Texture and Anisotroy

Part II:

Chapter 5. Evaluation and representation of macrotexture data

Normalization and contouring of pole figures



The standard unit of orientation intensity is in m.r.d., i.e., the intensity of a random standard sample = 1.

Contouring of pole figures







Contouring of pole figures



FIGURE 5.2

(See color insert following page 240 for Figure 5.2b.) {111} Pole figure plotted with contour lines (logarithmic progression; regions with intensity lower than 0.5 are dotted); (b) same pole figure as in (a) plotted with colored contour lines; (c) same pole figure as in (a) plotted in gray shades (aluminum alloy AA 5005-H22, partially recrystallized).

Inverse pole figures

for the extrusion axis of titanium

Inverse pole figure of titanium deformed by extrusion to a von Mises equivalent strain of 1.75 (inverse pole figure of the extrusion axis). (Adapted from Rollett, A.D. and Wright, S.I., *Texture*

Definition of orientation distribution function

- Literature: mathematical function is always available to describe the (continuous) orientation density; known as "orientation distribution function."
- From probability theory, however, remember that, strictly speaking, *distribution function* is reserved for the cumulative frequency curve (only used for volume fractions in this context).

Orientation distribution function (ODF)

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

$$g = g(\varphi_1, \phi, \varphi_2)$$

$$dg = \frac{1}{8\pi^2} \sin \Phi \cdot d\phi_1 \cdot d\Phi \cdot d\phi_2$$

dV is the volume of crystallites that have the orientation g within the element of orientation dg, and V is the total sample volume.

Schematic representation of a microstructure consisting of different grains *i* of volume V_i with different orientations. Similar orientations *g* within an orientation range *dg* are color coded with the same gray value.

Fundamental equation of ODF computation

Relation of PFs to OD

- A pole figure is a projection of the information in the orientation distribution.
- Equivalently, can integrate along a line in the OD to obtain the intensity in a PF.

How to determine f

The computational methods for OD analysis:(a) Series expansion method(b) Direct method

Series expansion method

$$P_{h}(y) = \frac{1}{2\pi} \int_{\gamma=0}^{2\pi} f(g) d\gamma \quad \longrightarrow \quad \frac{1}{2\pi} \int_{0}^{2\pi} T_{l}^{mn}(g) d\gamma = \frac{2}{2l+1} \cdot k_{l}^{*m}(h) \cdot k_{l}^{n}(h)$$

$$f(g) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \sum_{n=-l}^{l} C_{l}^{mn} T_{l}^{mn}(g)$$

$$P_{h}(y) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} F_{l}^{n}(h) \cdot k_{l}^{n}(y)$$

$$F_l^n(h) = \frac{4\pi}{2l+1} \sum_{m=-l}^l C_l^{mn} \cdot k_l^{*m}(h)$$

unknown coefficients

Definitions of parameters

The C_l^{mn} coefficients can be determined up to l=L if the coefficients $F_l^n(h)$ are known for 2L+1 pole figures.

h: the number different pole figures

m: the different crystal symmetry

Solution of series expansion method

$$F_{l}^{n}(h) = \frac{4\pi}{2l+1} \sum_{m=-l}^{l} C_{l}^{mn} \cdot k_{l}^{*m}(h) \qquad F_{l}^{n}(h) = \int P_{h}(y) \cdot k_{l'}^{*n'}(y) dy$$

$$\int P_{h}(y) \cdot k_{l'}^{*n'}(y) dy = \sum_{l=0}^{\infty} \sum_{n=-l}^{+l} F_{l}^{n}(h) \int k_{l}^{n}(y) \cdot k_{l'}^{*n'}(y) dy$$

$$\prod_{l=0}^{10} \frac{1}{10} \prod_{l=0}^{10} \frac{1}{10} \prod_{l=0}^{10$$

Truncation error

The truncation error is to truncate the series expansion of pole figure and ODF expansion. This is controlled by the index l.

This truncation error leads to broadening of the texture components as well as to minor artifact intensities in the vicinity of the strong texture components.

The truncation error is determined by the maximum value of l_{max} .

The higher the degree l_{max} of the expansion the sharper the function.

Truncation error

Φ

ODFs composed of two orientations—the Bs orientation (011)(211) at $(\phi_1, \phi_2, \phi_3) = (35^\circ, 45^\circ, 0^\circ)$ and the S orientation (123)(634) at $(60^\circ, 35^\circ, 65^\circ)$ —computed with different degrees of series expansion l_{max} : (a) $l_{max} = 12$; (b) $l_{max} = 22$; (c) $l_{max} = 34$. (d) Orientation density profile through the Bs peak (dashed line in [c]).

(d)

Ghost error

Ghost error is that intensities in the ODF may be missing (negative ghosts), or wrong intensities may appear (positive ghost).

These ghost errors are caused by the lack of the odd-order series expansion coefficients .

