Residual Stress Analysis by X-Ray Diffraction

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Those Propeller Stresses Had Better Be Compressive !!!

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Acknowledgements

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Outline

I. Propeller blades and stresses.

II. Why do we need compressive stresses?

III. How do we put compressive stresses in propellers?

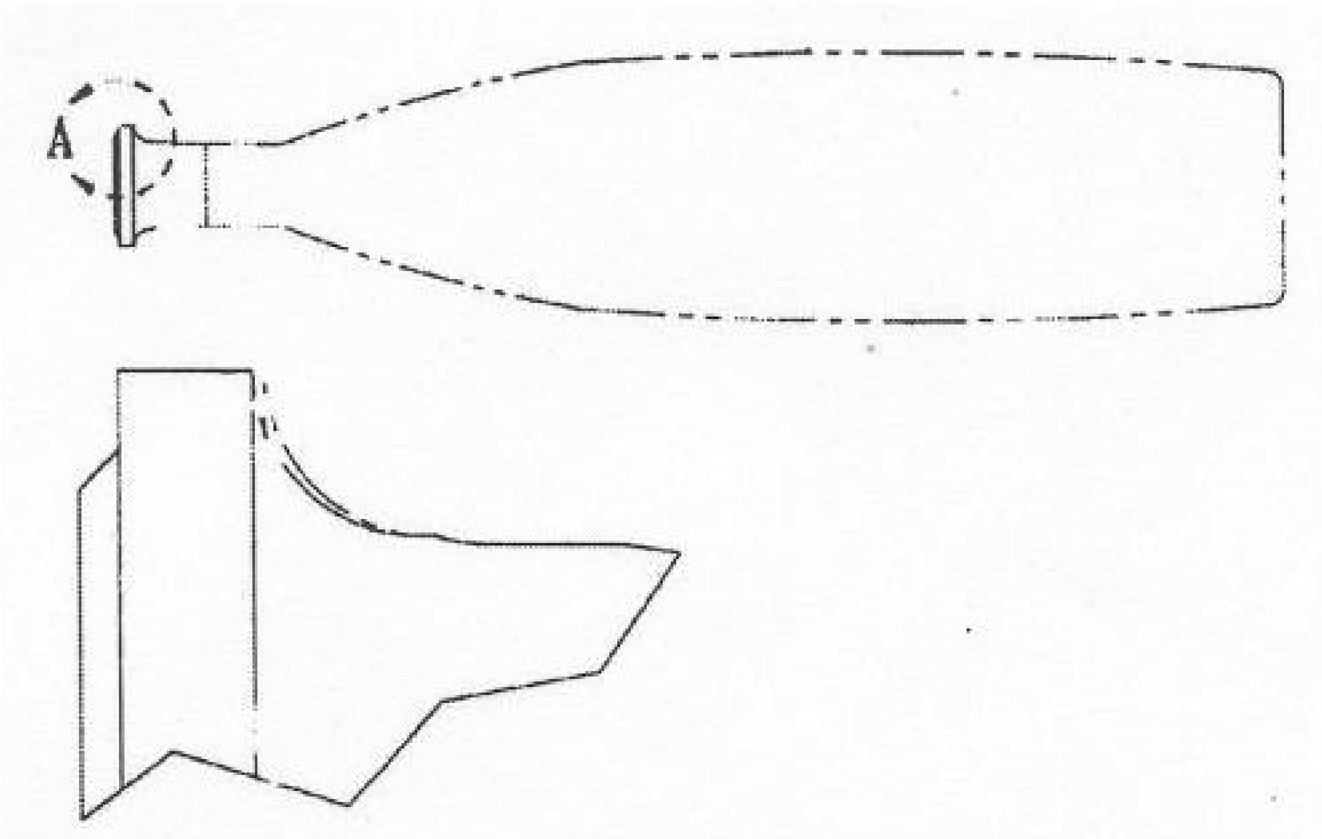
IV. How can we tell what the stresses are?

V. Results from the real world

VI. Conclusions

Propeller Blades and Stresses

Blade retention feature



Why Do We Need Compressive Stresses?

- Propeller assembly is a highly energetic rotating assembly
- Blades operate under severe load conditions
- Dominant bending loads are imposed at the inboard retention feature
- Airplanes and helicopters are merely fatigue machines that operate above ground (hopefully!)
- Compressive stresses extend fatigue life

How Do We Put Compressive Stresses in Propellers?

- Plastically deform (move material in) the critical stress areas of a propeller
- Common methods of imparting compressive stresses:
  - Shot peening
  - Compression rolling
- Both methods put a compressive stress at the surface and a <u>more</u> compressive stress beneath the surface

How Can We Tell What the Stresses Are?

- Strain gage blind hole drilling
- X-ray diffraction

X-Ray Diffraction
Residual Stress Measurement

Definition - A technique that combines physics, mechanics and alchemy to help one determine the useful life of a part.

Loading Versus Residual Stress

- *Loading Stress* - results from applied load: weight, torsion, bending, pressure, pushing, pulling etc.
- *Residual Stresses* - stresses that remain in the material after all external loads are removed. They result from differential cooling rates (Welding, Heat Treating, etc.) and plastic flow (Shot Peening, Cold Working, etc.).

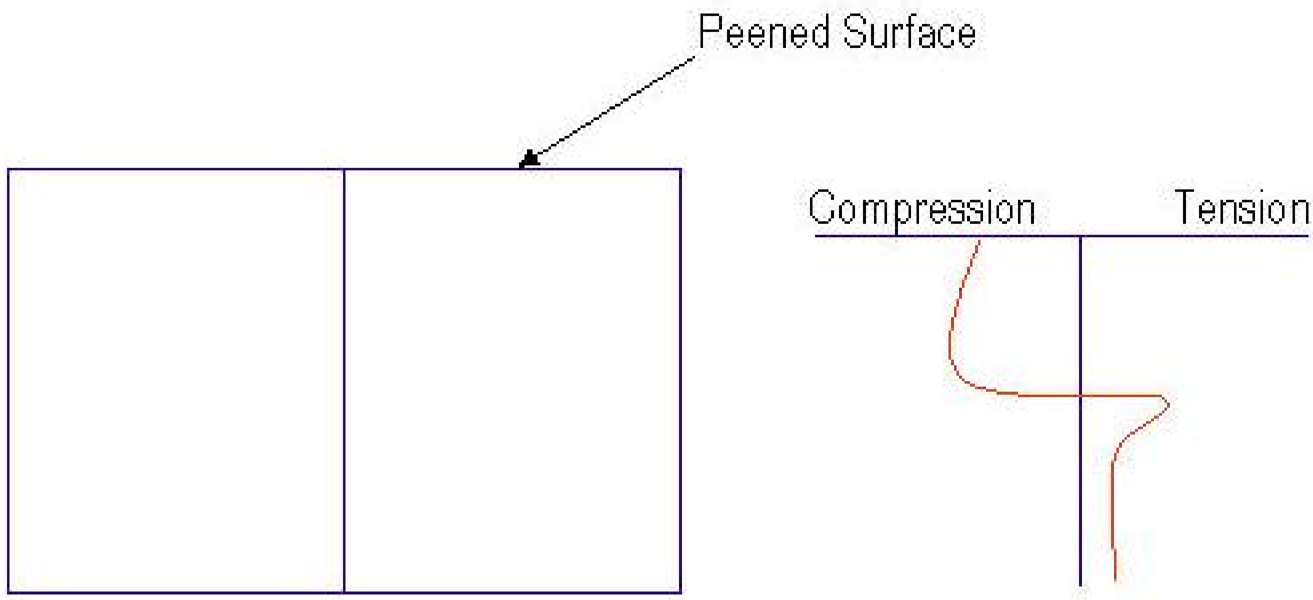
Origin of Residual Stress

- Introduction by mechanical, thermal, and/or chemical processes that result in a permanent, nonuniform change in shape or volume.

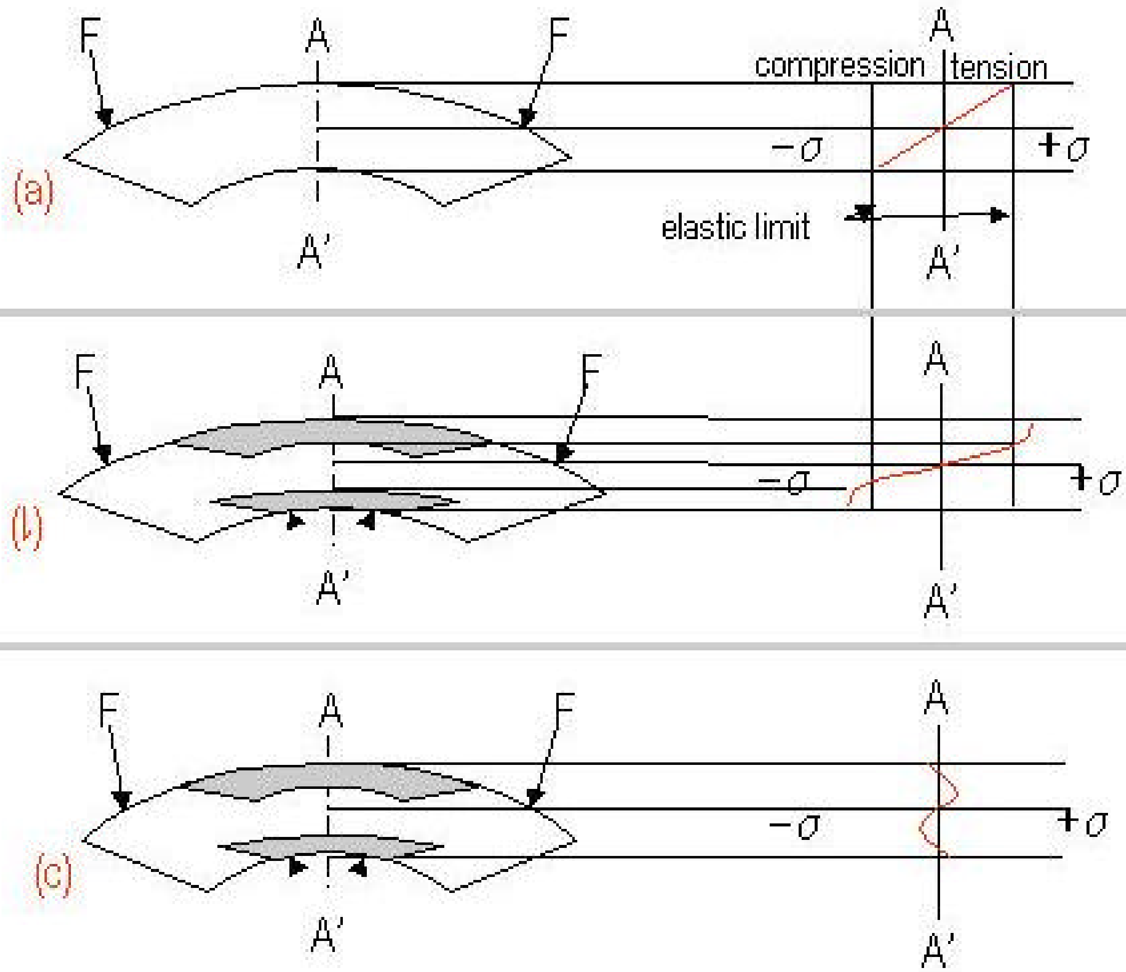
Mechanical Processes

- Surface Working
  - Shot Peening
  - Surface Rolling
  - Polishing
- Drawing
- Rolling
- Grinding and Machining
- Assembling

