

**SPring-8金属材料評価研究会 (第3回:ひずみ・応力分布測定の新手法)**

# **放射光X線応力測定の 基礎と実用例**

**新潟大学 鈴木賢治**

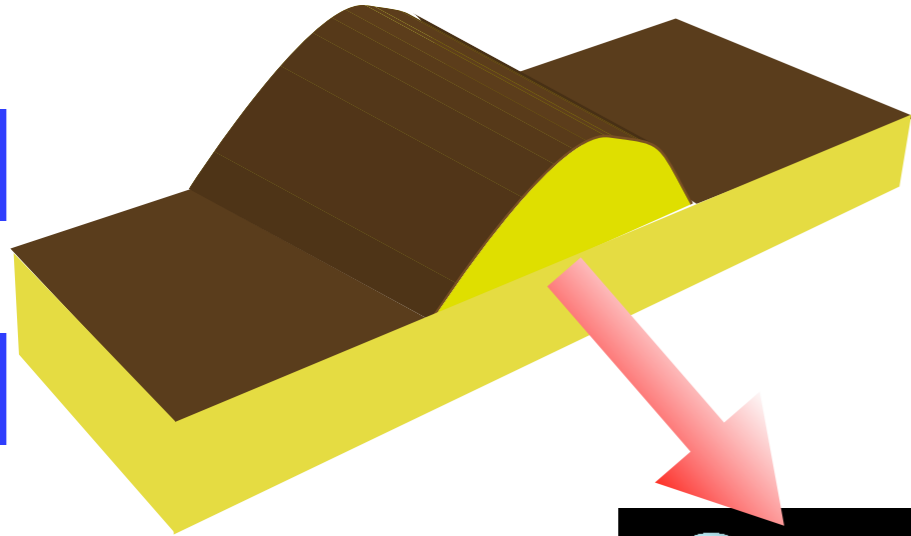
2010/8/26

SPring-8金属材料評価研究会 (第3回:ひずみ・応力分布測定の新手法)

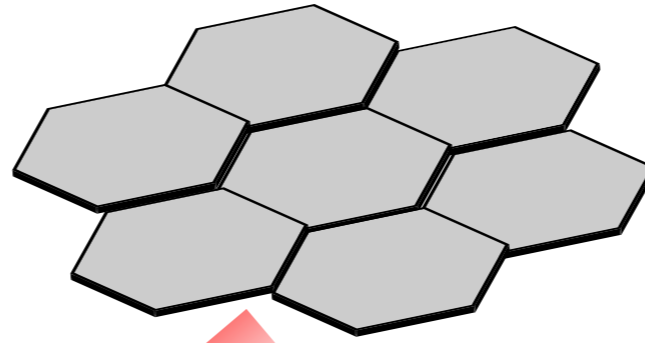
ゆうぼうと 7F 福寿 (技術交流会 : 7F 末広)

# 1. 新しい光源 シンクロトロン放射光, 中性子

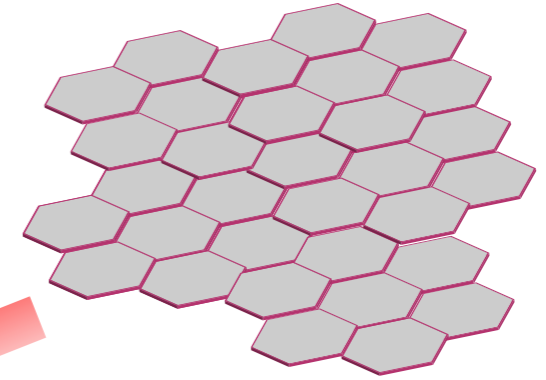
溶接



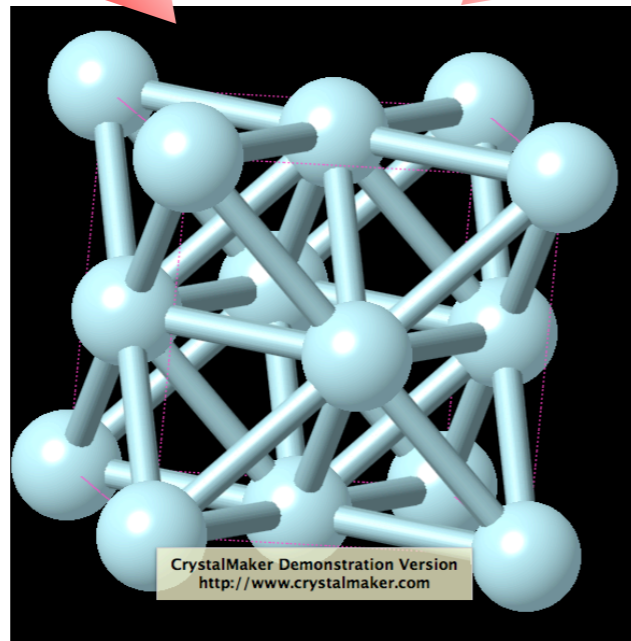
粗大粒



均質等方多結晶体



結晶



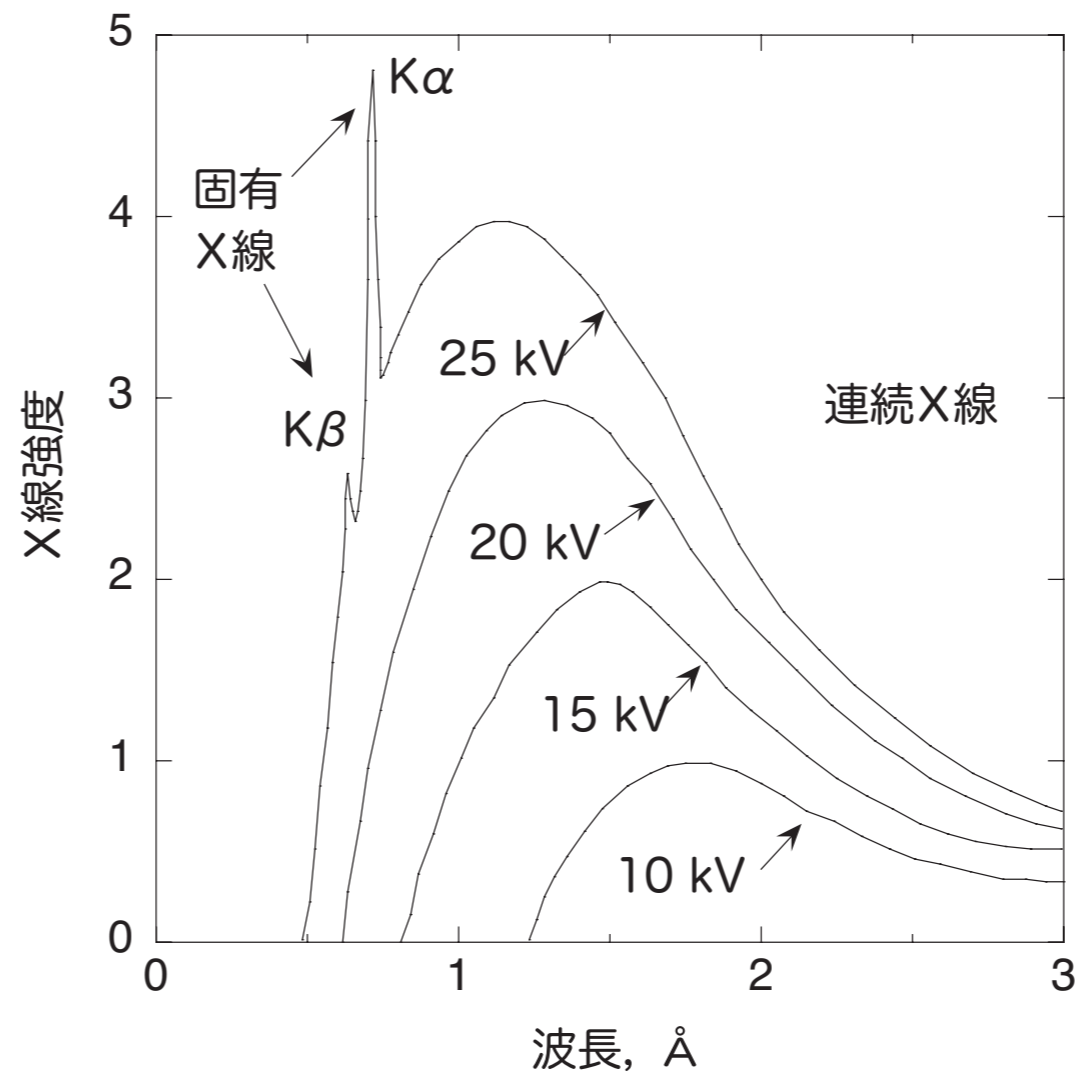
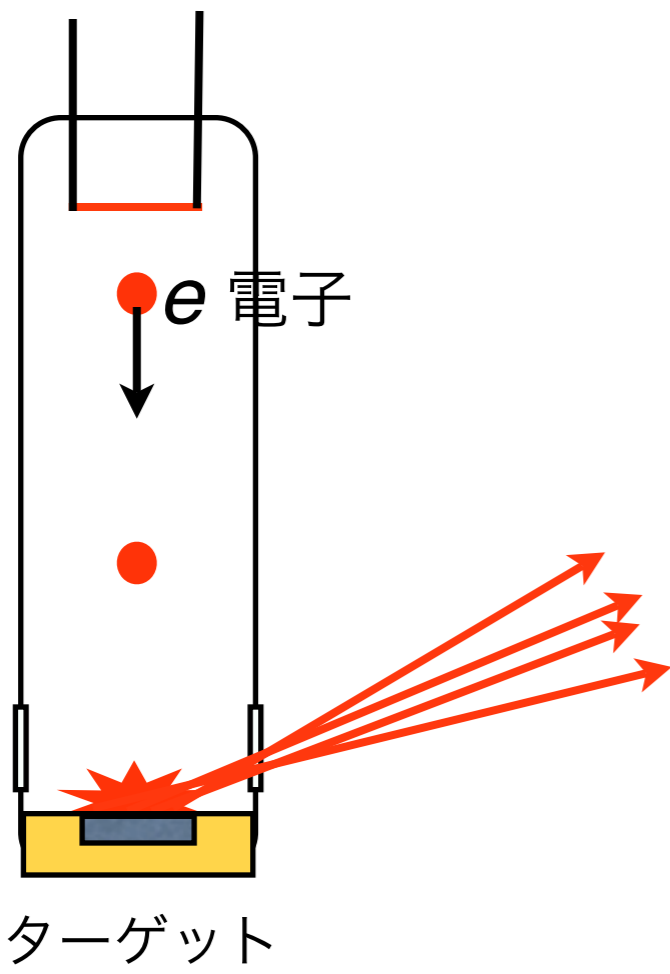
格子間距離

