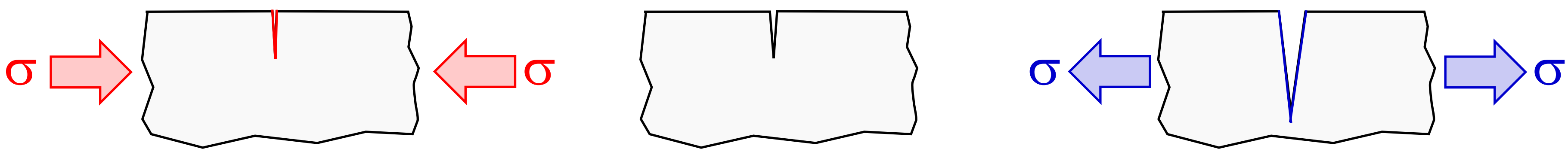
Analisi diffrattometrica di macro e microstrain

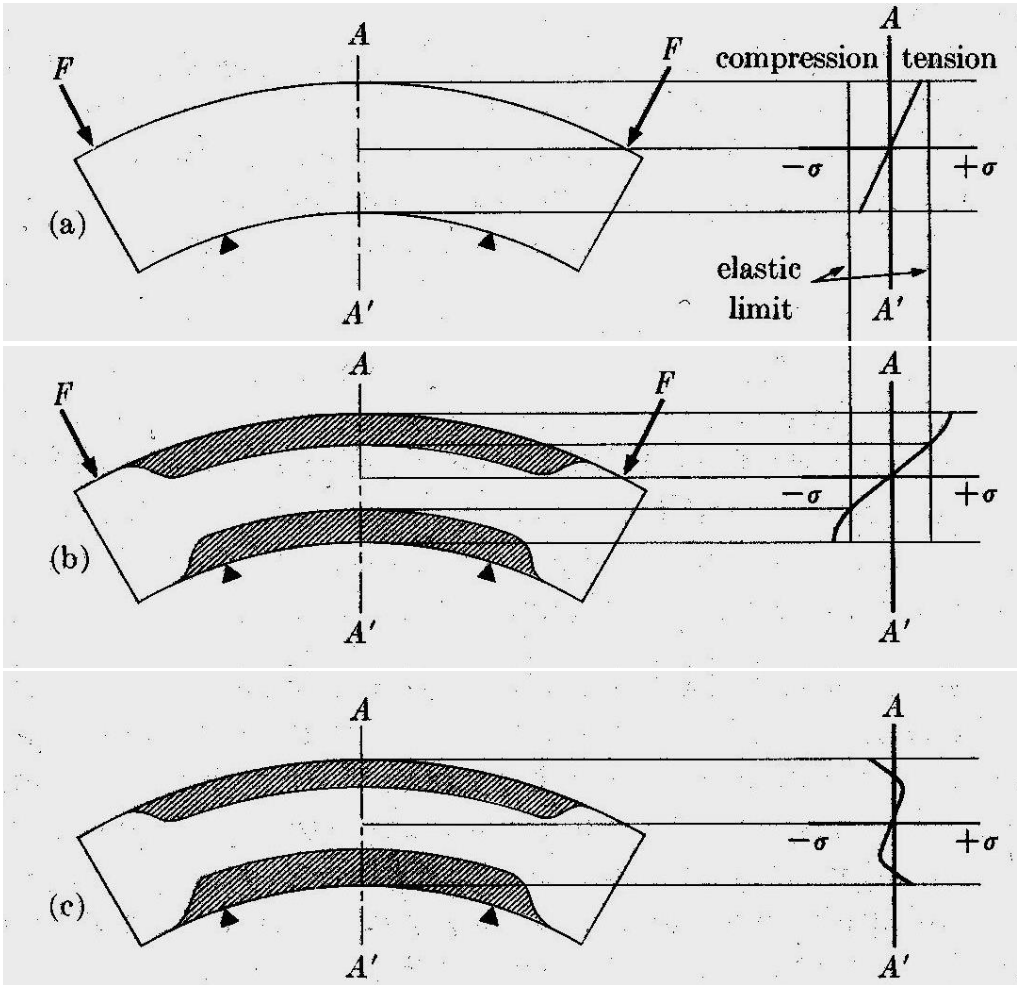
Paolo Scardi
Università degli Studi di Trento

MACROSTRAIN
E
TENSIONI RESIDUE



ORIGINE DELLE AUTOTENSIONI RESIDUE: UN ESEMPIO*

Possono originare da una prova di flessione, a causa della ripartizione non uniforme della deformazione plastica



(a) Carico entro limite elastico:

Deformazione reversibile

(b) Carico oltre limite elastico

Le regioni esterne si deformano plasticamente

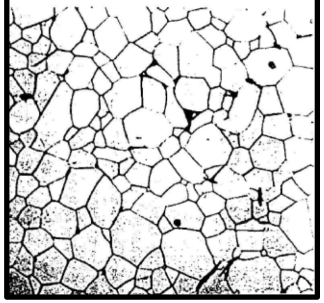
(c) Scarico

Deformazione parzialmente reversibile: si instaura un campo di sforzi residui

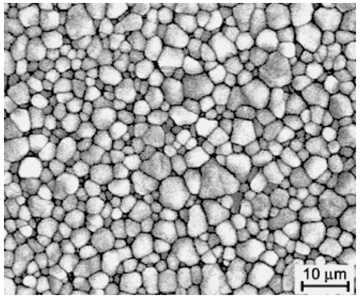
*** B.D. Cullity "Elements of X-ray diffraction" II Edition. Addison-Wesley, Reading, 1978**

DIFFRAZIONE DA POLVERI E POLICRISTALLINI

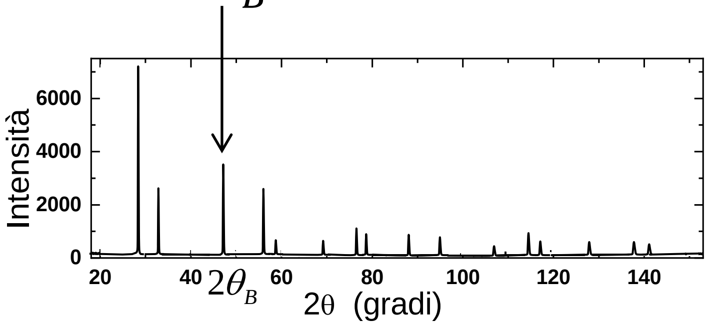
policristallino



polvere

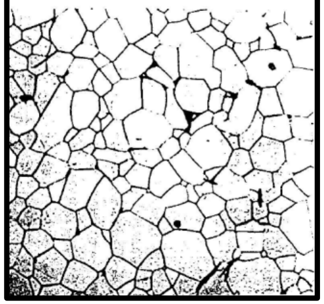


$\lambda = 2d\ sin\theta_B$ Legge di Bragg



DIFFRAZIONE DA POLVERI E POLICRISTALLINI

policristallino



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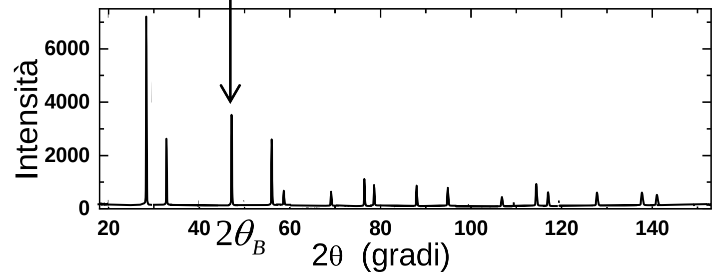
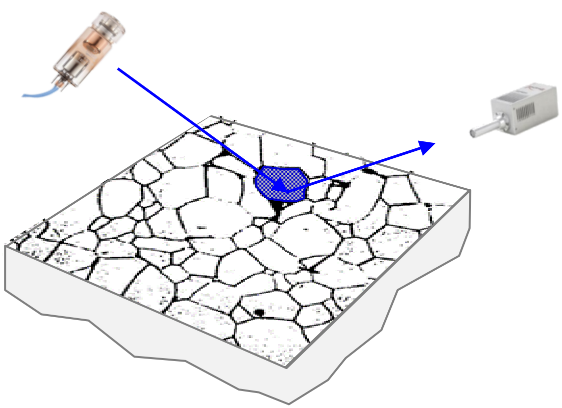
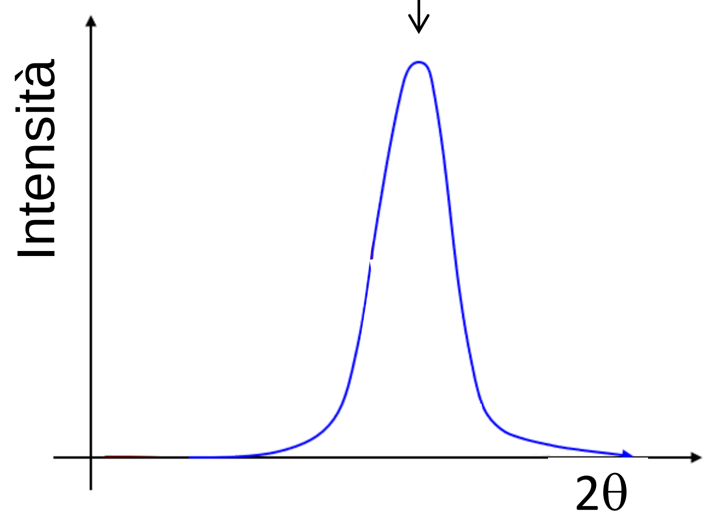