Shot Peening



Forming


F
A
F
A
compression
tension
−σ
+σ
(a)
elastic limit
A'
A'
F
A
F
A
−σ
+σ
(l)
A'
A'
F
A
F
A
−σ
+σ
(c)
A'
A'

Benefits of X-Ray Diffraction Residual Stress Analysis

- Can be nondestructive
- Accurate stress vs. depth with electropolishing
- Repeatable
- Fast

Benefits (continued)

- Understand and quantify grinding burn to prevent component failure
- Analyze residual stresses vs. fatigue to aid in useful life estimation
- Find cause of warping in machined components
- Analyze heat affected zones of weldments to determine need for stress relief

Why Residual Stresses Are Important

- Residual stresses may be harmful or beneficial
- Tensile residual stresses at surface are normally harmful, sometimes leading to brittle fracture in fatigue
- Compressive residual stresses at surface normally increase fatigue strength
- Residual stresses can be controlled in the manufacturing process

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History of Residual Stress
(X-Ray Diffraction - XRD)

X-Ray Diffraction Stress Measurements

- Measures elastic strains
- Direct, self calibrating technique
- Measures long range stresses at a point
- Can measure complex geometries
- Can measure phase-by-phase stresses

X-Ray Diffraction
Residual Stress Measurements

- If component is loaded, resultant stress will be the residual plus the applied stress
- Measurements can be made on most metals and ceramics; samples must be polycrystalline with relatively randomly oriented medium to fine grains
- Measurements can be made in a few minutes to an hour

X-Ray Diffraction
Residual Stress Measurements

- Nondestructive* surface measurement techniques
- Measures strains, stresses are calculated
- Gives absolute stress value
- Measures residual strain if sample is unloaded

* depth profiling can be destructive

Strain

$$\frac{\Delta l}{l_0} \quad \text{or} \quad \frac{\Delta d}{d_0}$$

Stress-Strain Relationship

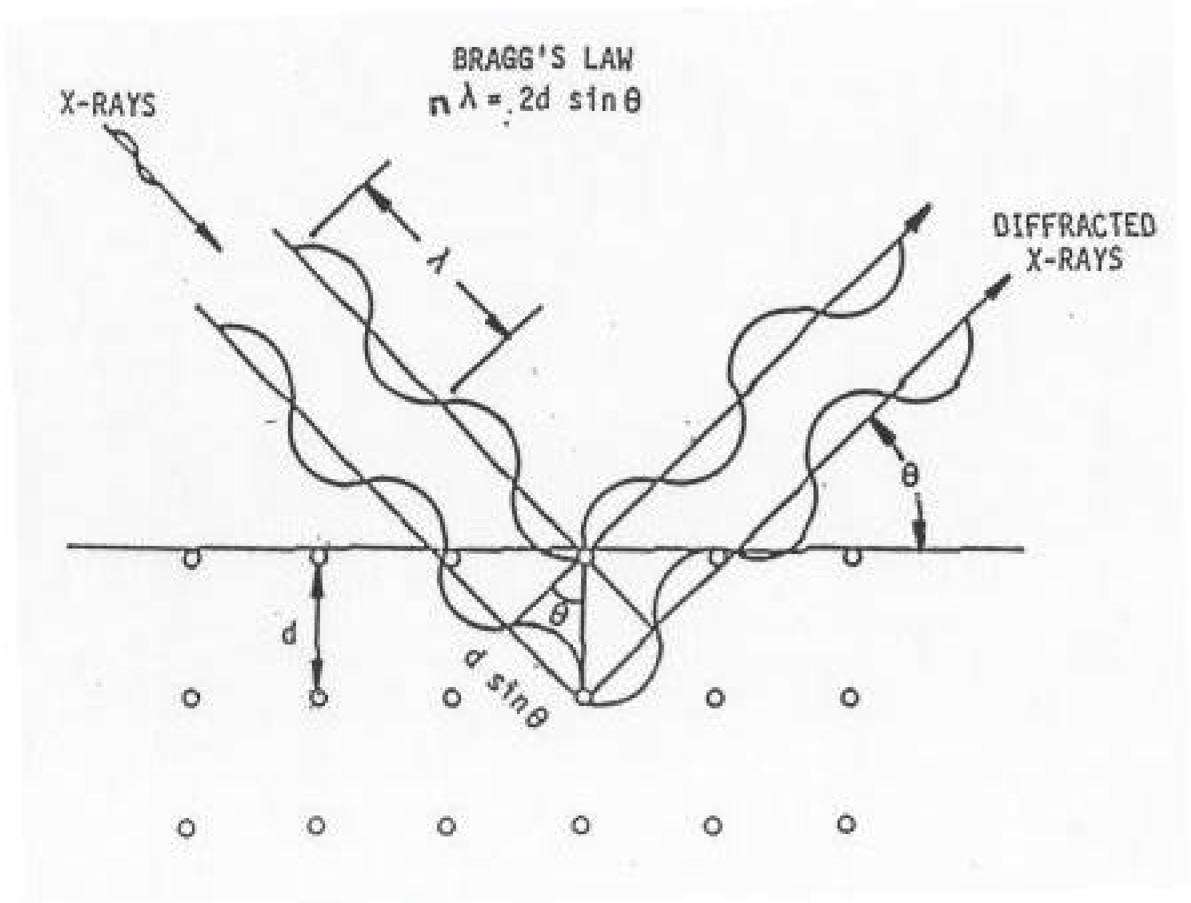
$$\varepsilon_{ii} = \frac{1}{E}\sigma_{ii}$$

$$\varepsilon_{jj} = \frac{-\nu}{E}\sigma_{ii}$$

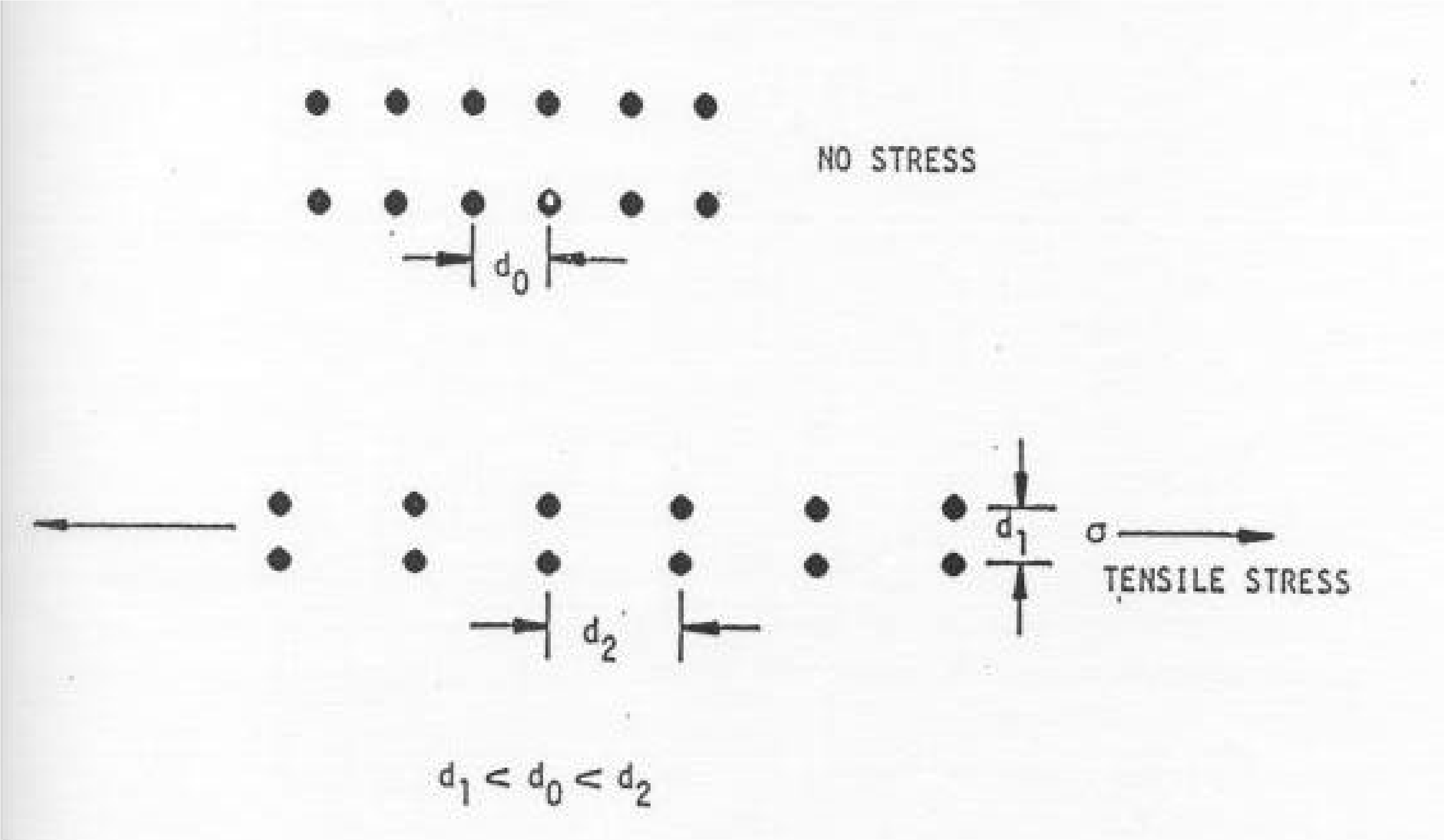
$$\varepsilon_{ii} = \frac{1}{E}\sigma_{ii} - \frac{\nu}{E}(\sigma_{jj} + \sigma_{kk})$$

