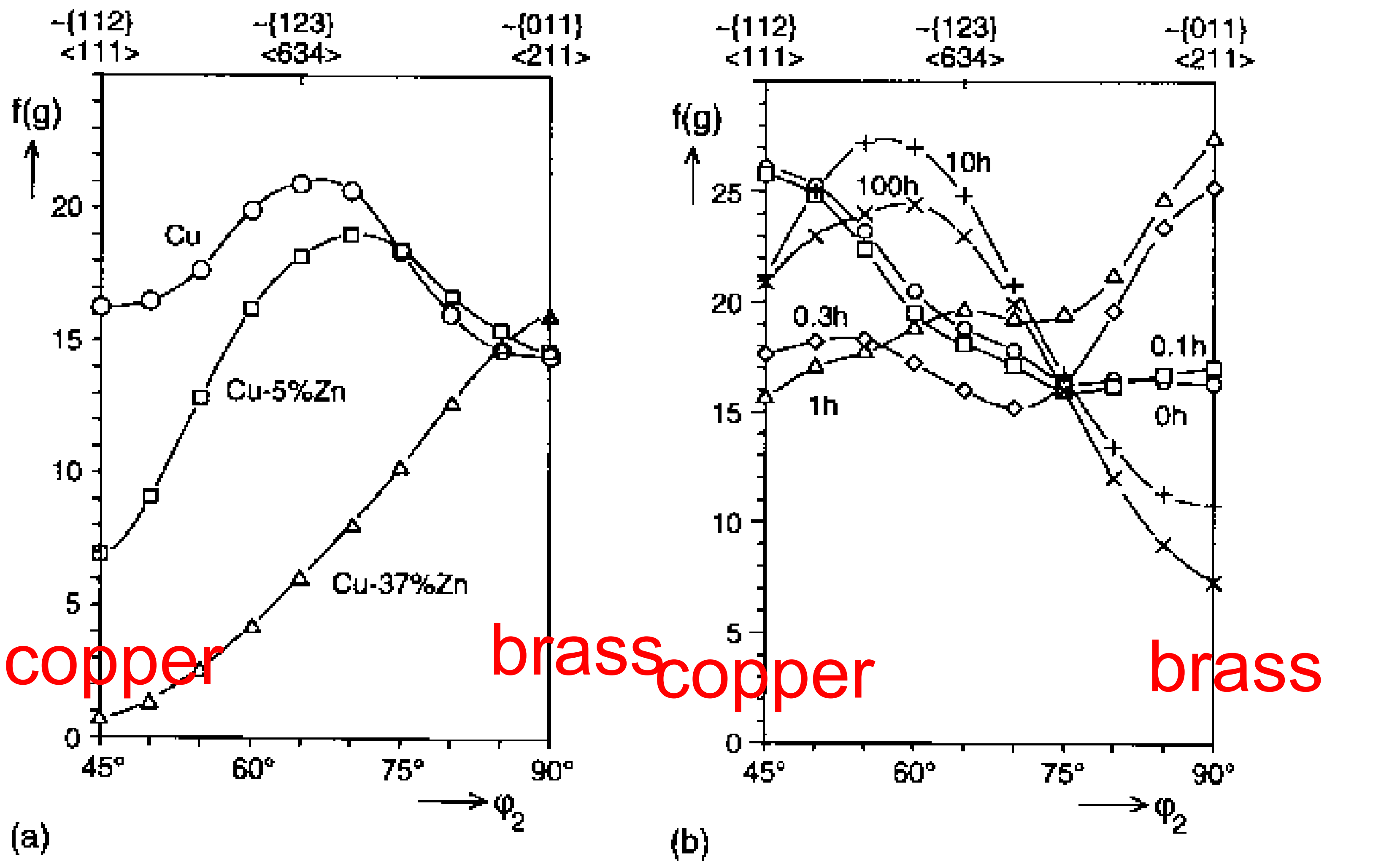
Effect of Alloying: Cu-Zn (brass); the texture transition



Zn content: (a) 0%, (b) 2.5%, (c) 5%, (d) 10%, (e) 20% and (f) 30% [Stephens PhD, U Arizona, 1968]