 $\neg mn_{-1}$

The odd-order C coefficients cannot .

$$f(g) = \tilde{f}(g) + \tilde{f}(g)$$

The even-order C coefficients can be derived from diffraction pole figures.

Example of ghost error

FIGURE 5.8

Rolling texture of an Al–Fe–Si alloy. (a) Reduced ODF f(g) as obtained from the experimental pole figures; (b) complete ODF f(g), that is, ODF from (a) plus subsequent ghost correction according to the method by Dahms and Bunge (1988, 1989).

Ghost error

Ghost correction according to the method by Dahms and Bunge (1988, 1989) at the *u*th iteration step in a 1-D representation. $f_{n-1}(g)$: ODF at the preceding iteration step; $f'_n(g)$: (complete) correction function to approximate the negative ranges of $f_{n-1}(g)$; $\tilde{f}'_n(g)$: odd part of the correction function $f'_n(g)$. (Adapted from Wagner, F. and Dahms, M. in *Advances and Applications of Quantitative Texture Analysis* (Eds. H. J. Bunge and C. Esling), DGM, Oberusel, Germany, 1991, 101.)

Direct method

Direct methods is to derive the ODF values f(g) directly from the pole figure data.

$$P_i = \sum_{j=1}^J \sigma_{ij} f_j$$

$$f_{0}(g) = N_{0} \cdot \prod_{i=1}^{I} \prod_{m_{i}=1}^{M_{i}} \left[P_{h_{i}}^{\exp}(y_{m_{i}}) \right]$$
$$f_{n+1}(g) = N_{n} \cdot f_{n}(g) \cdot \frac{f_{0}(g)}{\prod_{i=1}^{I} \prod_{m_{i}=1}^{M_{i}} \left[P_{h_{i}}^{\exp}(y_{m_{i}}) \right]^{1/I \cdot M_{i}}}$$

Direct method (WIMV)

Flow chart of ODF calculation according to the WIMV algorithm. (Adapted from Kallend, J.S., Texture and Anisotropy, Preferred Orientations in Polycrystals and their Effect on Materials Properties, Cambridge University Press, 1998.)

Comparison of series expansion and direct methods

Series expansion method:

- a fast, reliable method
- determine texture-related properties elastic modulus, elastic and plastic anisotropy

Direct method:

- no truncation error
- no ghost error
- for low-symmetry materials

Definition of Euler space

Euler space is 3D orientation space and its axes is composed of three Euler angle in an orthogonal coordinate system.

Definitions of Euler angles:

-Bunge $(\varphi_1, \Phi, \varphi_2)$ -Roe (ψ, Θ, Φ) -Kocks (Ψ, Θ, ϕ)

Spatial arrangement of the three components of the orientation (123)[634] with isotropic scatter of 10° in the reduced Euler angle space showing strong distortions at small angles Φ . (b) Same texture as in (a) plotted with iso-intensity lines in φ_2 sections ($\Delta \varphi_2 = 5^\circ$) through the Euler space.

Distortions in Euler space

The resulting spheres in the Euler space are far from being isotropic and show strong distortions for small angle.

(a)

Spatial arrangement of the three components of the orientation (123)[634] with isotropic scatter of 10° in the reduced Euler angle space showing strong distortions at small angles Φ . (b) Same texture as in (a) plotted with iso-intensity lines in φ_2 sections ($\Delta \varphi_2 = 5^\circ$) through the Euler space.

Representation of Cartesian Euler space

Intensity distribution of Euler space sections

FIGURE 5.12

(See color insert following page 240.) (a) Contouring of a 3-D orientation distribution to derive the standard 2-D presentation of ODF sections; (b) orientation distribution of (a), plotted with iso-intensity lines; (c) orientation distribution of (a), plotted with gray shades; (d) orientation distribution of (a), plotted with colors (ODF $\phi_2 = 0^\circ$ section).

Representation of Cylindrical Euler space

FIGURE 5.13

Representation of the orientation space in a cylindrical Euler space. (a) Cylinder axis parallel to φ_2 ; the projection of texture on the base ($\varphi_2 = 0^\circ$) corresponds to a pole figure (COD). (b) Cylinder axis parallel to φ_1 ; the projection of texture on the base ($\varphi_1 = 0^\circ$) corresponds to an inverse pole figure (SOD).

Example of COD: rolling texture

FIGURE 5.14

Texture of hot-rolled aluminum AA 6016 represented in the cylindrical Euler space (φ_2 sections, COD). (a) Rolling texture at the center layer of the sheet, depicting orthonormal sample symmetry. The sections $\varphi_2 = 0^\circ$, 45°, and 90° as well as the (projected) pole figure are symmetrical with respect to TD. Also, note symmetries between sections $\varphi_2 = 15^\circ$ and 75° and $\varphi_2 = 30^\circ$ and 60°. (b) Shear texture at the sheet surface, depicting monoclinic sample symmetry. The various semicircles show no symmetry with respect to TD, representing the deviation of the strain state from orthonormal sample symmetry.