Bragg's Law

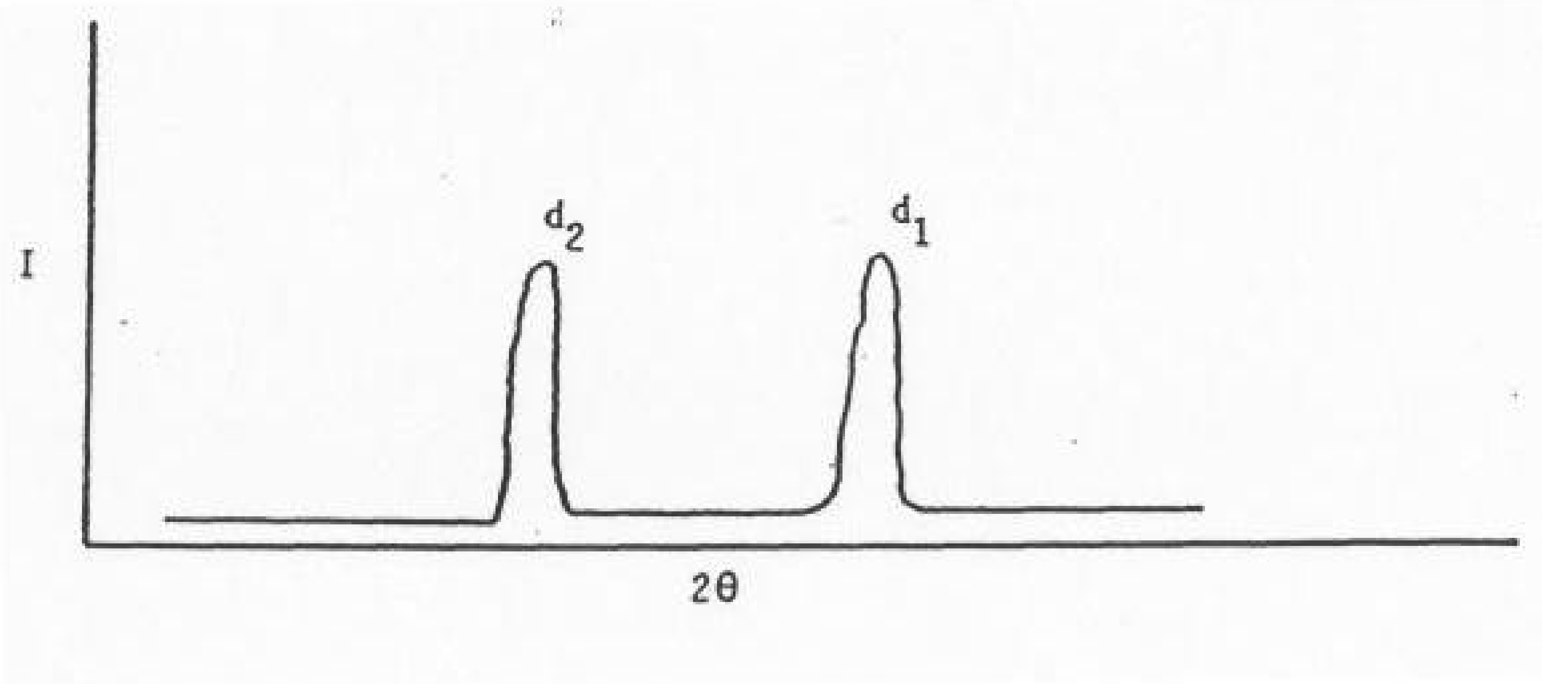
Used to Measure Crystal Lattice Parameter, "d"



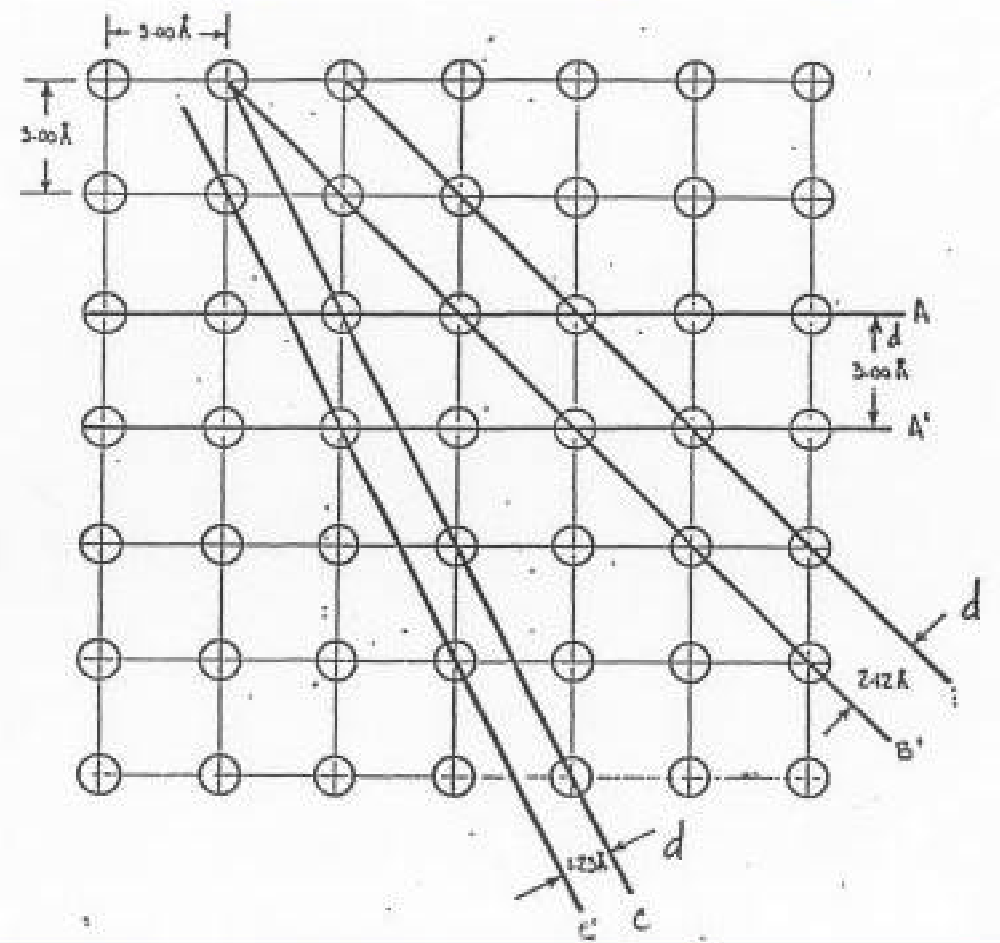
Effects of Tensile Stress on a Crystal Lattice Structure