高エネルギー放射光, 2次元検出器

X線応力測定

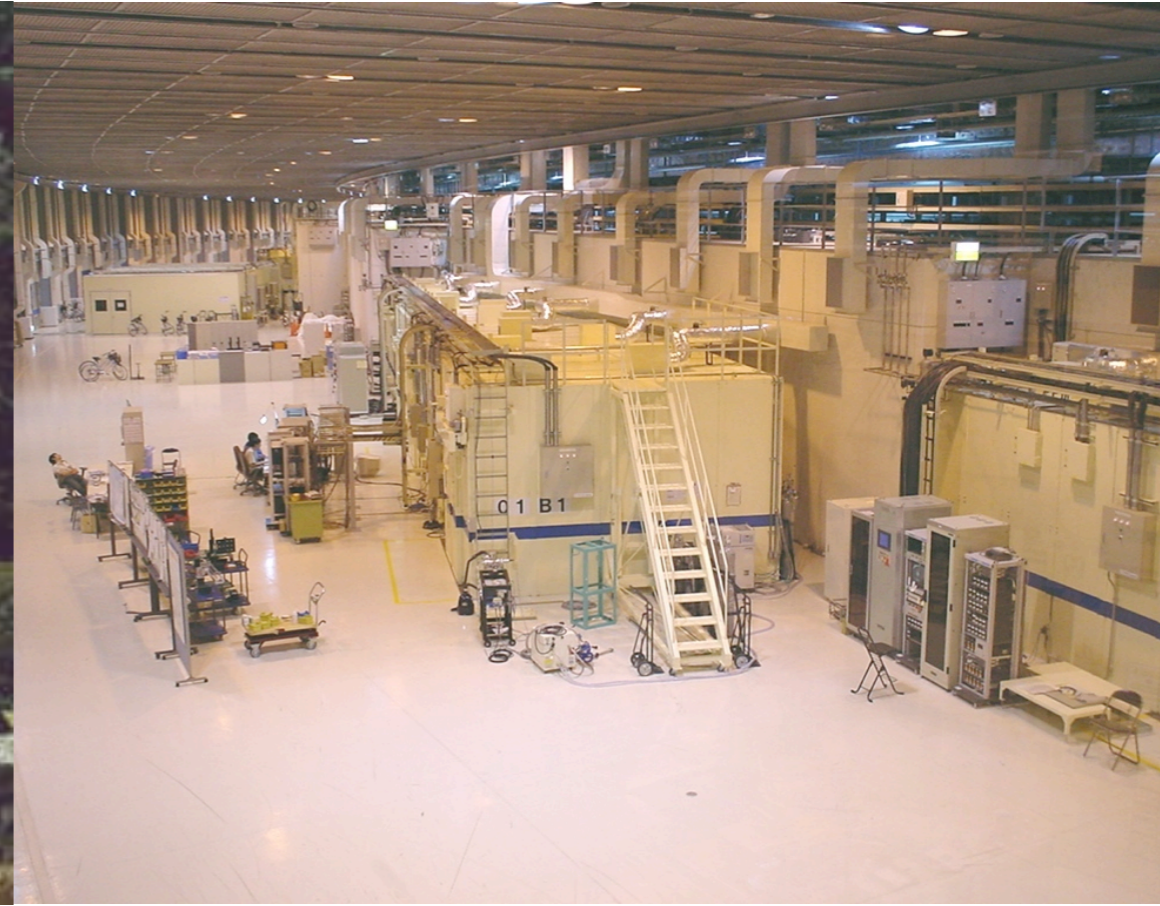


# ラボ X 線 X 線管球



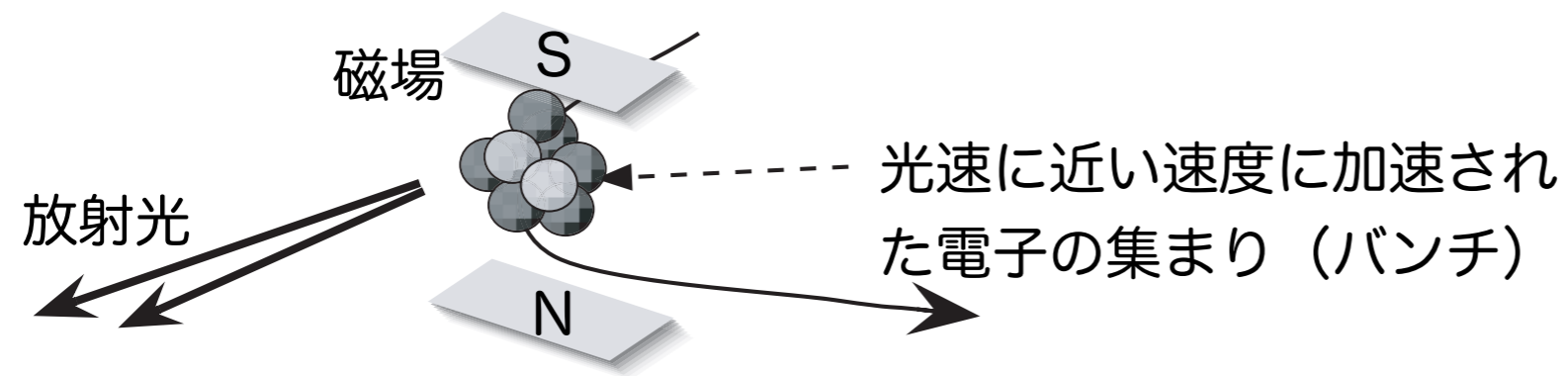
波長分布 (ノイズ)  
低強度  
指向性悪い

# シンクロトロン放射光

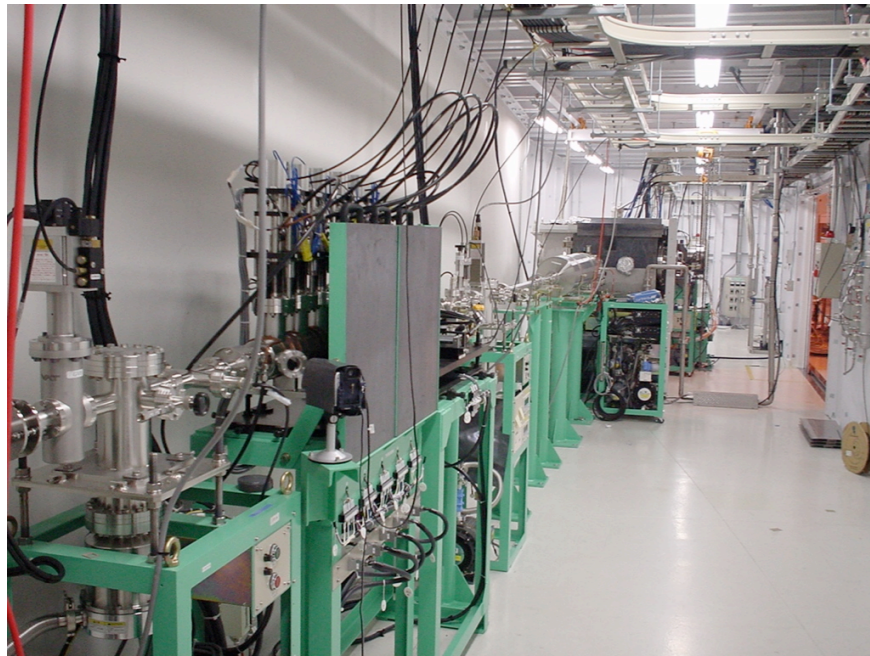


SPring-8 全景

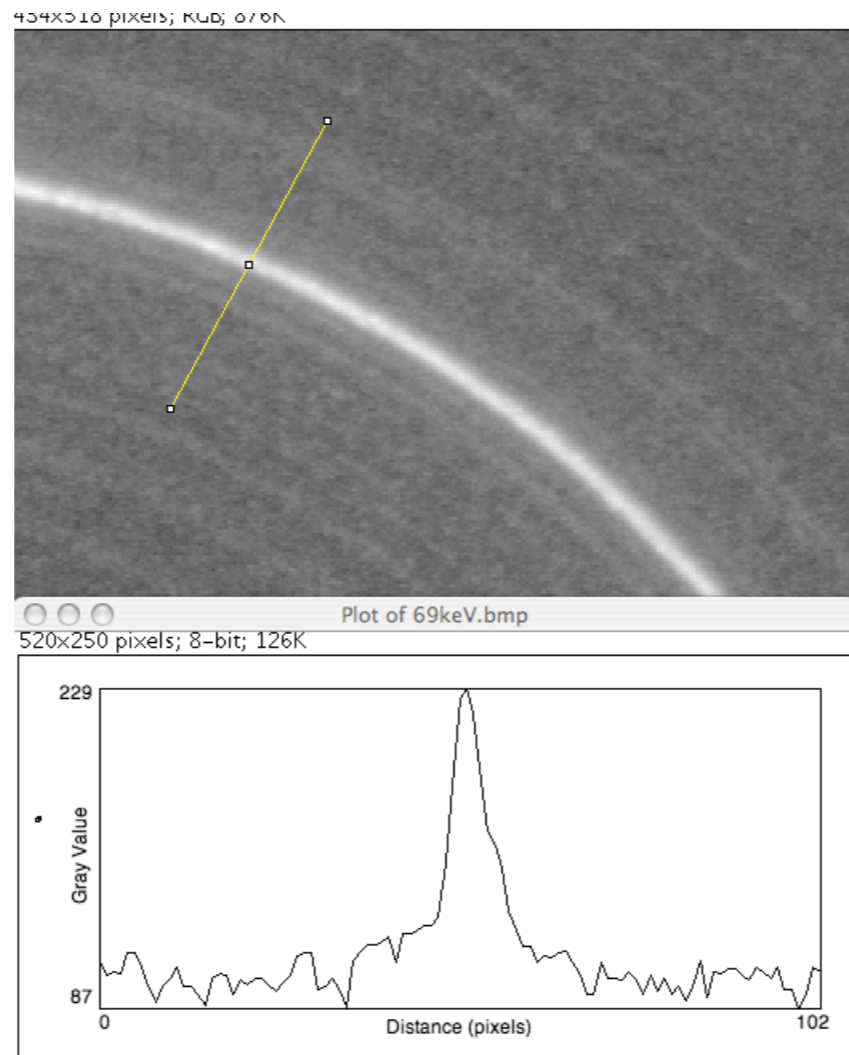
SPring-8の実験ハッチ



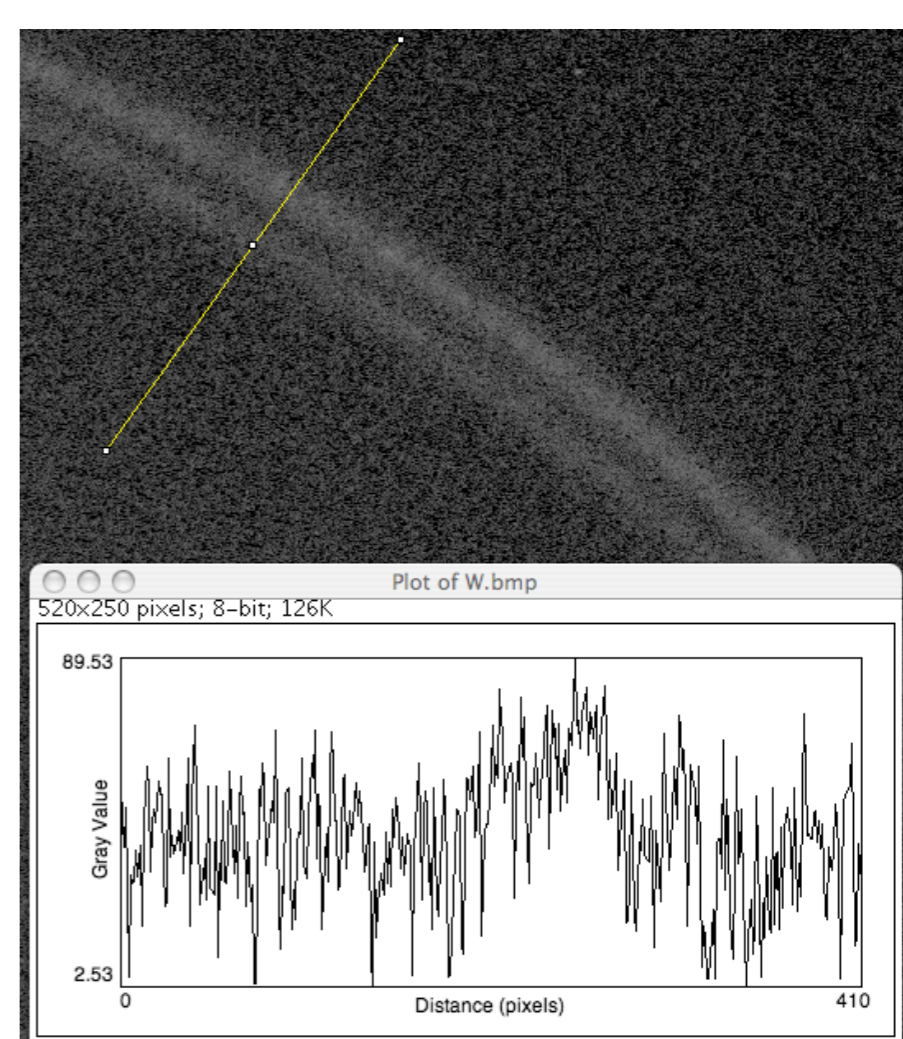
# 放射光の調整



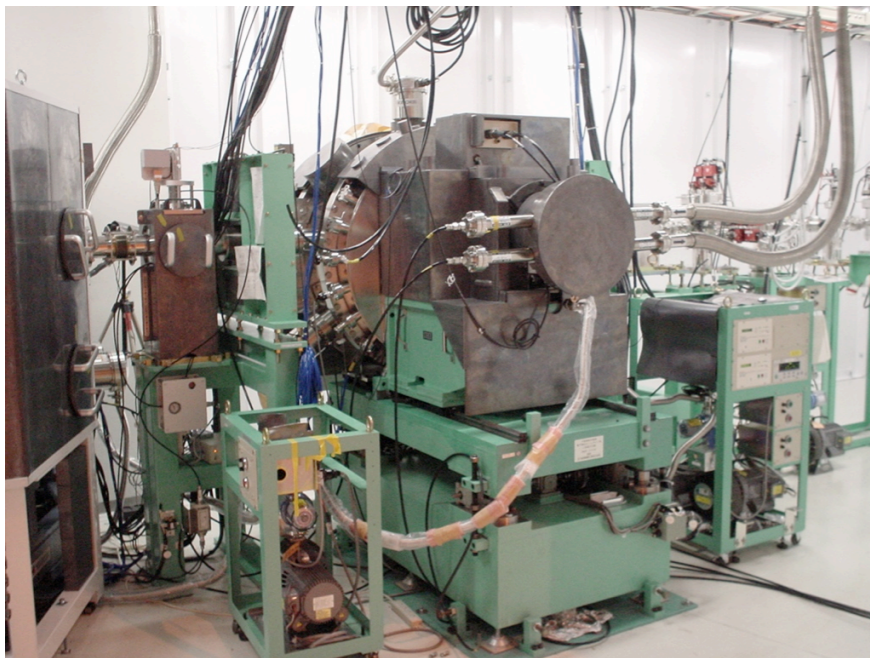
光学ハッチ



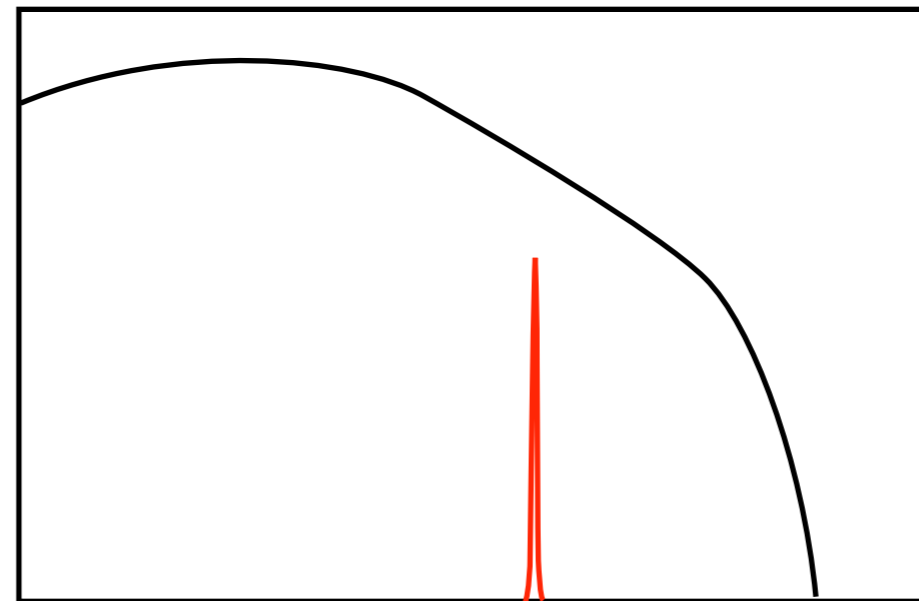
放射光



ラボX線

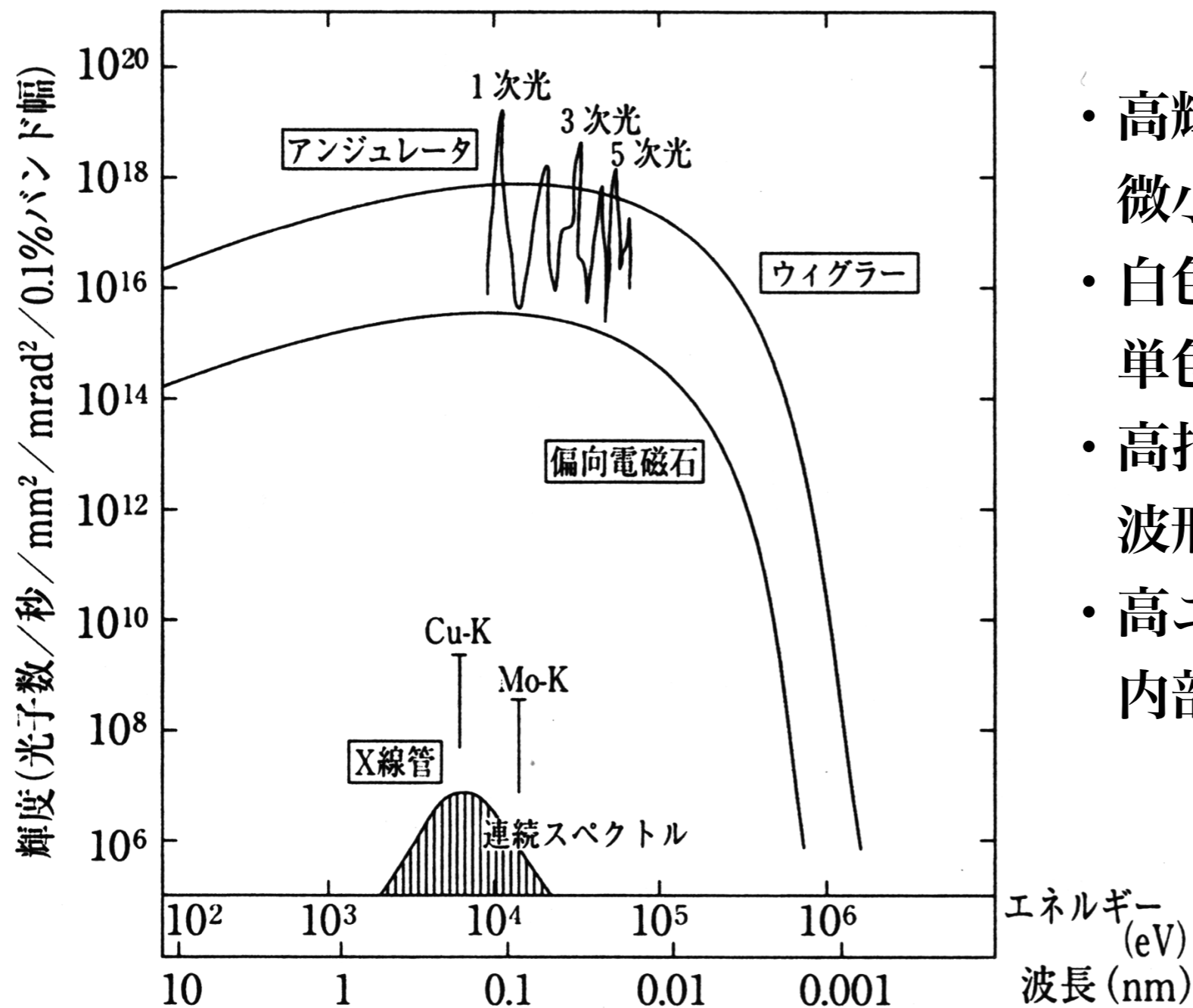


分光器



分光器による単色化

# SPring-8 (Super Photon Ring 8 GeV)



- 高輝度光  
微小領域, 薄膜
- 白色X線  
単色X線, エネルギー分散法
- 高指向性  
波形分離, 測定精度
- 高エネルギーX線  
内部応力

# 中性子



# ド・ブロイ波

$$\lambda = \frac{h}{mv} = \frac{395.6}{v \text{ [m/s]}} \text{ [nm]}$$

中性子もその速度に応じて波動として振る舞う。

中性子源として、

- 核分裂による中性子=原子炉
- 核破砕による中性子=高強度陽子加速器



J-PARC

# X線, 放射光および中性子の侵入深さ

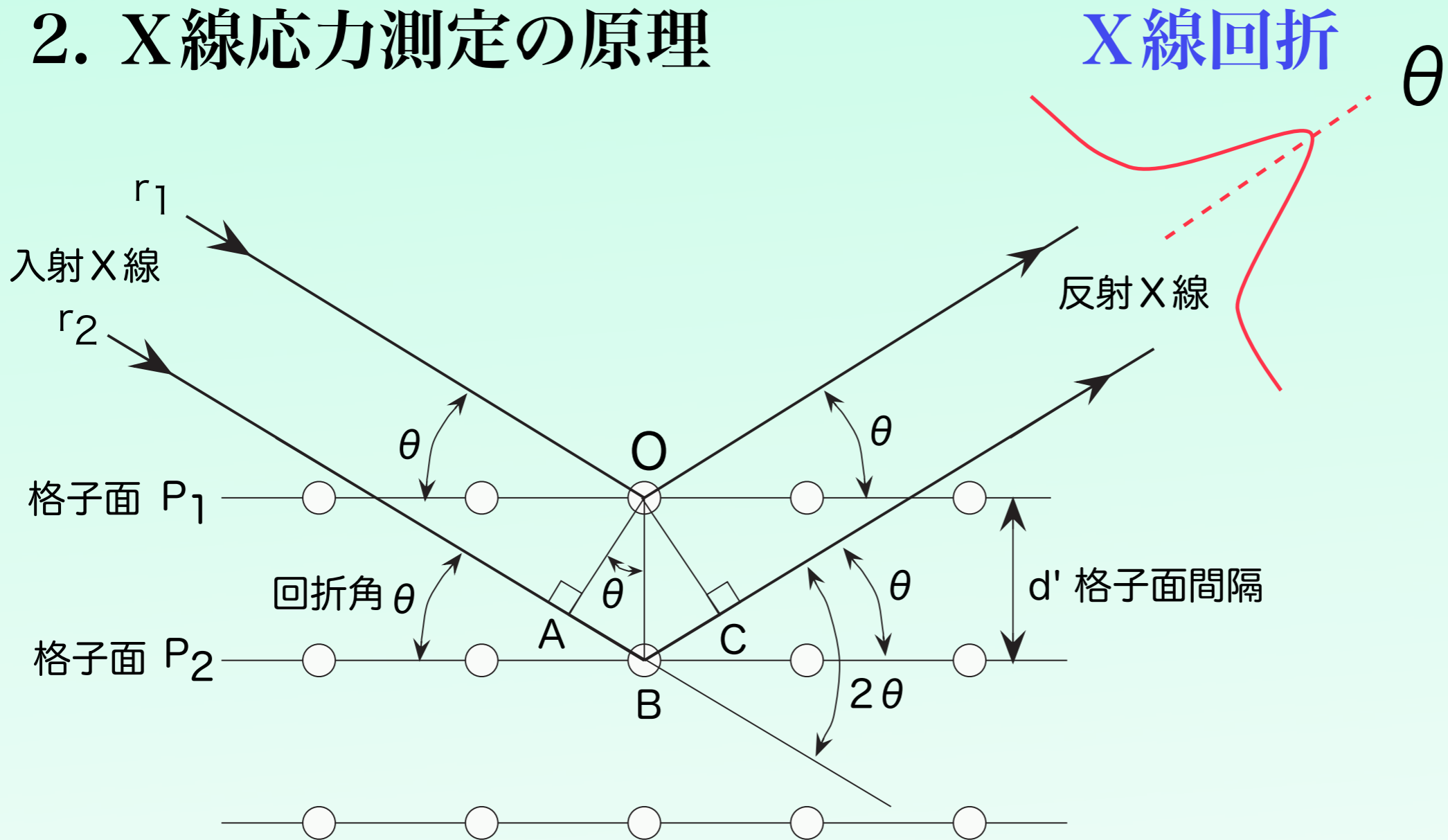
光源, keV	対象材料中への減衰距離, mm				
	Al	Ti	Fe	Ni	Cu
Cu- $K\alpha$ (8)	0.074	0.011	0.004	0.023	0.022
放射光 (40)	6.5	1.0	0.35	0.24	0.23
放射光 (70)	15.4	3.8	1.4	1.0	1.3
放射光 (150)	27	13	6	5	5
熱中性子	1230	50	85	40	53