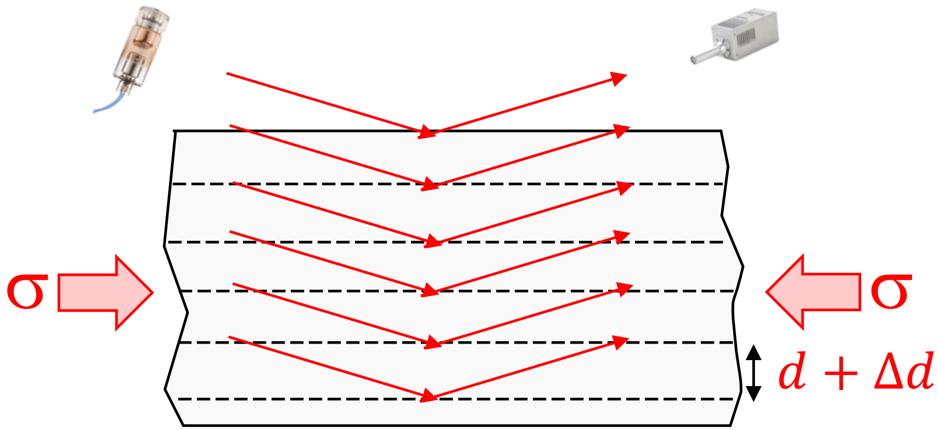


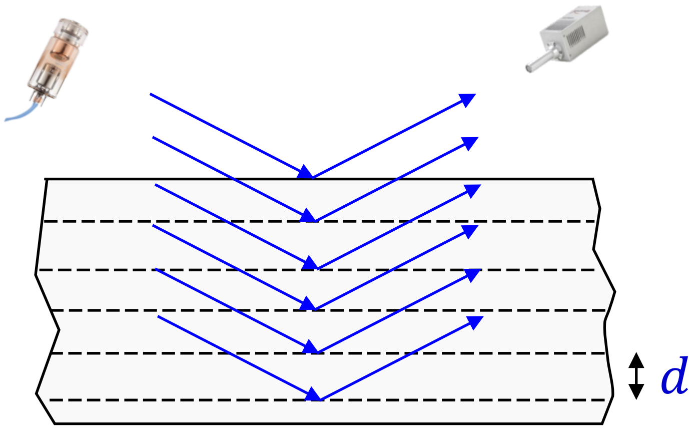


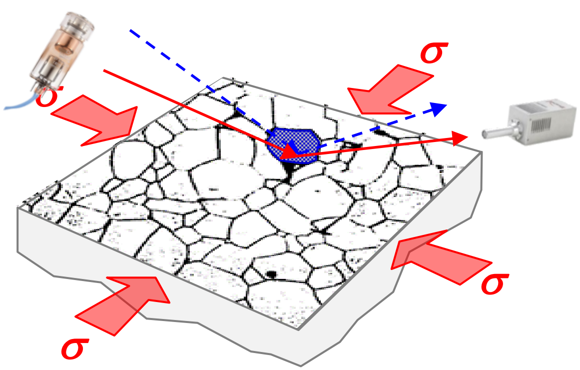
MACROSTRAIN → SPOSTAMENTO DEL PICCO

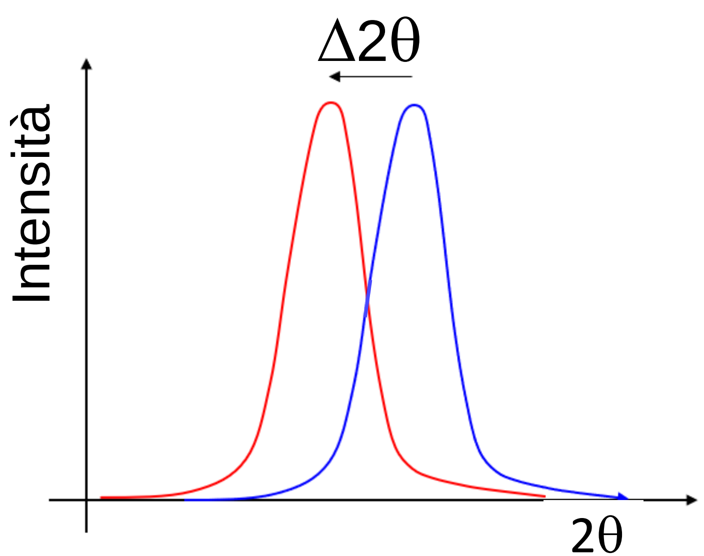
$\boldsymbol{d} \uparrow \quad \boldsymbol{\theta} \downarrow$

$\lambda = 2d\ sin\theta_B$ Legge di Bragg



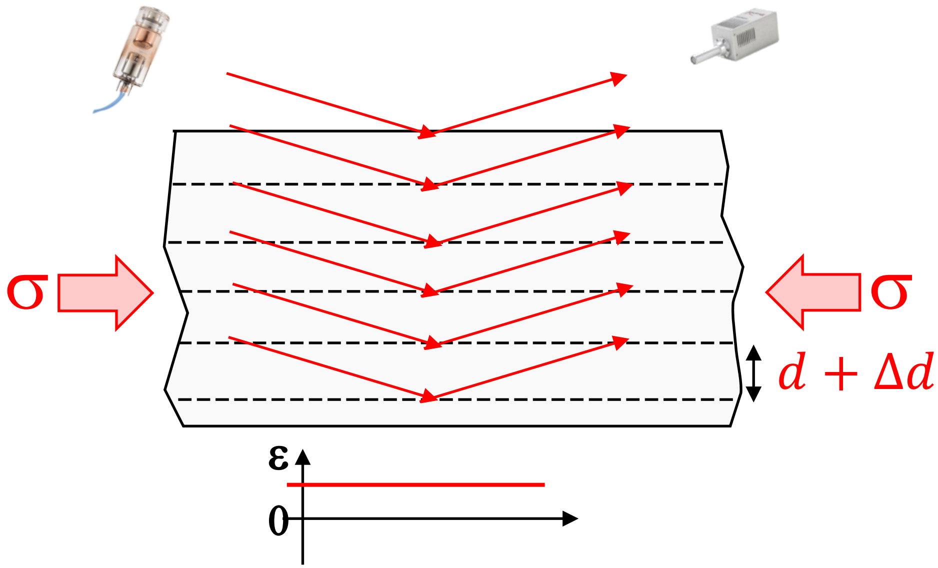


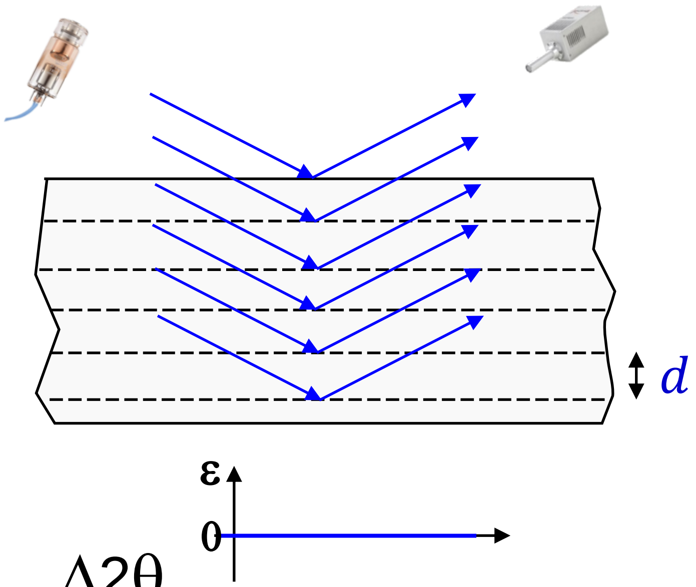


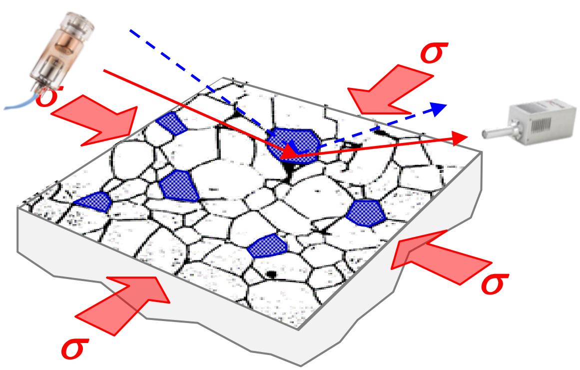


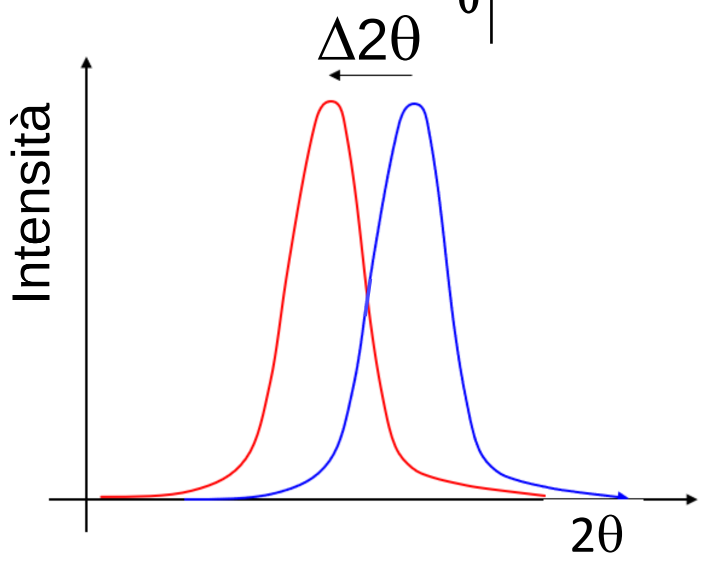
MACROSTRAIN → SPOSTAMENTO DEL PICCO

Grani cristallini come "strain gauge". Lo strain è ottenuto dallo spostamento $\Delta(2\theta) \rightarrow \Delta d \rightarrow \varepsilon = \dfrac{\Delta d}{d} = -\dfrac{2\nu}{E}\sigma$