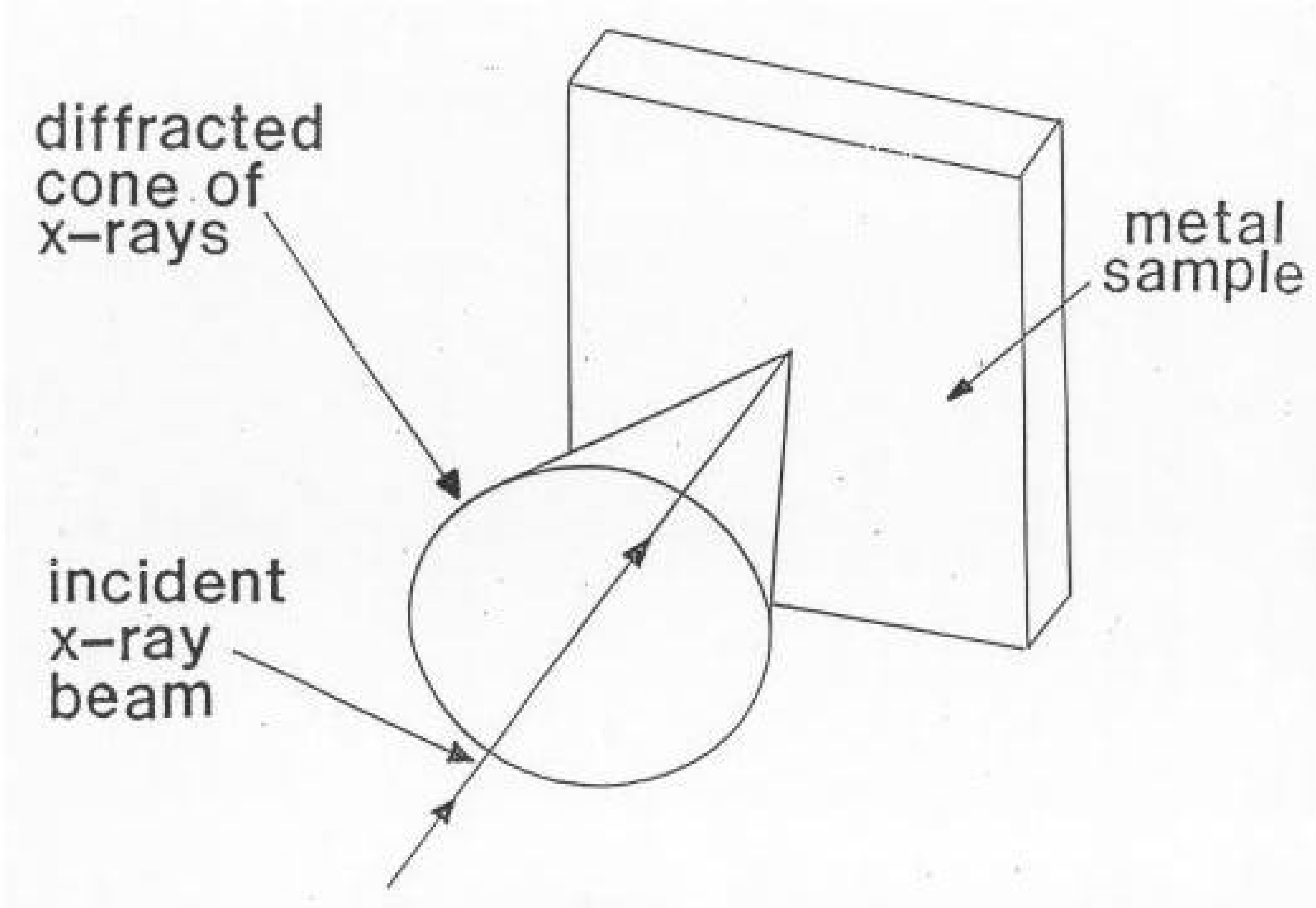
Diffraction Pattern

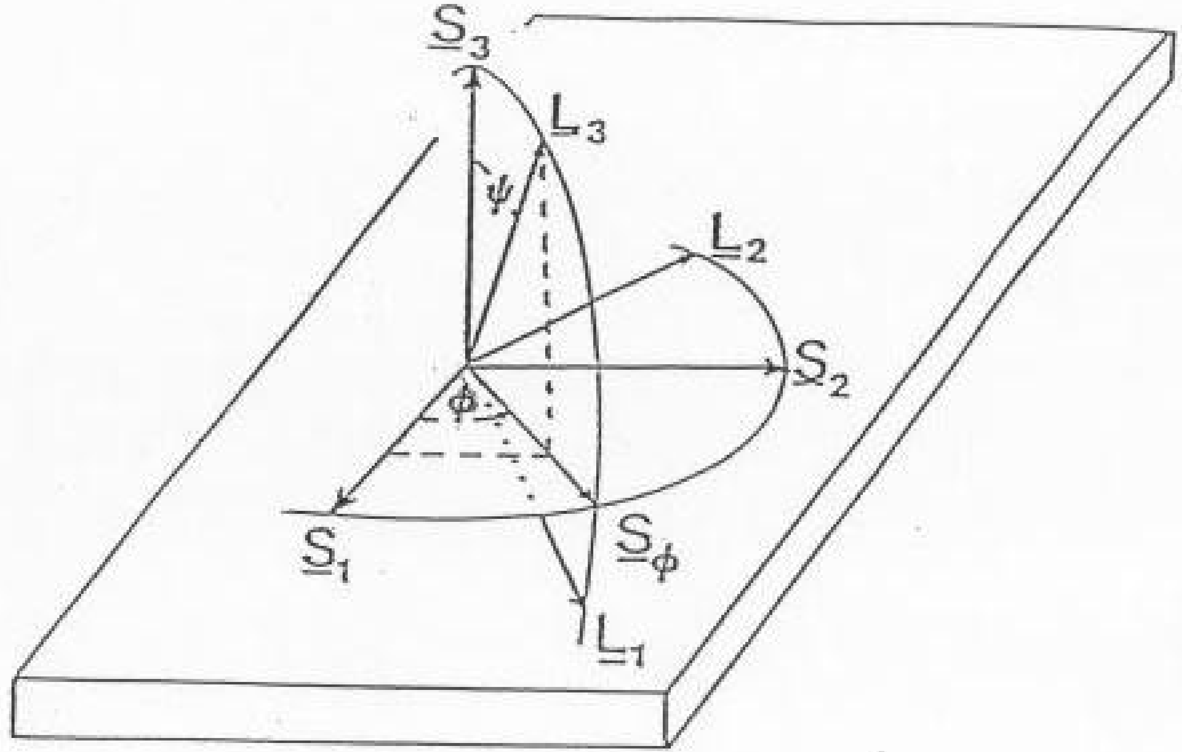


Interplanar Spacings



Incident and Diffracted Beams





S3
L3
ψ
L2
S2
φ
S1
Sφ
L1

Stress-Strain Equation for XRD

$$(\varepsilon_{33})\,\phi\psi = \frac{d\phi\psi - d_o}{d_o}$$

$$(\varepsilon_{33})\,\phi\psi = a_{3k}\; a_{3l}\; \varepsilon_{kl}$$

$$a_{1k} = \begin{vmatrix} \cos\phi\;\cos\psi & \sin\phi\;\cos\psi & -\sin\psi \\ -\sin\psi & \cos\phi & o \\ \cos\phi\;\sin\psi & \sin\phi\;\sin\psi & \cos\psi \end{vmatrix}$$

$$\begin{aligned}(\varepsilon_{33})\,\phi\psi = \frac{d\phi\psi - d_o}{d_o} &= \varepsilon_{11}\cos^2\phi\sin^2\psi + \varepsilon_{12}\sin^2\phi\sin^2\psi \\ &+ \varepsilon_{22}\sin^2\phi\sin^2\psi + \varepsilon_{33}\cos^2\psi \\ &+ \varepsilon_{13}\cos^2\phi\sin^2\psi + \varepsilon_{23}\sin^2\phi\sin^2\psi \\ &= 1/2S_2[\sigma_{11}\cos^2\phi + \sigma_{12}\sin^2\phi\sin^2 + \sigma_{22}\sin^2\phi]\,\sin^2\psi \\ &+ 1/2S_2\sigma_{33}\cos^2\psi + S_1[\sigma_{11} + \sigma_{22} + \sigma_{33}] \\ &+ 1/2S_2[\sigma_{13}\cos\phi + \sigma_{23}\sin\phi]\,\sin^2\psi\end{aligned}$$

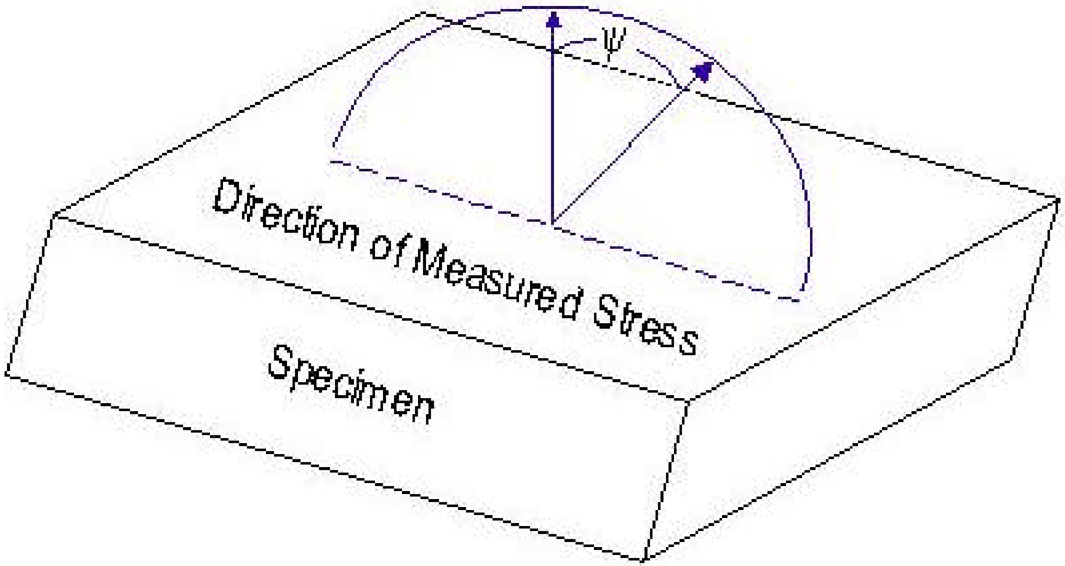
Assuming $\sigma_{33} = \sigma_{13} = \sigma_{23} = 0$

$$\frac{d\phi\psi - d_o}{d_o} = 1/2S_2[\sigma_{11}\cos^2\phi + \sigma_{12}\sin^2\phi + \sigma_{22}\sin^2\phi]\,\sin^2\psi + S_1[\sigma_{11} + \sigma_{22}]$$

$$\frac{d\phi,\,\psi = o - d_o}{d_o} = S_1[\sigma_{11} + \sigma_{22}]$$

$$\frac{d_{\phi,\psi} - d_o}{d_o} - \frac{d_{\phi\psi=o} - d_o}{d_o} = \frac{d_{\phi\psi} - d_{\phi\psi=o}}{d_o} = ½\, S_2\, \sigma_\phi \sin^2\psi$$

$$1/2\,S_2 = \frac{1+\nu}{E} \qquad S_1 = \frac{-\nu}{E}$$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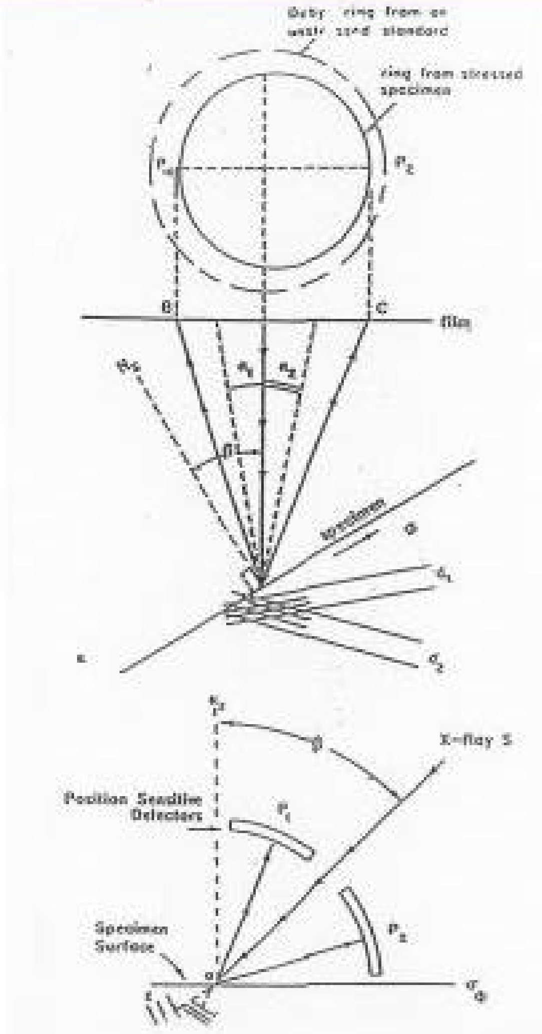
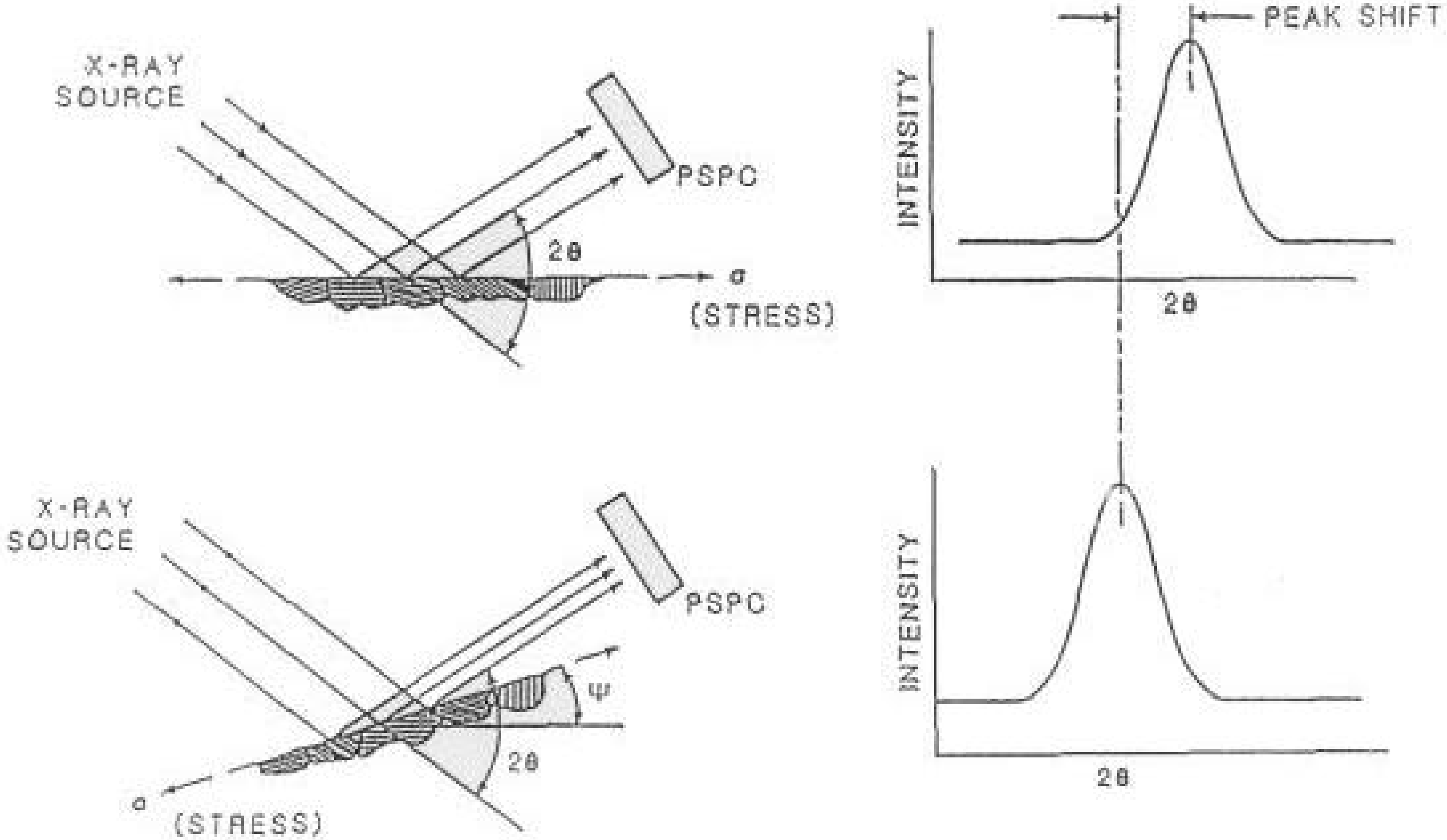
Direction of Measured Stress
Specimen

