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Residual Stress Measurements in Automotive Components via X-Ray Diffraction

F. Cuccia

Proto Mfg. Inc. Taylor, MI USA

www.protoxrd.com

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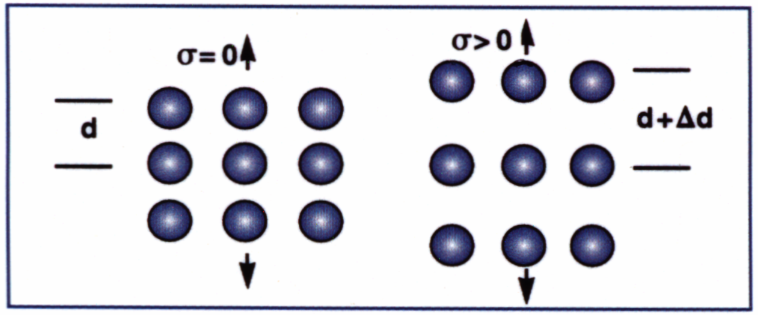
Introduction to XRD

How X-ray Diffraction works

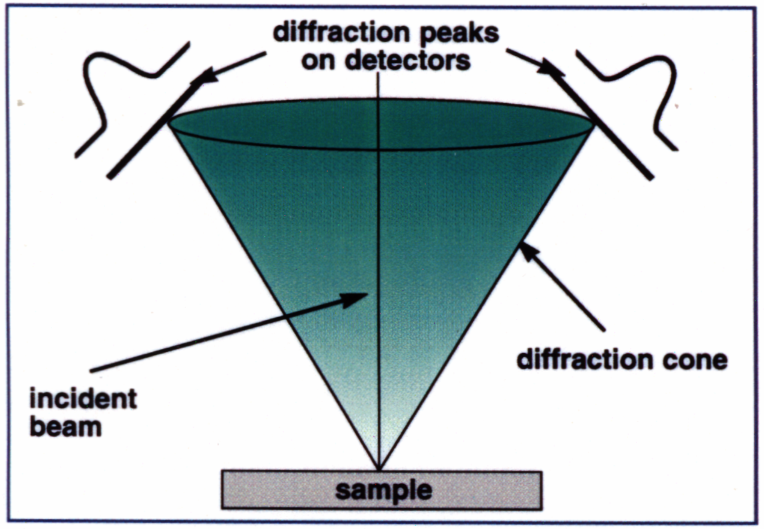
- Soft x-rays constructively interfere with the crystals in the material

- The diffraction "cone" angle "θ" varies with change in "d" to strain as per Bragg's Law:

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



Changes in stress cause changes in atomic lattice spacing "d".



Elasticity - Hooke's Law

Elasticity

- Hooke's law (1D):