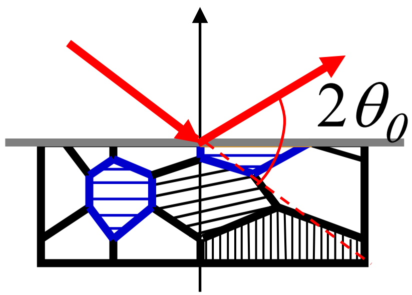


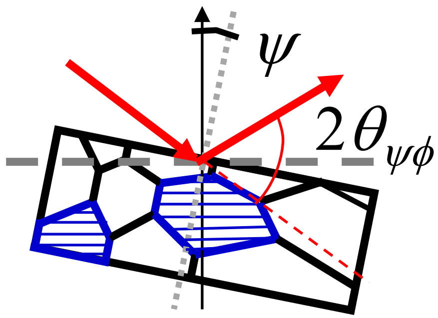




X-RAY RESIDUAL STRESS ANALYSIS – XRSA

$\varepsilon_{\psi\phi}$ è misurato per diverse inclinazioni (ψ-tilting) e rotazioni (ϕ) per le quali sono coinvolti grani diversi



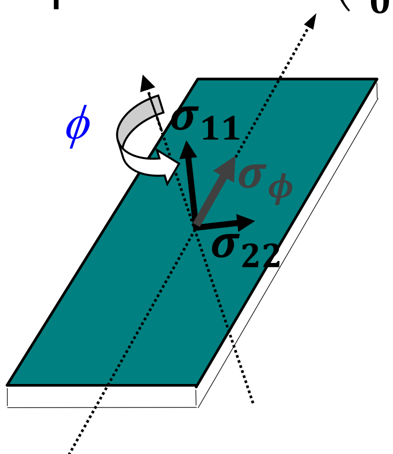


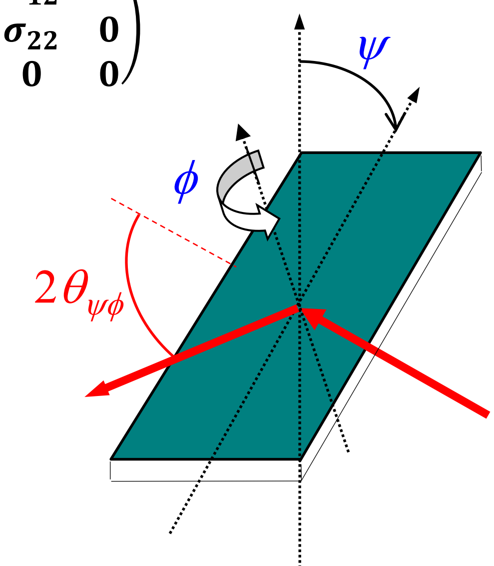
$$d_{\psi\phi} = 2sin\theta_{\psi\phi}/\lambda \;\rightarrow\; \varepsilon_{\psi\phi} = \frac{d_{\psi\phi} - d_0}{d_0}$$

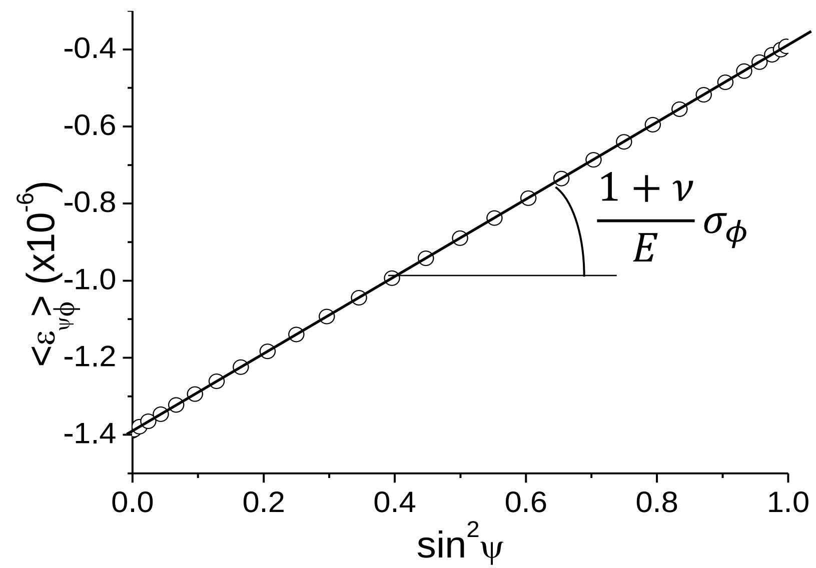
$$\varepsilon_{\psi\phi} = \frac{1+\nu}{E}\sigma_\phi sin^2\psi - \frac{\nu}{E}(\sigma_{11} + \sigma_{22})$$

$$\sigma_\phi = \sigma_{11}cos^2\phi + \sigma_{12}\sin 2\phi + \sigma_{22}sin^2\phi$$

stato di sforzo planare $\begin{pmatrix} \boldsymbol{\sigma_{11}} & \boldsymbol{\sigma_{12}} & \mathbf{0} \\ \boldsymbol{\sigma_{12}} & \boldsymbol{\sigma_{22}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{pmatrix}$







X-RAY RESIDUAL STRESS ANALYSIS – XRSA

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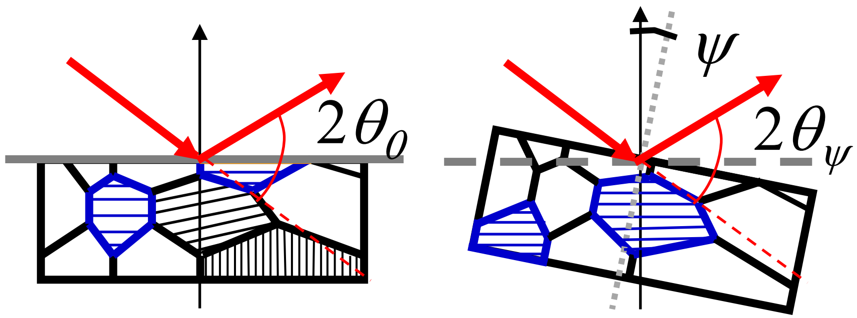
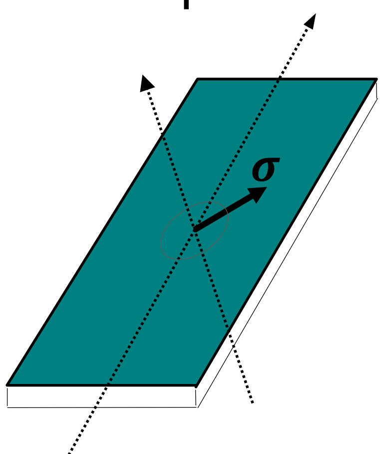


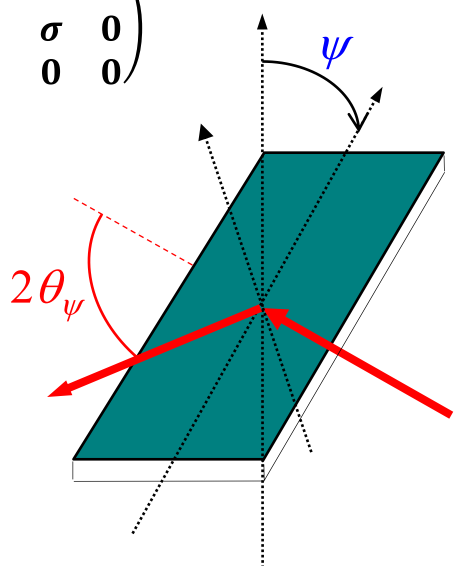
$$d_\psi = 2sin\theta_\psi/\lambda \quad \rightarrow \quad \varepsilon_\psi = \frac{d_\psi - d_0}{d_0}$$

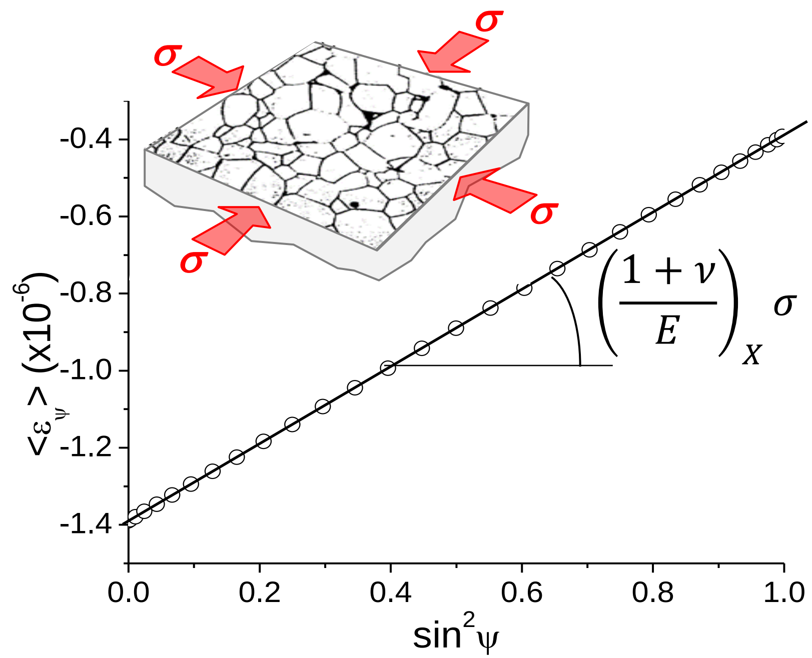
$$\varepsilon_\psi = \sigma\left(\frac{1+\nu}{E}\right)_X sin^2\psi - 2\sigma\left(\frac{\nu}{E}\right)_X$$

stato di sforzo
planare equiassiale

$$\begin{pmatrix} \sigma & 0 & 0 \\ 0 & \sigma & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