Alloy, Precipitation Effects

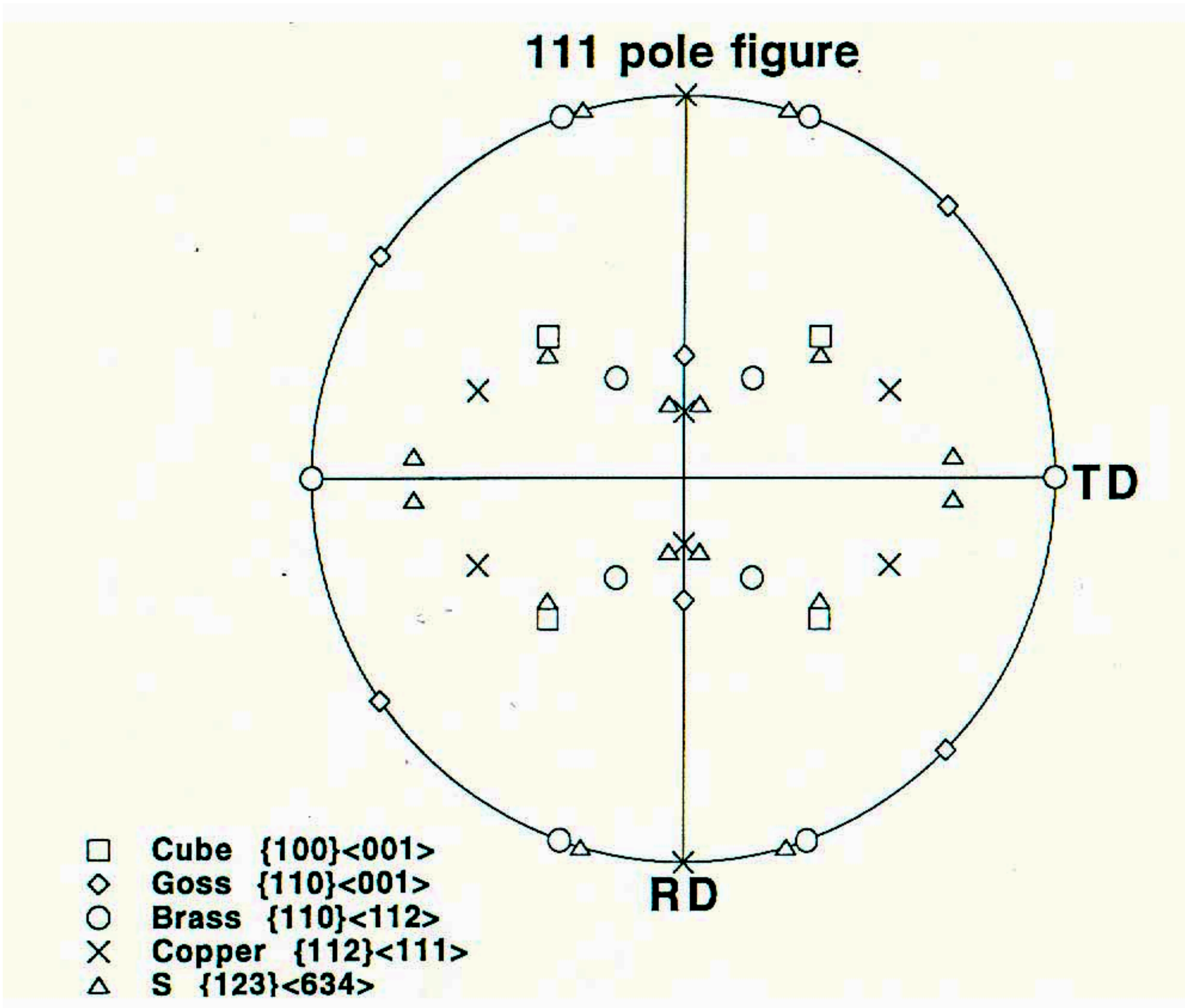




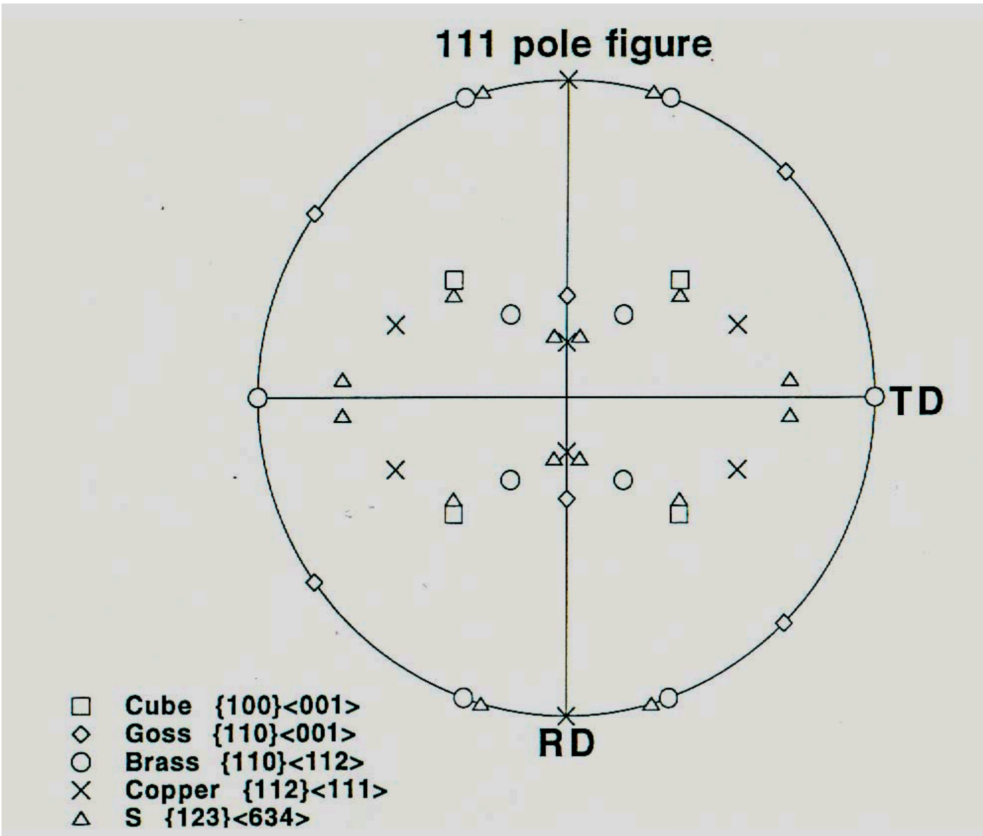
Hirsch & Lücke, 1988 , Acta metall. **36**, 2863 Engler et al., 1989, Acta metall. **37**, 2743