Single Exposure Technique



$$\sigma_\phi = \frac{E}{1+\upsilon}\left\{\frac{\cot\left[\frac{1}{2}(\theta_1+\theta_2)\right]}{\sin^2(\beta+\eta)-\sin^2(\beta-\eta)}\right\}$$

Double and Multiple Exposure Technique

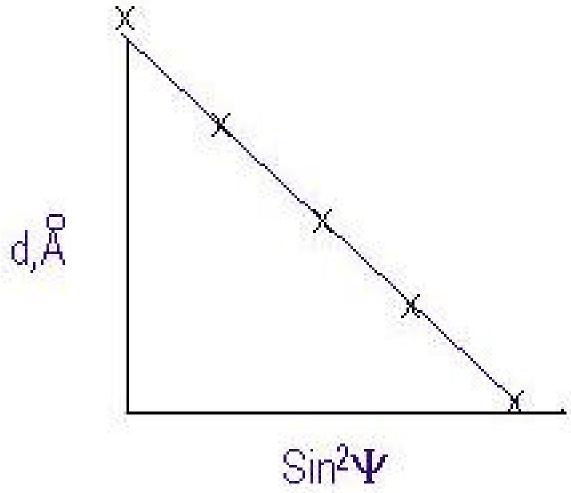


Multiple Exposure ($\sin^2\psi$) Technique

$$\sigma_\Phi = \frac{d_{\Phi\psi} - d_{\Phi\psi = o}}{1/2 S_2 \sin^2\psi d_o} = \frac{m}{(1+\nu)/E\, d_{\Phi\Psi = o}}$$

Multiple Exposure ($\sin^2\psi$) Technique

$$\sigma_{\Phi} = \frac{d_{\Phi\psi} - d_{\Phi\psi=0}}{1/2 S_2 \sin^2\psi d_0} = \frac{m}{\frac{(1+\nu)}{E} d_{\perp}}$$



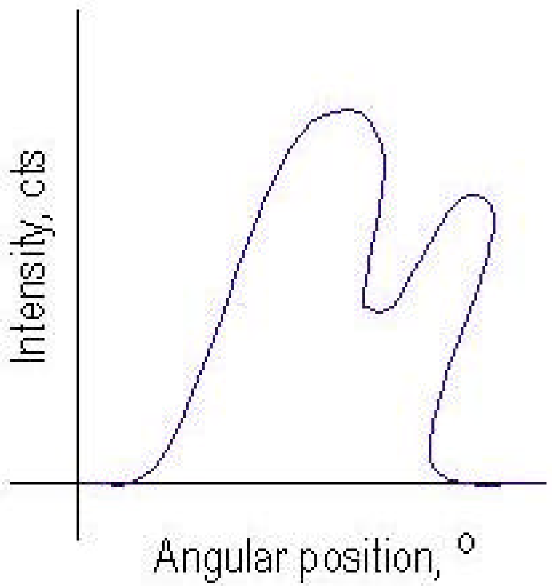
X-Ray Diffraction Stress Measurement

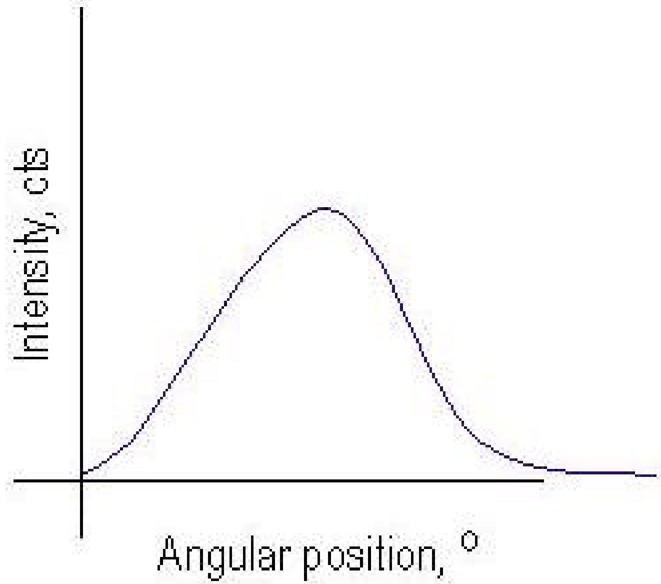
- Can distinguish metallurgical and mechanical conditions such as:
  - large grain size
  - preferred orientation
  - stress gradients
  - surface distortion
  - shear stresses
  - plastic strain indication
  - hardness in steels

X-Ray Diffraction Stress Measurements

- Peak width analysis
  - Indication of plastic strain
  - Can be calibrated to indicate hardness in steels

Peak Width Analysis

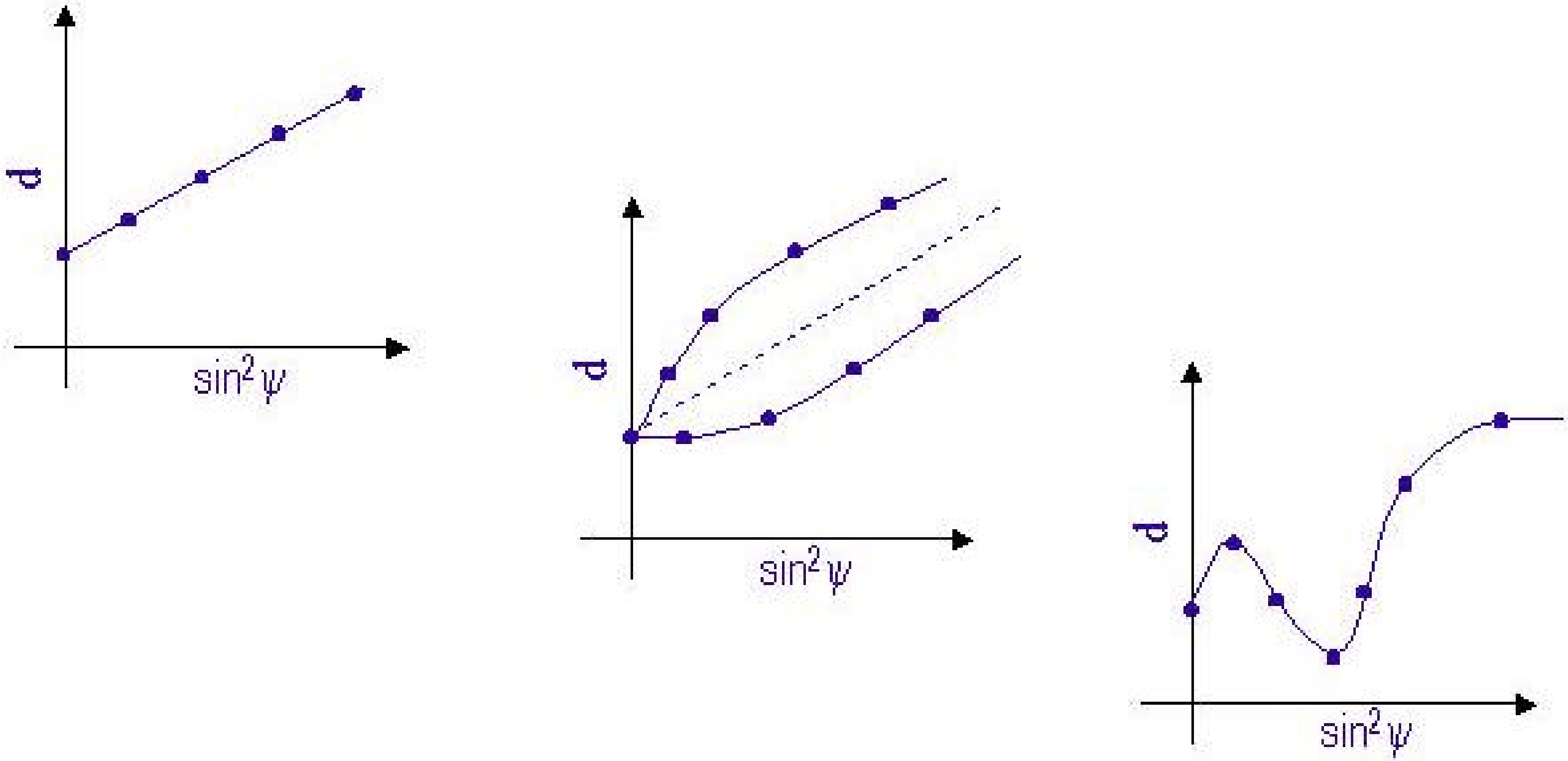




X-Ray Diffraction Stress Measurements

- Depth profiling corrections
  - Stress Gradient corrections
  - Layer removal correction