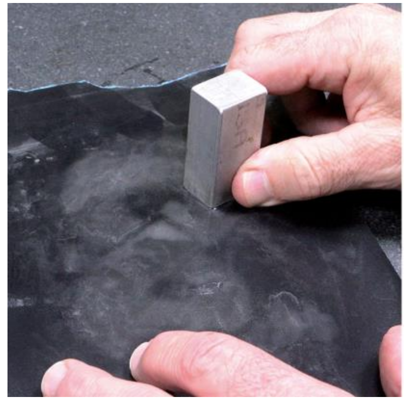


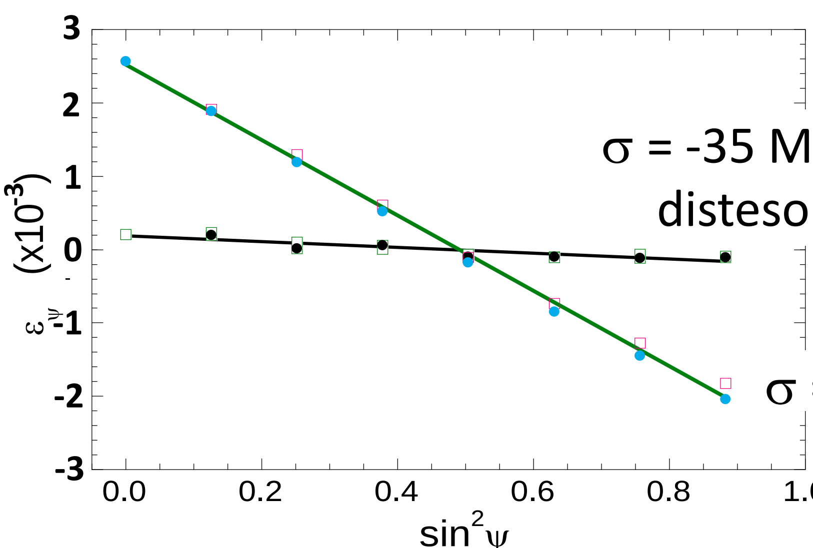




X-RAY RESIDUAL STRESS ANALYSIS – XRSA

Effetto di lappatura/lucidatura di componenti meccanici in lega di Ti (Ti-6Al-4V)





σ = -35 MPa
disteso

σ = -450 MPa
lucidato

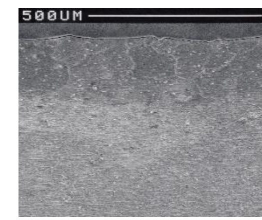
$$\varepsilon_\psi = \frac{d_\psi - d_0}{d_0}$$

Surf. Eng., 14 [6] 513–518 (1998)

misura attraverso
lo spessore
(residual stress profile)

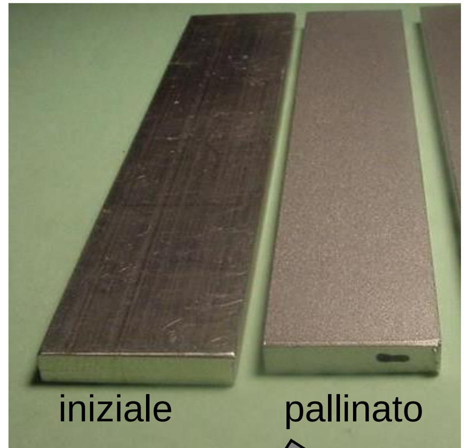
⇩

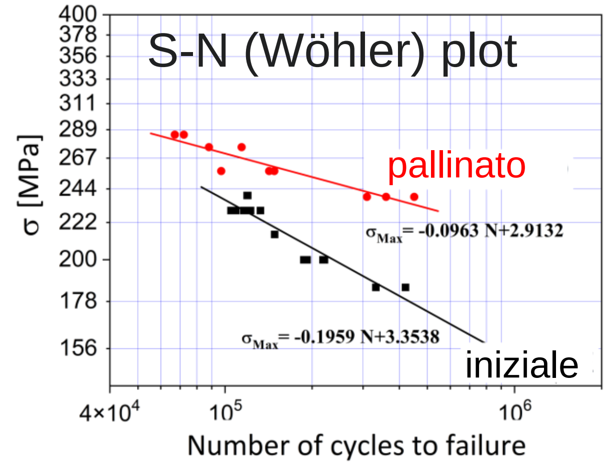
Norma
SAE J784a

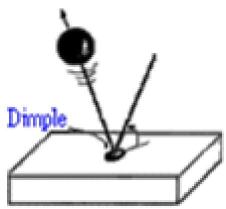


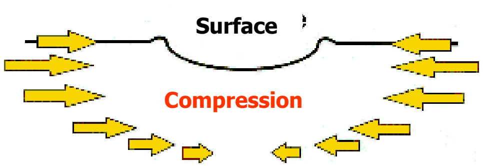
X-RAY RESIDUAL STRESS ANALYSIS – XRSA

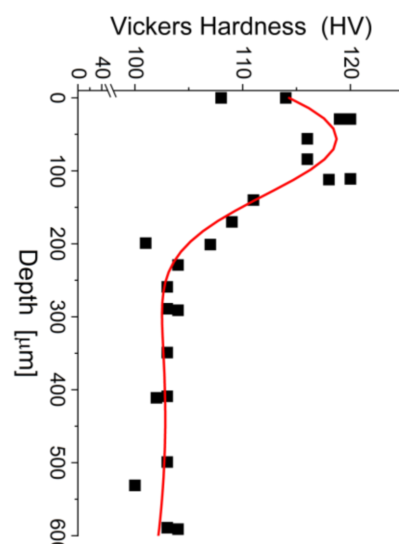
Pallinatura di componenti meccanici in lega di Al (AA 6082 T5)

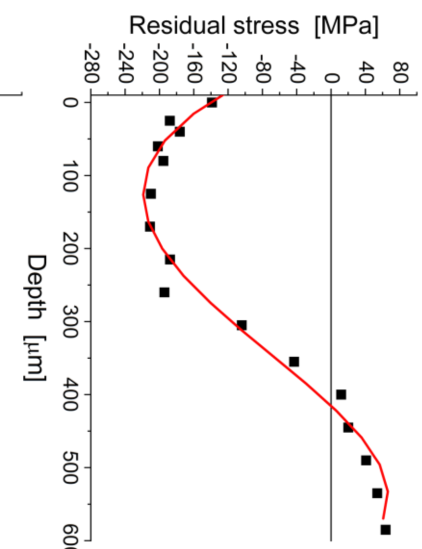








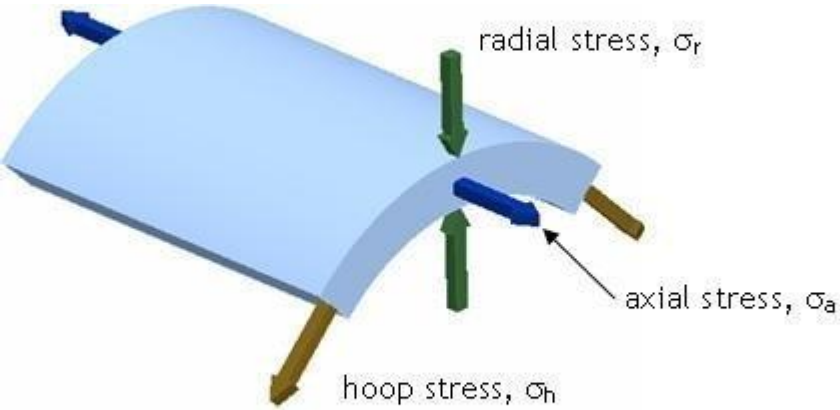


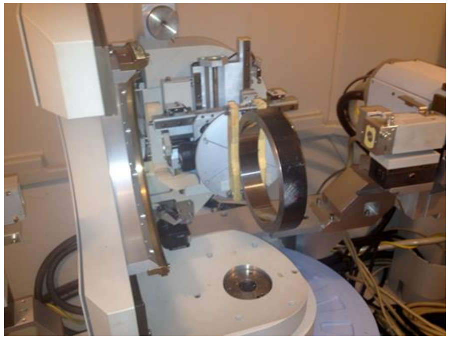


Int. J. Fatigue, 31 1225–1236 (2009)

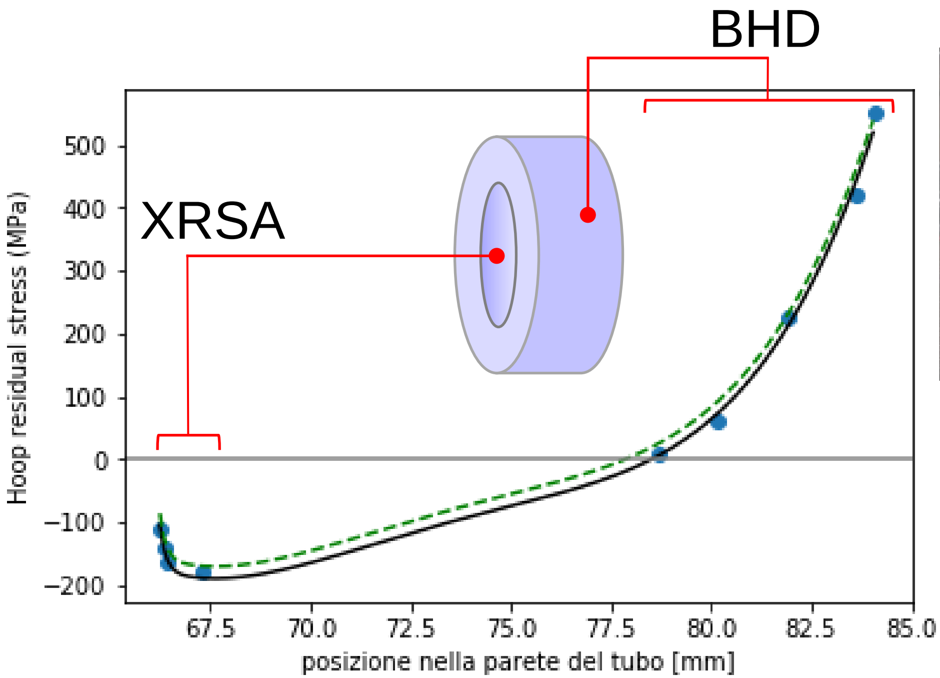
X-RAY RESIDUAL STRESS ANALYSIS – XRSA

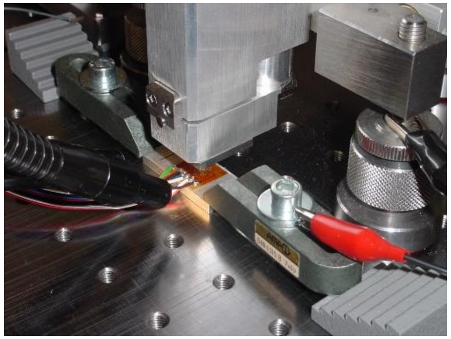
misura dello “hoop stress” in tubi d’acciaio