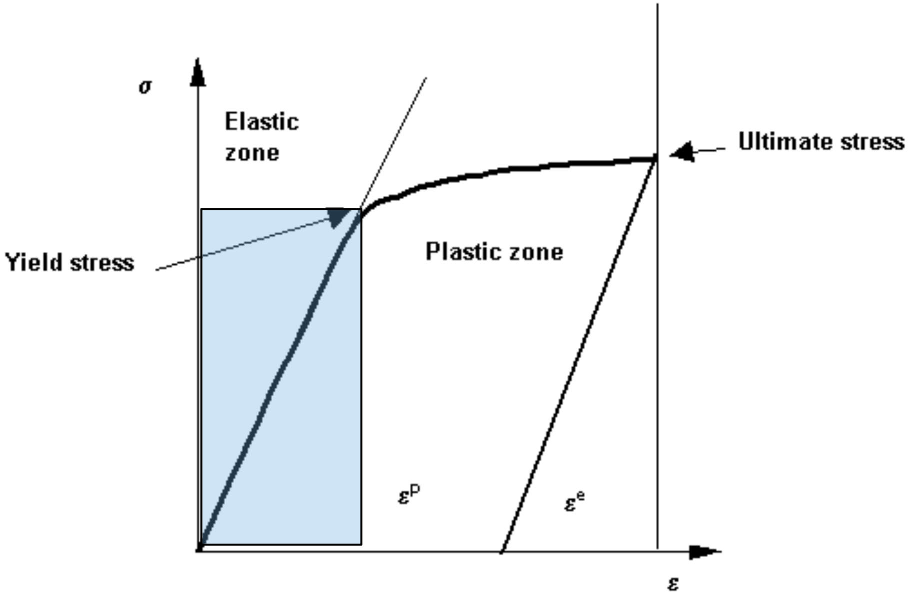
$$\sigma = E\varepsilon$$

E: Young's modulus

$$\sigma_{11} = E\varepsilon_{11}$$

$$\frac{\varepsilon_{22}}{\varepsilon_{11}} = \frac{\varepsilon_{33}}{\varepsilon_{11}} = \nu, \varepsilon_{22} = \varepsilon_{33} = -\frac{\nu}{E}\sigma_{11}$$

The loading is reversible



Stress – Strain curve

- Hooke's law (3D) :

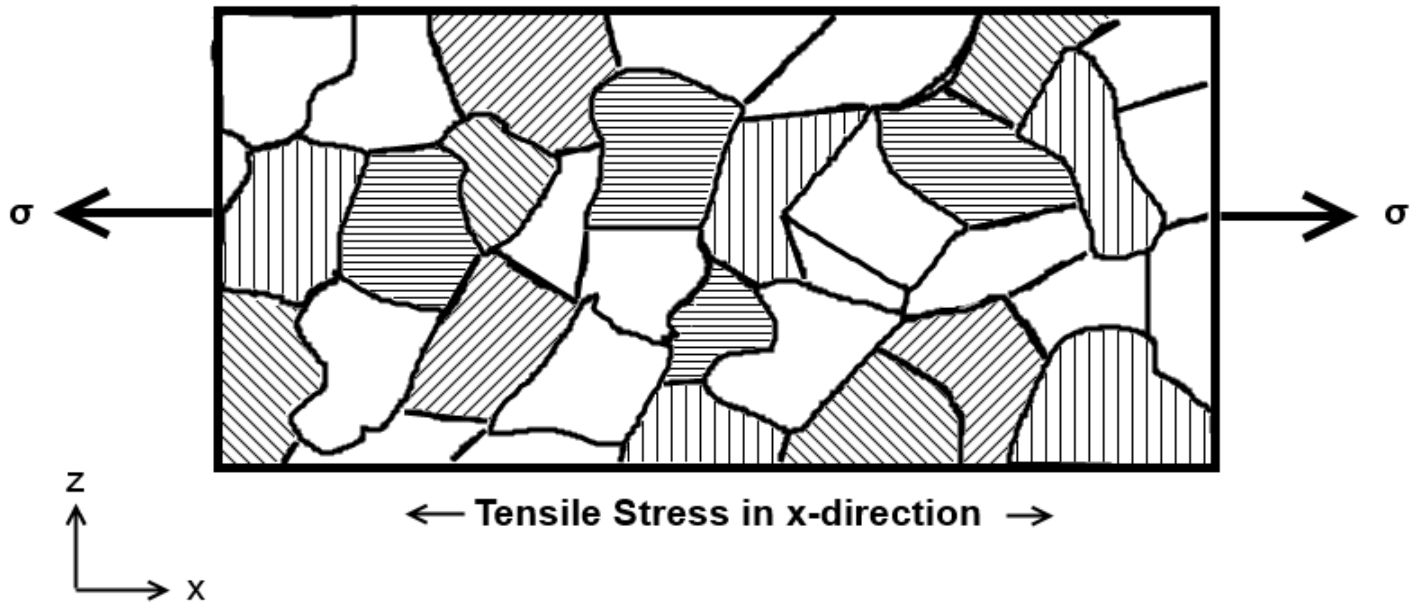
$$\varepsilon_{ij} = \frac{1+\nu}{E}\sigma_{ij} - \delta_{ij}\frac{\nu}{E}\sigma_{kk}$$