表面から内部=高エネルギー放射光

深部の応力=中性子回折



## 2. X線応力測定の実理



$$AB = d \sin \theta$$

$$\text{光路差} = AB + BC = 2 d \sin \theta$$

波長:  $\lambda$

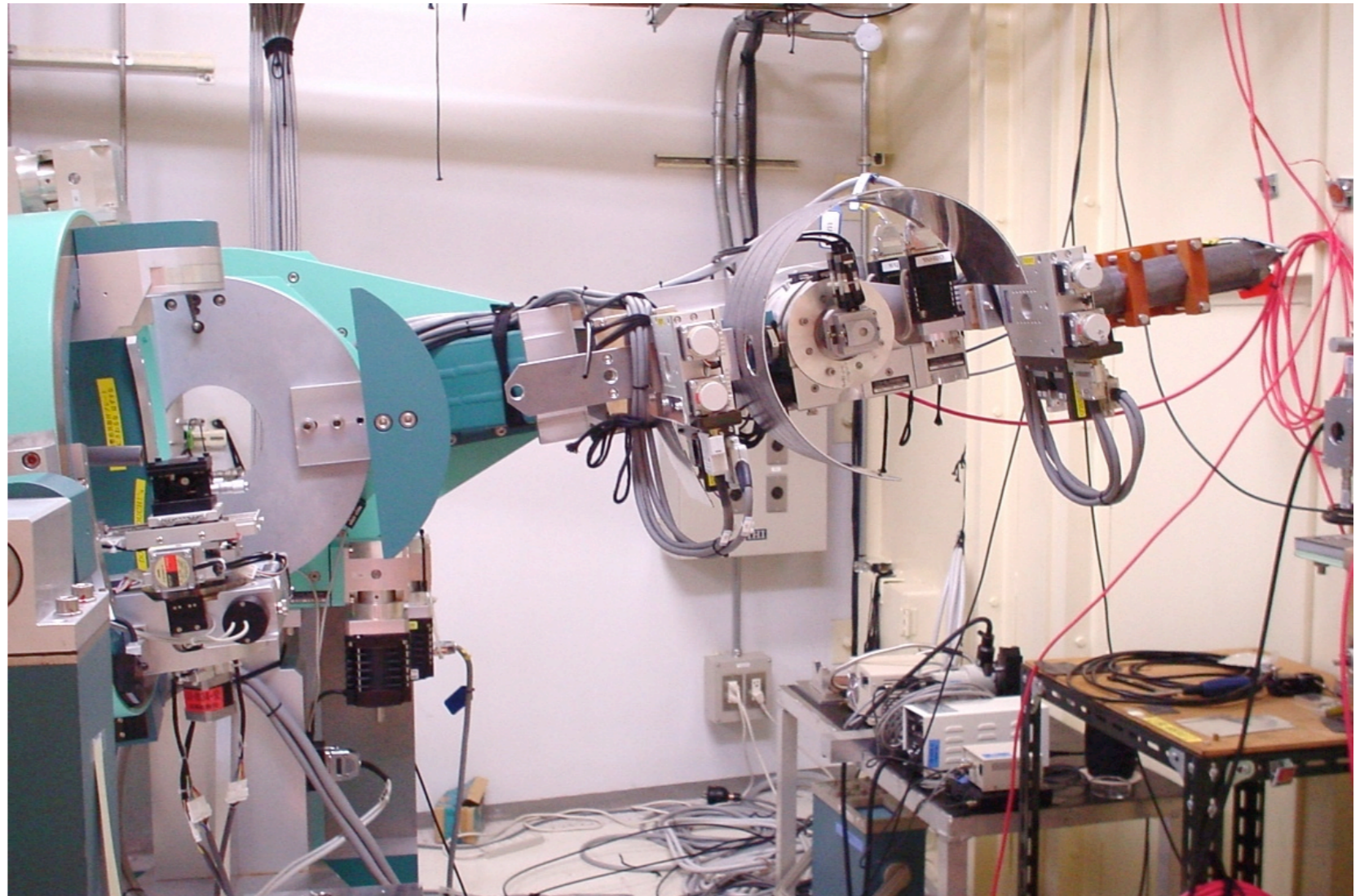
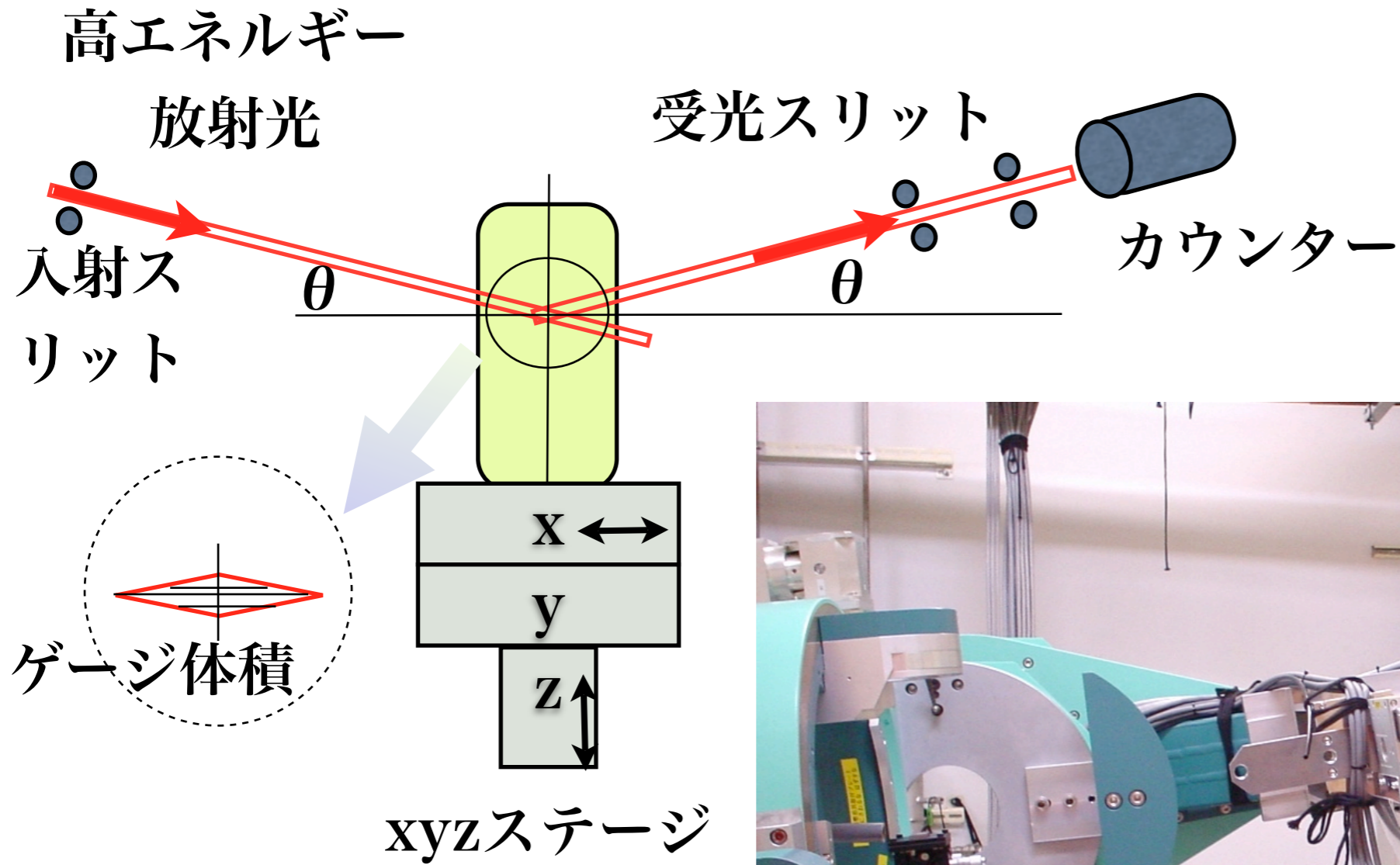
$$\lambda = 2 d \sin \theta \quad (\text{ブラッグ条件})$$

$$\text{格子面間隔} \quad d = \lambda / 2 \sin \theta$$

$$\varepsilon = (d - d_0) / d_0$$

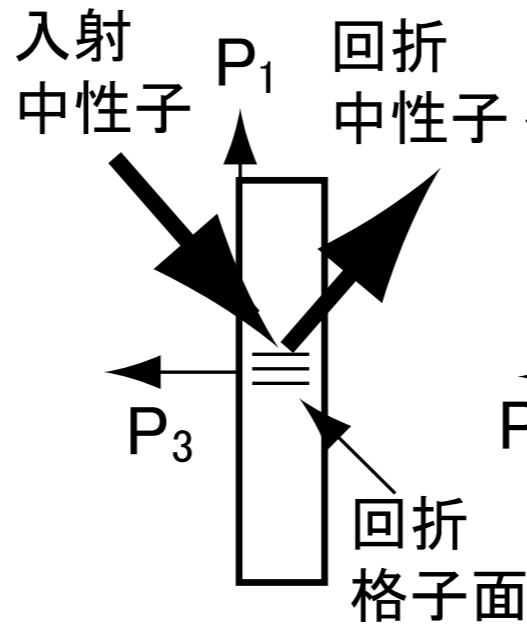
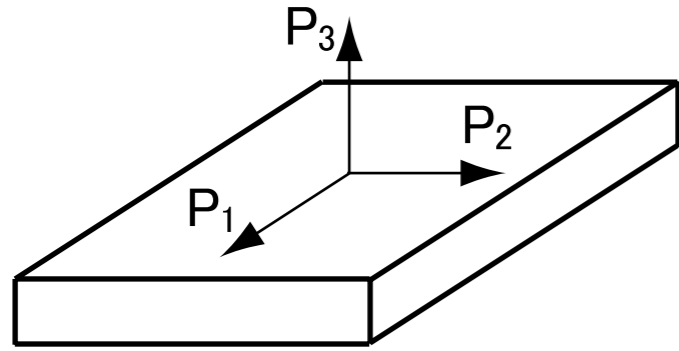
$d_0$ : 無ひずみの回折角

# 3. ひずみスキャニング法

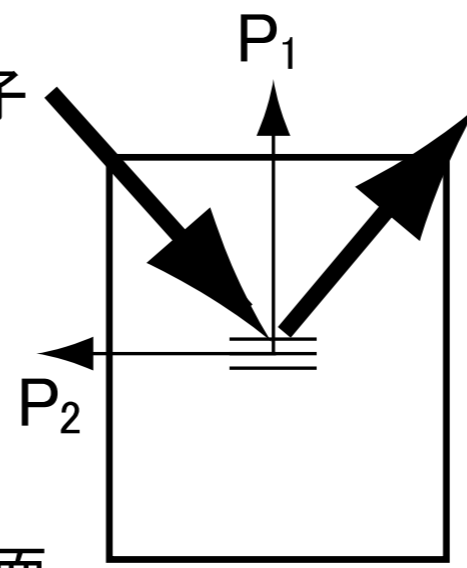


BL46XU in SPring-8

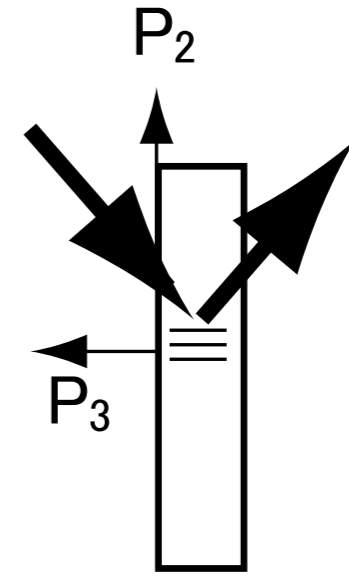
# 3軸応力測定



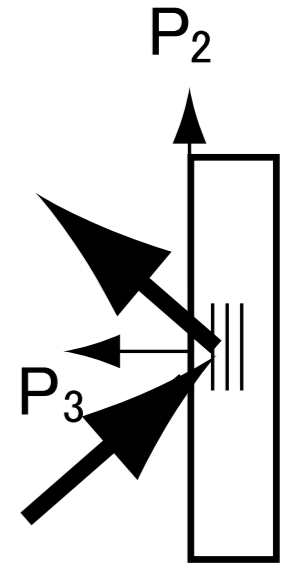
$\epsilon_1$  測定



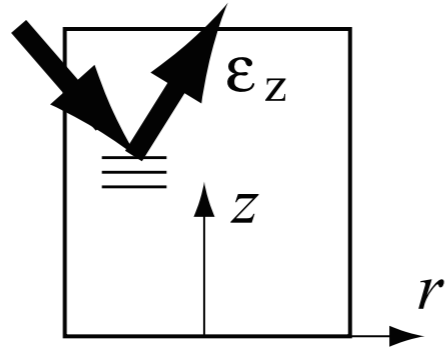
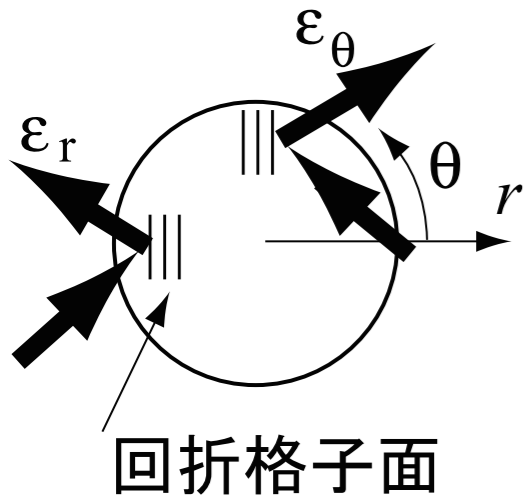
$\epsilon_1$  測定



$\epsilon_2$  測定



$\epsilon_3$  測定



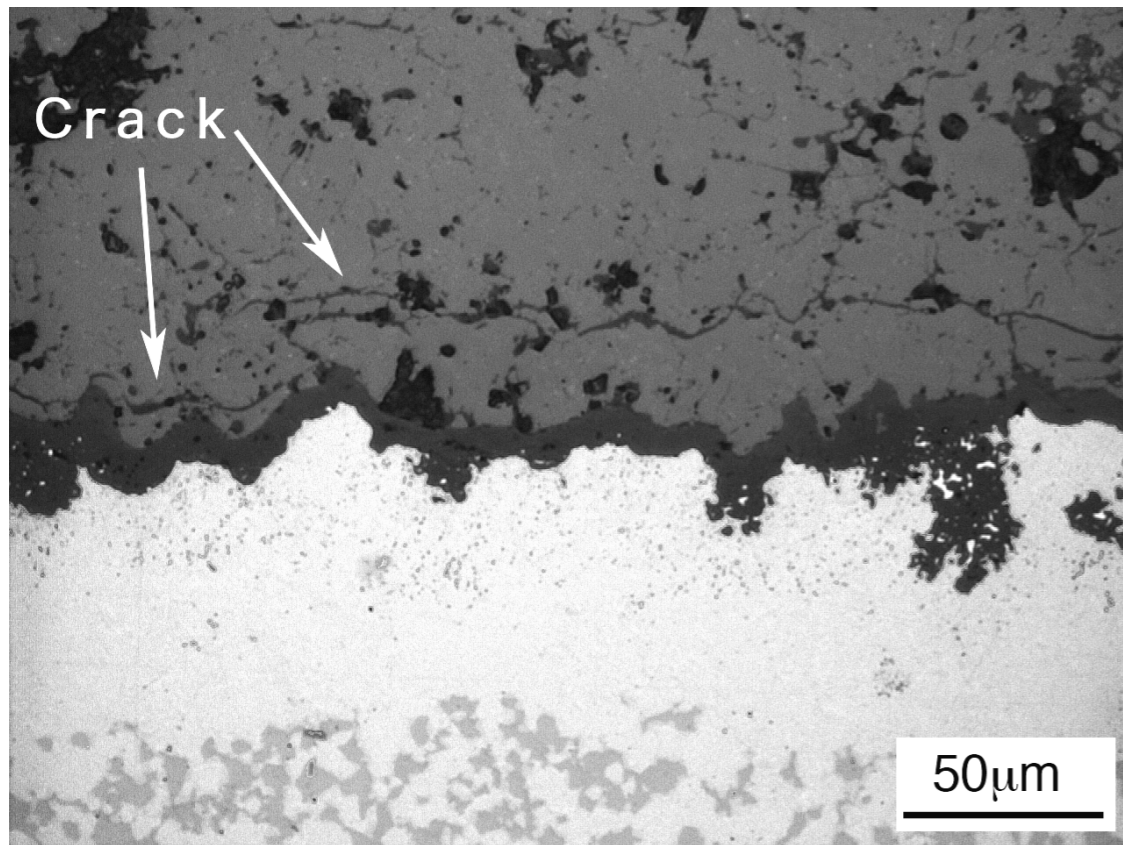
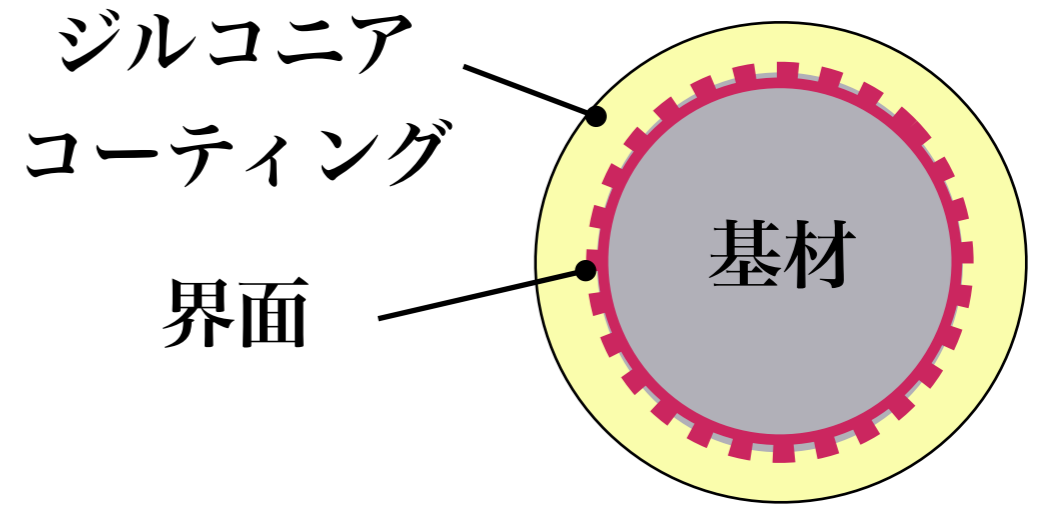
$$\sigma_x = \frac{E}{1+\nu} \left[ \epsilon_x + \frac{\nu}{1-2\nu} (\epsilon_x + \epsilon_y + \epsilon_z) \right]$$

$$\sigma_y = \frac{E}{1+\nu} \left[ \epsilon_y + \frac{\nu}{1-2\nu} (\epsilon_x + \epsilon_y + \epsilon_z) \right]$$

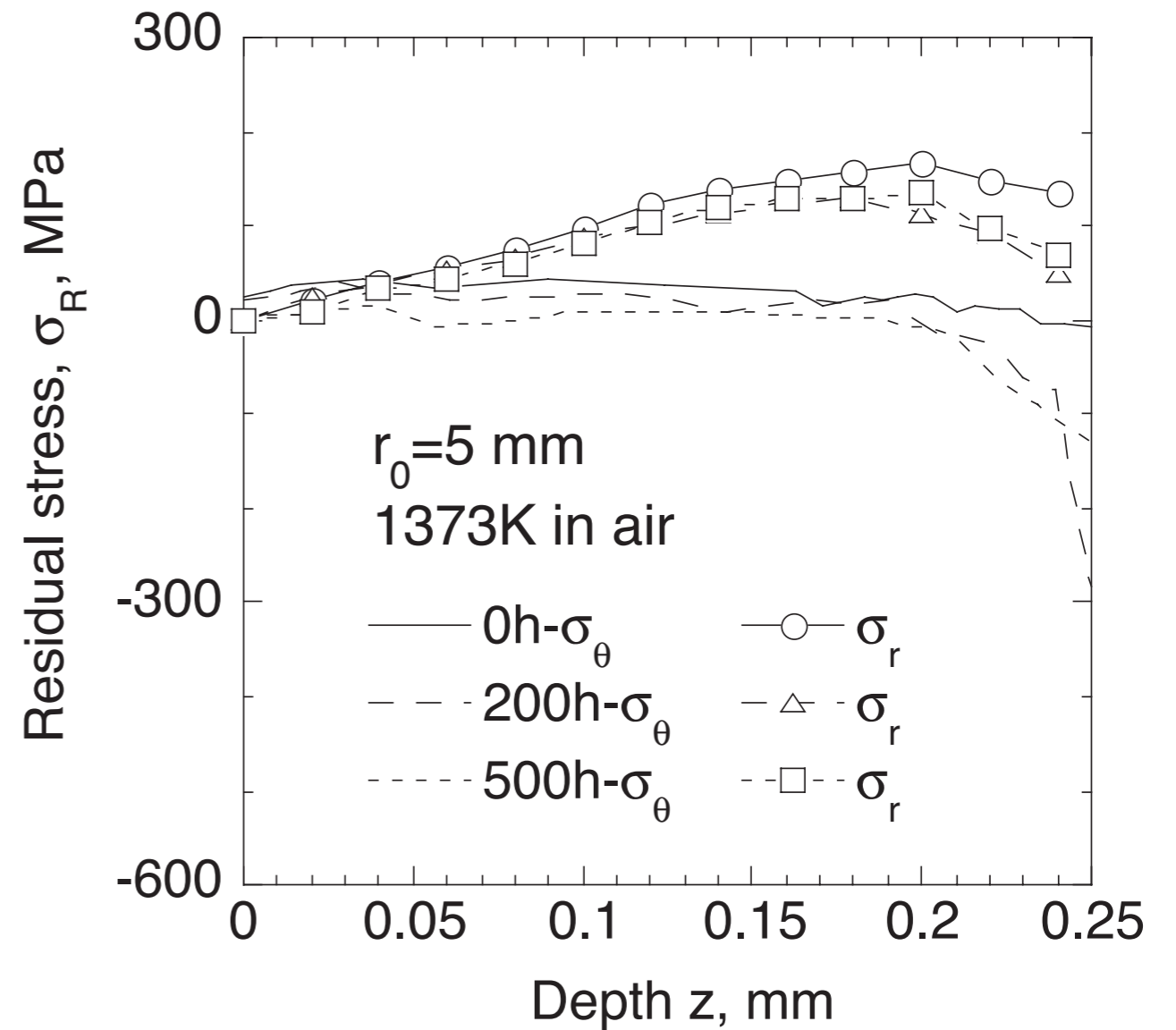
$$\sigma_z = \frac{E}{1+\nu} \left[ \epsilon_z + \frac{\nu}{1-2\nu} (\epsilon_x + \epsilon_y + \epsilon_z) \right]$$

