Parte 2

Introduction to Quantitative Texture Analysis

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Introduction

Texture forming transformations in steels:

1. Solidification

2. Phase transformation from austenite to ferritic phase
   (during hot rolling or subsequent annealing).

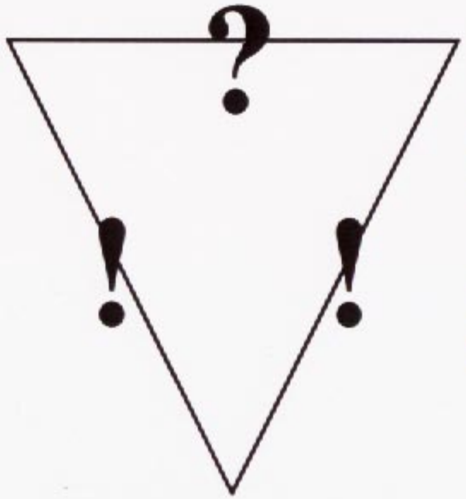
3. Deformation
   (during cold or warm rolling, deep drawing, stretching,...)

4. Recrystallization and grain growth.
   (during annealing)

Introduction

Processing Conditions

- hot rolling
- cold rolling
- annealing
- chemistry



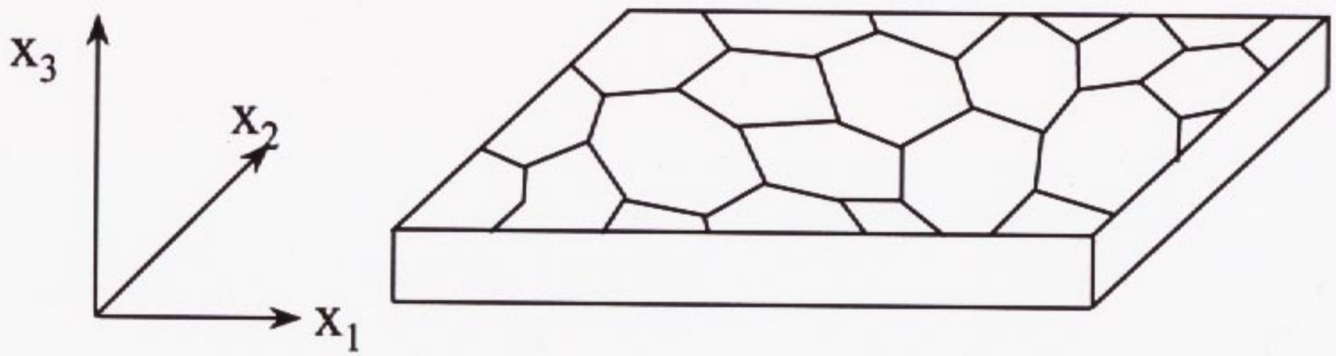
Material Properties

- mechanical properties
(e.g.: yield strength, tensile strength, elongation, drawability,...)
- electrical properties
- magnetic properties

Physical Material Parameters:

- grain size
- second phase, inclusions, precipitates,...
- **texture**

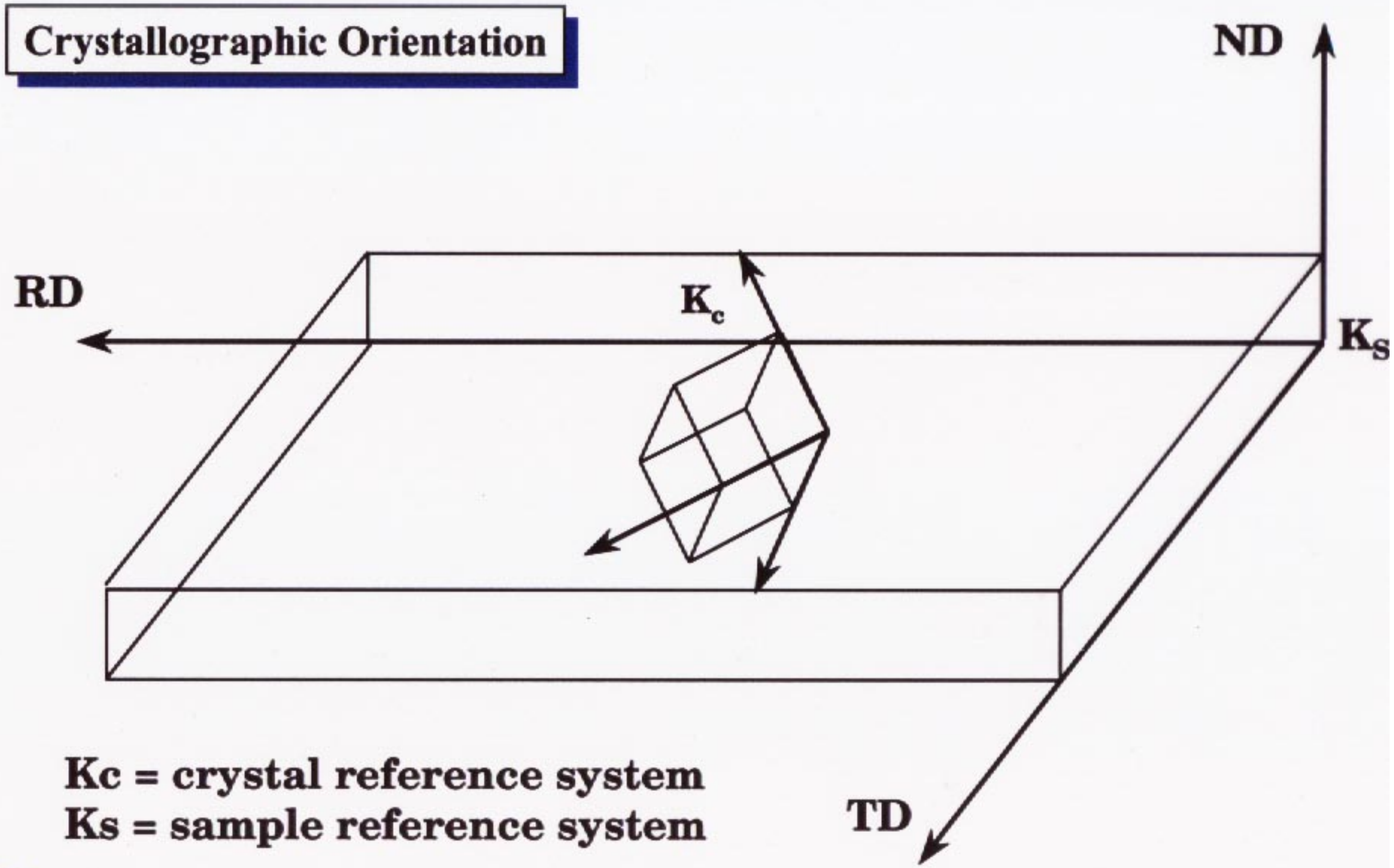
Polycrystalline material = aggregate of single crystallites
with individual orientation w.r.t. sample reference system.



Textured Material = Material in which the individual crystallites occupy preferrential orientations

≍ Textureless or Random Textured material

Crystallographic Orientation



Kc = crystal reference system
Ks = sample reference system

Representation of single crystal orientations

→ Transformation from sample to crystal reference system
= Three degrees of freedom

1. Orientation Matrices

$$[g] = \begin{array}{c} \begin{array}{ccc} \mathbf{RD} & \mathbf{TD} & \mathbf{ND} \end{array} \\ \begin{bmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{33} \\ g_{31} & g_{32} & g_{33} \end{bmatrix} \end{array}$$

$$\sum_k g_{ik} g_{jk} = \delta_{ij}$$

$$\sum_k g_{ki} g_{kj} = \delta_{ij}$$

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2. Miller Indices (for sheet materials)

(h k l)[u v w]

(h k l)

→ crystallographic plane (hkl) // rolling plane

[uvw]

→ crystallographic direction [uvw] // rolling direction

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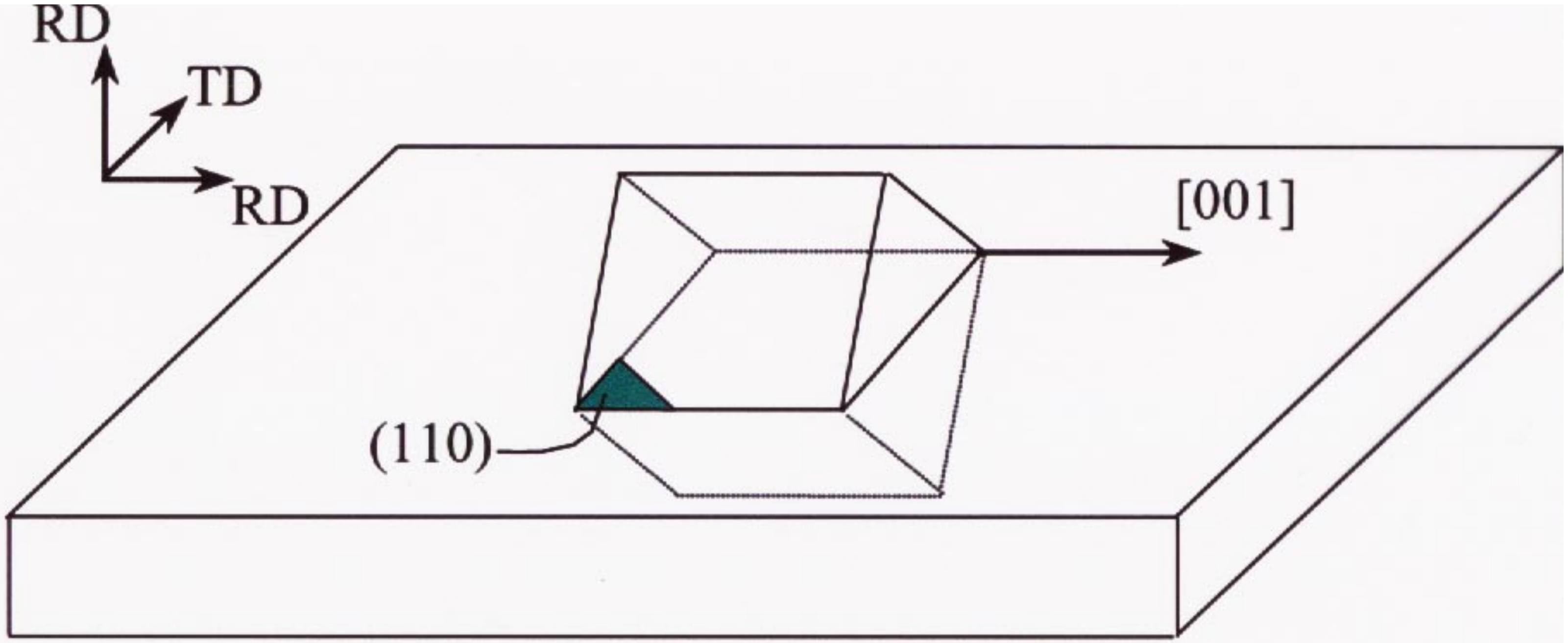