Examples of d-spacing Versus $\sin^2\psi$ Plots



Monitor and Control Quality of Many Processes

- Shot Peening
- Grinding
- Heat Treating
- Plating
- Welding
- Forging

Aerospace Applications

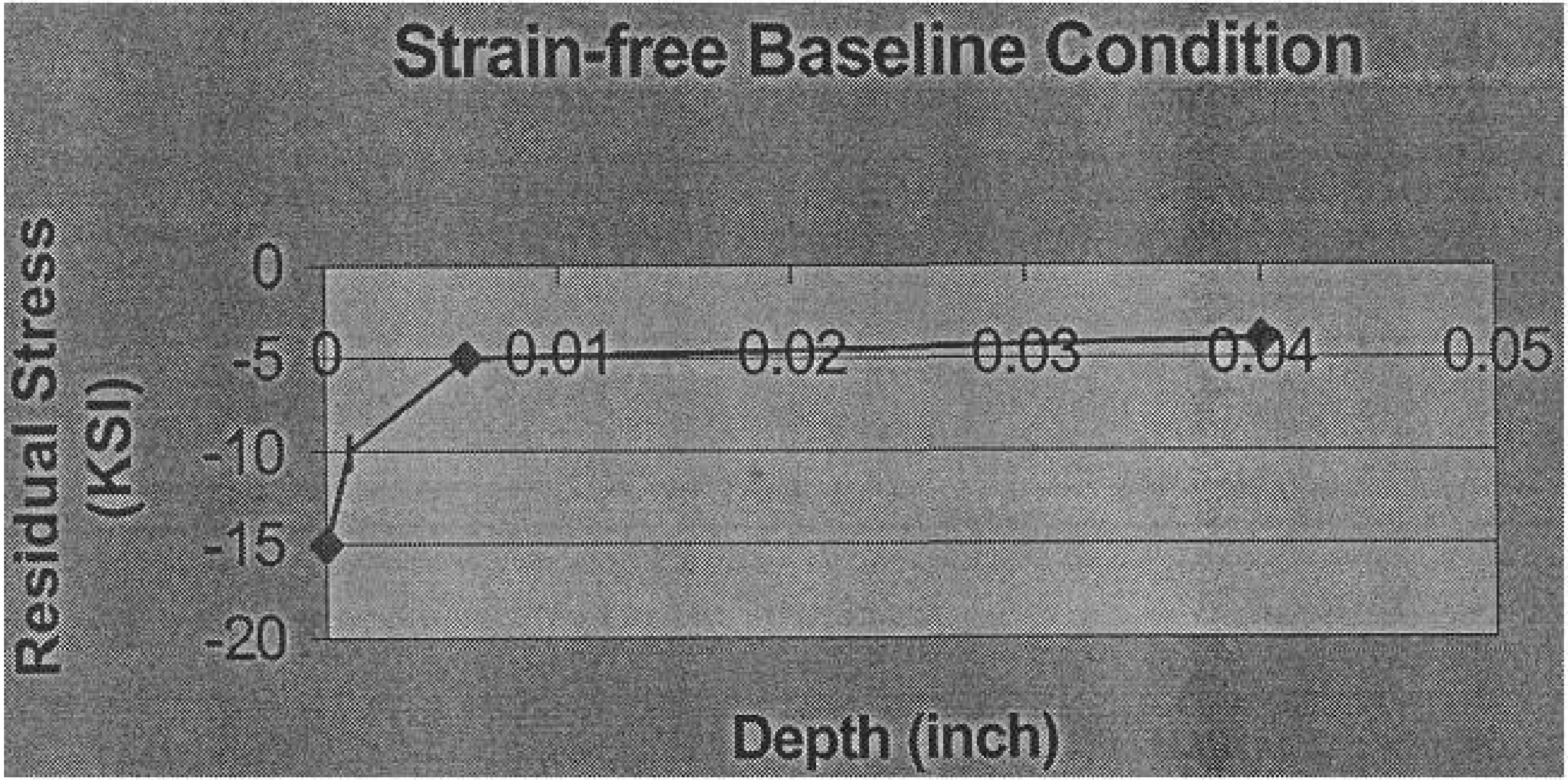
- Engine Components
  - Fan Blades, Compressor Blades, Turbine Blades, Disks, Diffusers, Bearings, Propeller Blades
- Rocket Monitor Cases
- Structures
  - Landing Gears, Skins, Wheels, Bulkhead, Wing Spars

The TEC 4000 X-Ray Diffraction System

Materials Testing Division TEC

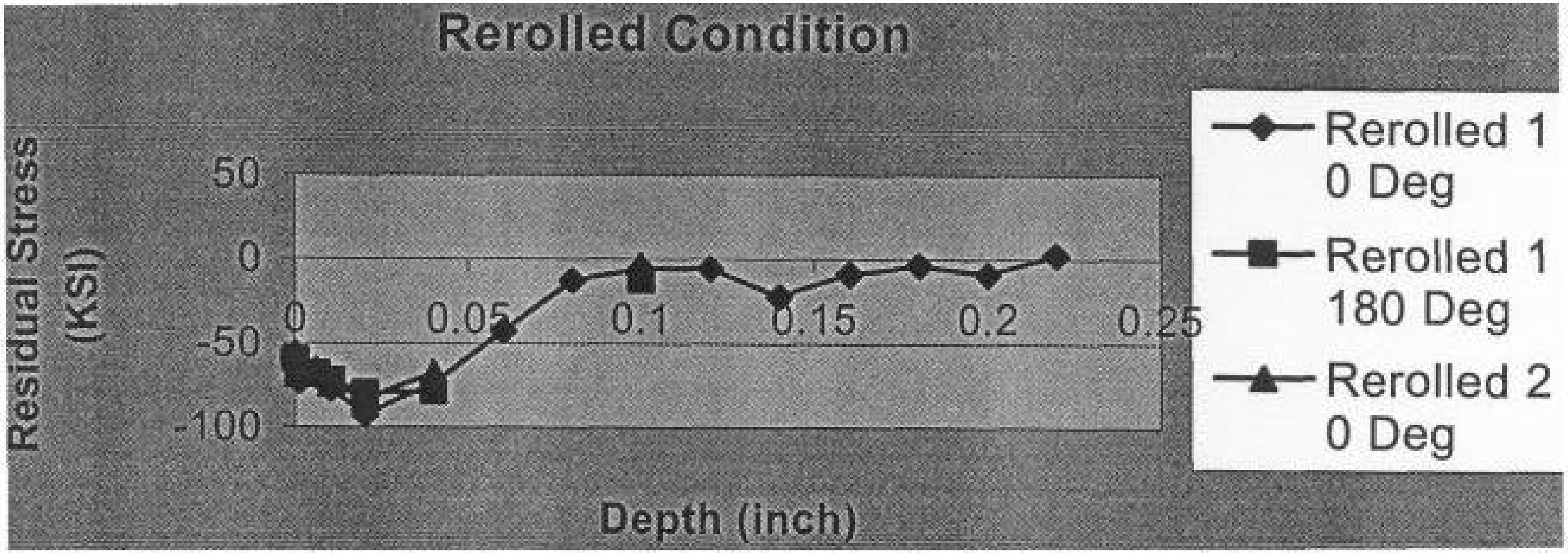
Results

Residual stress profile in strain-free baseline propeller blade sample.