# ひずみスキャンニング測定例

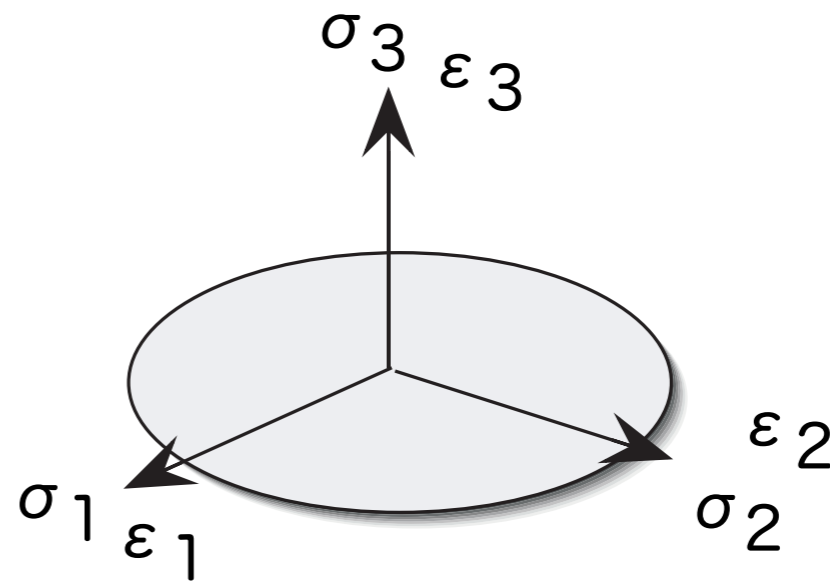
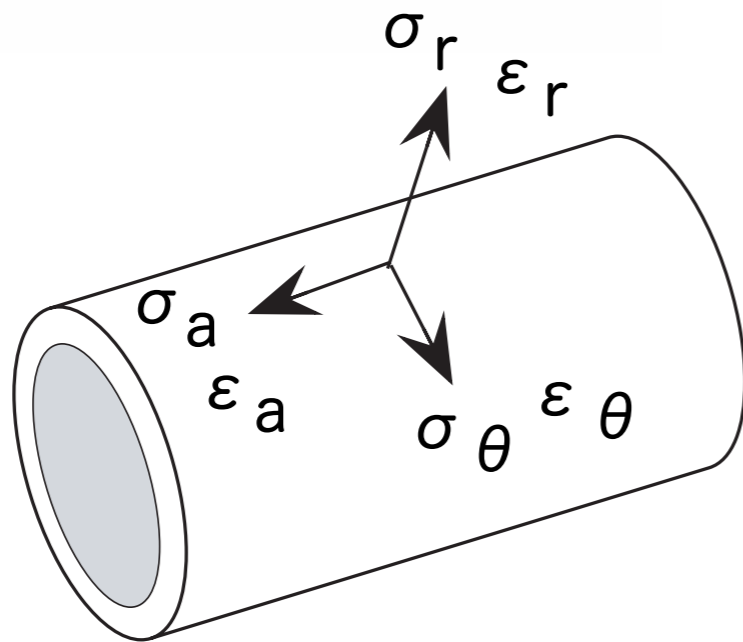
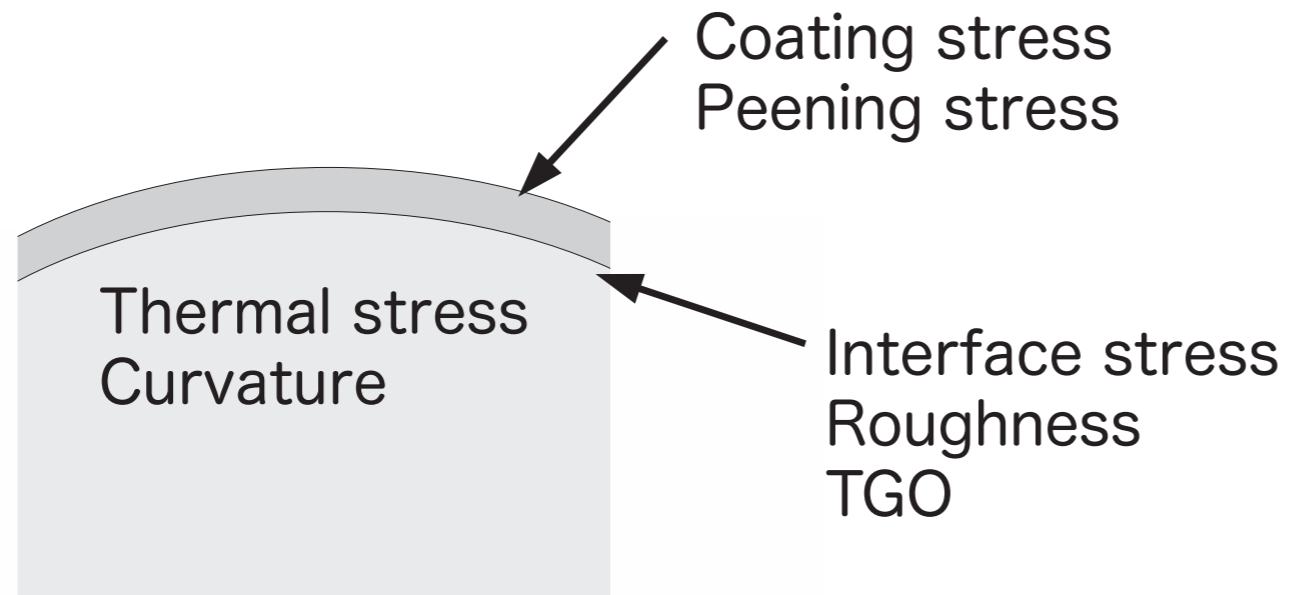
プラズマ溶射遮熱コーティング



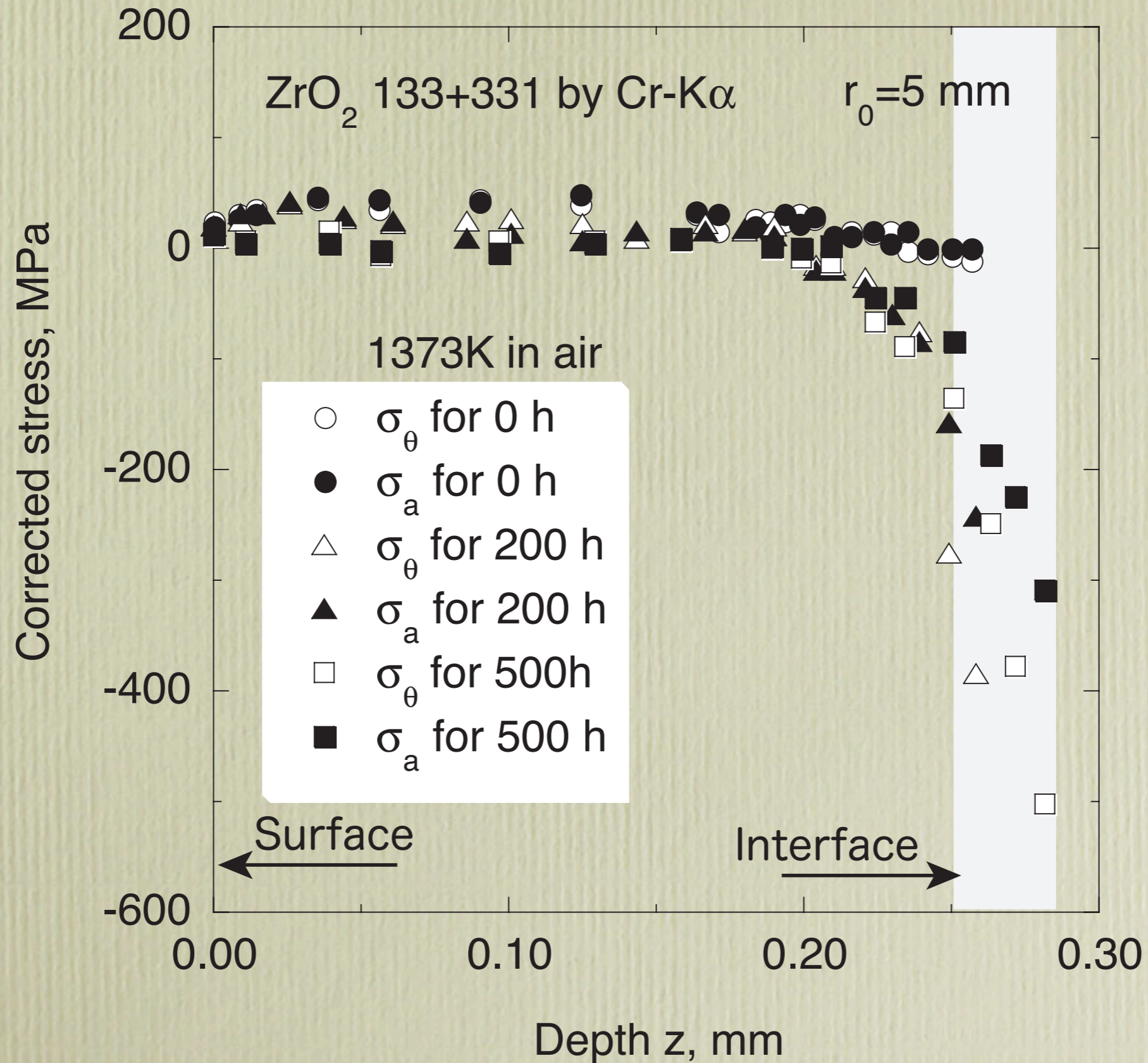
1373K, 500h



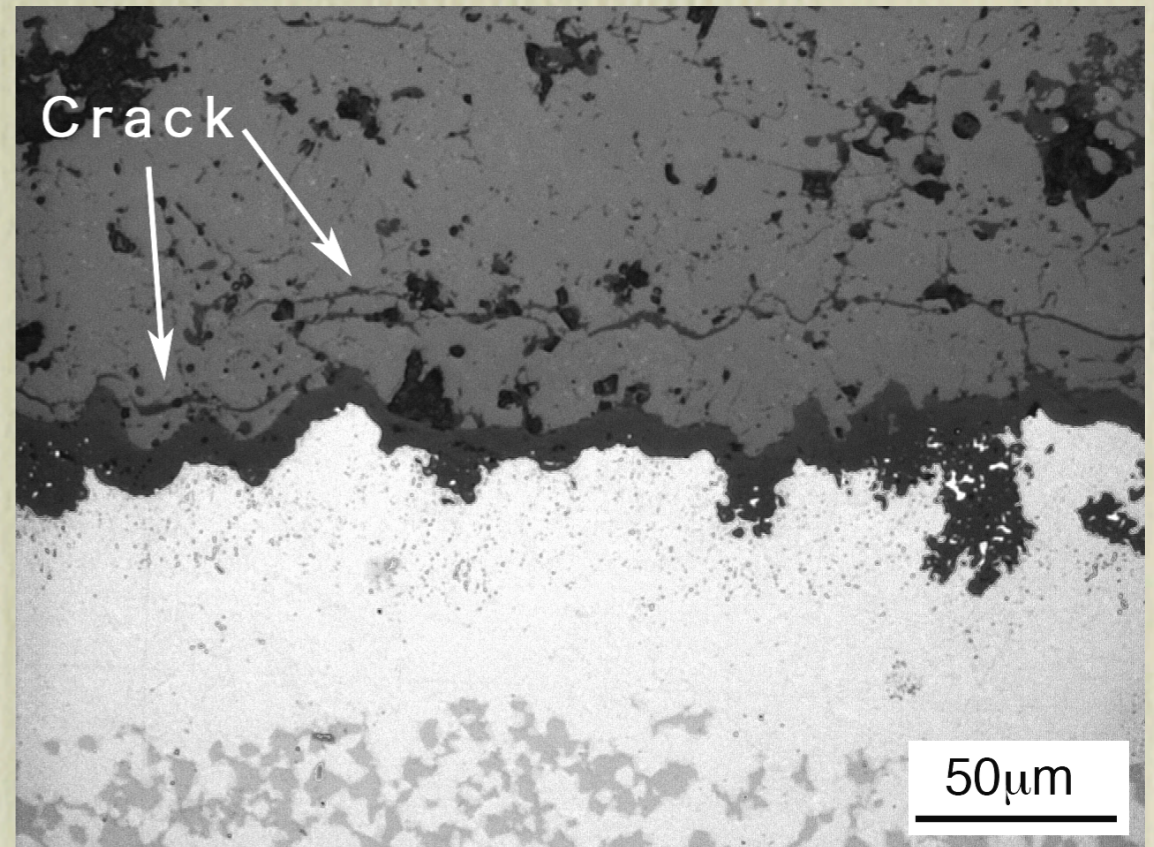
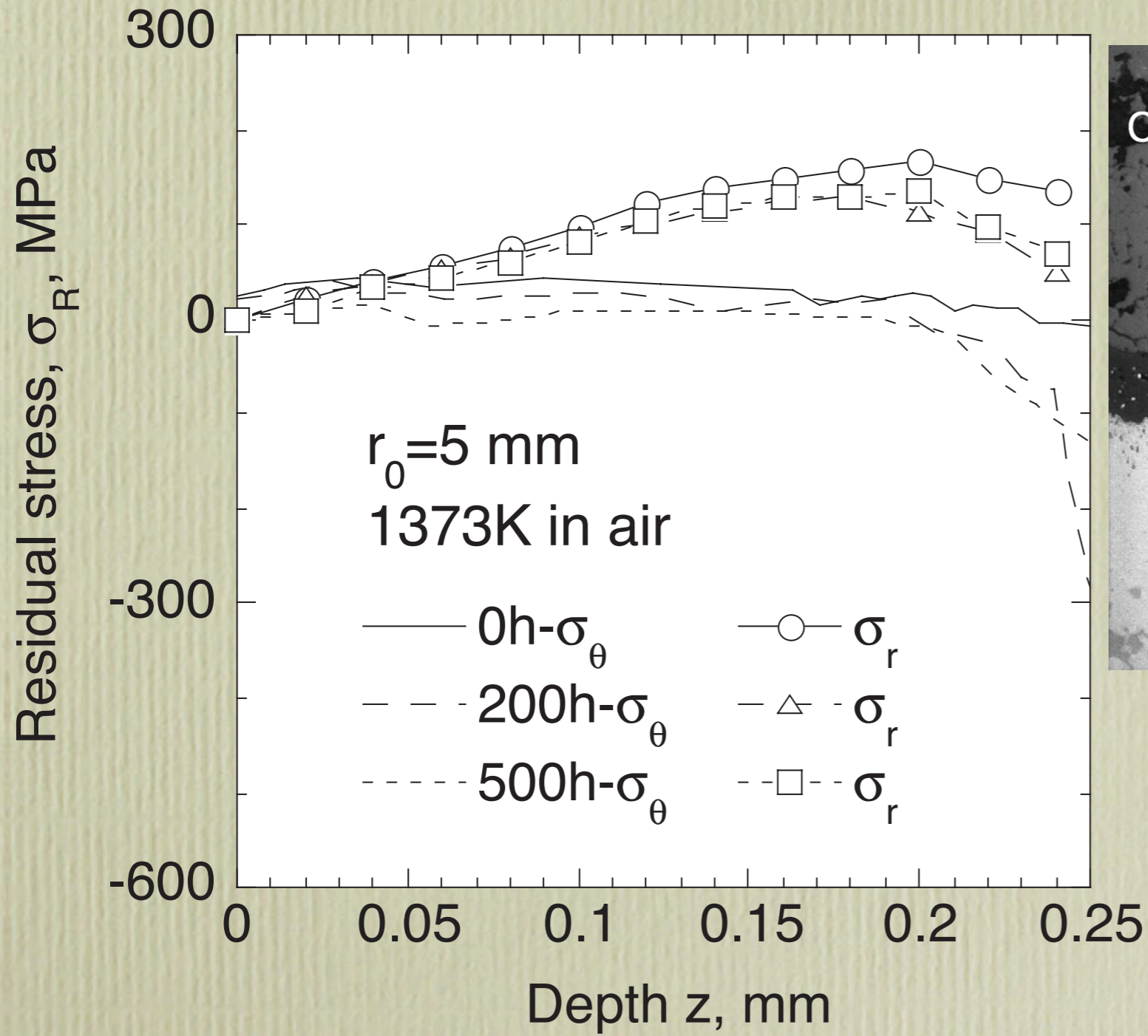
# プラズマ溶射遮熱コーティングコーティング