(110) [001]

Goss orientation = ~~(001)[110]~~

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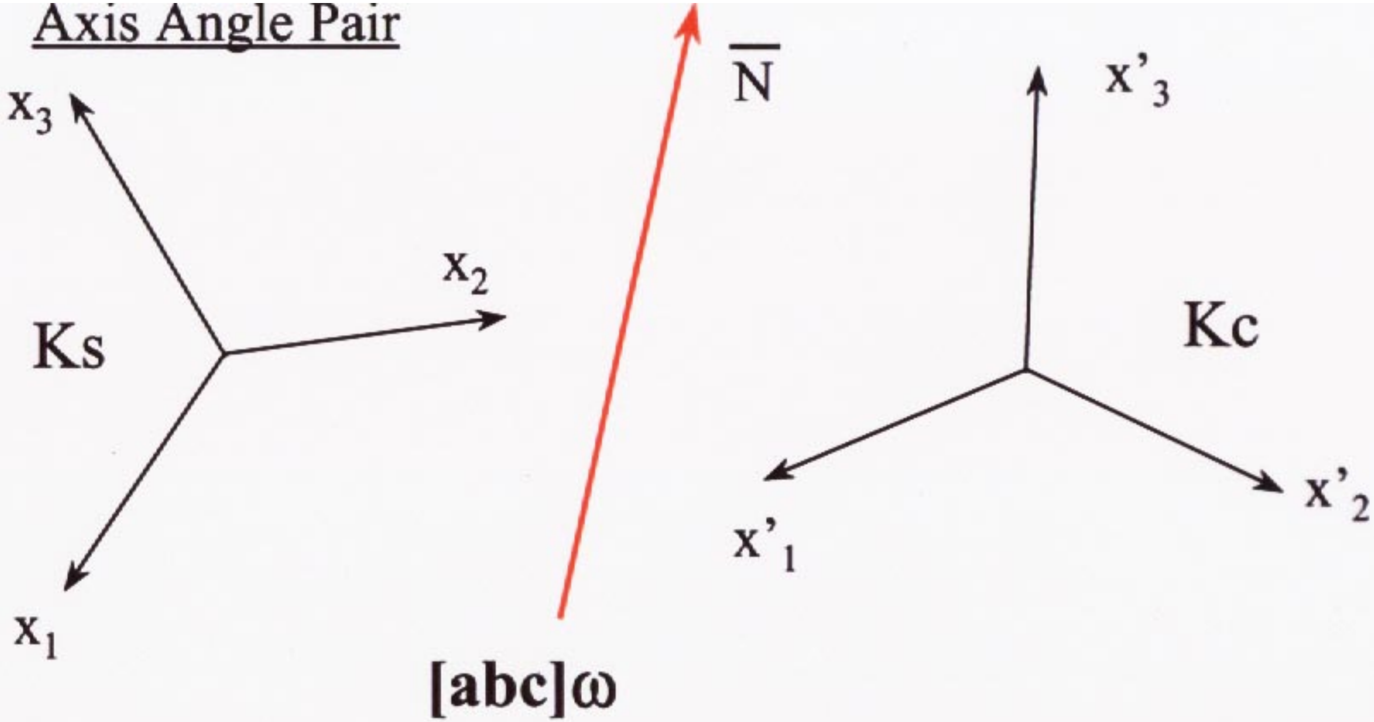
Axis Angle Pair

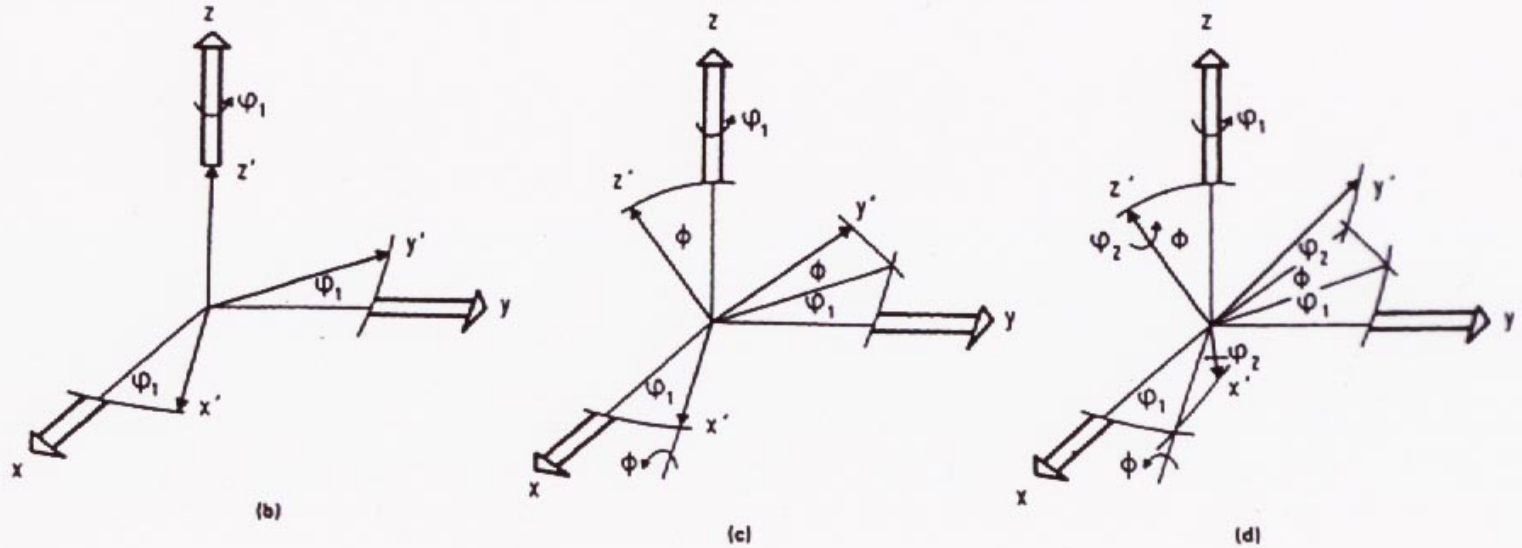


Rodrigues-Frank representation

$$\overline{R} = \overline{N} \, . \, \tan(\omega/2)$$

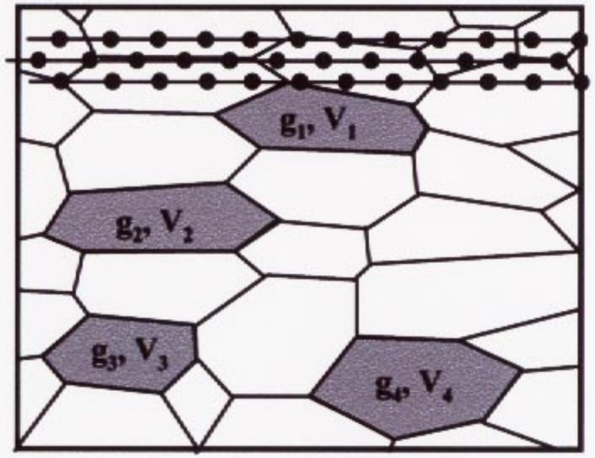
Euler Angles:

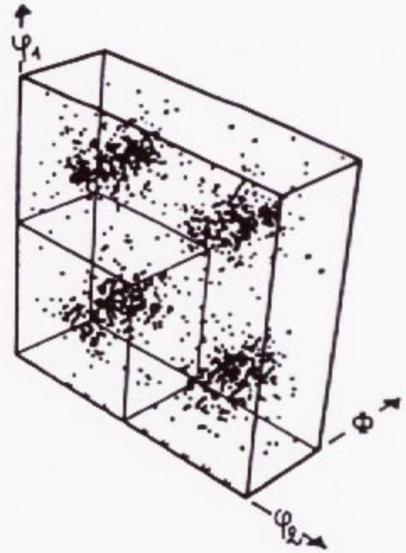
Bunge notation: φ_1, Φ, φ_2



Roe notation: Ψ, Ξ, Φ
(2nd rotation around y')

The Orientation Distribution Function (ODF)