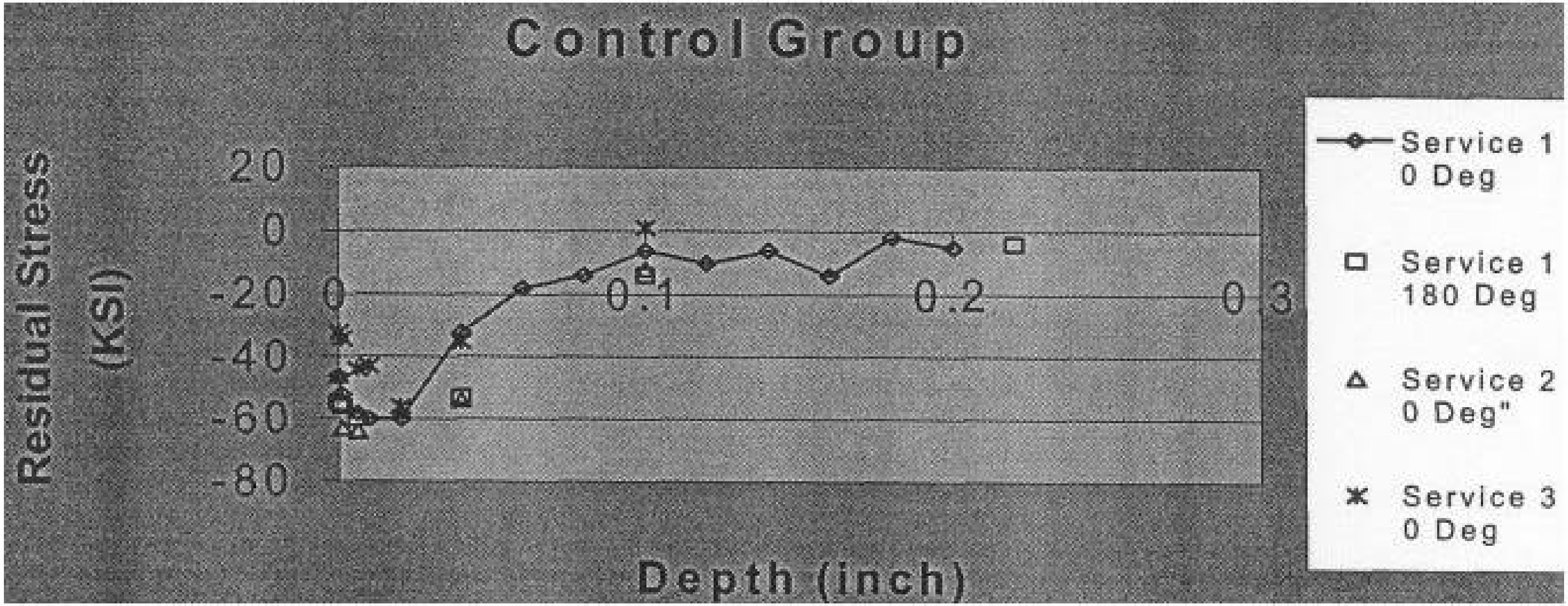
Results

Residual stress levels after cold rolling, as measured in the shank



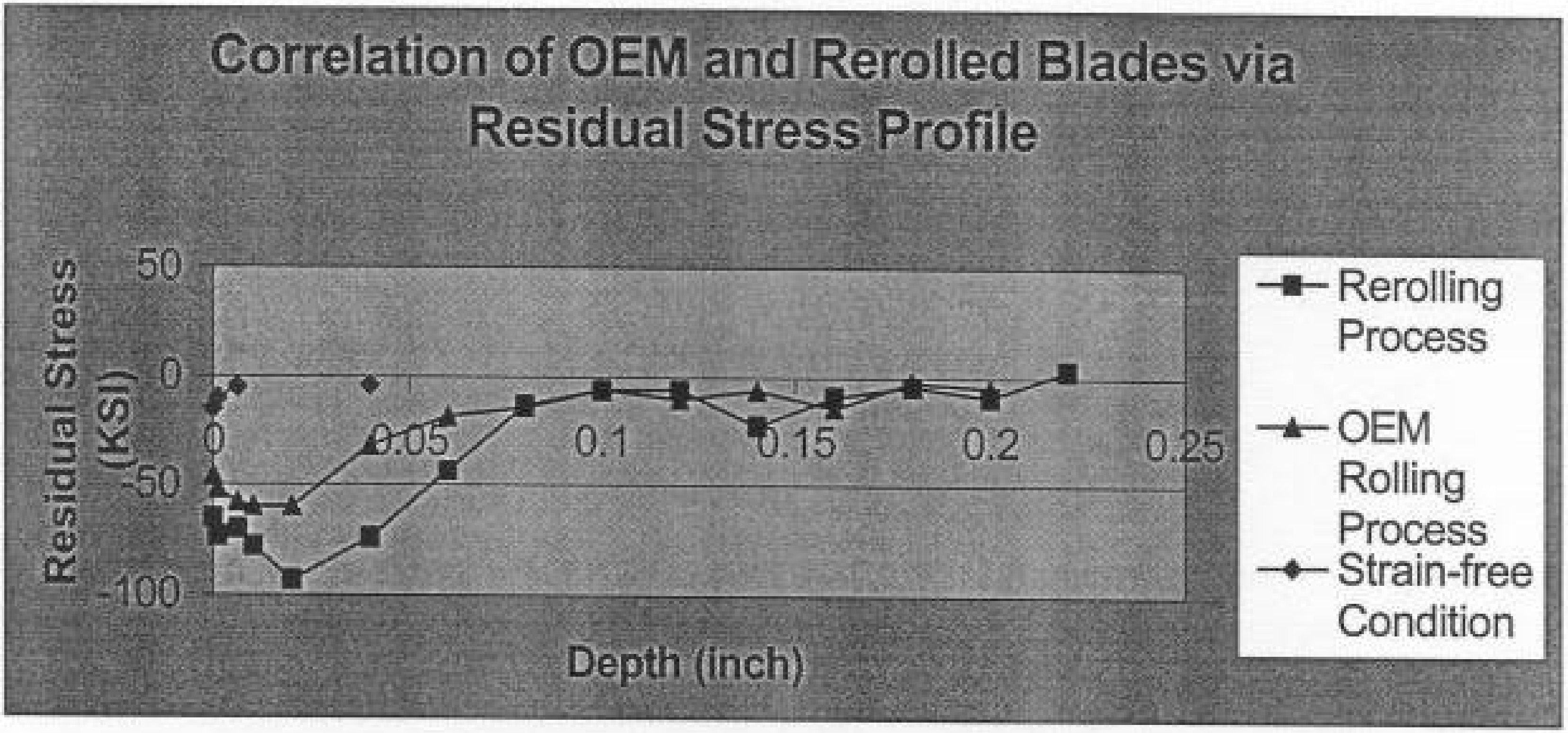
Results

Residual stress profiles of the group of OEM-rolled service blades



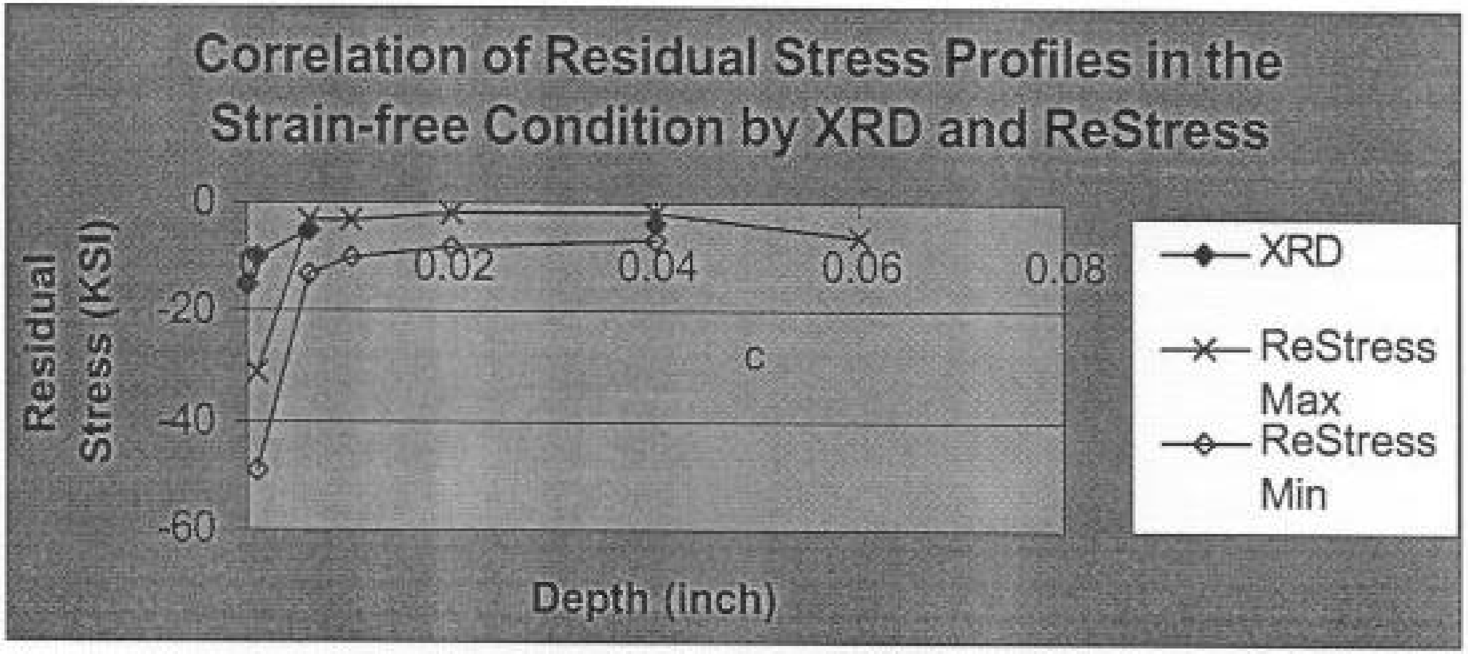
Results

Comparison of residual stress profiles resulting from organic rerolling and OEM rolling



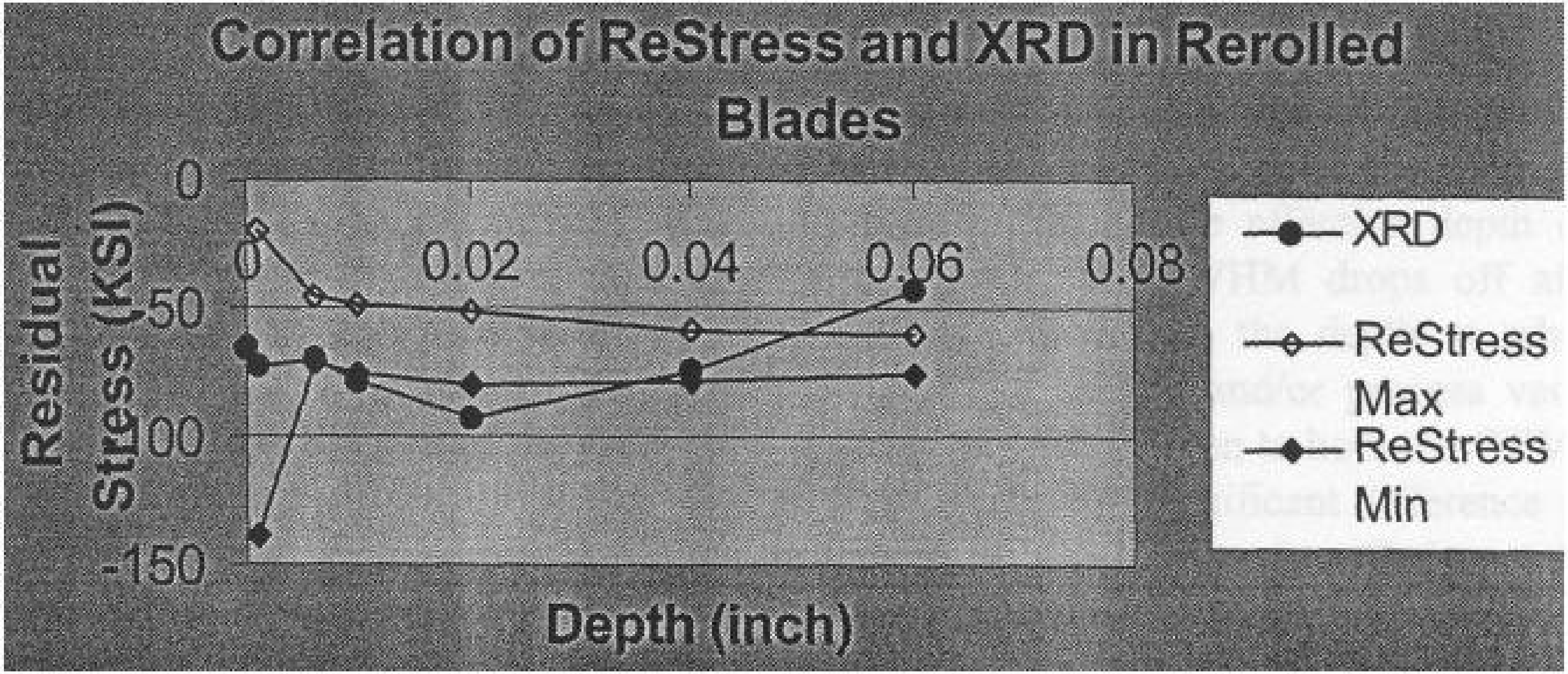
Results

Correlation of principle residual stresses by x-ray diffraction and equivalent uniform stresses by Restress in the strain-free case