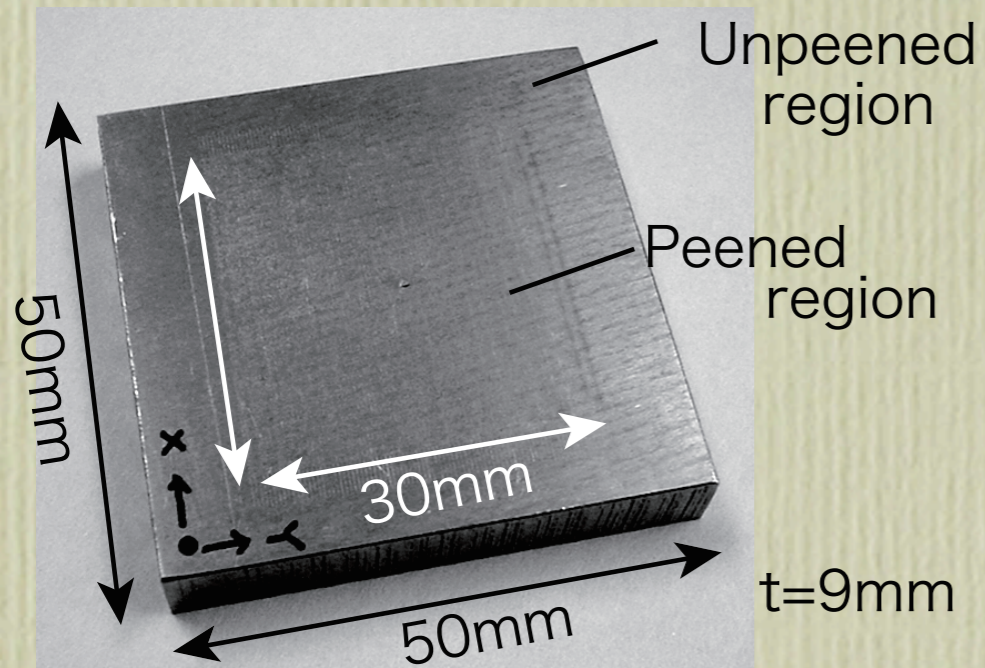
# TBC残留应力分布



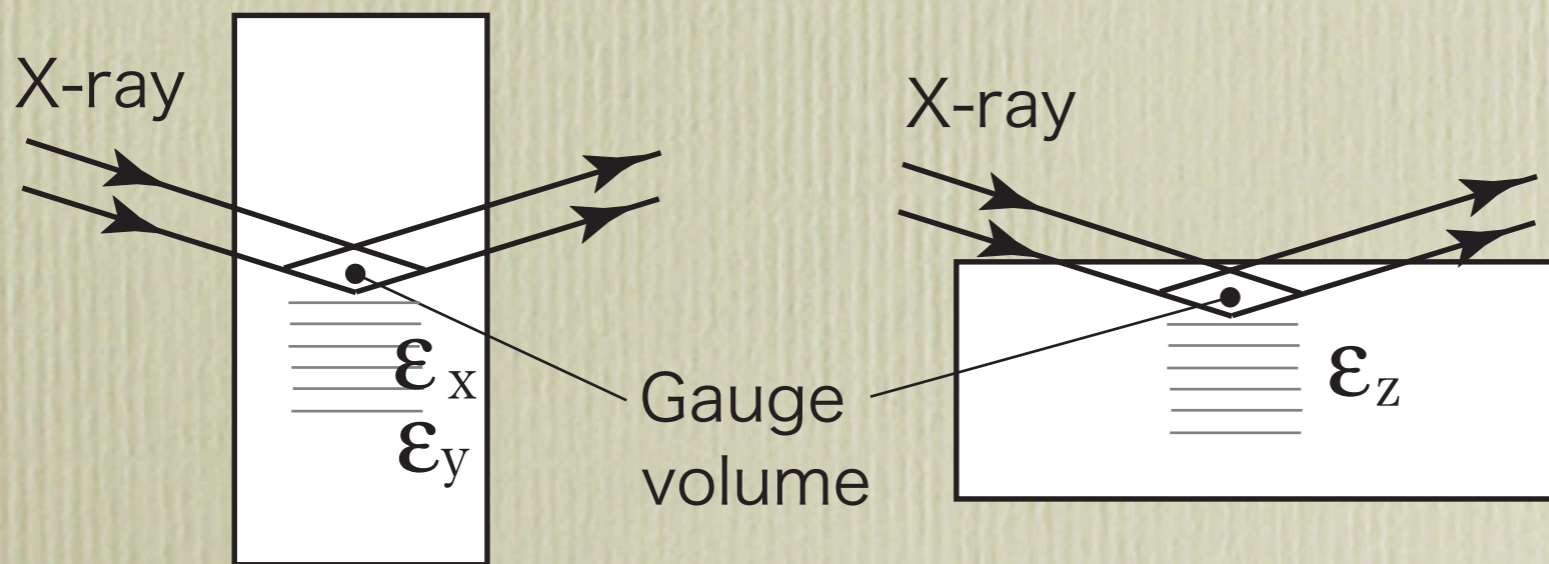
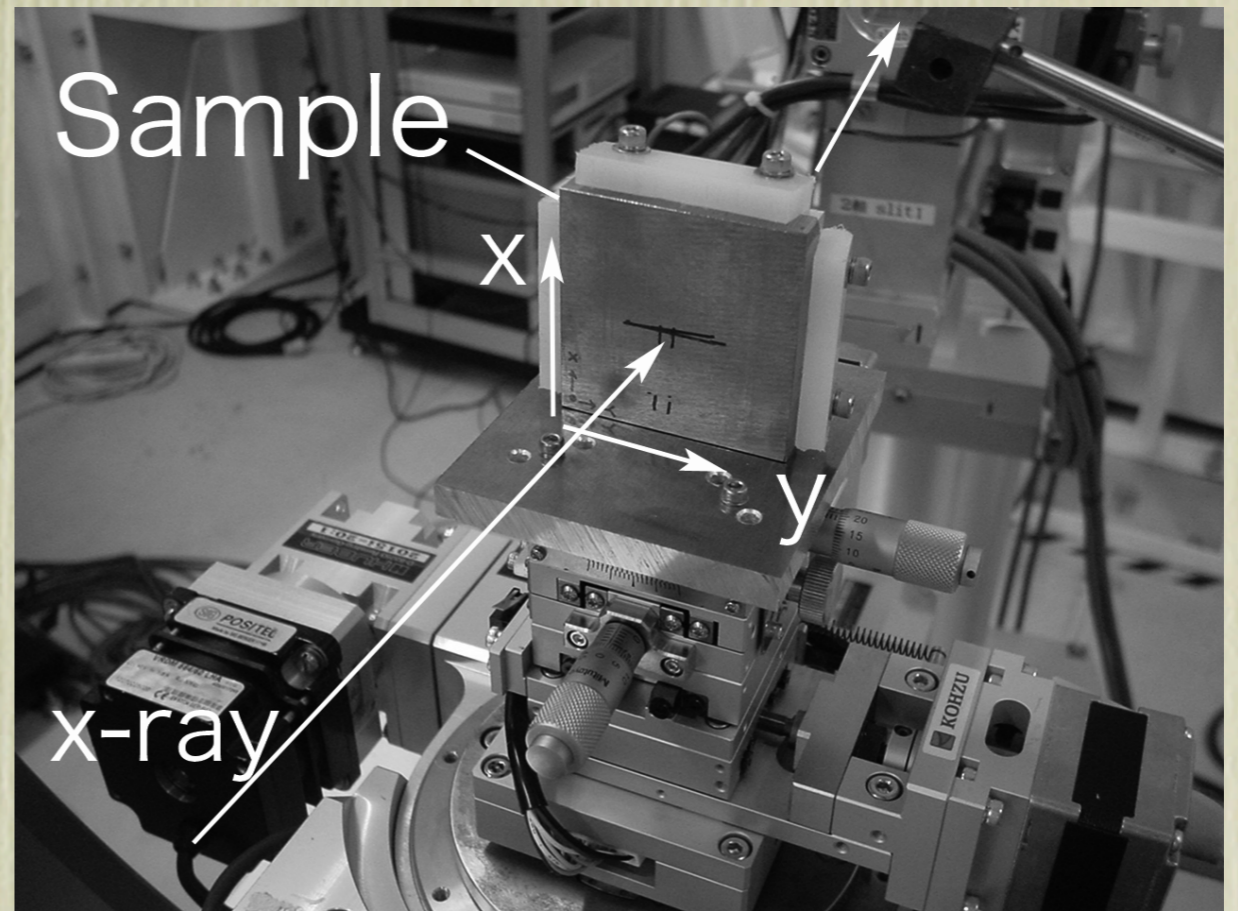
# はく離応力