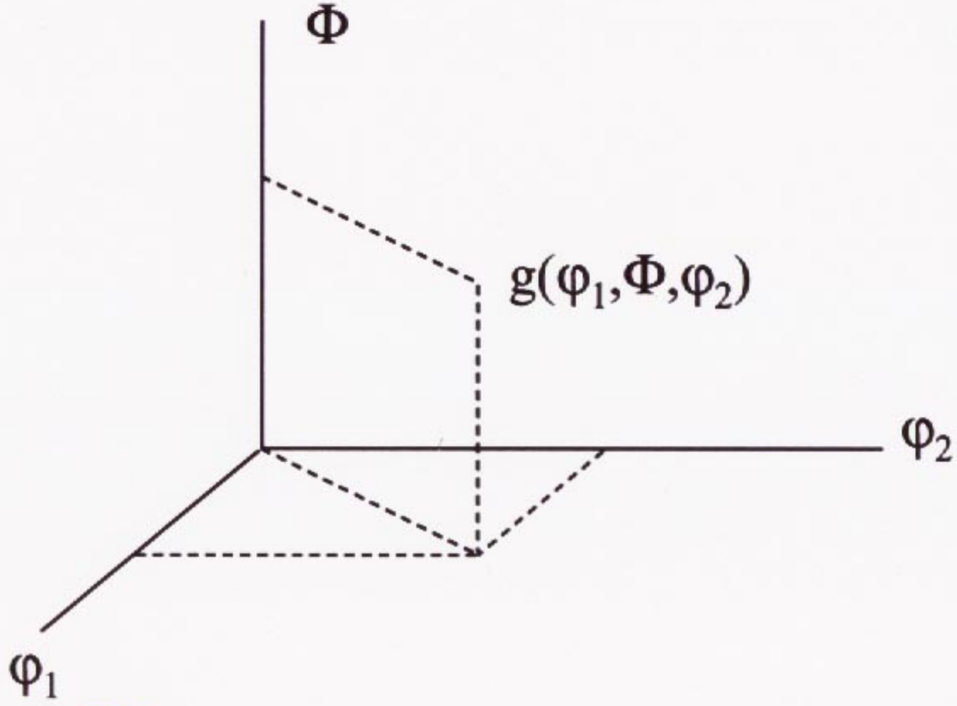




$$\frac{dV}{V} = f(g)dg$$

dV/V is the volume fraction of orientation in an infinitesimal environment of g ($g \pm dg$)

Euler Space



Properties:

cyclic: $0 < \varphi_1 < 2\pi$

$0 < \Phi < \pi$

$0 < \varphi_2 < 2\pi$

non-bijective

non-Euclidean:

$$dg = \sin\Phi \, d\varphi_1 \, d\Phi \, d\varphi_2$$

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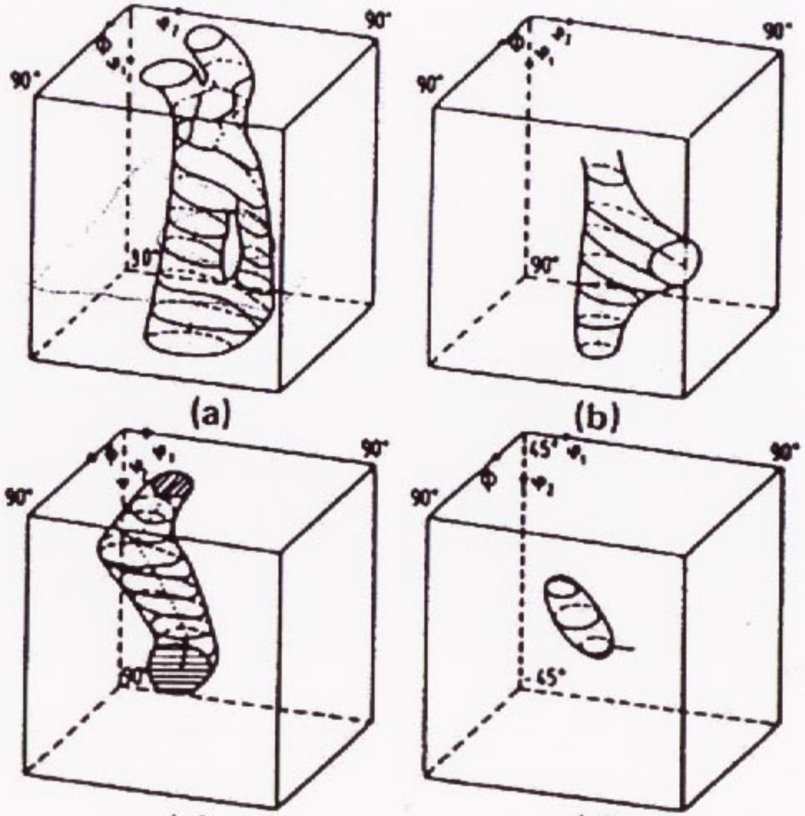
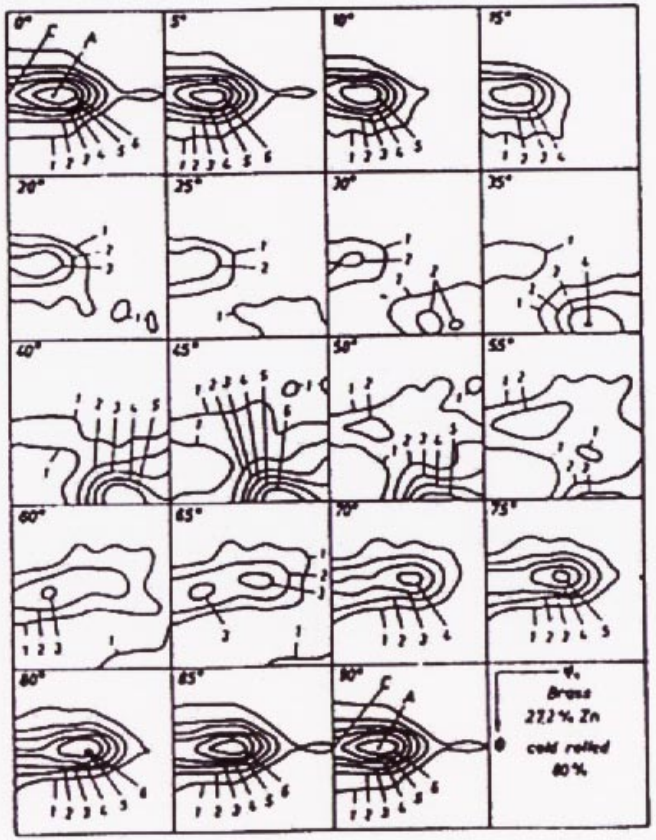
Iso-intensity surfaces



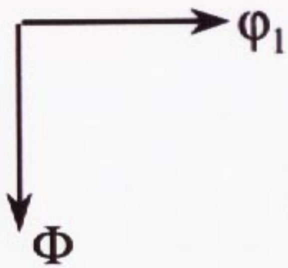
(a) (b) (c) (d)

Iso-intensity lines on equidistant sections



φ_2 = constant sections

$\Delta\varphi_2$ = 5°



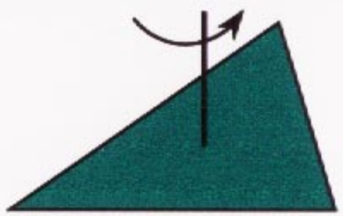
units = x random intensity

Crystal Symmetry

Definition of object symmetry
Symmetry operators

"Object has not changed after being subjected to symmetry operators"

Symmetry axes: 2-fold, 3-fold, 4-fold,….



Crystal Symmetry

Cubic crystal (BCC, FCC, Primitive)

- 24 equivalent ways of attaching right-handed orthogonal reference system to a cube

- 24 symmetry elements in cubic symmetry group

- 24 symmetrical equivalent points to represent one single cubic orientation in Euler space

Crystal Symmetry

Cubic crystal (BCC, FCC, Primitive)

Total Euler Space

$$0 < \varphi_1 < 2\pi$$
$$0 < \Phi < \pi$$
$$0 < \varphi_2 < 2\pi$$

$$V = \int_0^{2\pi}\int_0^{\pi}\int_0^{2\pi} \sin\phi \, d\varphi_1 d\phi d\varphi_2 = 8\pi^2$$

Fundamental Zone:

$$V' = \frac{V}{24}$$

- No Linear Boundaries
- Convenient Zone:

$$0 < \varphi_1 < 2\pi$$
$$0 < \Phi < \pi/2$$
$$0 < \varphi_2 < \pi/2$$

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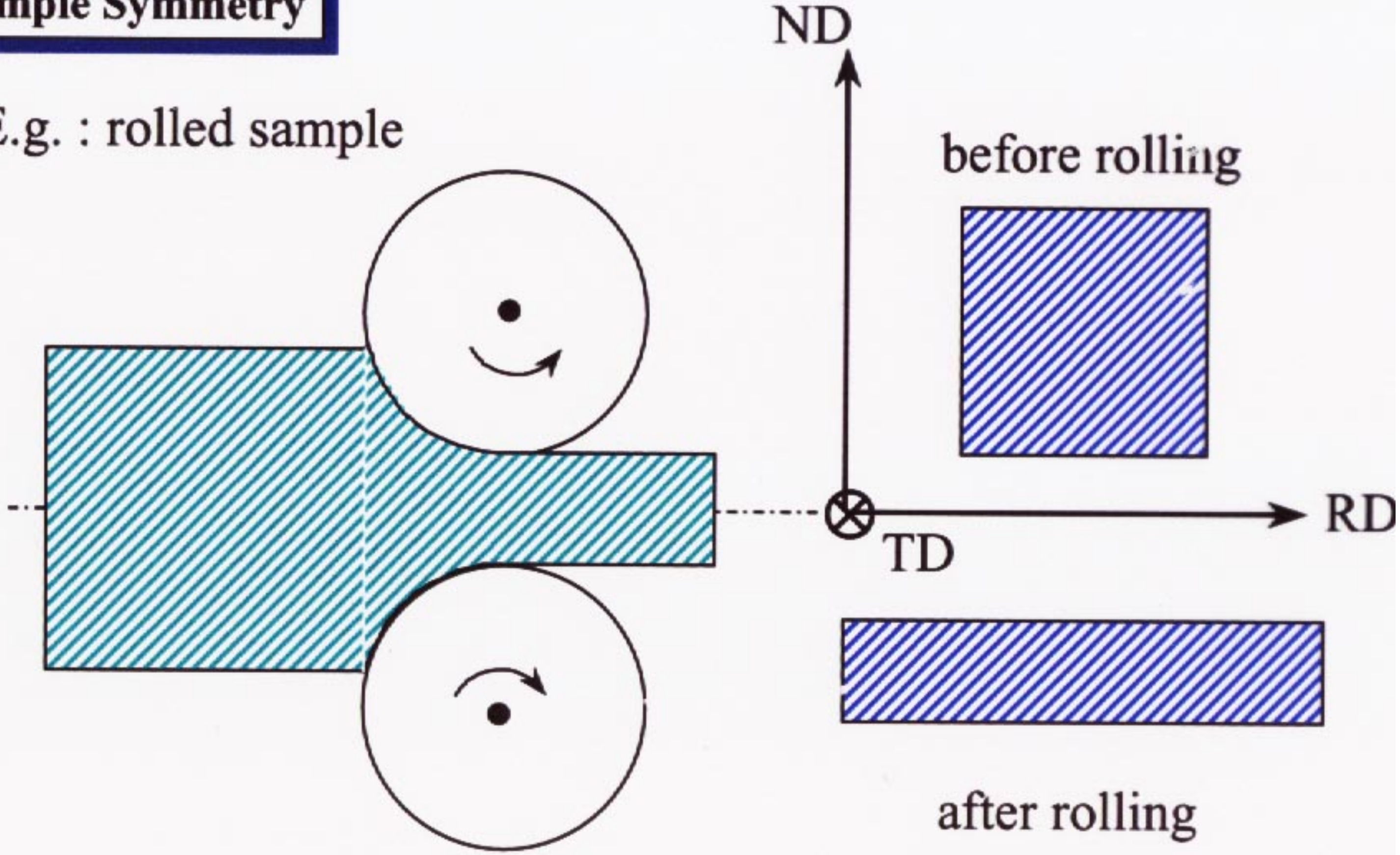
Sample Symmetry

E.g. : rolled sample



3 two-fold axes: RD, TD, ND → orthorombic sample symmetry

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Orthorombic Sample Symmetry = 4 symmetry elements

- Further reduction in fundamental zone of Euler Space with factor 4

- (Convenient) Fundamental zone for orthorombic sample and cubic crystal symmetry:

$$\left| \begin{array}{l} 0 < \varphi_1 < \pi/2 \\ 0 < \Phi < \pi/2 \\ 0 < \varphi_2 < \pi/2 \end{array} \right.$$

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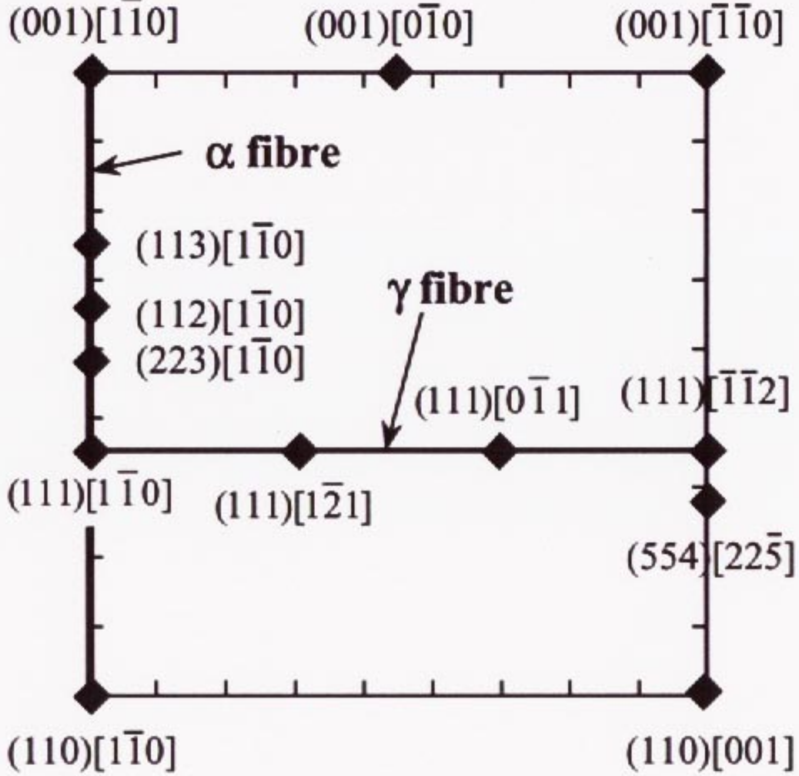
For BCC materials (e.g. low carbon steels) :

All important rolling and recrystallization components are represented in $\varphi_2 = 45°$ section (with boundaries 0-90°)



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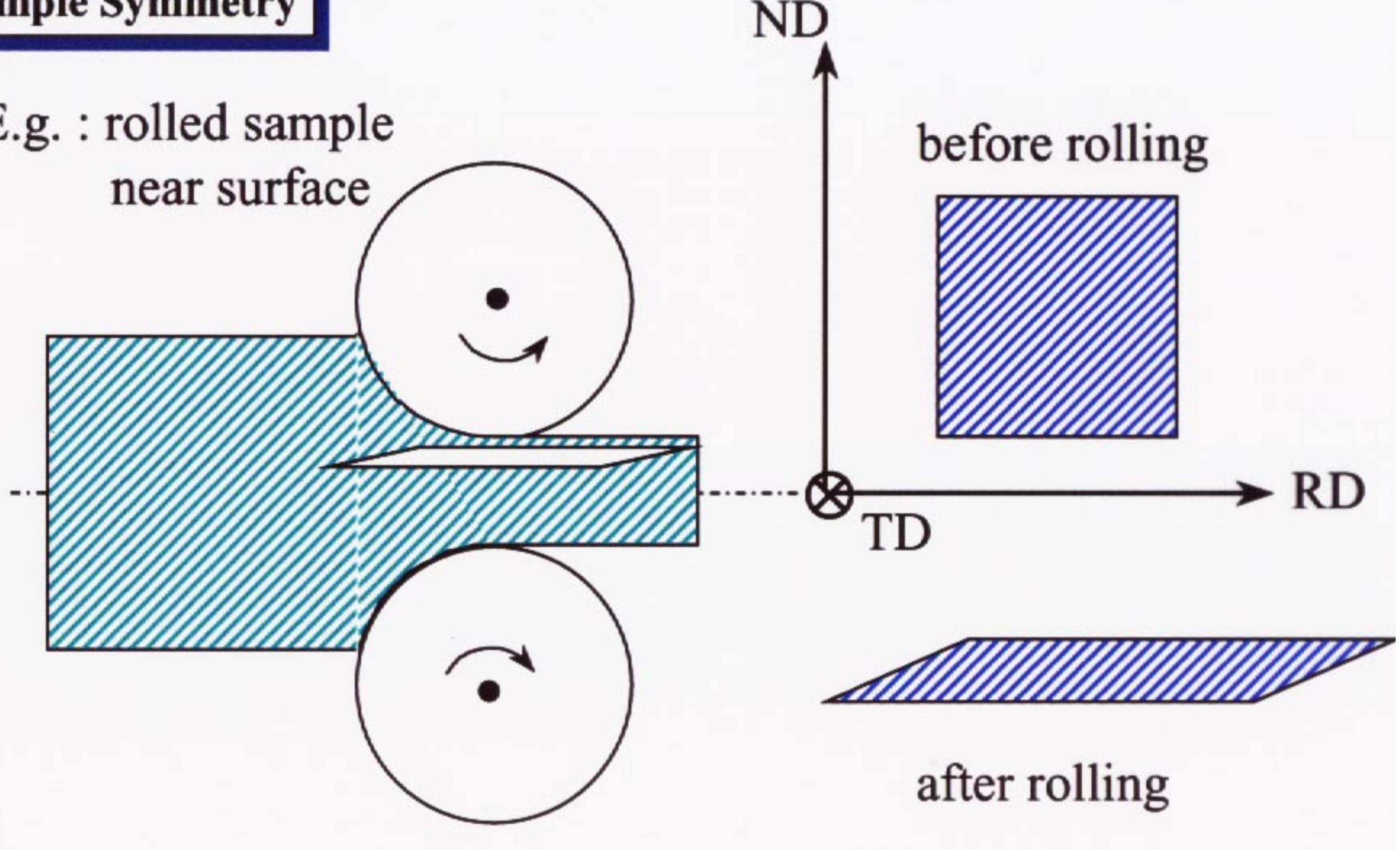
Sample Symmetry

E.g. : rolled sample near surface



1 two-fold axes: TD → monoclinic sample symmetry

Monoclinic Sample Symmetry = 2 symmetry elements

- Reduction in fundamental zone of Euler Space with factor 2

- (Convenient) Fundamental zone for monoclinic sample and cubic crystal symmetry:

$$\left| \begin{array}{l} -\pi/2 < \varphi_1 < \pi/2 \\ 0 < \Phi < \pi/2 \\ 0 < \varphi_2 < \pi/2 \end{array} \right.$$