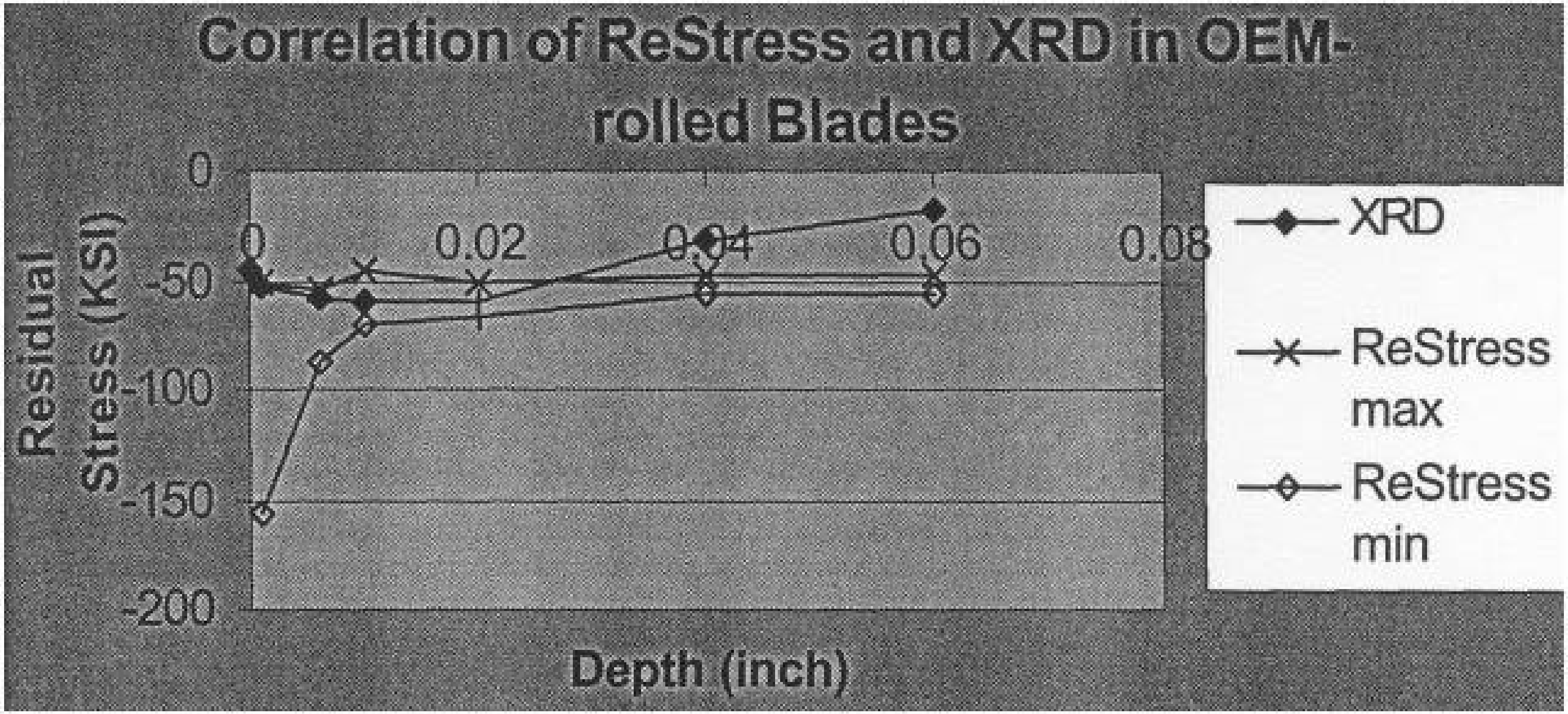
Results

Correlation of principle residual stresses by x-ray diffraction and equivalent uniform stresses by Restress in the re-rolled case

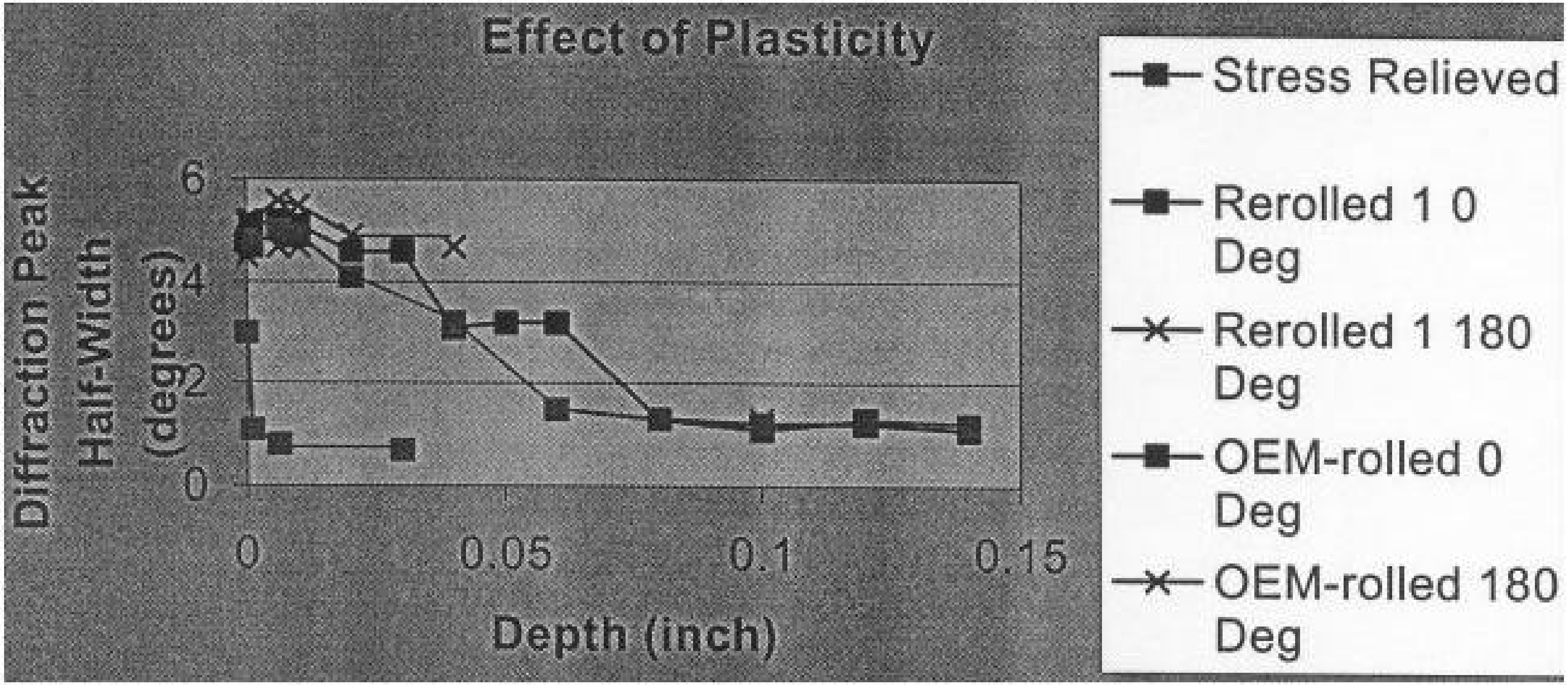


Results

Correlation of principle residual stresses by x-ray diffraction and equivalent uniform stresses by Restress in the OEM-rolled case

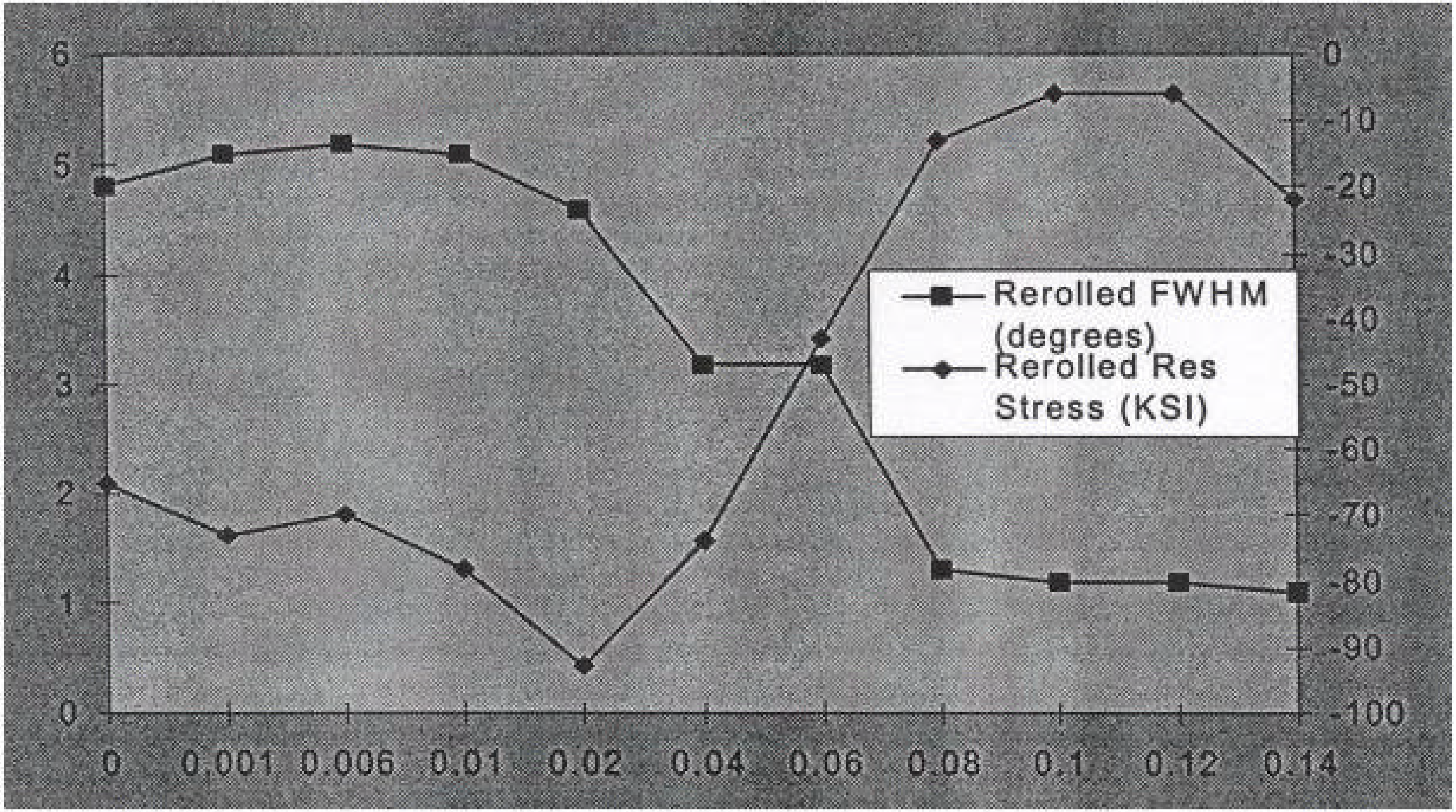


Results
Depth of plasticity in rerolled and OEM-rolled conditions



Results

Correlation of Residual Stress and Diffraction Peak Width Profiles



Conclusions

- Due to severity of service conditions, beneficial compressive stresses can be induced by rolling propellers during manufacturing
- Blades can be rerolled to restore beneficial stresses that fade during service
- Stress levels at and through the surface can be determined by x-ray diffraction