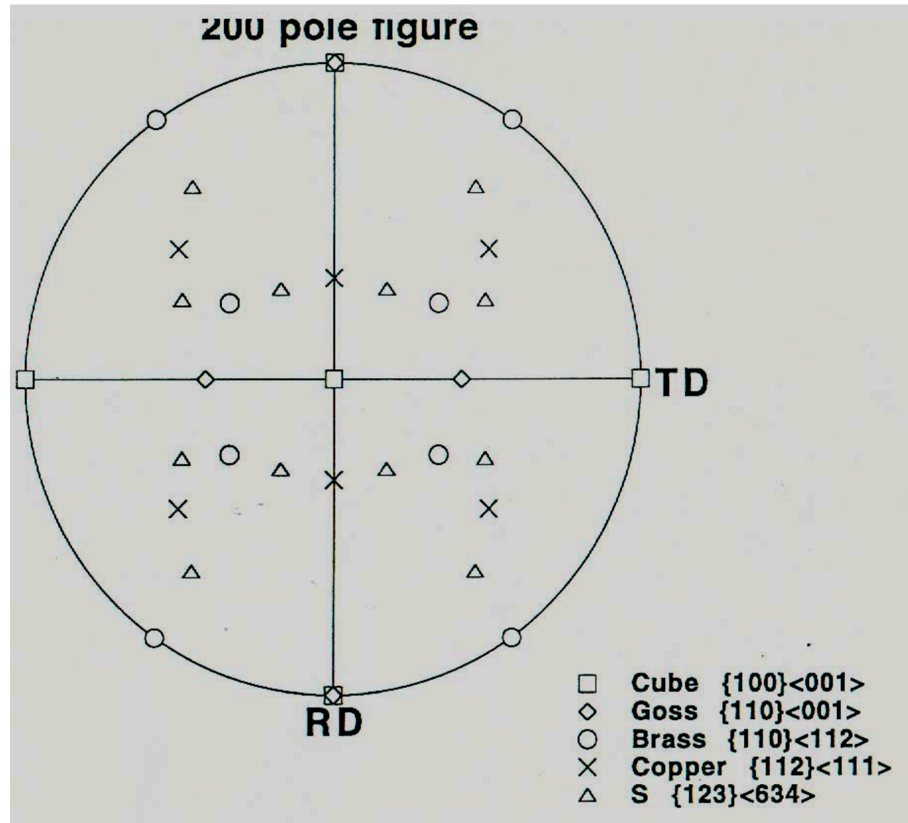
Summary: part 1

- Typical textures illustrated for FCC metals as a function of alloy type (stacking fault energy) and deformation character (strain type).
- Pole figures are recognizable for standard deformation histories but orientation distributions provide much more detailed information. Inverse pole figures are also useful, especially for uniaxial textures.
- Measure strain using von Mises equivalent strain.
- Plane strain (rolling) textures concentrate on characteristic lines ("partial fibers") in orientation space.
- Uniaxial textures align certain crystal axes with the deformation axis.



111 pole figure
TD
RD
Cube {100}<001>
Goss {110}<001>
Brass {110}<112>
Copper {112}<111>
S {123}<634>


111 pole figure
TD
RD
Cube {100}<001>
Goss {110}<001>
Brass {110}<112>
Copper {112}<111>
S {123}<634>


200 pole figure
TD
RD
Cube {100}<001>
Goss {110}<001>
Brass {110}<112>
Copper {112}<111>
S {123}<634>