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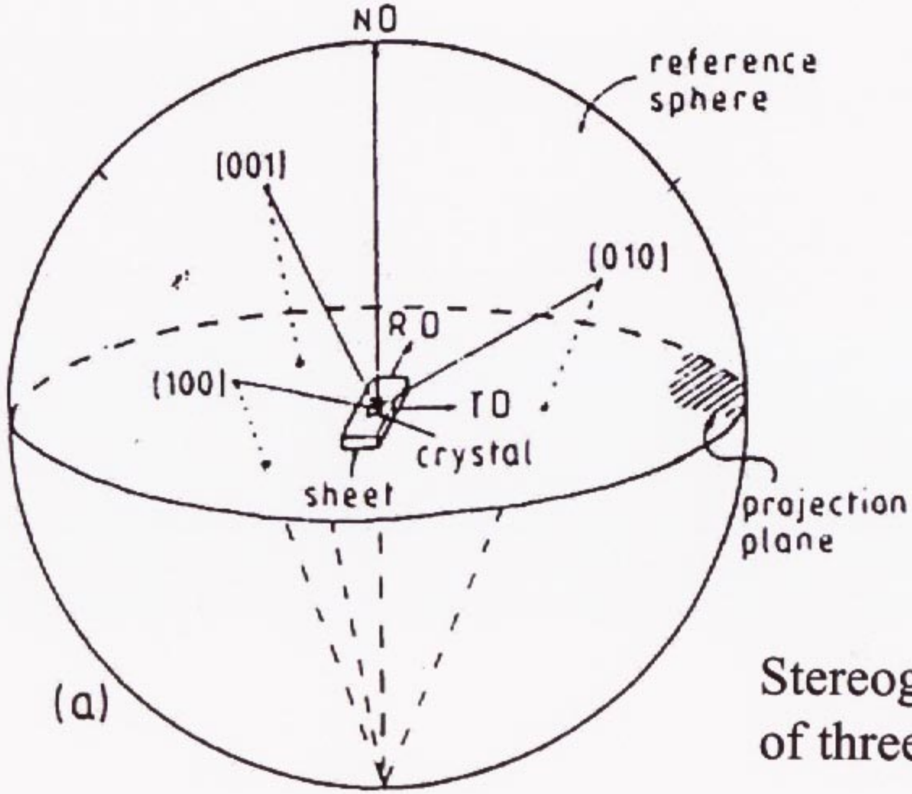
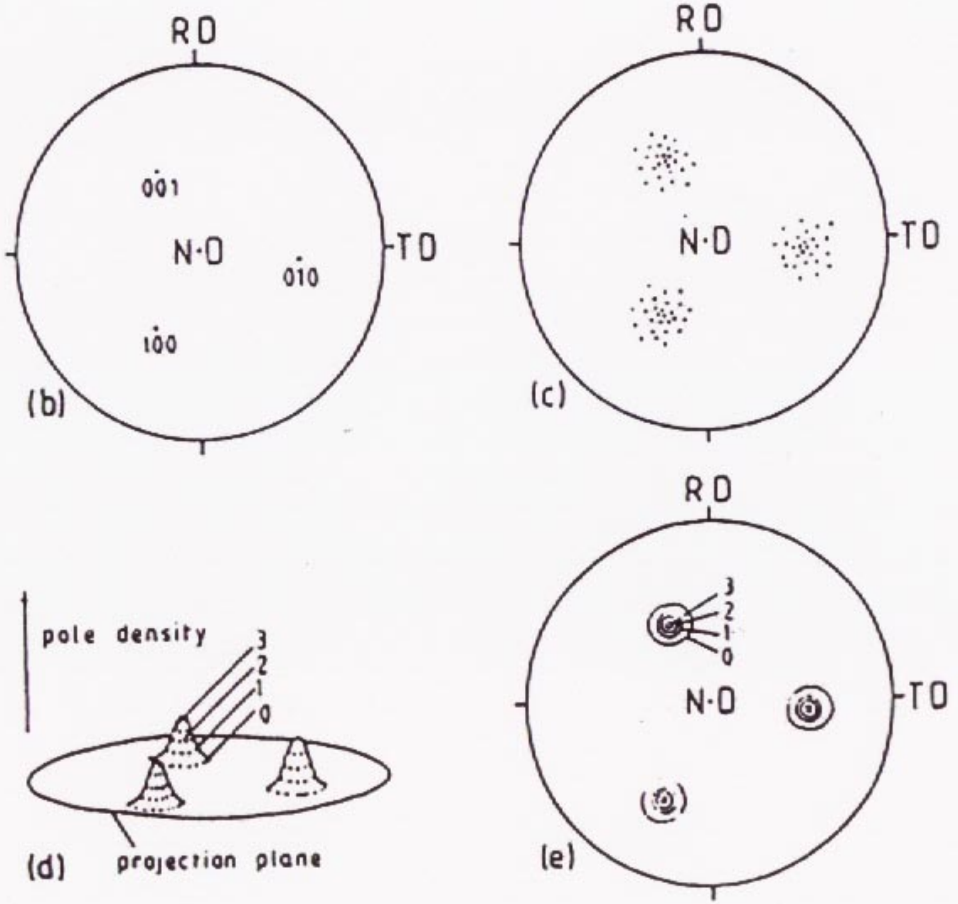
The Pole Figure



Stereographic projection of three <100> poles

The Pole Figure



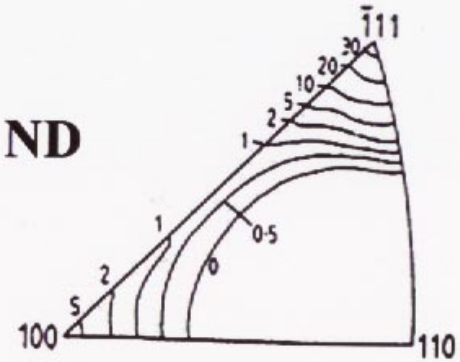
The Pole Figure

- Distribution of <hkl> crystallographic poles w.r.t. to sample reference system
- Sample reference system + crystal pole <hkl> must be represented in the pole figure
- Displays the sample symmetry
  (orthorombic vs. monoclinic symmetry)
- Cannot represent the complete texture

The Inverse Pole Figure

- Distribution of sample direction (e.g. RD, TD or ND) w.r.t to crystal reference system
- Crystal reference system + sample direction must be represented in the pole figure
- Displays the crystal symmetry
- Cannot represent the complete texture

ND



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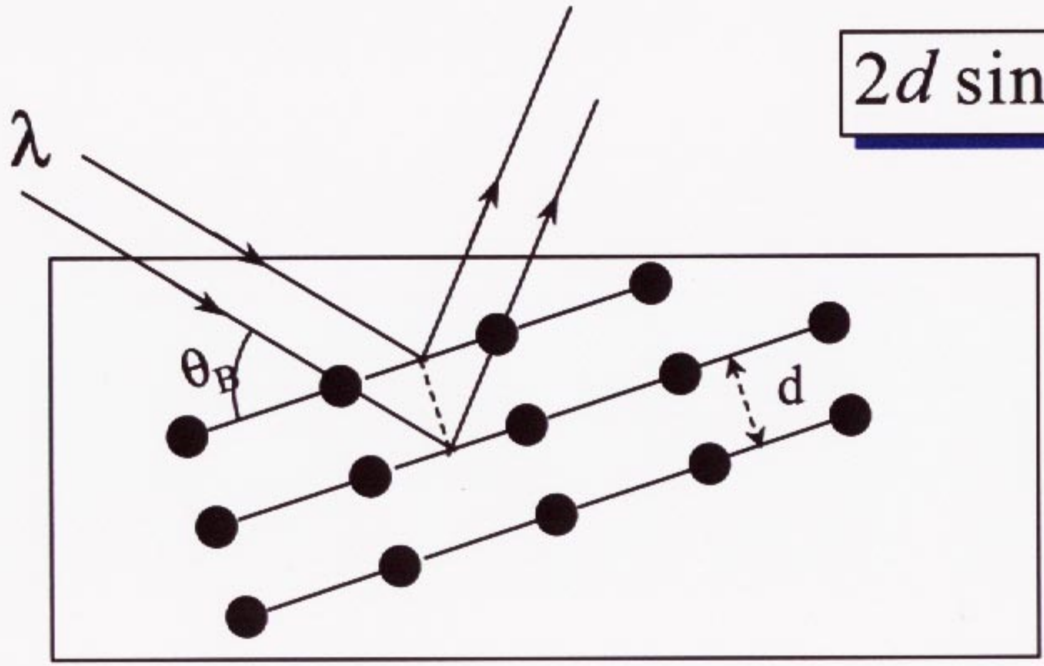
Measuring Pole Figures by X-ray Diffraction