X-ray Residual Stress Analysis



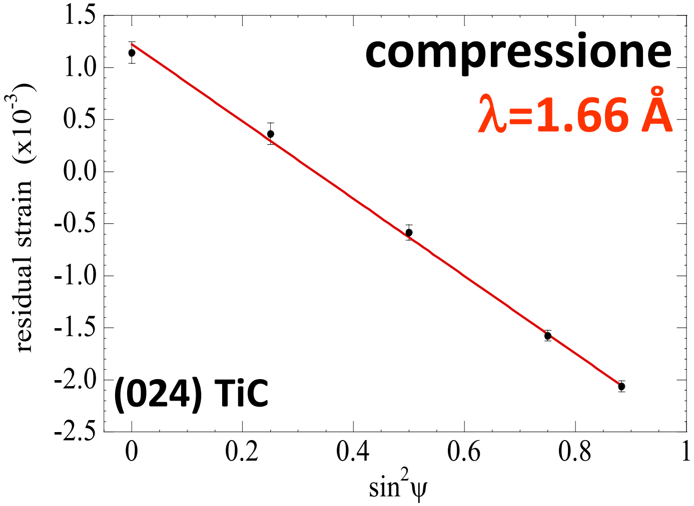


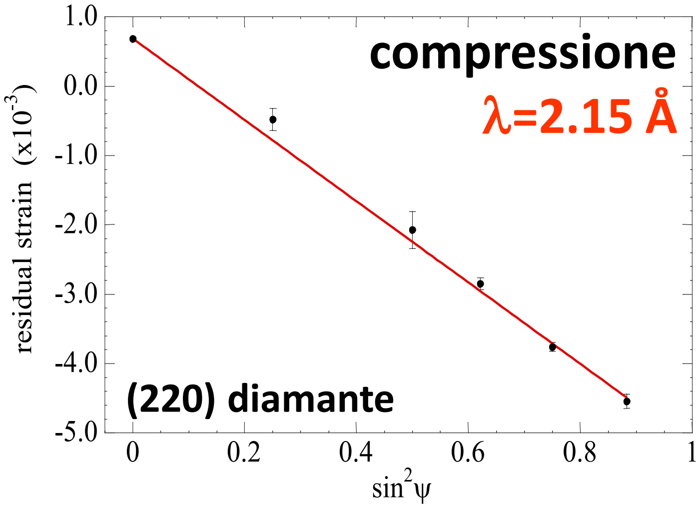
Blind Hole Drilling

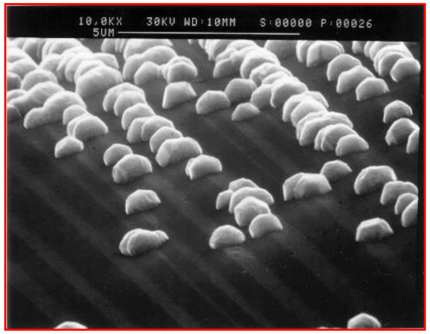
Mater. Perform. Charact., 7 [4] 536–44 (2018)

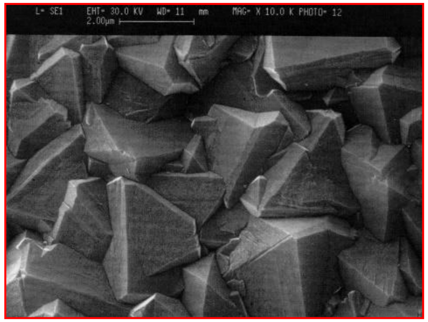
X-RAY RESIDUAL STRESS ANALYSIS – XRSA

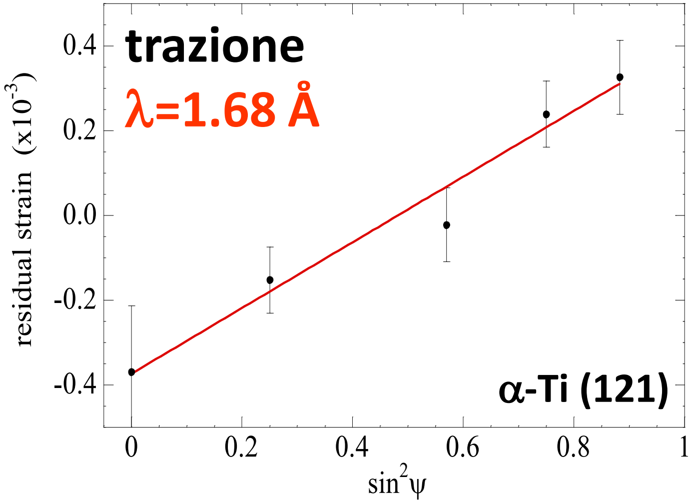
sforzo residuo in utensili di titanio diamantati:
XRSA in luce di sincrotrone (SRXRD)

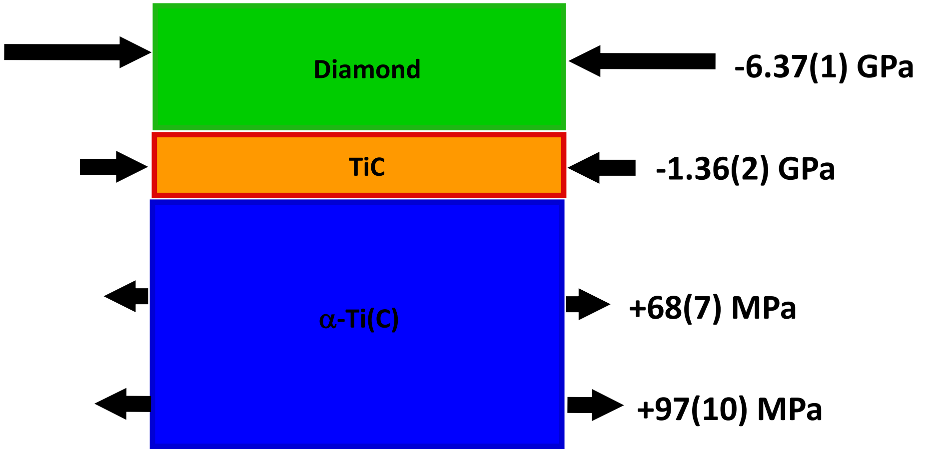












Diam. Relat. Mater., 6 807–811 (1997)

MICROSTRAIN

EFFETTO DELLO STRAIN SULLA DIFFRAZIONE

$$\lambda = 2d\sin\theta$$

$$\Delta\lambda = 0 = 2\Delta d\sin\theta + 2d\cos\theta\,\Delta\theta$$

$$0 = 2\Delta d\sin\theta + d\cos\theta\,\Delta 2\theta$$

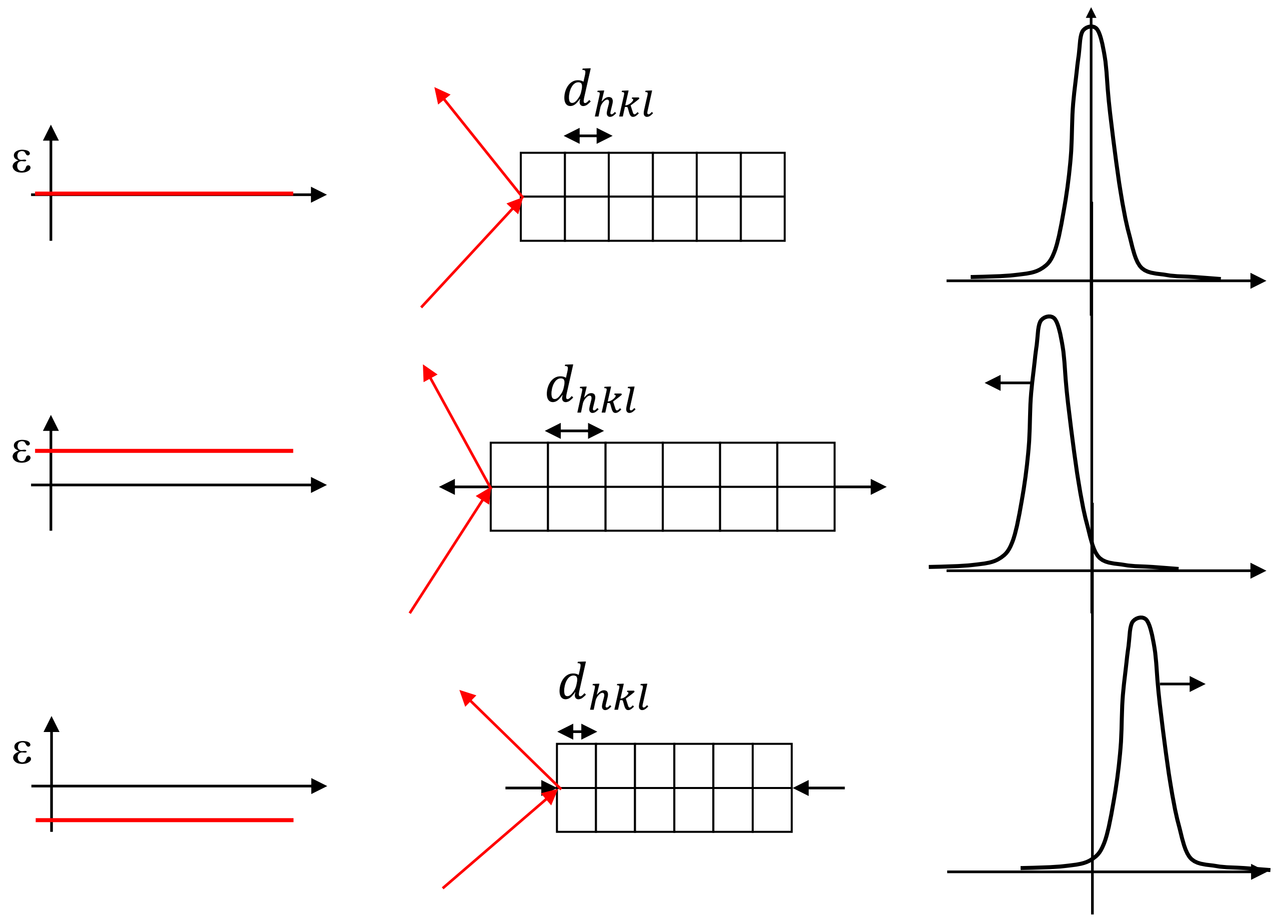
introducendo lo strain, $\varepsilon = \dfrac{\Delta d}{d}$