# レーザーショックピーニングの残留応力分布



Ti6Al4V

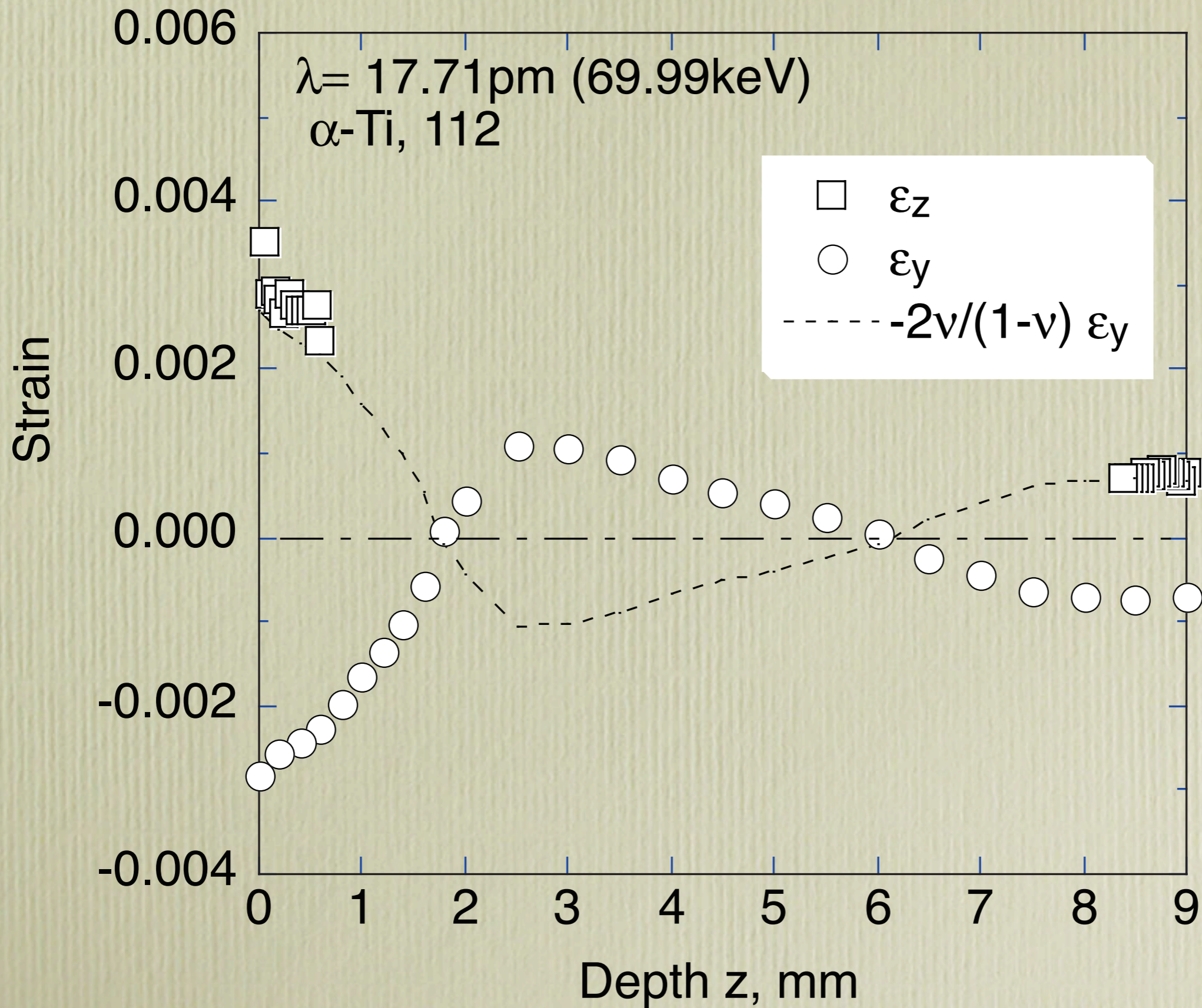


Transmission

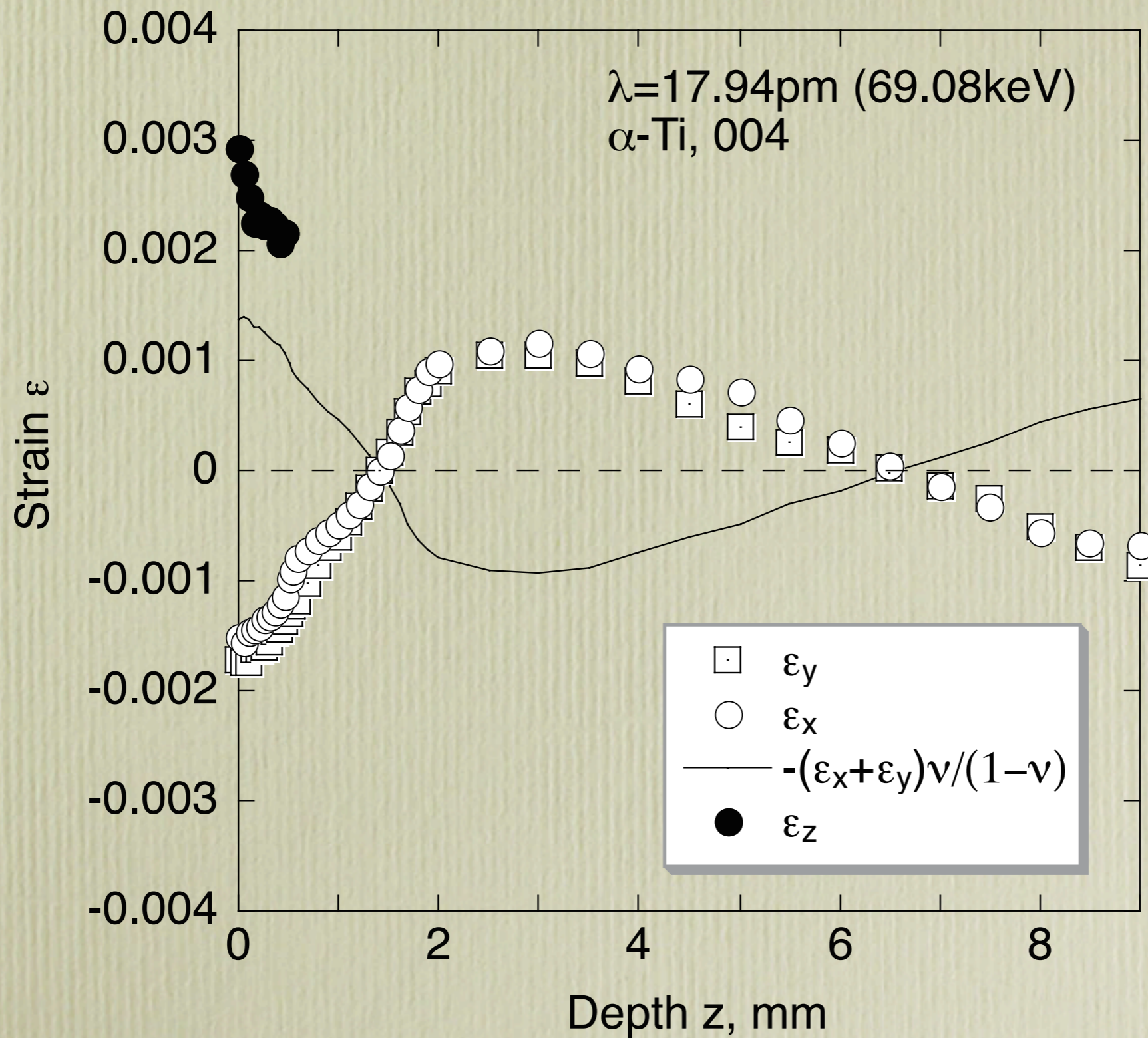
Reflection



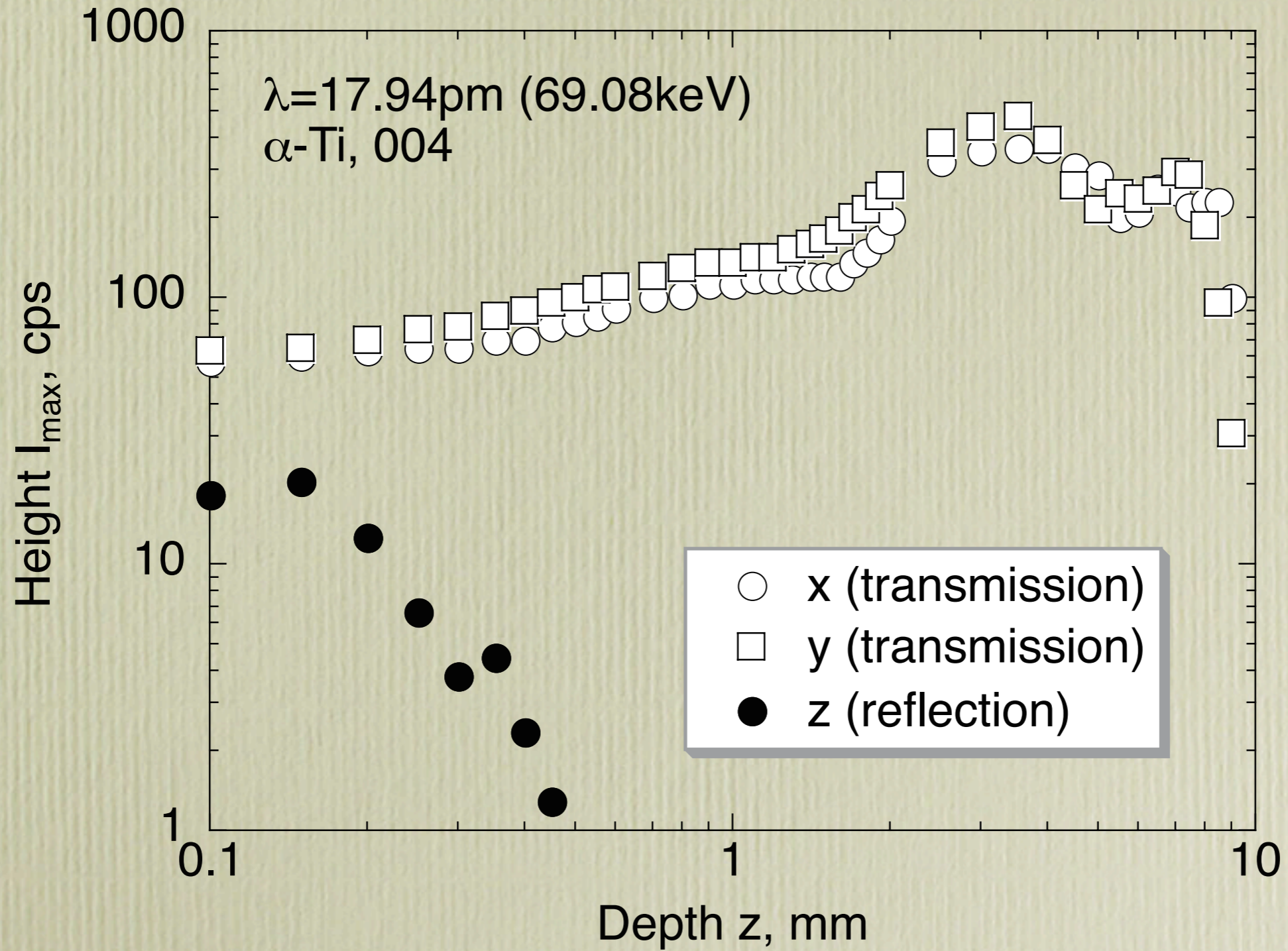
# 残留応力分布



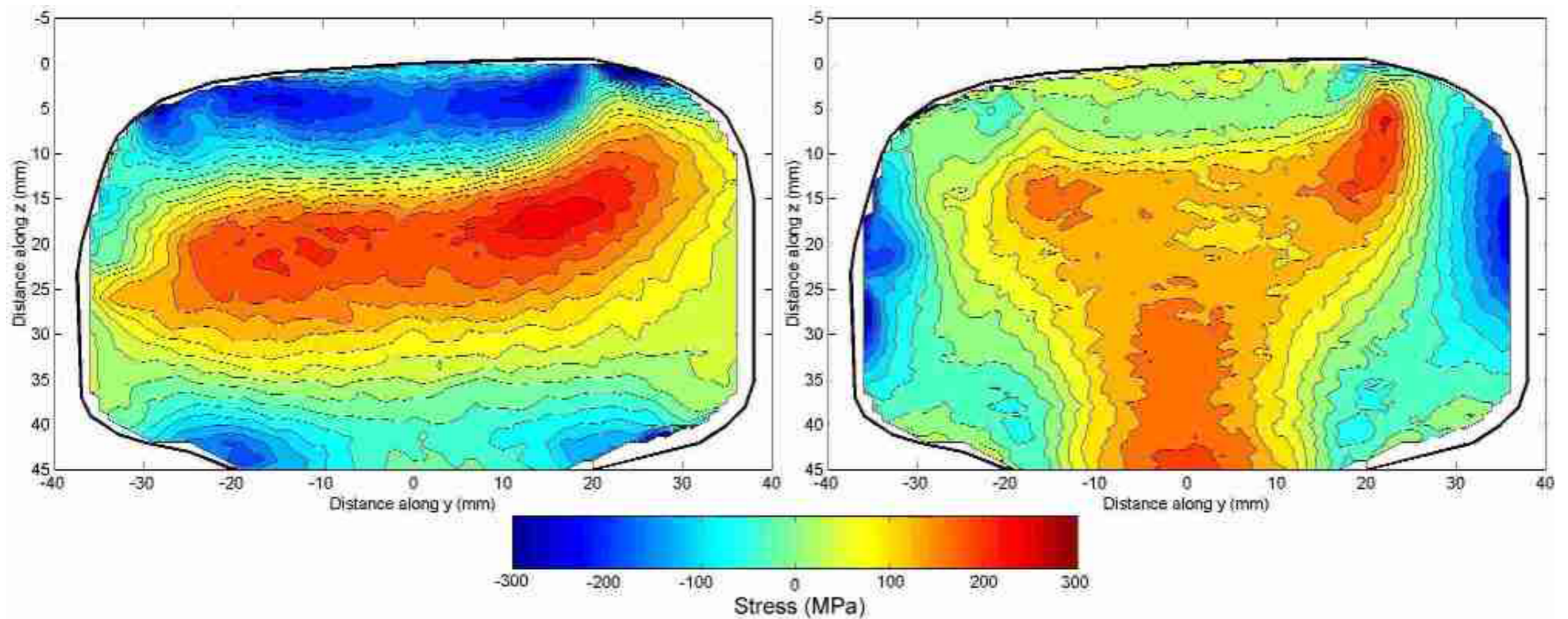
# 粒間ひずみの影響



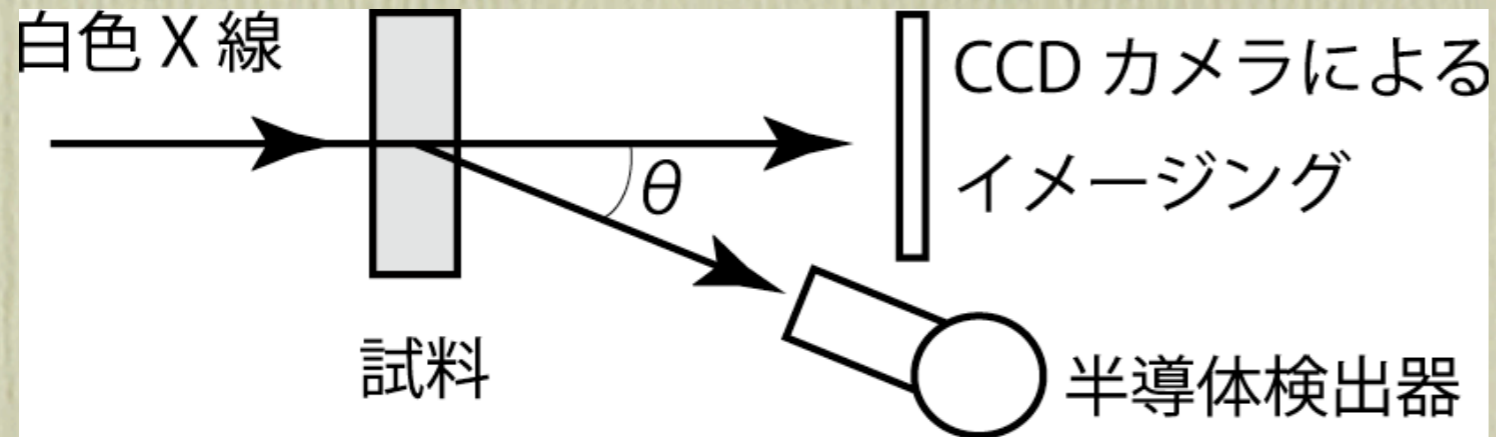
# 反射法と透過法



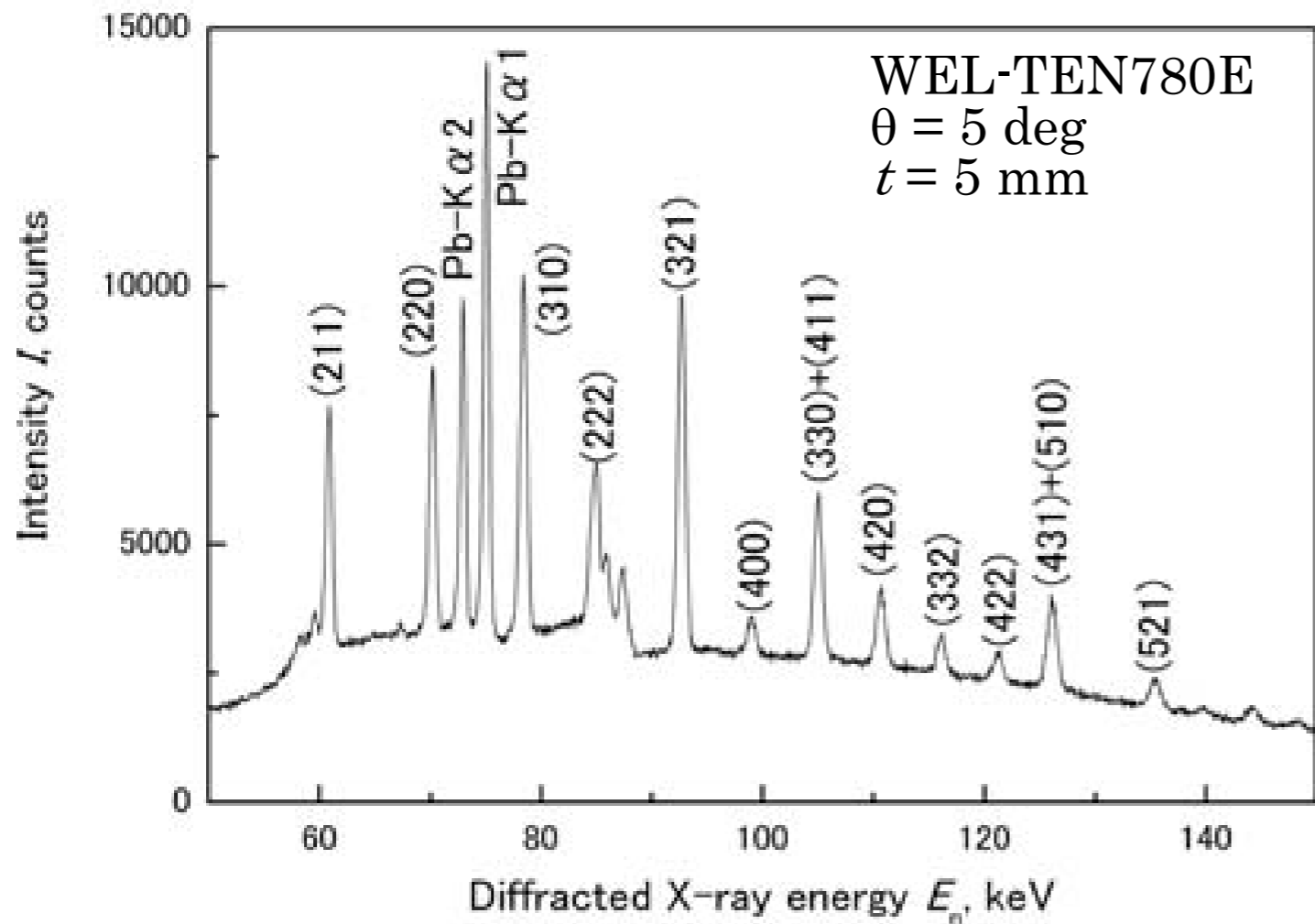
## 鉄道レールの残留応力分布



# 放射光白色X線とイメージング



$$\lambda = \frac{hc}{E}$$

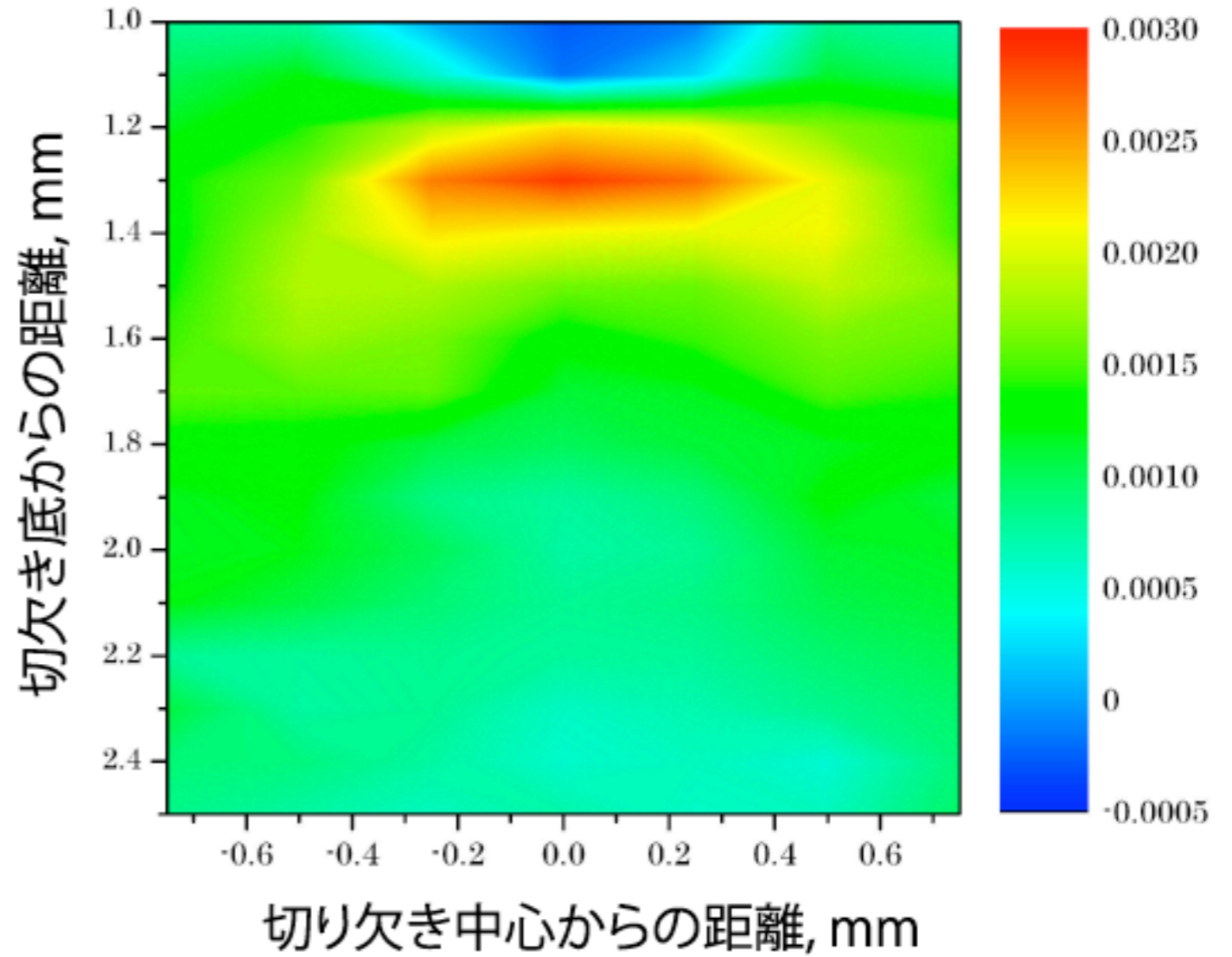


$$\varepsilon = \frac{d - d_0}{d_0} = \frac{E_0 - E}{E}$$

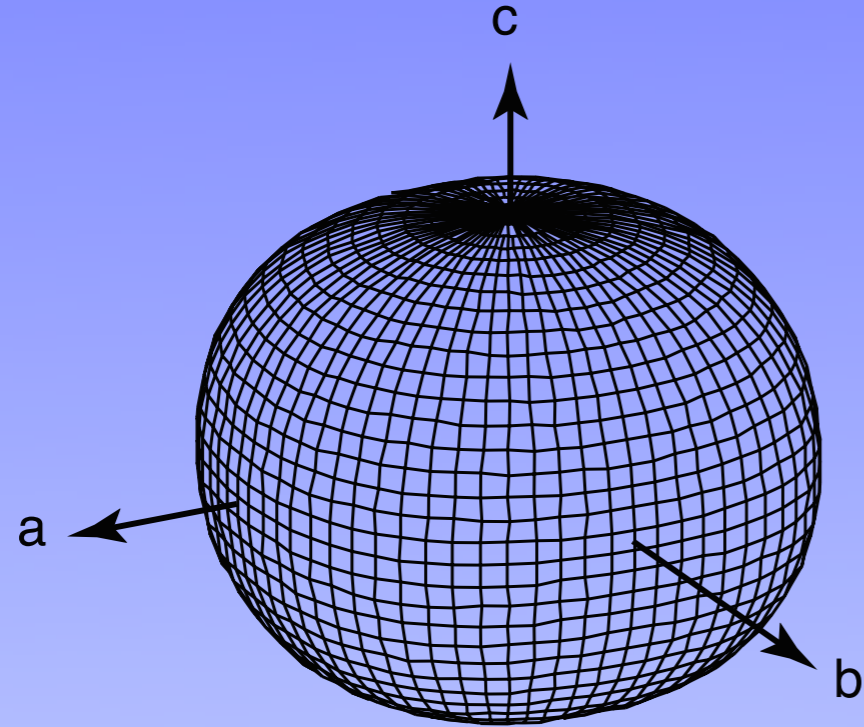
# 放射光白色X線とイメージング

切欠き深さ 0.3mm  