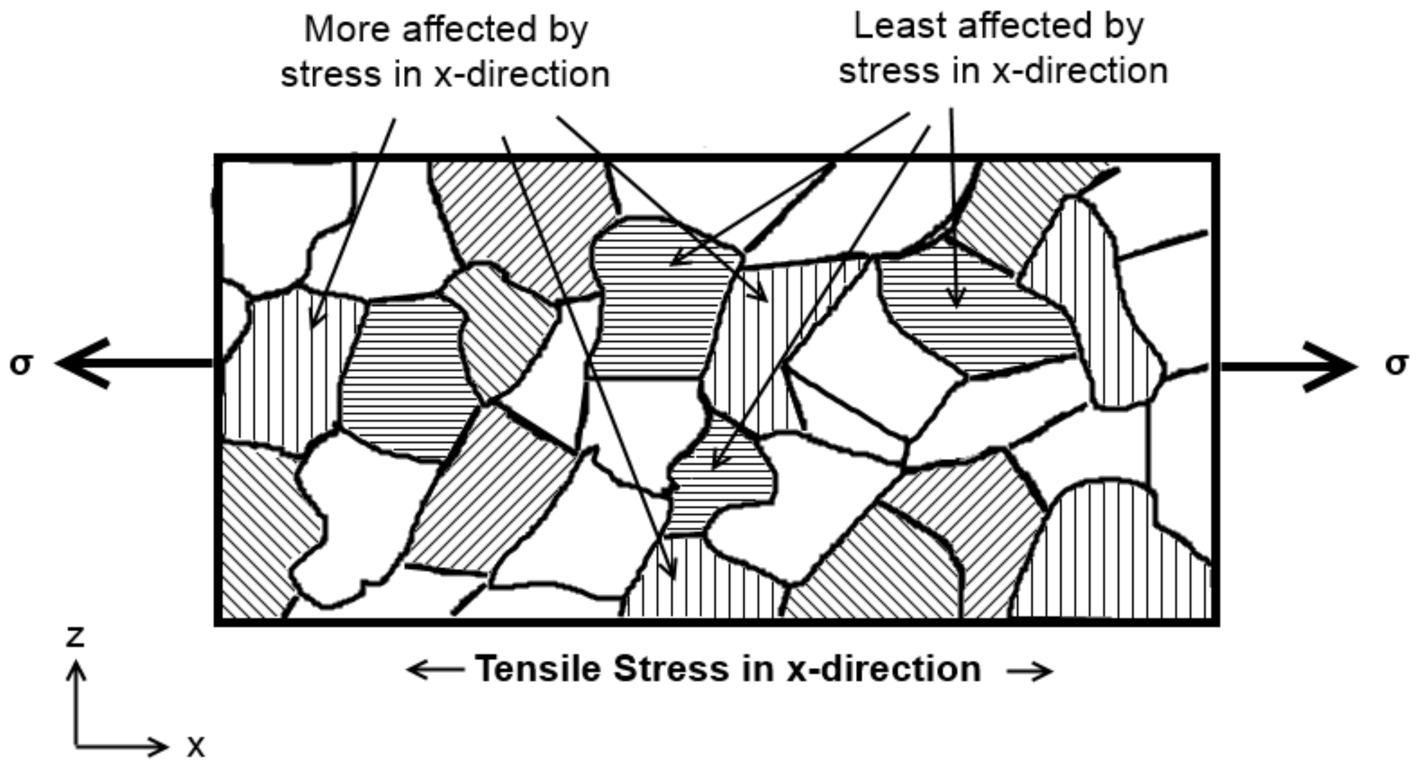
$d_{ij}=0$ if $i \neq j$, $d_{ij}=1$ if $i = j$