Example of COD: shear texture

FIGURE 5.14

Texture of hot-rolled aluminum AA 6016 represented in the cylindrical Euler space (φ_2 sections, COD). (a) Rolling texture at the center layer of the sheet, depicting orthonormal sample symmetry. The sections $\varphi_2 = 0^\circ$, 45°, and 90° as well as the (projected) pole figure are symmetrical with respect to TD. Also, note symmetries between sections $\varphi_2 = 15^\circ$ and 75° and $\varphi_2 = 30^\circ$ and 60°. (b) Shear texture at the sheet surface, depicting monoclinic sample symmetry. The various semicircles show no symmetry with respect to TD, representing the deviation of the strain state from orthonormal sample symmetry.

Rolling texture of pure Cu: PF

3 main texture components:

- Cu: {112}<111>
- S: {123}<634>
 - Bs: {011}<211>

Rolling texture of pure Cu: ODF

- 3 main texture components:
- Cu: {112}<111>
- S: {123}<634>
- Bs: {011}<211>

Orientation tube of pure Cu

α- fibre: {011}//RD Goss-Bs β–fibre: Bs-S-Cu

At low deformation: α-fibre At high deformation: β-fibre

Typical fibers in fcc metals and alloys

Designation	Miller Indices { <i>hkl</i> }⟨ <i>uvw</i> ⟩	Euler Angles $\phi_1 \Phi \phi_2$
Copper (Cu)	$\{112\}\langle111\rangle$	90° 30° 45°
S	{123}<634>	59° 34° 65°
Brass (Bs)	$\{011\}\langle 211\rangle$	35° 45° 0°/90°
Goss	$\{011\}\langle100\rangle$	0° 45° 0°/90°

Rolling texture of brass (Cu-37%Zn)

1 main texture components: -Bs: {011}<211>

Alloying changes the materials' stacking fault energy (SFE).

Typical SFE: Al, Ni: >200 mJ/m² Cu, Au: 50-60 mJ/m² Alloys: 20 mJ/m²

Rolling texture of brass: ODF

1 main texture components: -Bs: {011}<211>

Effect of second phase particles (Al-1.8% Cu)

Effect of texture changing

- 1. Stacking faulting energy
- 2. Second phase particles
- 3. Initial texture
- 4. Deformation modes

Effect of initial texture

FIGURE 5.19

Correlation of texture and earing in AA 3104 can body stock. (a) Texture at final gauge (H19), showing a rolling texture superimposed on a cube texture retained from the recrystallized hot strip; (b) cup drawn from hot strip, showing pronounced 0°/90° earing; (c) cup drawn from final gauge sheet, showing very weak earing with mixed 0°/90° and 45° ears. (Adapted from Engler, O. and Hirsch, J., Mater. Sci. Eng., A452-453, 640, 2007.)

Effect of deformation modes

FIGURE 5.20

(a) Inverse pole figure of the compression direction of copper after compression to a strain of ~1; (b) pole figure of the extrusion texture of an Al–Li alloy. (Courtesy of J. Hirsch.)

Effect of deformation modes

TABLE 5.2

Characteristic Fibers in fcc Metals and Alloys

Fiber	Fiber Axis	Euler Angles ^a
α	(011)//ND	0°,45°,0°—90°,45°,0°
γ	$\langle 111 \rangle / / ND$	60°,54.7°,45°—90°,54.7°,45°
τ	$\langle 011 \rangle / / TD$	90°,0°,45°—90°,90°,45°
β	b	90°,35°,45°—35°,45°,90°

^a Typical values without symmetry considerations.
 ^b Defined by the maximum intensity rather than by exact crystallographic position.

Rolling texture of Ti-Nb IF steel

FIGURE 5.21

Rolling texture of a Ti and Nb microalloyed interstitial-free steel in the Euler space (90% rolling reduction). (a) Conventional representation of the ODF in φ_1 sections; (b) $\varphi_2 = 45^\circ$ section displaying the intensity distribution of the α - and γ -fiber orientations; (c) schematic representation of the most important orientations in bcc materials in the $\varphi_2 = 45^\circ$ section. (Courtesy of M.Y. Huh.)

ODF section for bcc IF steel (cold rolled)

Orientation intensity of low C steel

FIGURE 5.22

Development of the rolling texture fibers of a low-carbon steel with increasing rolling reduction. (Data from Hölscher, M., Raabe, D., and Lücke, K., Steel Res., 62, 567, 1991.)