$$\Delta 2\theta = -2\tan\theta\,\frac{\Delta d}{d} = -2\varepsilon\tan\theta$$

EFFETTO DELLO STRAIN SULLA DIFFRAZIONE

$$\Delta 2\theta = -2\varepsilon \tan \theta_B$$

Uno strain uniforme causa uno *spostamento* della posizione del picco

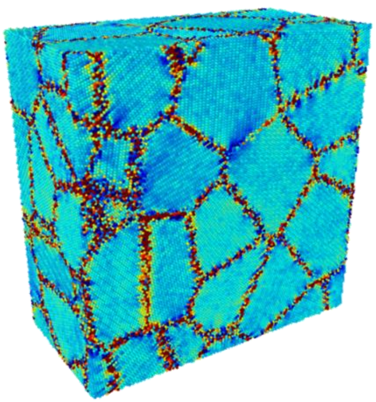


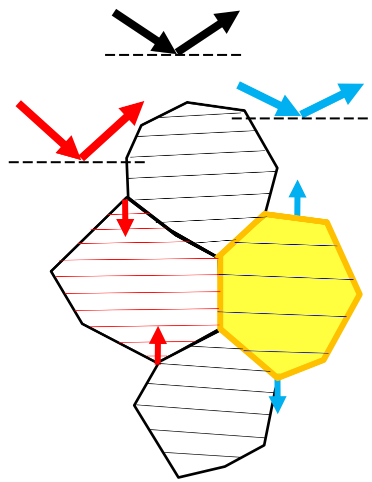
⟹ X-ray residual strain/stress analysis

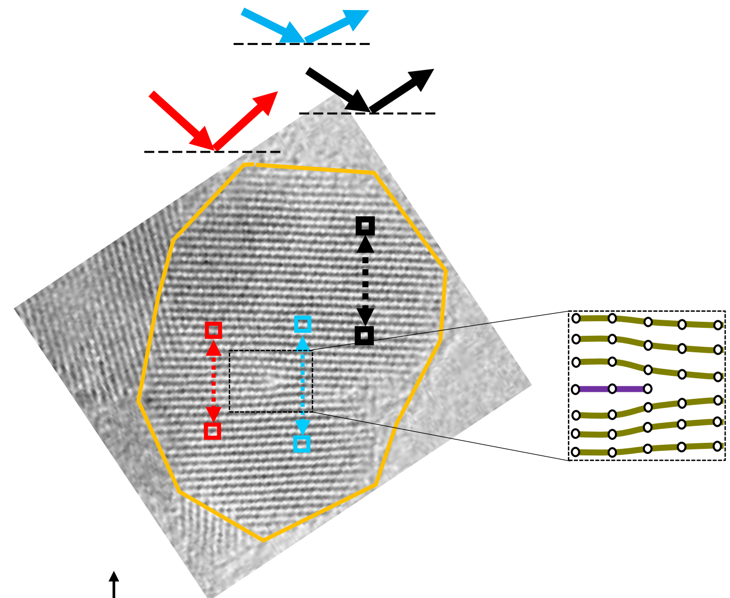
EFFETTO DEL MICROSTRAIN SULLA DIFFRAZIONE

strain non uniforme → distribuzione di strain, *p(ε)*. La media può essere zero (ad es. in polveri), ma non il microstrain (r.m.s. strain $\sqrt{\langle\varepsilon^2\rangle}$):

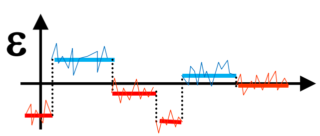
$$e \propto \sqrt{\langle\varepsilon^2\rangle} = \langle(\Delta d/d)^2\rangle$$

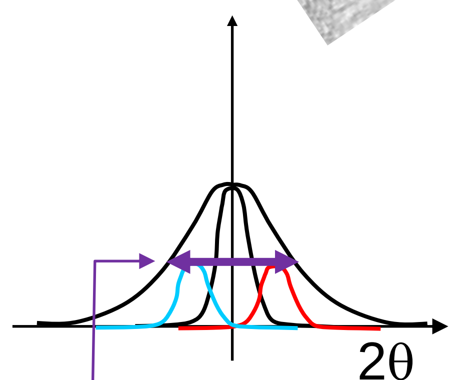






microstrain





FWHM – Full Width at Half Maximum

EFFETTO DEL MICROSTRAIN SULLA DIFFRAZIONE

strain non uniforme → distribuzione di strain, $p(\varepsilon)$. La media può essere zero (ad es. in polveri), ma non il microstrain (r.m.s. strain $\sqrt{\langle \varepsilon^2 \rangle}$):

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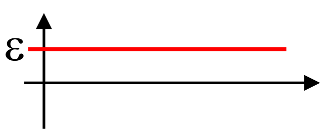
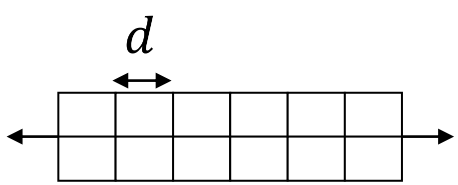
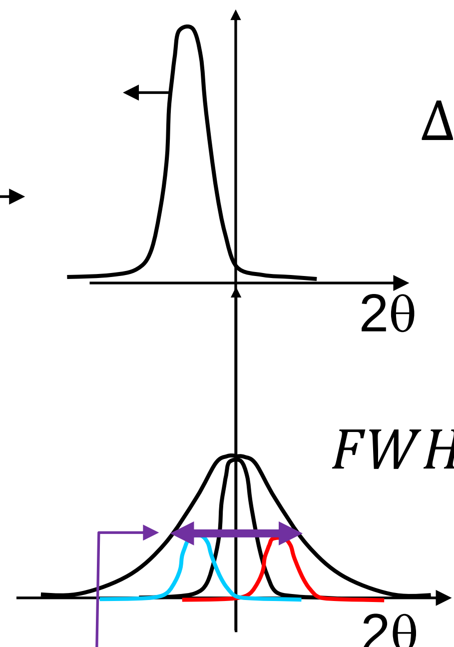
macrostrain



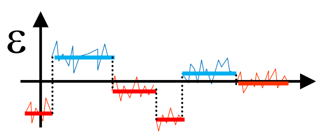


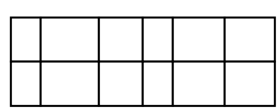


$$\Delta 2\theta = -2\varepsilon \tan \theta_B$$

$$FWHM = -2e \tan \theta_B$$

microstrain





FWHM – Full Width at Half Maximum

EFFETTO DEL MICROSTRAIN SULLA DIFFRAZIONE

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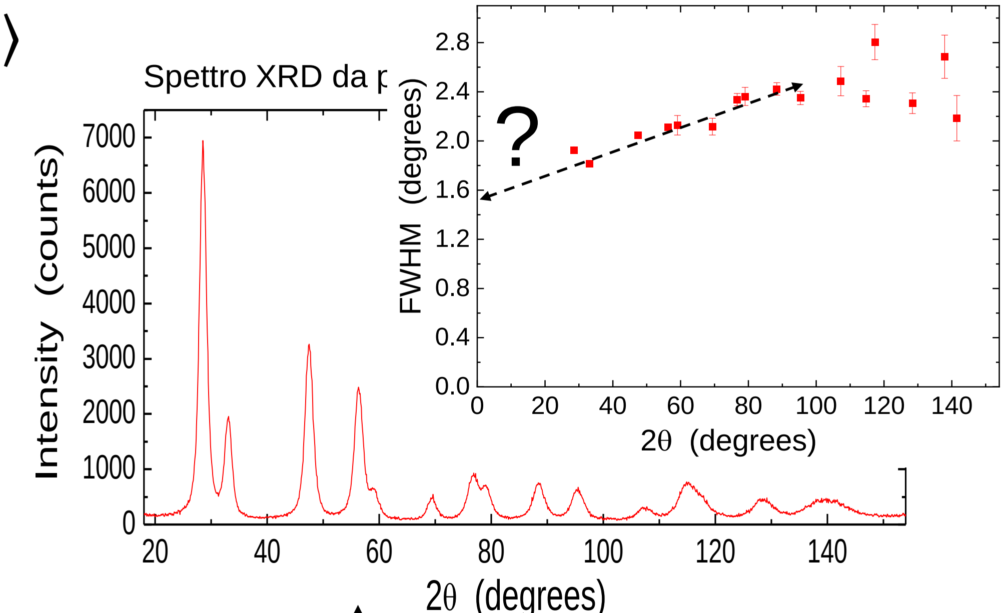
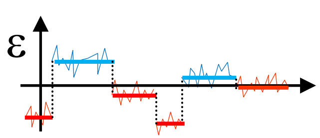
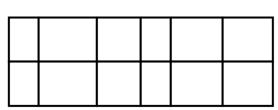
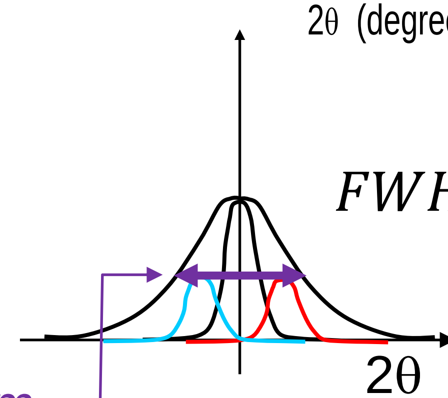