き裂長さ 1.03mm

← き裂先端



# 4.巨視的および微視的残留応力

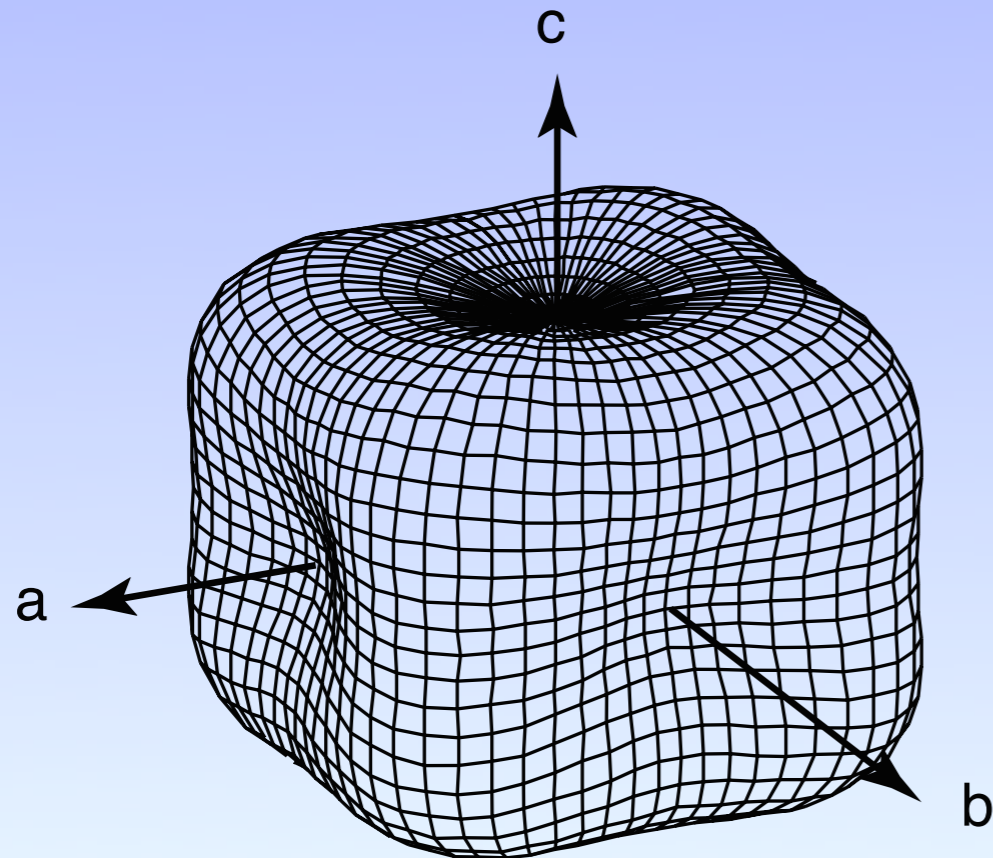


Al,  $A \approx 1.23$

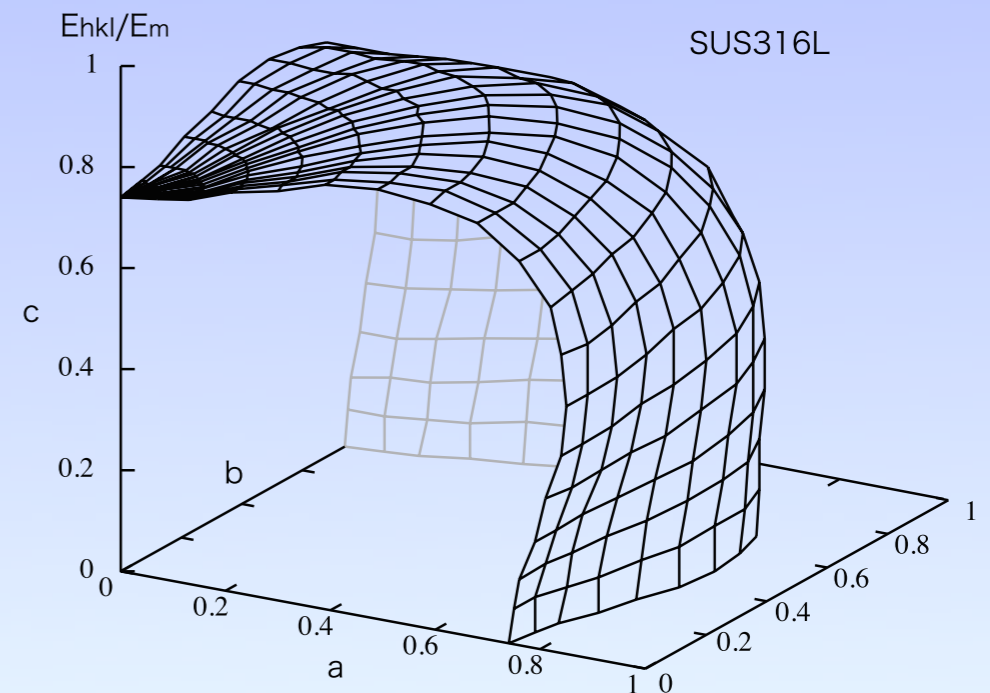
弾性異方性パラメータA

$$A = \frac{2C_{44}}{C_{11} - C_{12}}$$

Kröner モデル

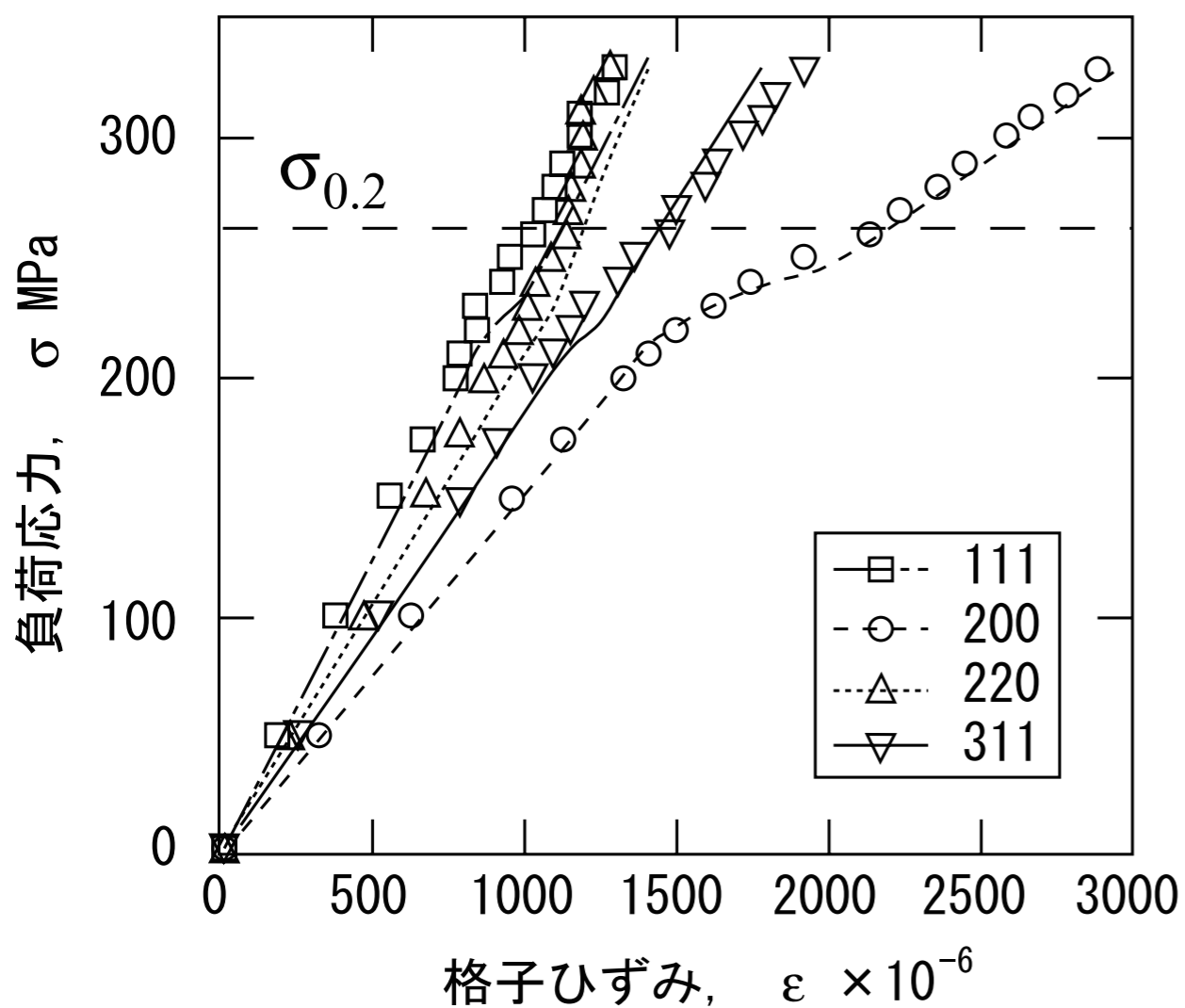


SUS316,  $A=3.26$

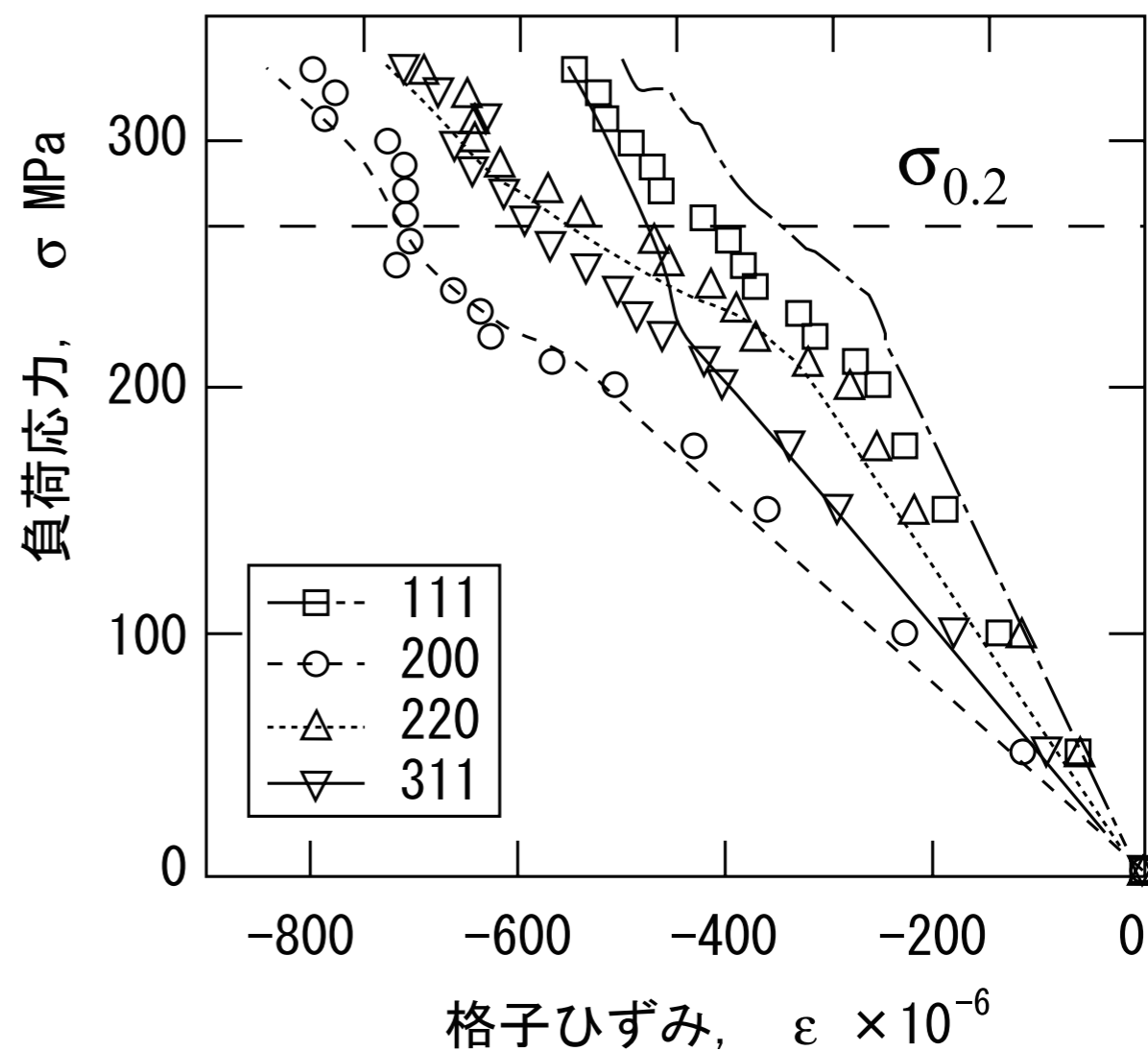


# 弾塑性におけるの異方性, 結晶方位依存性

## 引張方向



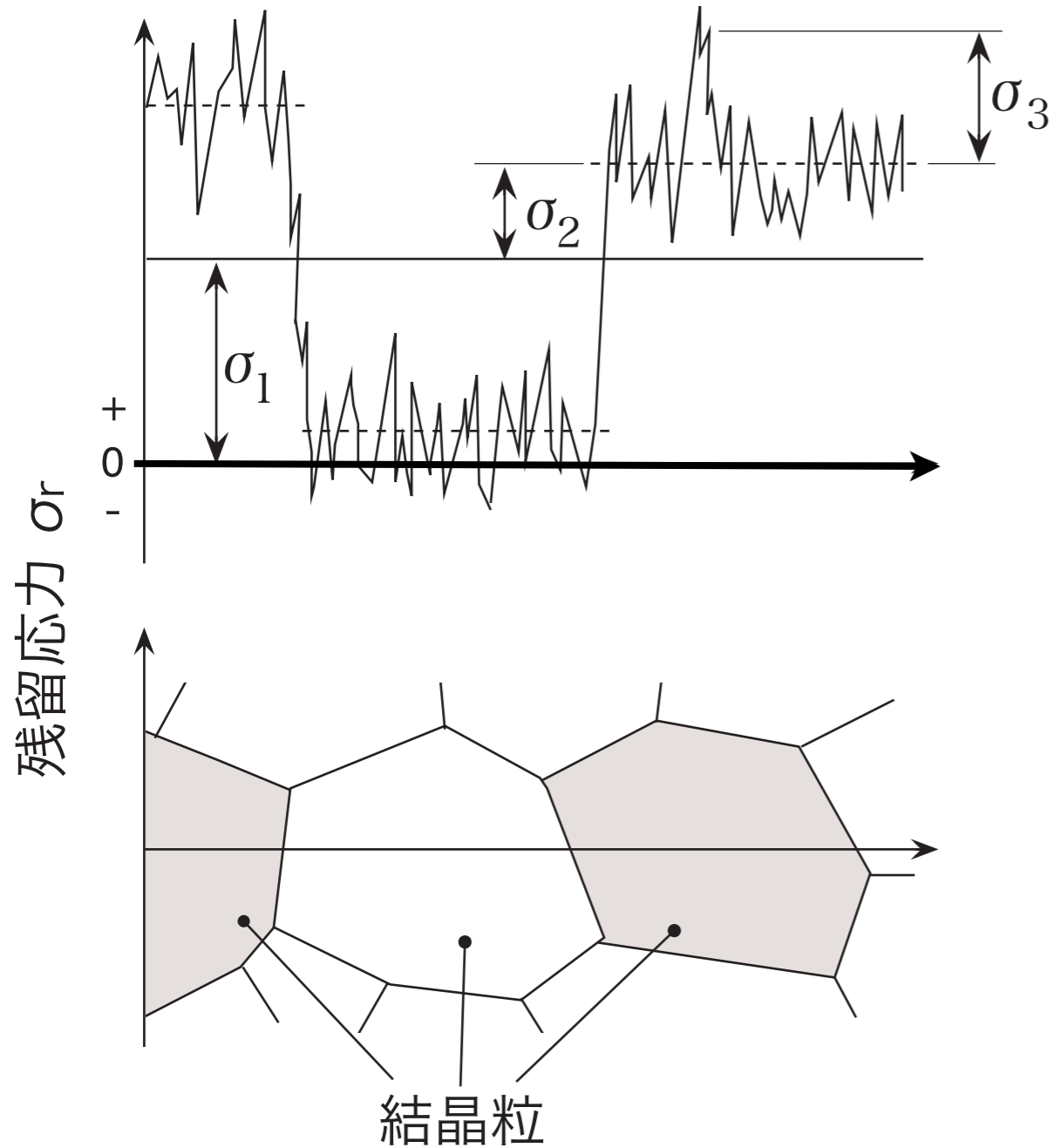
## 引張方向垂直



ステンレスの引張試験 (中性子法)



# 巨視的応力と微視的応力



$\sigma_1$  : 第1種応力(巨視的応力)

$\sigma_2$  : 第2種応力(微視的応力)

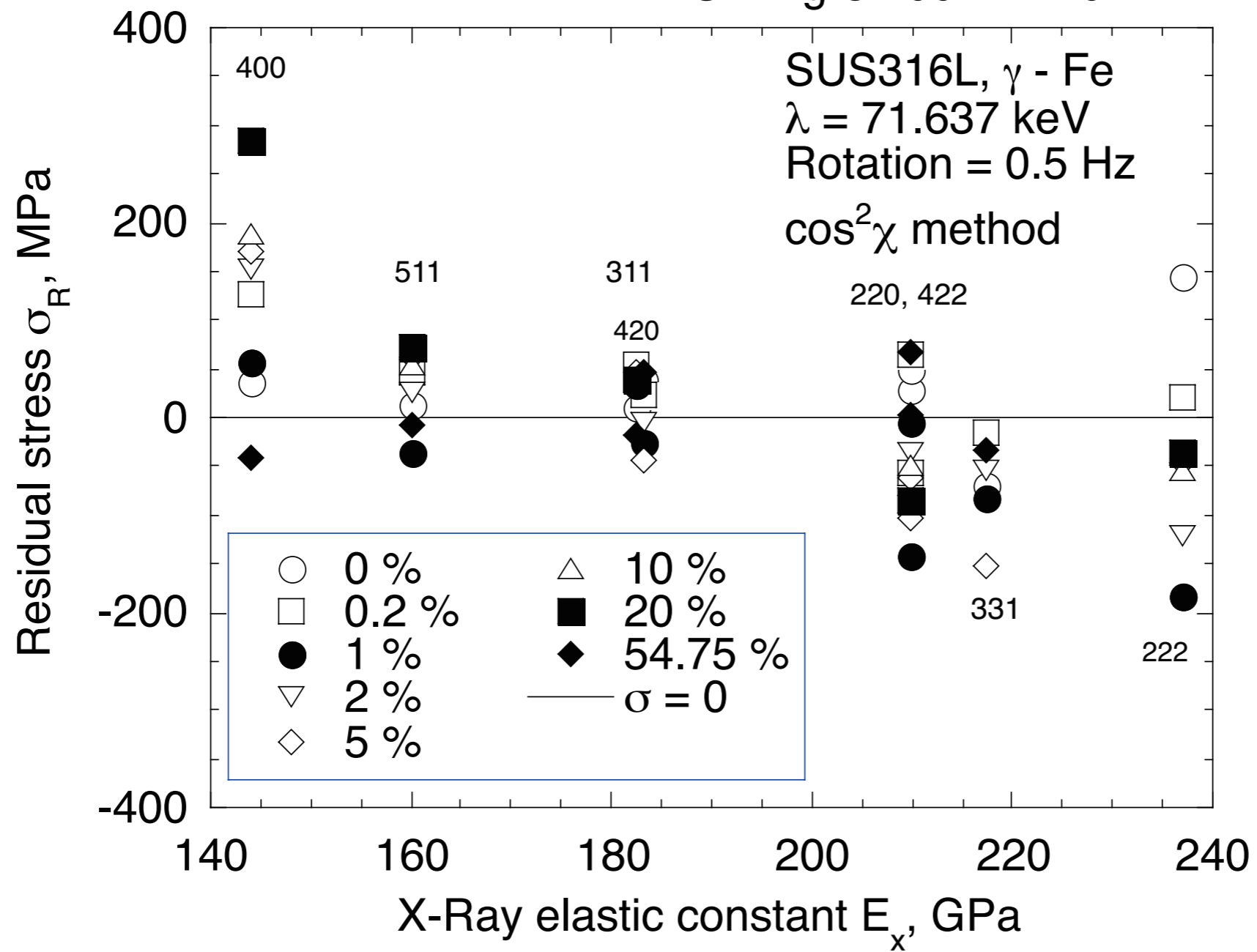
$\sigma_3$  : 第3種応力(微視的応力)