Bragg diffraction

$$2d \sin\theta_B = n\lambda$$



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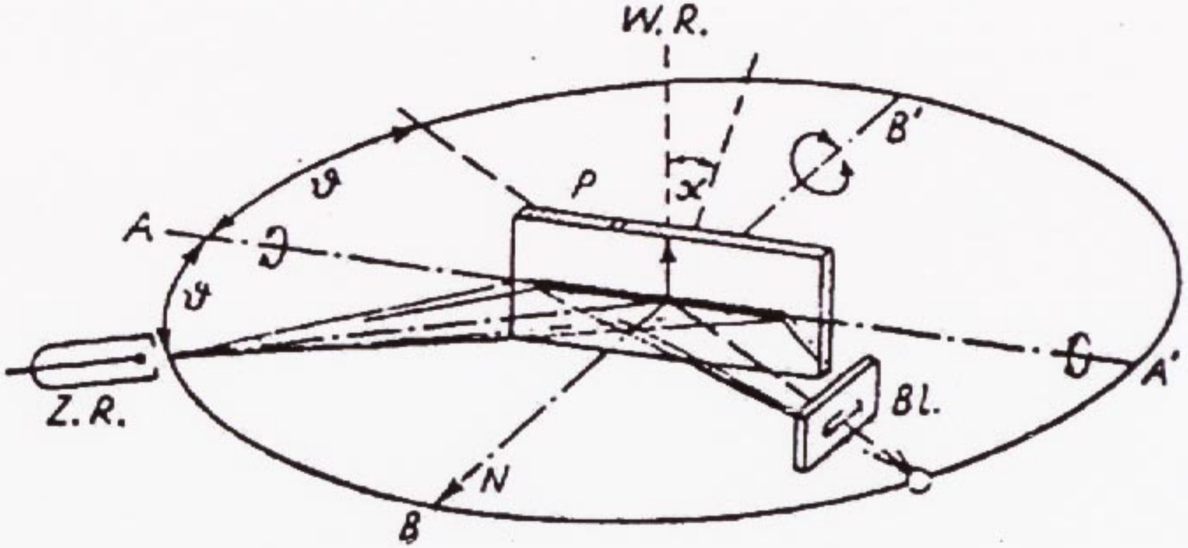
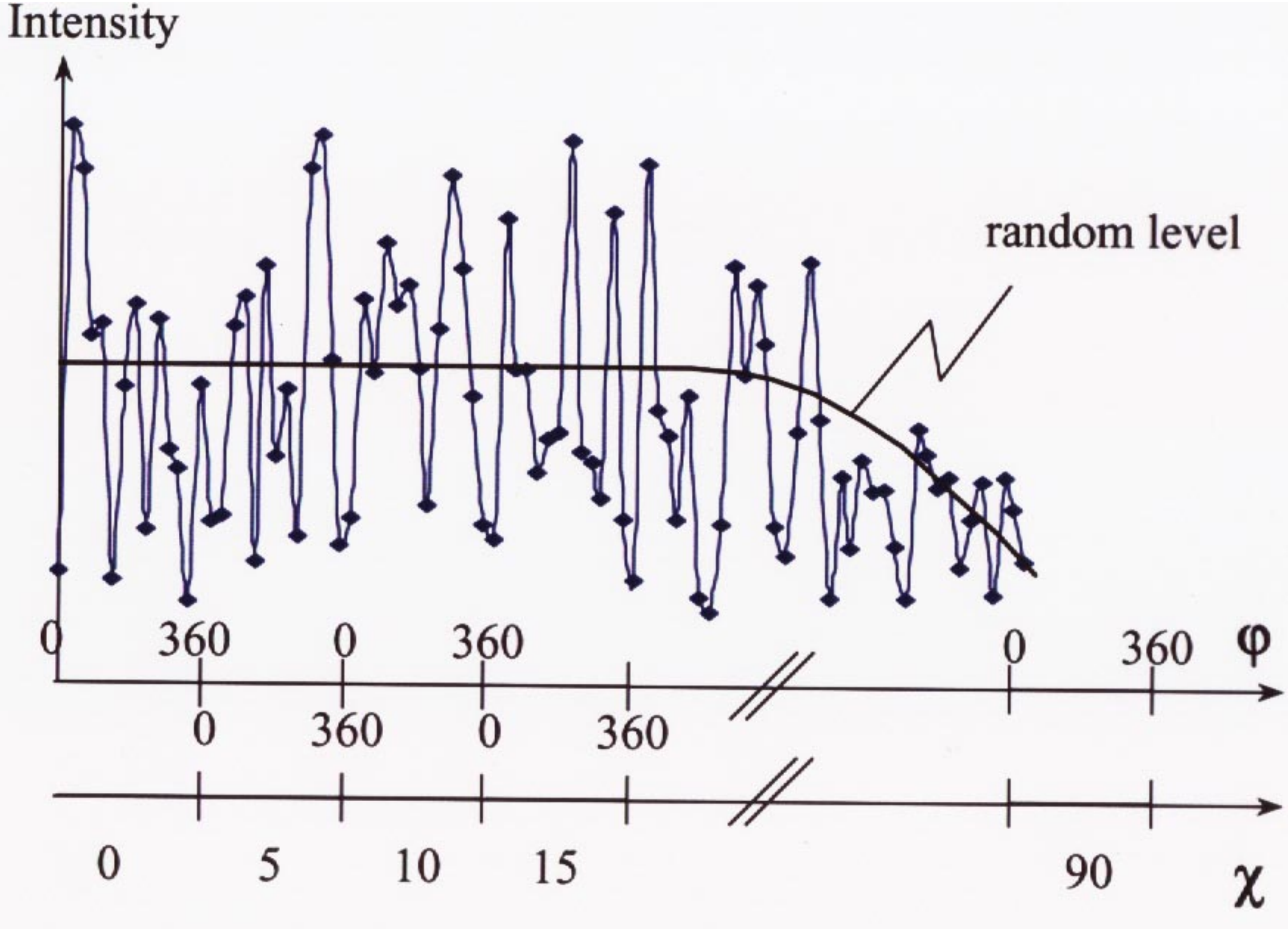
The Texture Goniometer



Diffraction vector = fixed
Sample rotates



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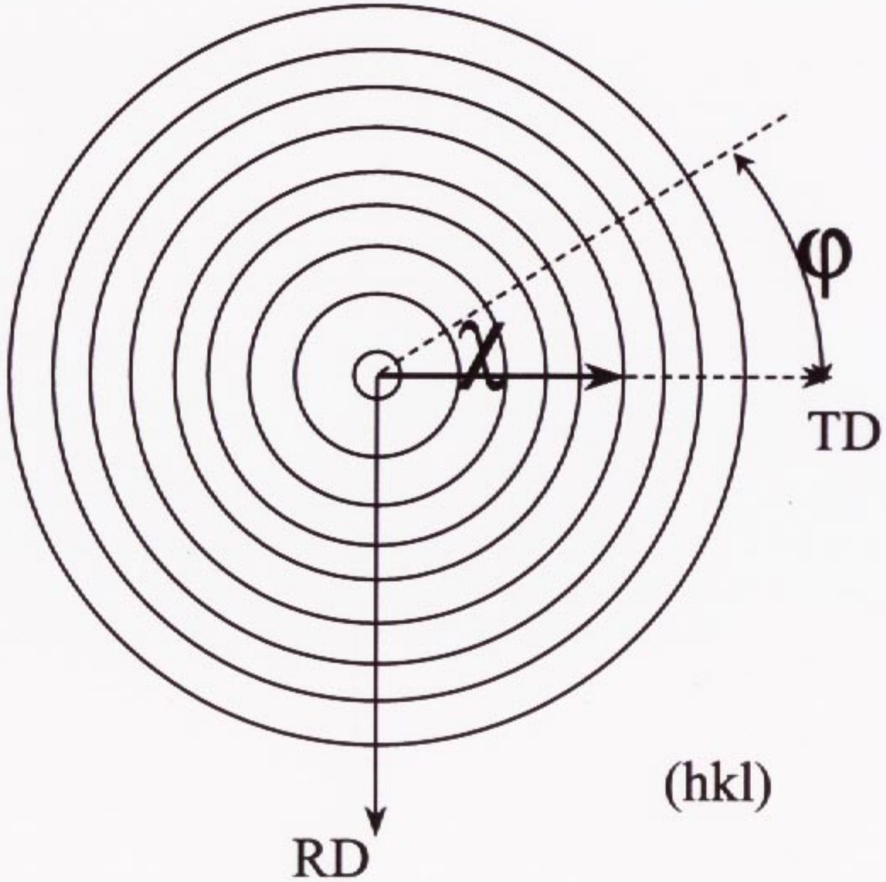
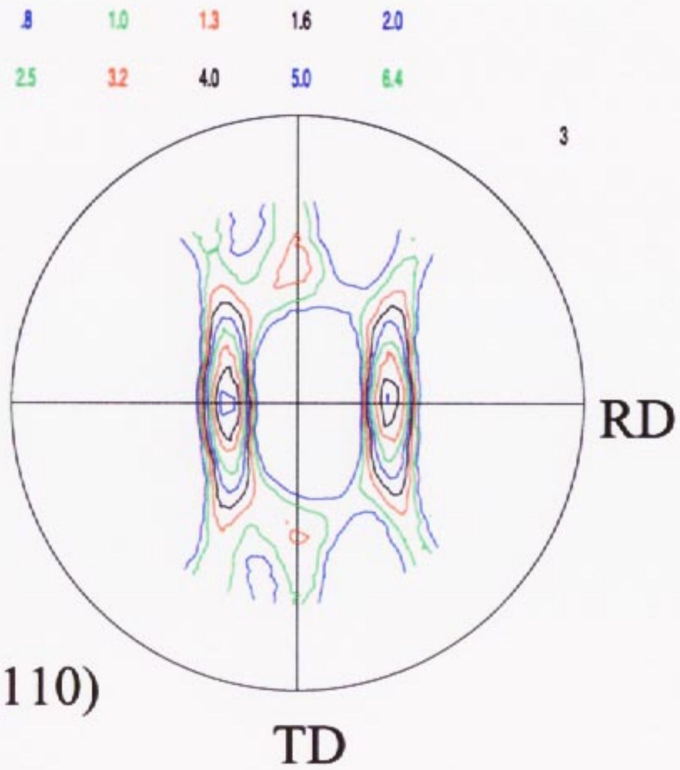
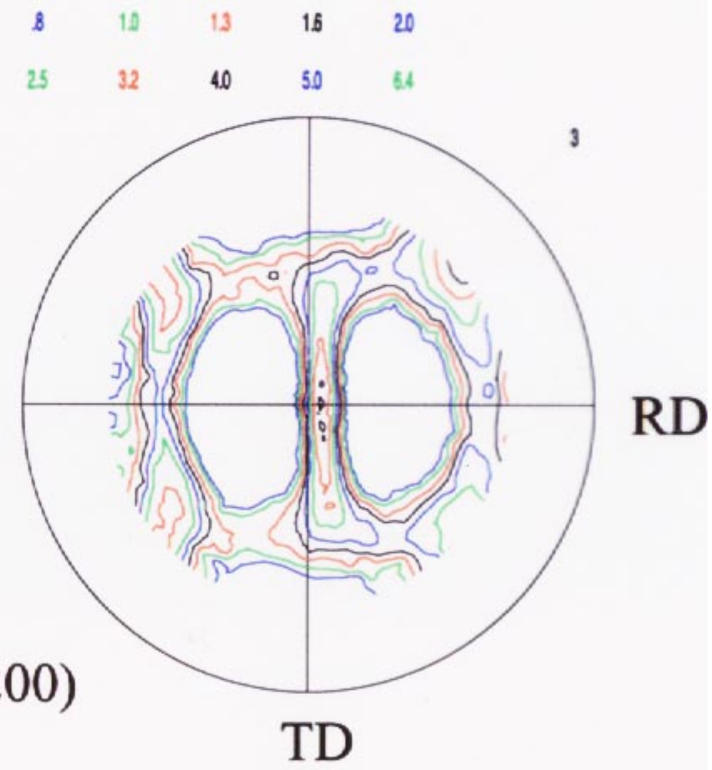
Diffraction vector $\bar{k}$ describes concentric circles on stereographic projection