microstrain





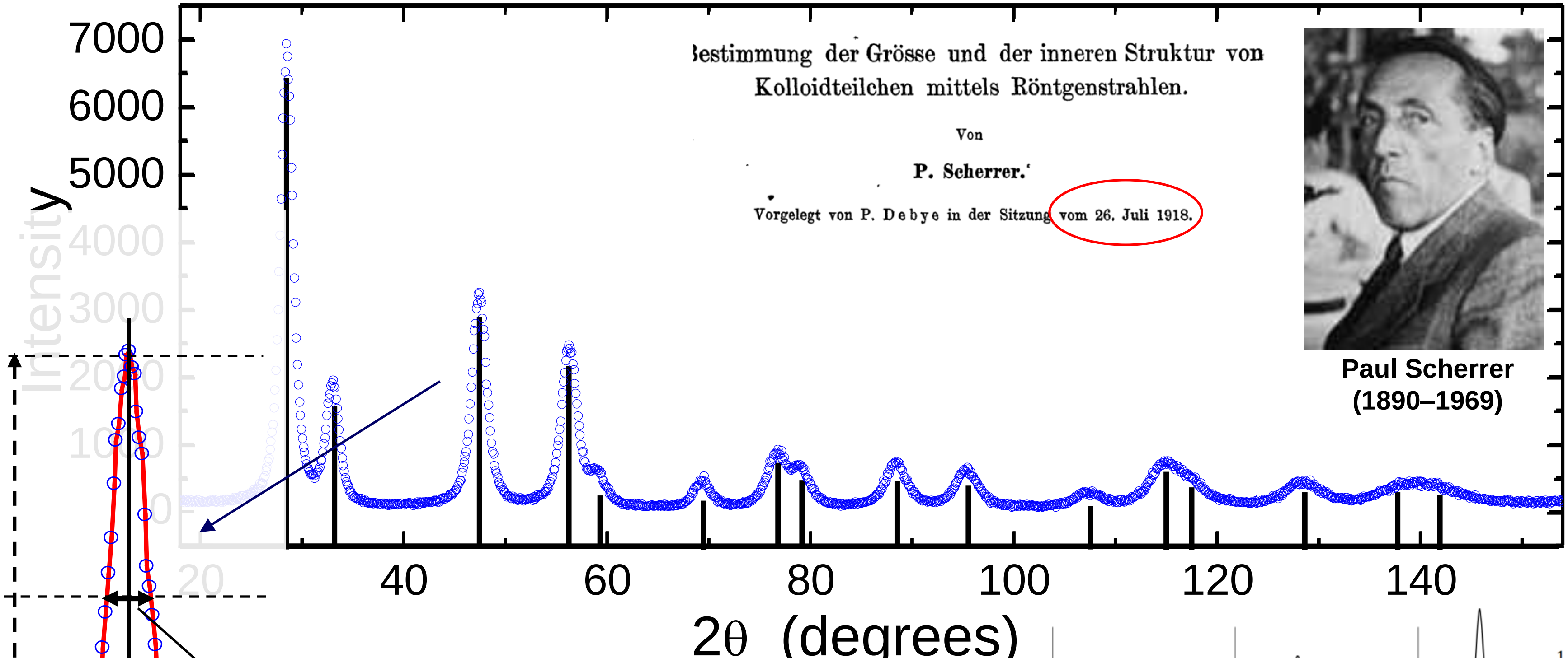


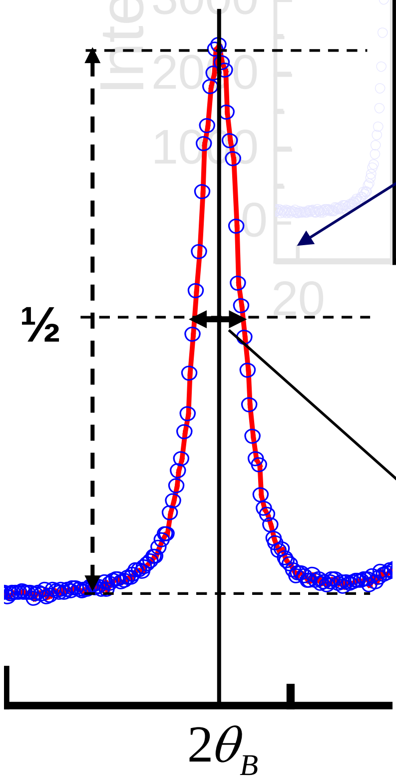
$$FWHM = -2e \tan \theta_B$$

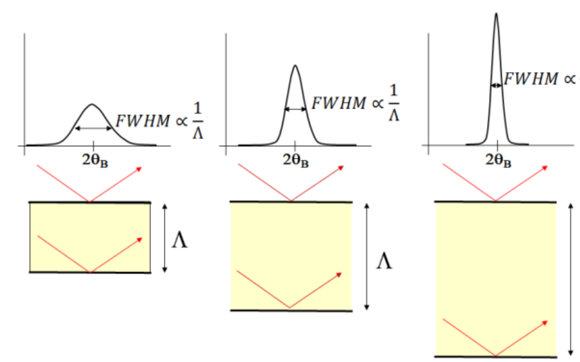
FWHM – Full Width at Half Maximum

DIFFRAZIONE DA NANOCRISTALLI: FORMULA DI SCHERRER

Spettro XRD da polvere di ceria (CeO_2) nanocristallina







$$FWHM \cong \frac{0.94\,\lambda}{\Lambda \cos\theta_B}$$

Λ : dimensione *efficace* del dominio cristallino (cristallite)

λ : lunghezza d’onda dei raggi X

EFFETTO “SIZE – MICROSTRAIN” IN DIFFRAZIONE

Effetto combinato di dimensione (*size*) dei cristalliti e *microstrain*:
una semplice approssimazione lineare

$$FWHM \cong \frac{0.94\,\lambda}{\Lambda \cos\theta_B} + 2e\tan\theta_B$$

dimensione cristalliti

microstrain

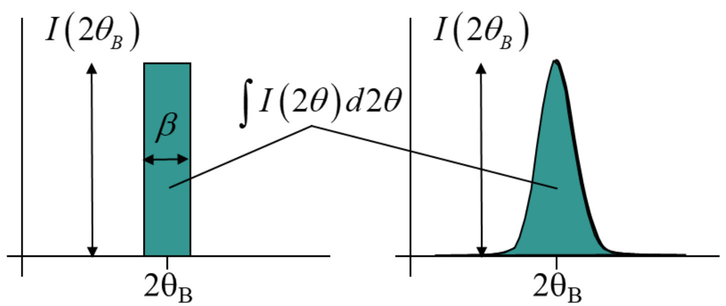
$$\beta \cdot \frac{\cos\theta_B}{\lambda} \cong \frac{K_\beta}{\Lambda} + 2\sqrt{\langle \varepsilon^2 \rangle} \cdot \frac{1}{d_B}$$

dimensione cristalliti

microstrain

Ampiezza integrale

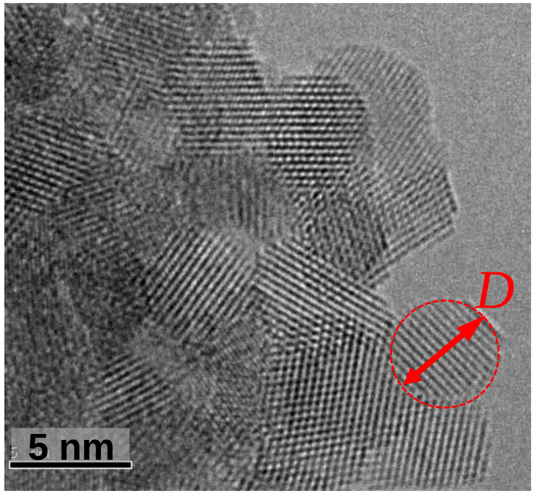
$$\beta = \frac{area\ del\ picco}{intensità\ massima} = \frac{\int I(2\theta)\,d2\theta}{I(2\theta_B)}$$