Texture evolution of Fe-17%Cr steel

FIGURE 5.23

Texture of (a) hot strip and (b) cold strip of ferritic stainless steel Fe–17%Cr (ODF $\varphi_2 = 45^{\circ}$ section, sheet center). (Data from Huh, M.Y. and Engler, O., *Mater. Sci. Eng.*, A308, 74, 2001.)

Effect of c/a on hex texture

The rolling texture is influenced by the c/a ratio and the slip systems.

HCP texture

Pyramidal-< a > $\{10\overline{1}1\} < 11\overline{2}0 >, 6$

Hot-rolling texture of Mg alloy AZ31

Rolling texture of Ti sheet

FIGURE 5.26

Rolling texture of titanium sheet: (a) 50% cold rolled, (b) 90% cold rolled, (c) position of important orientations of hexagonal materials in Euler space (ODF $\varphi_2 = 0^\circ$ and 30° sections, intensity levels 1–2–3–4–5–7–9). (Adapted from Inoue, H. and Inakazu, N., *Proc. ICOTOM 8*, TMS, Warrendale, PA, 1988.)

Rolling texture of 80% cold-rolled ZnCuTi alloy

FIGURE 5.27

Rolling texture of 80% cold-rolled ZnCuTi alloy sheet (ODF $\varphi_1 = 90^\circ$ section). (Adapted from Philippe, M.J., Wagner, F., Mellab, F.E., Esling, C., and Wegria, J., Acta Metall. Mater., 42, 239, 1994.)

RX texture of cold-rolled fcc metals

FIGURE 5.28

Recrystallization texture of cold-rolled fcc metals: (a) aluminum, (b) copper, and (c) brass (Cu-37%Zn) ({111} pole figure).

RX texture of cold-rolled Cu alloys

Cu-8%Mn

Cu-37%Zn

RX texture of fcc metals and alloys

TABLE 5.4

Miller Indices and Euler Angles of the Most Important Recrystallization Texture Orientations of fcc Metals and Alloys (Approximated)

Designation	Miller Indices { <i>hkl</i> }⟨ <i>uvw</i> ⟩	Euler Angles $\phi_1 \Phi \phi_2$
Cube	{001}(100)	0° 0° 0°/90°
Cube _{RD}	$\{013\}\langle100\rangle$	0° 22° 0°/90°
Cube _{ND}	$\{001\}\langle310\rangle$	22° 0° 0°/90°
Cube-twin (first generation)	{122}(212)	27° 48° 27° or 63° 48° 63°
Goss	$\{011\}\langle100\rangle$	0° 45° 0°/90°
BR	{236}(385)	80° 31° 35°
U (transition)	{258}(121)	$45^{\circ} \ 35^{\circ} \ 20^{\circ}$
R	$\{124\}\langle 211\rangle$	53° 36° 60°
Р	$\{011\}\langle 122\rangle$	$65^\circ 45^\circ 0^\circ / 90^\circ$
Q	$\{013\}\langle231\rangle$	$45^\circ\ 15^\circ\ 10^\circ$

Cube-RX texture of hot-rolled aluminum AA3104

RX texture of cold-rolled aluminum alloys

Characteristic recrystallization texture of cold-rolled aluminum alloys. (a) Cube + R texture of commercial purity Al; (b) Goss + Q texture of Al–3%Mg; (c) weak PSN recrystallization texture of AlFeSi with large second-phase particles.

RX texture of Ti-alloyed IF steel

FIGURE 5.32

Recrystallization texture of a Ti-alloyed interstitial-free steel showing a pronounced γ fiber: (a) φ_1 sections; (b) $\varphi_2 = 45^\circ$ section (90% cold rolled, annealed for 1 h at 700°C). (Courtesy of M.Y. Huh.)

RX texture of ferritic stainless steel Fe-17%Cr

FIGURE 5.33

Texture of recrystallization annealed ferritic stainless steel Fe–17%Cr (ODF φ_2 = 45° section, sheet center). (Data from Huh, M.Y. and Engler, O., *Mater. Sci. Eng.*, A308, 74, 2001.)

RX texture of cold-rolled Ta

FIGURE 5.34

Annealing texture of cold-rolled tantalum showing strong recovery. (a) 80% rolled, annealed for 1 h at 1000°C (ODF, ϕ_1 sections); (b) rolled by various rolling degrees, annealed for 1 h at 1000°C (γ -fiber plots). (Courtesy of D. Raabe.)

RX texture at section 45 for IF steel

The recrystallization texture is similar to the rolling texture, but much of α -fibre is eliminated on recrystallization, especially in the range of (001)[1-10] to (112)[1-10]. The γ -fibre is unchanged.

RX texture of Zr

FIGURE 5.35

(a) Rolling and (b) recrystallization texture of zirconium (90% cold rolled, annealed for 350 min at 650°C, ODF $\varphi_1 = 0^\circ$ section). (Adapted from Zhu, K.Y. et al., *Mater. Sci. Forum*, 550, 545, 2007.)