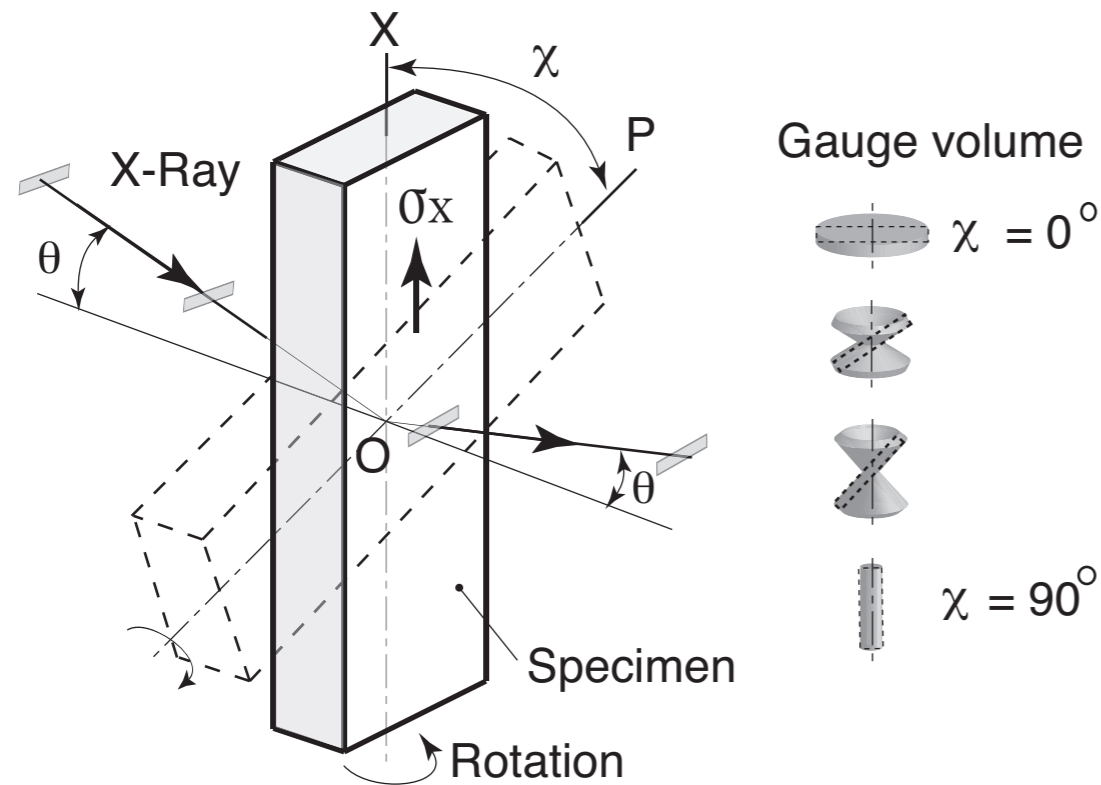
弾性異方性の大きい材料

- ・ オーステナイト系ステンレス
- ・ Ni基合金

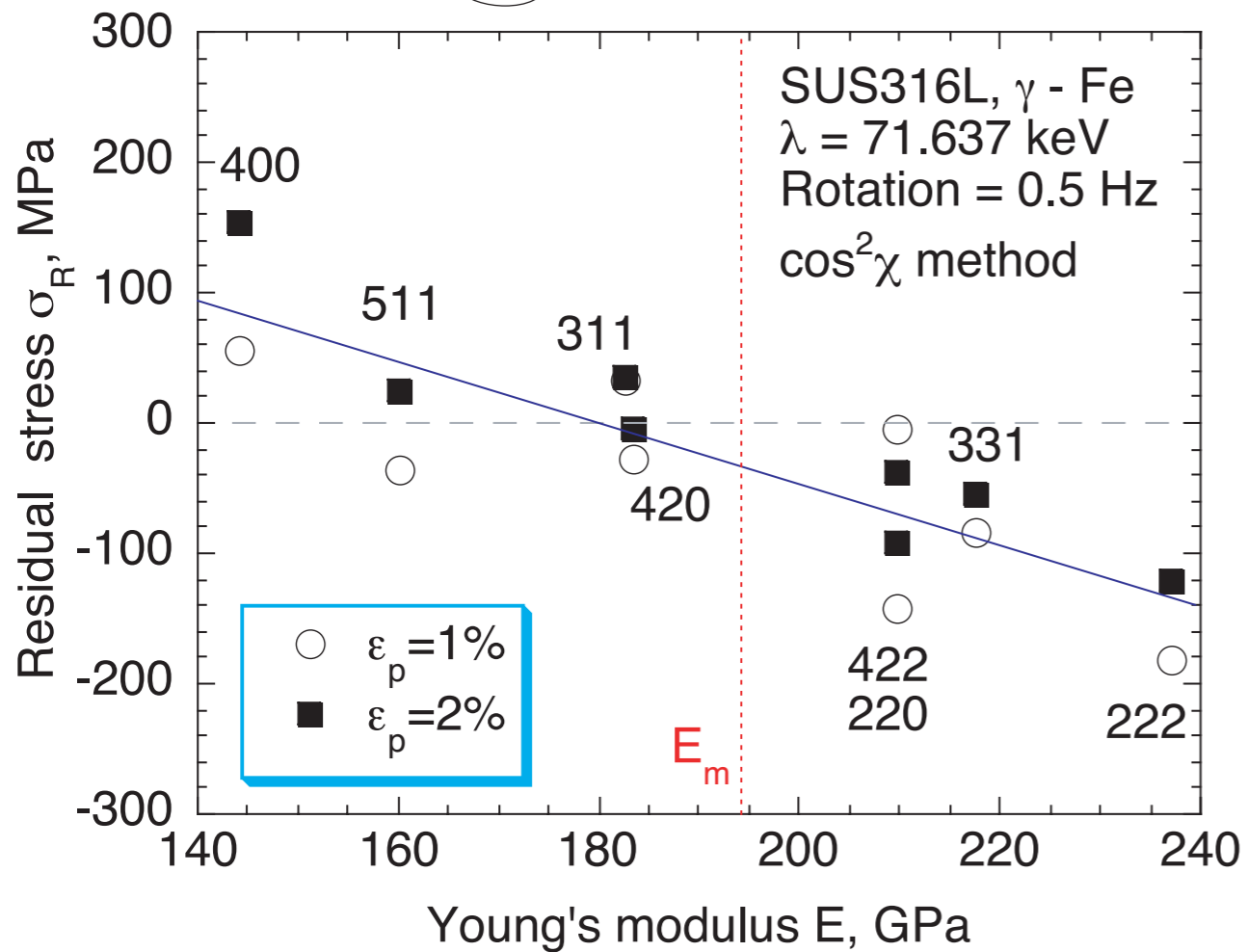
などは塑性変形に伴い微視的残留応力が生じやすい。

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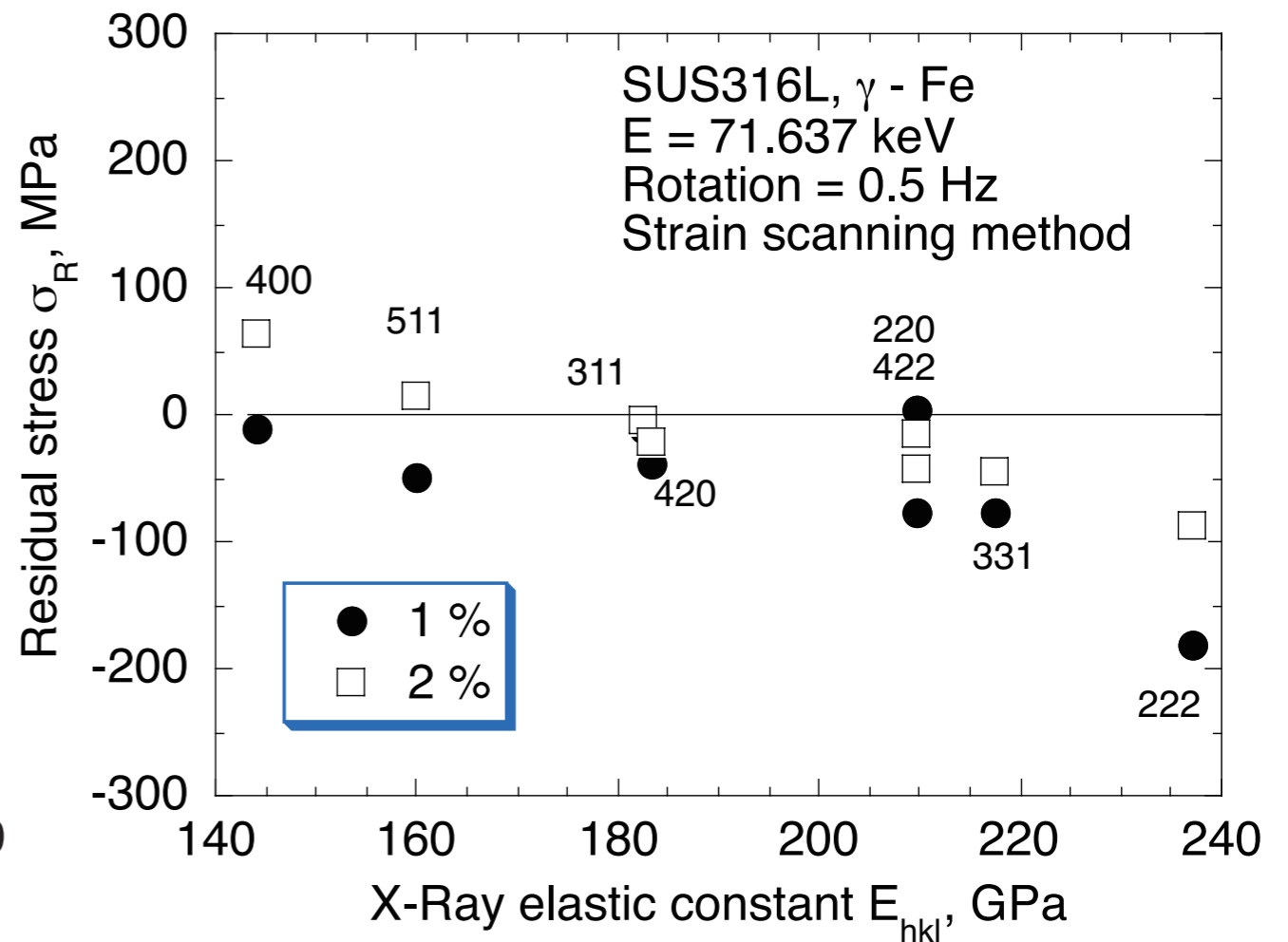




# 塑性変形による 微視的残留応力



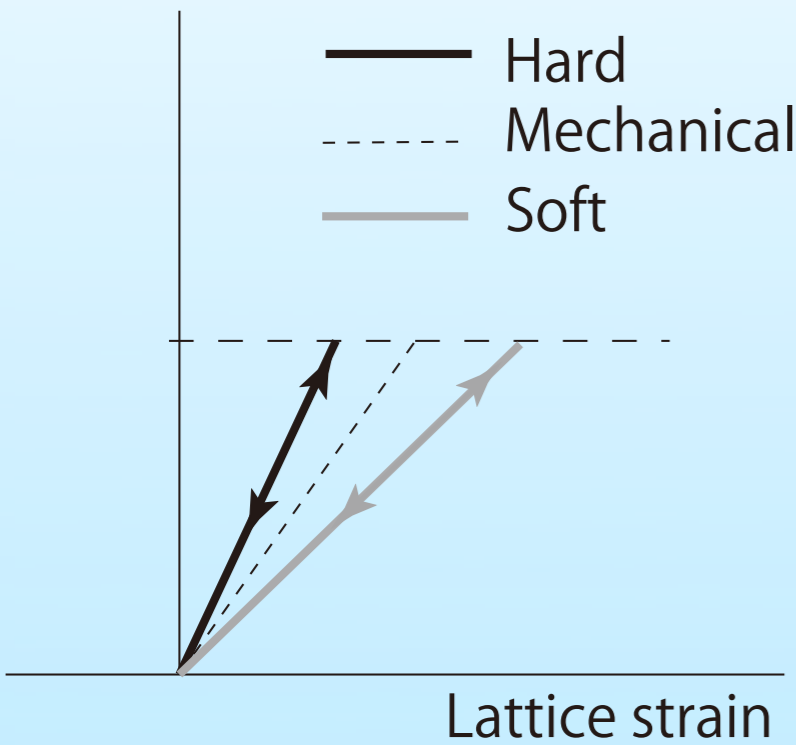
(a)  $\cos^2 \chi$  法



(b) ひずみスキャンニング法

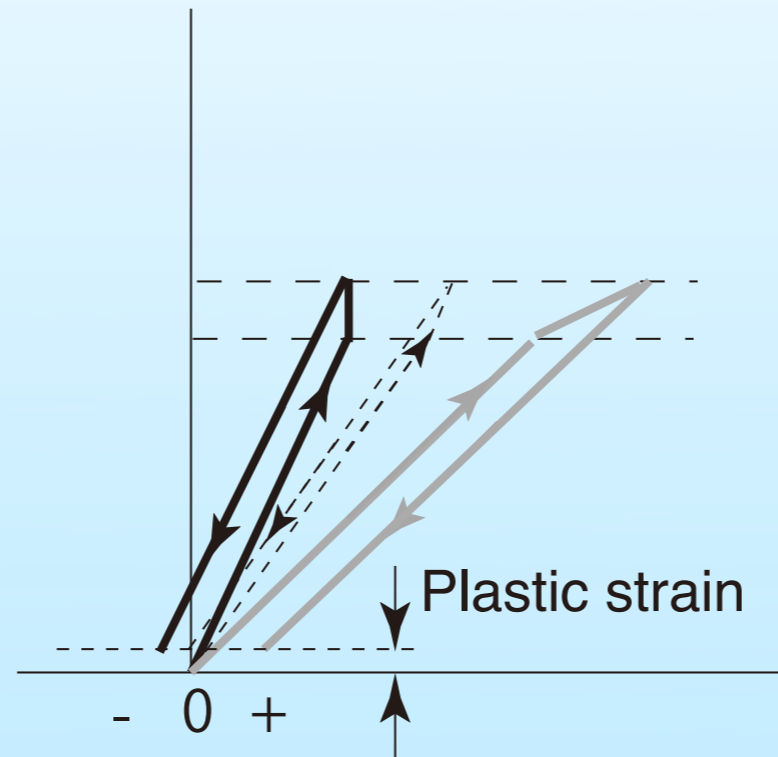
# 弾塑性におけるの異方性, 結晶方位依存性

Applied strain



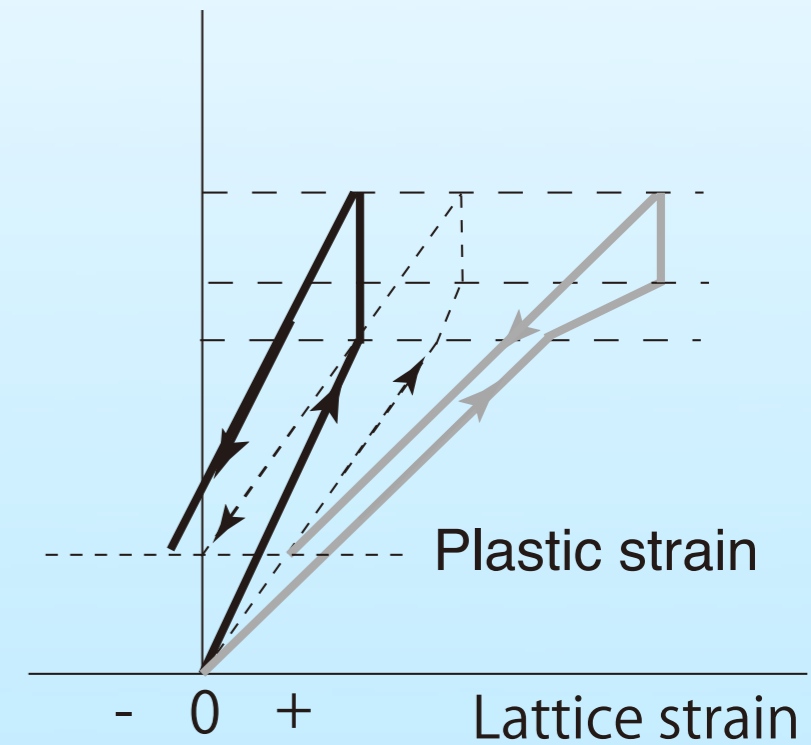
(a) Elastic strain

Applied strain



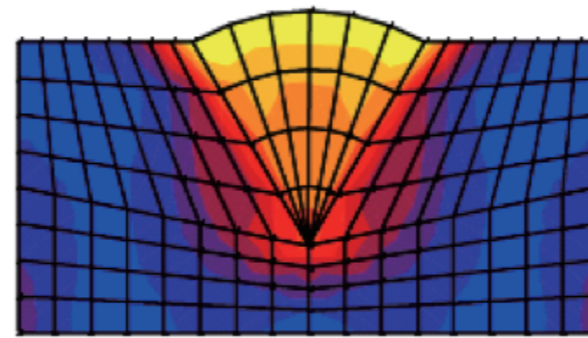
(b) Small plastic strain

Applied strain

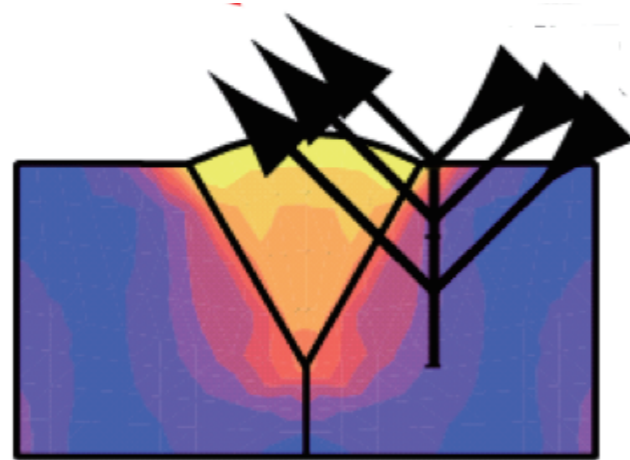


(c) Large plastic strain

# 3次元応力マップシステムの実現



数値解析



比較・検定




3次元実応力マップ

1. 正確な初期値, 境界条件のデータ
2. 計算結果と実測データの比較
3. 構造解析の高信頼性・高度化の実現
4. シミュレーションできない連続体を超える問題の実測

# EU の産業利用, 残留応力用 放射光施設 FaME38

FaME38 aims to provide the extra support required to enable European Engineers to make the best use of neutron and X-ray beam facilities. The 40-month start-up phase of the project is funded by an EPSRC grant of 2.5M Euro that is administered through the University of Salford on behalf of seven collaborating research institutions. Matching on-site support is provided by ILL/ESRF.

<http://www.esrf.eu/news/pressreleases/FaME38/index.html/>

## Facility for Materials Engineering


The Institut Laue Langevin (ILL) and the European Synchrotron Radiation Facility (ESRF) are respectively the European centres for research using neutron and synchrotron X-ray beams. They share a joint site in Grenoble, France, and provide advanced research facilities for European universities, research institutes and industries.

In 2002 a support Facility for Materials Engineering, FaME38, was inaugurated at the joint ILL-ESRF site. Its aim is to provide the support required to enable European engineers to make the best use of advanced neutron and synchrotron X-ray scientific facilities. FaME38 will develop user-friendly and efficient non-destructive 'strain scanners for engineering components', equivalent to body-scanners now routinely used in medicine.

FaME38 is funded to provide:

- a Technical Centre equipped with a co-ordinate measuring machine (CMM) to determine complex and distorted component shapes,
- facilities to simulate and optimise strain scans off-line before starting measurements on-line,
- a Materials Laboratory with micro-structural characterisation and static-dynamic thermo-mechanical loading equipment,
- a Knowledge and Training Centre to provide technical and scientific know-how.

Academic users are helped to plan experiments, and are assisted with data collection, processing and analysis. Industrial users can be provided with a full measurement and data analysis service as required. The facilities have so far been used mostly in connection with aerospace, fast transport, energy and materials industry research and to determine residual stress fields in critical components, often to validate stress calculation codes.

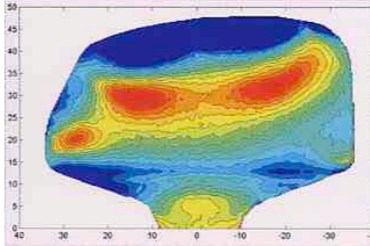


The joint ILL-ESRF site in Grenoble, France

**FaME38 at ILL-ESRF**  
6 rue Jules Horowitz  
BP156  
38042 Grenoble Cedex 9  
France


**Contacts details:**  
Tel: +33 (0) 4 76 20 79 44  
Fax: +33 (0) 4 76 20 79 43  
E-mail: FaME38@ill.fr or FaME38@esrf.fr  
Web: http://www.ill.fr/FaME38

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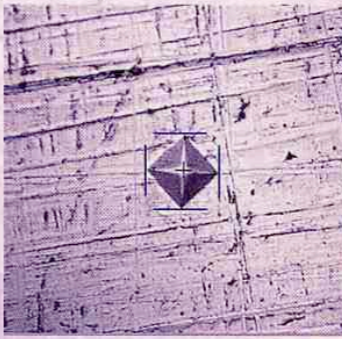
The residual stress profile in a worn railway rail as determined by high energy synchrotron X-ray diffraction

- ▶ Residual stress determination using **synchrotron X-ray and neutron diffraction**
- ▶ In-situ testing
- ▶ Stress and strain mapping




- ▶ Precise digitisation of experimental samples
- ▶ Improved experimental efficiency by the use of accurate positioning procedures
- ▶ Simulation of experiments
- ▶ Sample mounting to a common standard

- ▶ Hardness testing of components
- ▶ Metallographic analysis facilities
- ▶ Fatigue testing (static and dynamic)
- ▶ Advanced sample environments




Hardness testing measurements

- ▶ Tomographic imaging
- ▶ Texture analysis
- ▶ Microstructural characterisation
- ▶ New techniques (contour method, stroboscopy)

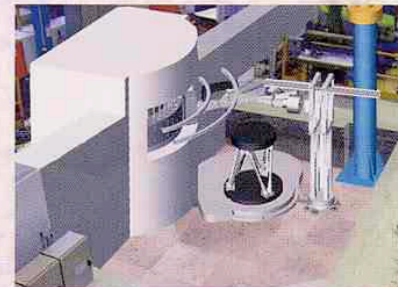


Slice through 3D virtual model showing the nucleation of a crack. The model is generated using synchrotron radiation tomography at the ESRF (Courtesy P J Withers)



European industry requires advanced materials and technologies

- ▶ Facilitate commercial exploitation of the **ILL-ESRF** facilities by European industries
- ▶ Encourage use of central facilities
- ▶ Provide a knowledge and training centre for engineers, academics and students



SALSA, the next generation engineering instrument at the ILL

- ▶ Provide expert advice to the **ILL-ESRF** for development of current and future facilities
- ▶ Develop improved data analysis methods
- ▶ Enable engineering research that is not currently feasible

# まとめ

- 「百聞は一見にしかず」のごとく，応力を実測すると思ってもよらない結果やアイデアが見つかることも多い。
- シミュレーションと実測を徹底して進める欧州連合，日本は如何に。
- SPring-8を使えば，見えなかったものも見える。
- SPring-8 は，産業利用にもっとも適している。
- より内部また表面は，中性子とラボX線との相補的利用
- 新しい測定法は，技術進歩も早い。