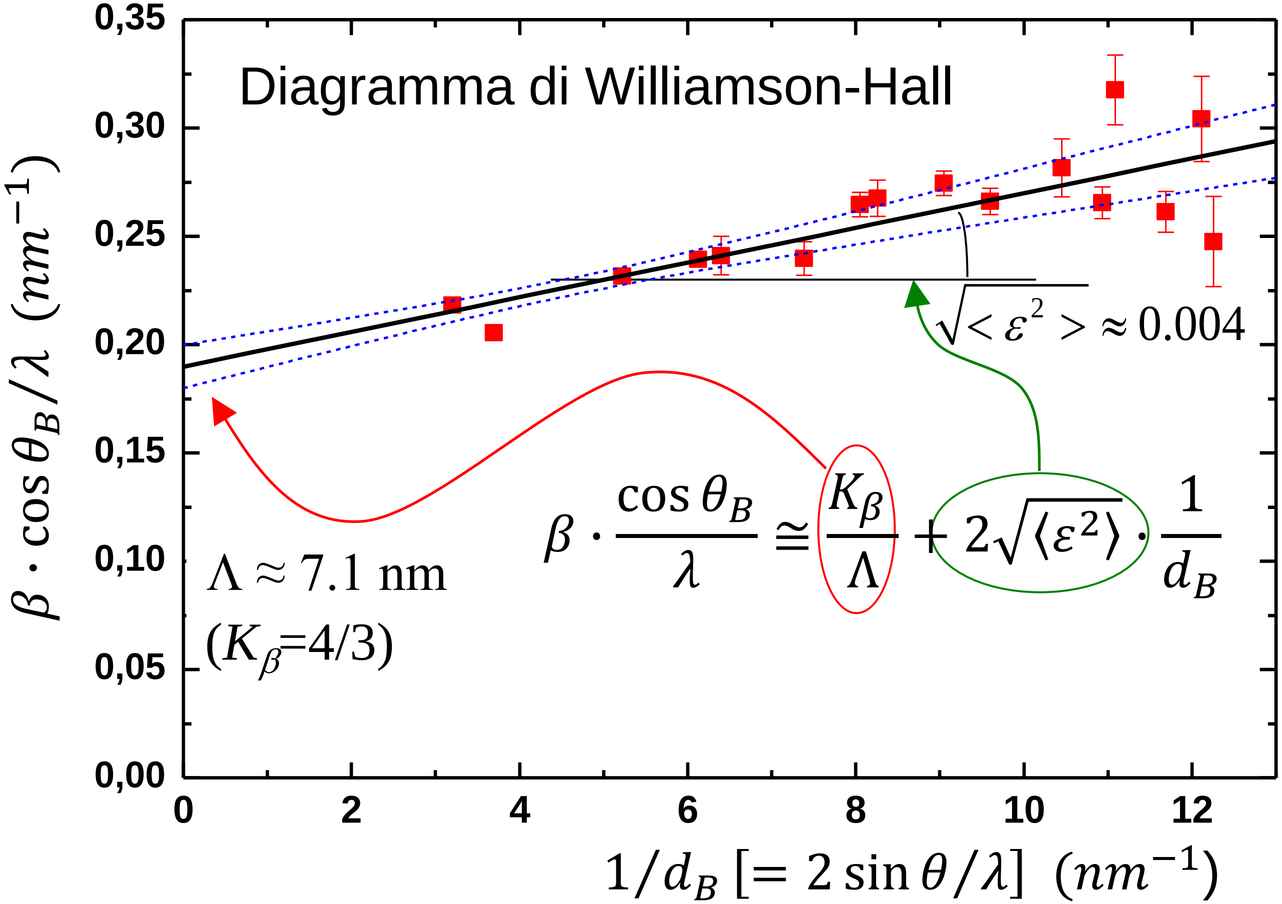


EFFETTO "SIZE – MICROSTRAIN" IN DIFFRAZIONE

Effetto combinato di dimensione (*size*) dei cristalliti e *microstrain*: una semplice approssimazione lineare

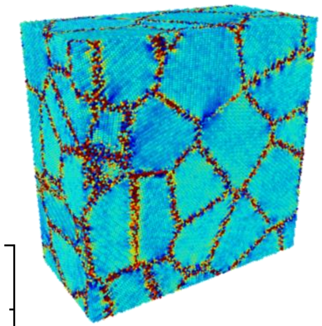
Intercetta (→ Λ) e pendenza (→ $\sqrt{\langle \varepsilon^2 \rangle}$)

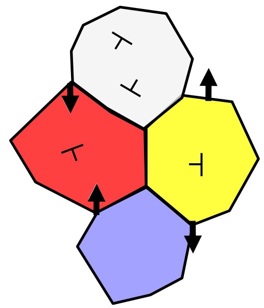




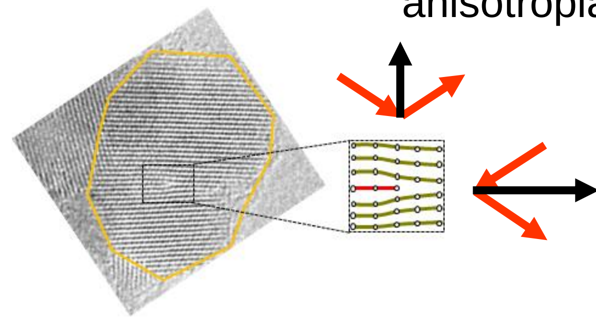
EFFETTO "SIZE – MICROSTRAIN" IN DIFFRAZIONE

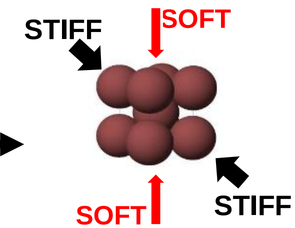
Macinazione ad alta energia di polvere di acciaio ferritico

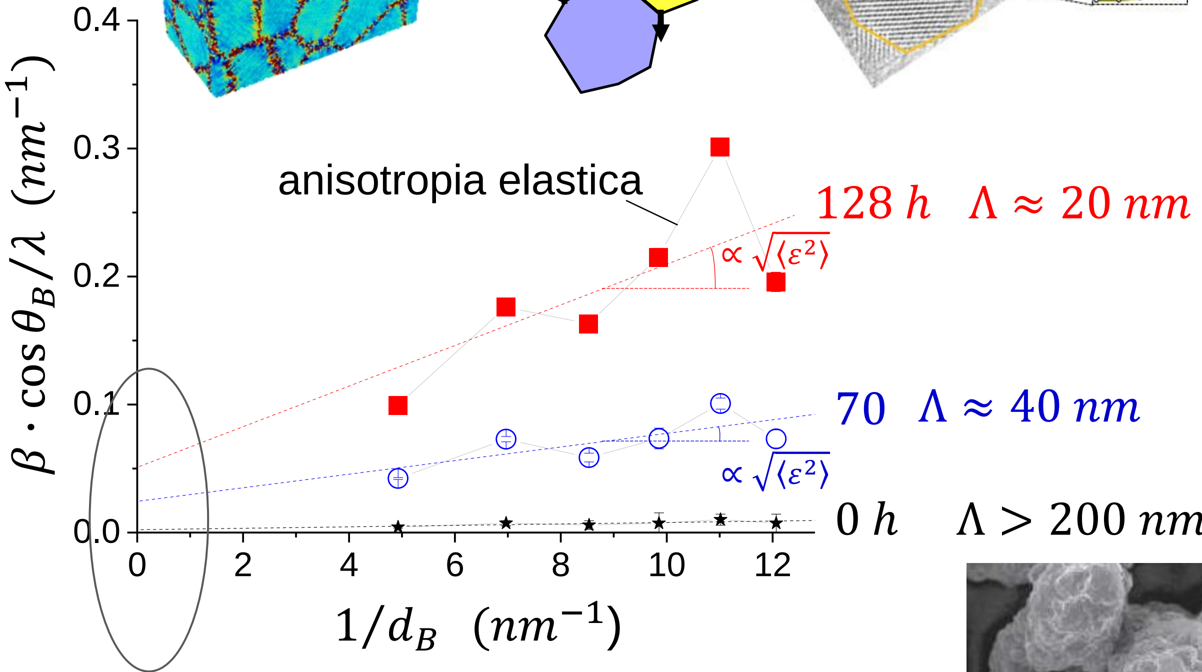


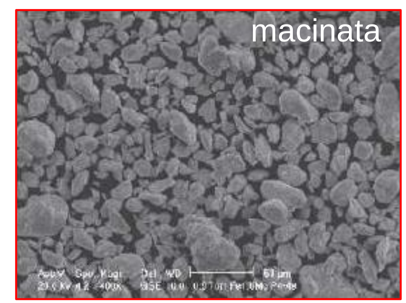


anisotropia elastica









$$\beta \cdot \frac{\cos\theta_B}{\lambda} \cong \frac{K_\beta}{\Lambda} + 2\sqrt{\langle\varepsilon^2\rangle} \cdot \frac{1}{d_B}$$

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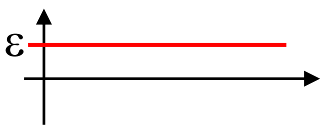
CONCLUSIONI

Macrostrain → spostamento dei picchi

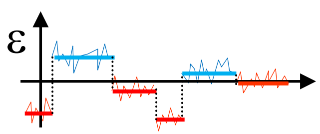
Microstrain → allargamento dei picchi

macrostrain

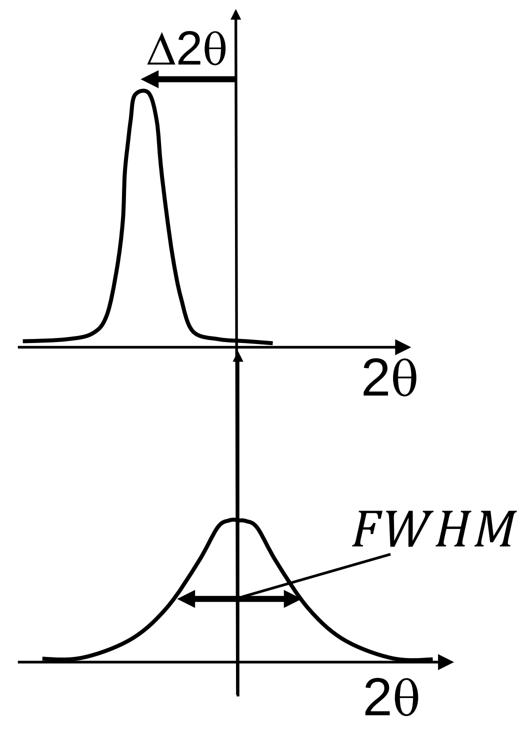


$$\Delta 2\theta = -2\varepsilon \tan\theta_B$$

microstrain



$$FWHM \cong \frac{0.94\,\lambda}{\Lambda \cos\theta_B} + 2e\tan\theta_B$$



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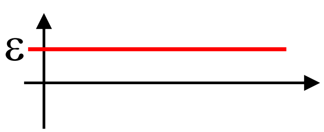
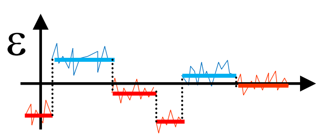
macrostrain



$$\Delta 2\theta = -2\varepsilon \tan\theta_B$$

+

microstrain



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