Measured Pole Figure (orthorombic symmetry)



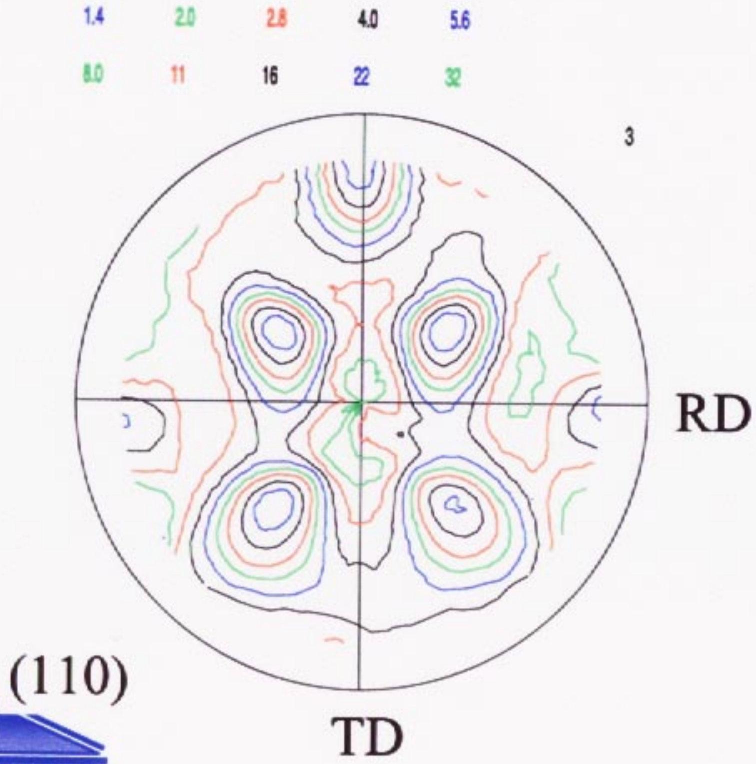
(110)

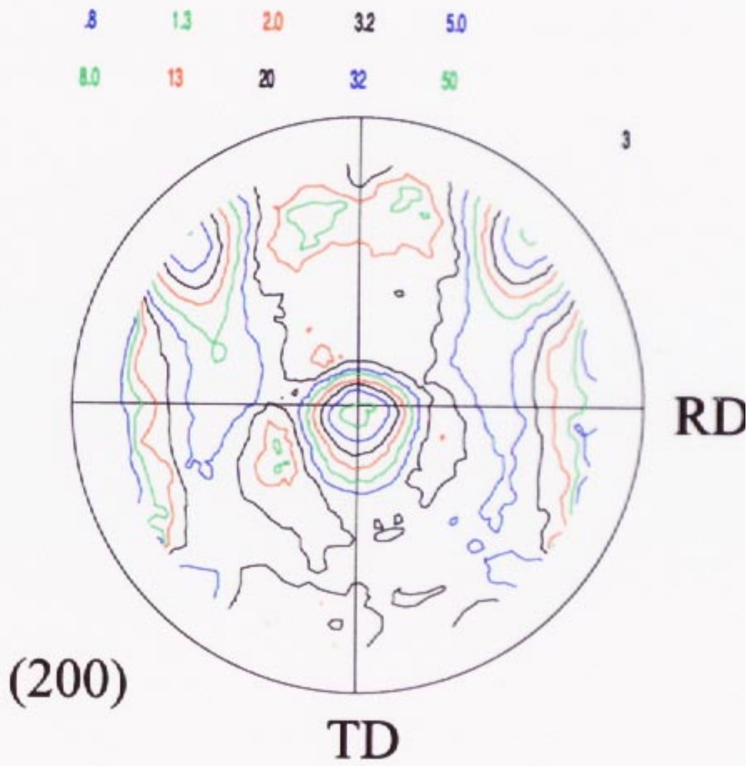


(200)

Measured Pole Figure

(monoclinic symmetry)





Pole Figures Inversion

$$p_{(hkl)}(\chi,\varphi)=\frac{1}{2\pi}\int_0^{2\pi} f\left(\varphi_1,\phi,\varphi_2\right)d\Gamma$$

Γ denotes path through E.S corresponding to rotation about (hkl)

$$\boxed{F_l^{\nu}=\frac{4\pi}{(2l+1)}\sum_{\mu=1}^{M(l)} C_l^{\mu\nu}\dot{k}_l^{*\mu}(\xi,\eta)}$$

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Pole Figures Inversion (Harmonic Method)

$$f(\varphi_1,\phi,\varphi_2) = \sum_{l=0}^{\infty}\sum_{\mu=1}^{M(l)}\sum_{\nu=1}^{N(l)} C_l^{\mu\nu}\ddot{T}_l^{\mu\nu}(\varphi_1,\phi,\varphi_2)$$

$$p(\chi,\varphi) = \sum_{l=0}^{\infty}\sum_{\nu=1}^{N(l)} F_l^{n}\dot{k}_l^{n}(\chi,\varphi)$$

$\ddot{T}_l^{\mu\nu}$ = generalized spherical harmonics

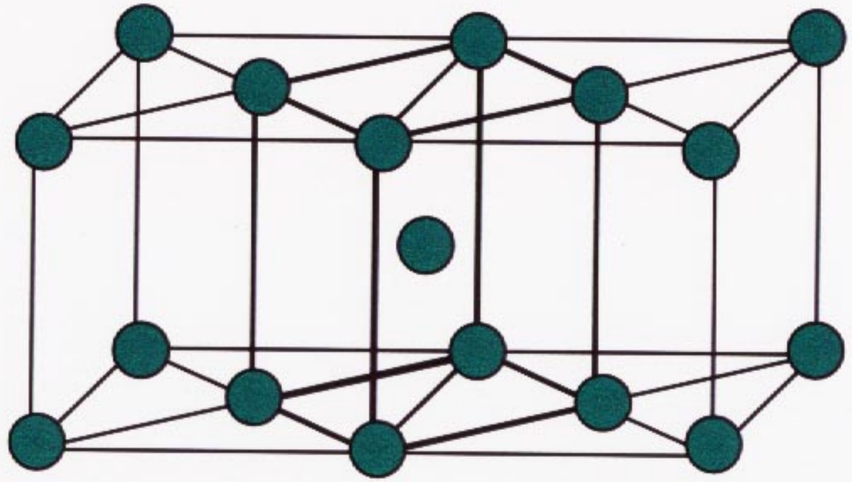
$\dot{k}_l^{n}$ = symmetrized spherical harmonics

F = pole figure coefficients (known)

C = ODF coefficients (unknown)

Transformation texture of a low carbon steel

FCC → **BCC**

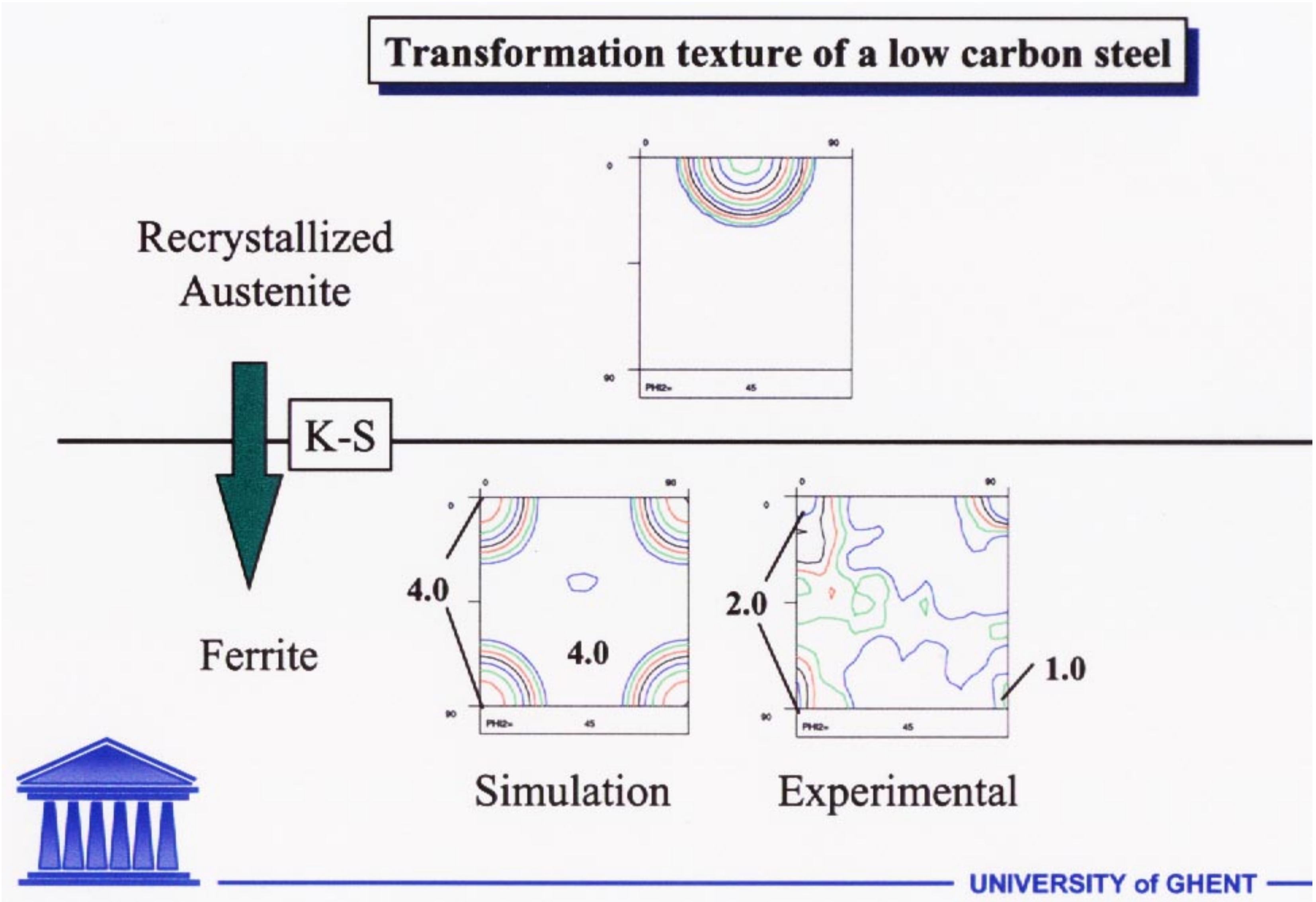


<u>Bain</u>
(001)γ // (001)α
[001]γ // [001]α

↔ <001>45deg

<u>Kurdjumow-Sachs</u>
(111)γ // (110)α
[101]γ // [111]α

↔ <112>90deg


Transformation texture of a low carbon steel
Recrystallized Austenite
K-S
Ferrite
4.0
4.0
2.0
1.0
Simulation
Experimental
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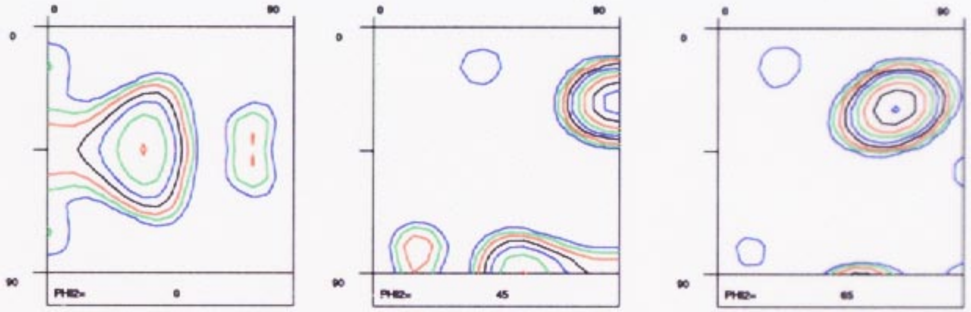
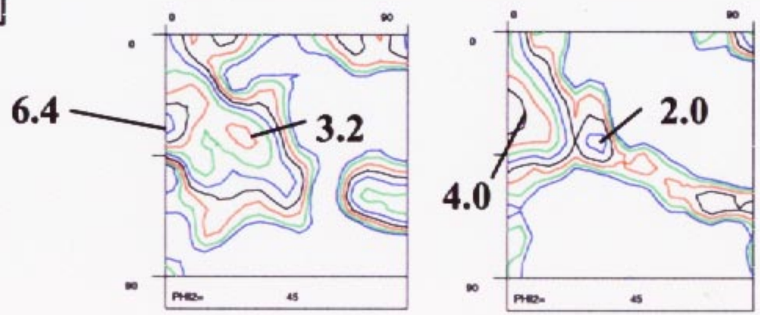
Transformation texture of a low carbon steel

Deformed
Austenite



K-S

Ferrite



Simulation Experimental

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Deformation texture of a low carbon steel

Taylor Theory

Basic Assumptions:

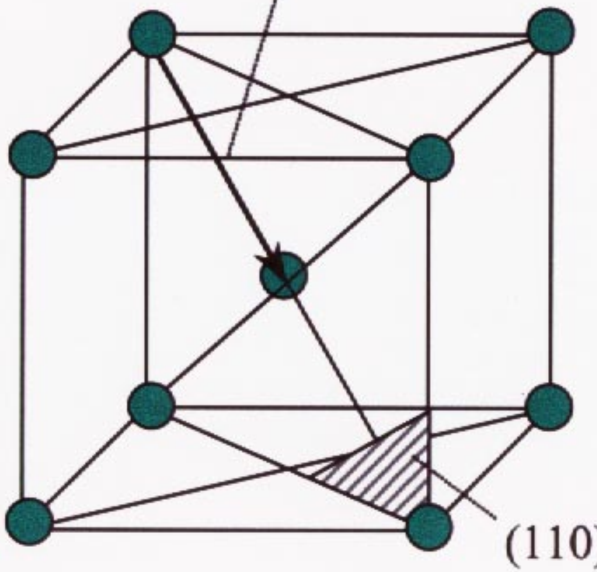
- macroscopic strain = microscopic strain
- dissipated plastic power is minimized

→ Imposed displacement tensor **E**
accommodated by combination of 5 slip systems (out of 24)

↓

Crystal rotation:
initial orientation $g_i \longrightarrow$ final orientation g_f

Deformation texture of a low carbon steel



Dislocation Glide

Slip planes: {110} + {211}

Slip directions: <111>

24 slip systems

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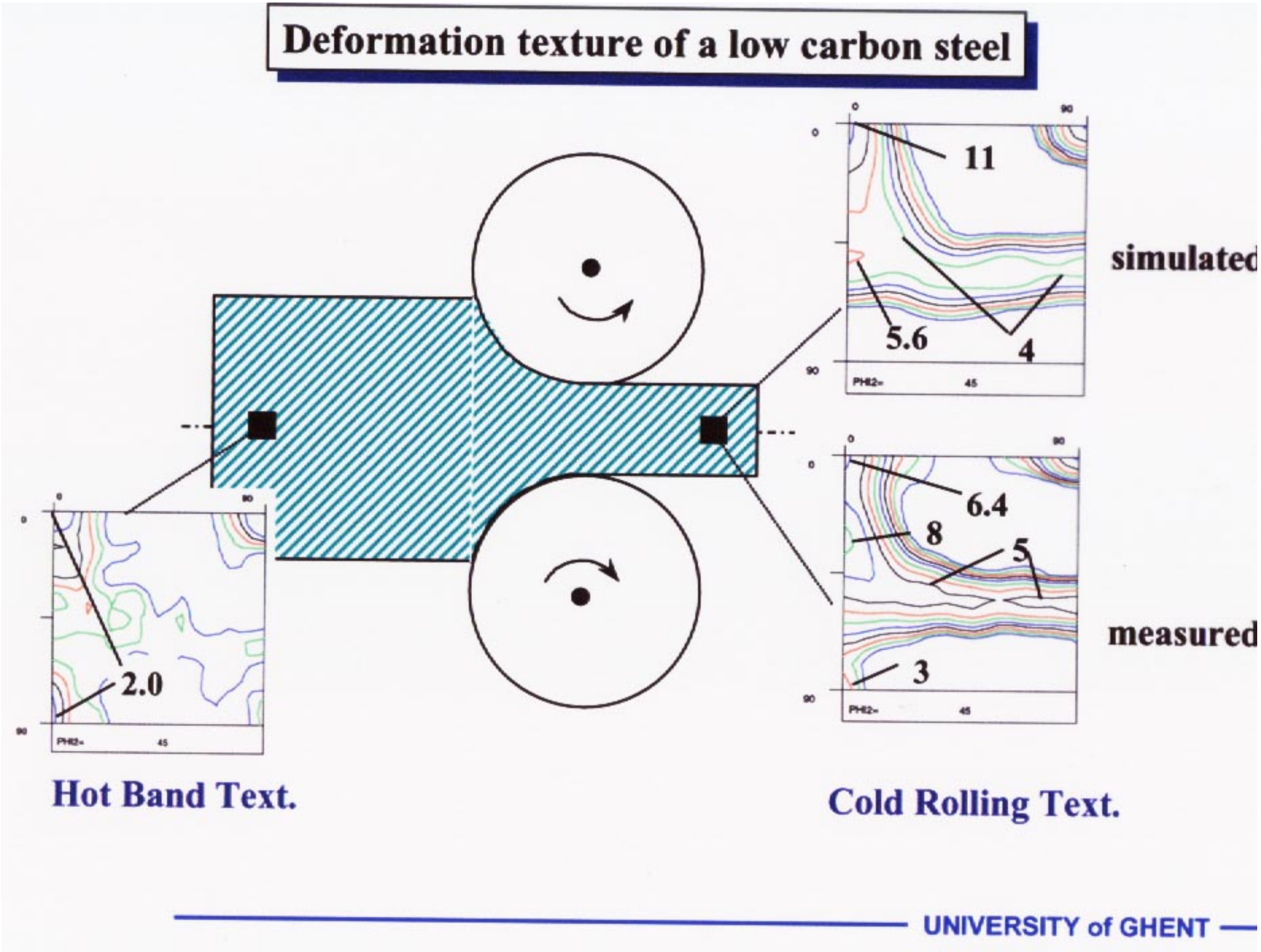
Deformation texture of a low carbon steel
11
simulated
5.6
4
6.4
8
5
measured
3
2.0
Hot Band Text.
Cold Rolling Text.
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Recrystallization texture of a low carbon steel