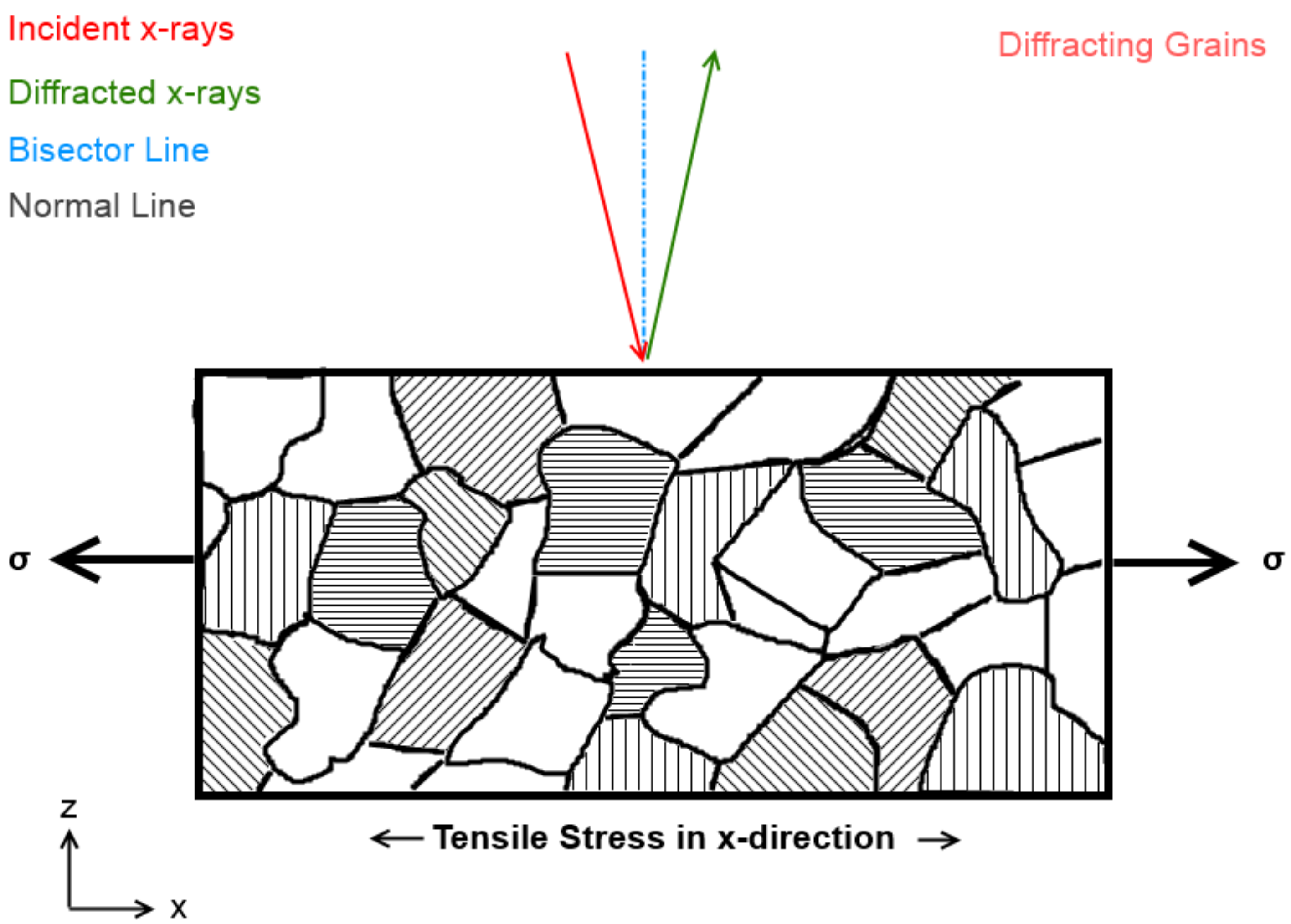
Technique Requirements

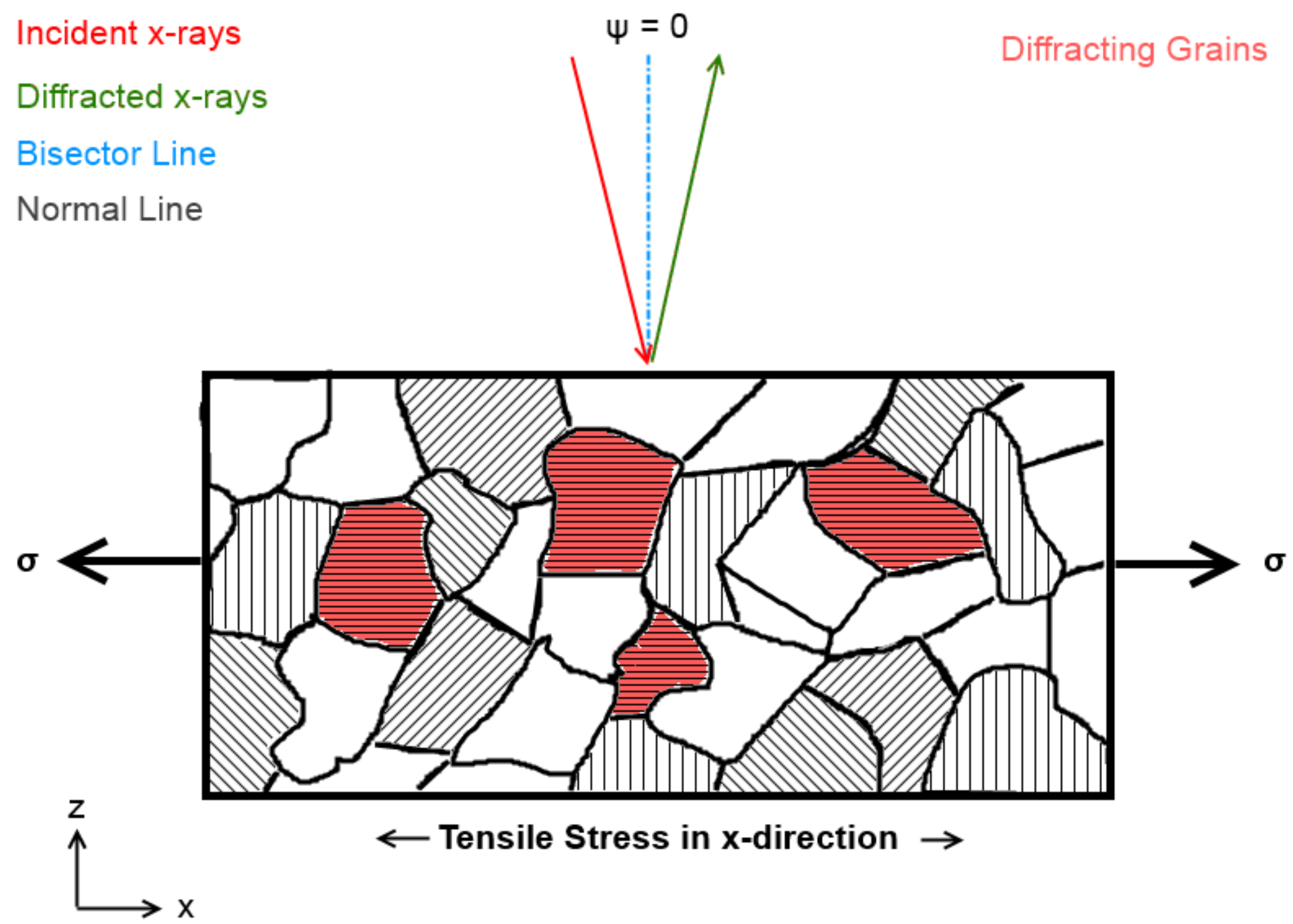
- Material must be crystalline or poly-crystalline.
- Requires “Line of Sight” access to measurement surface.
- Parts can be typically measured as is, heavy combustion byproducts should be alkaline cleaned. No mechanical cleaning techniques should be applied as they may alter the residual stress.
- Requires competent operator, technician level and above. (Proto offers training programs)

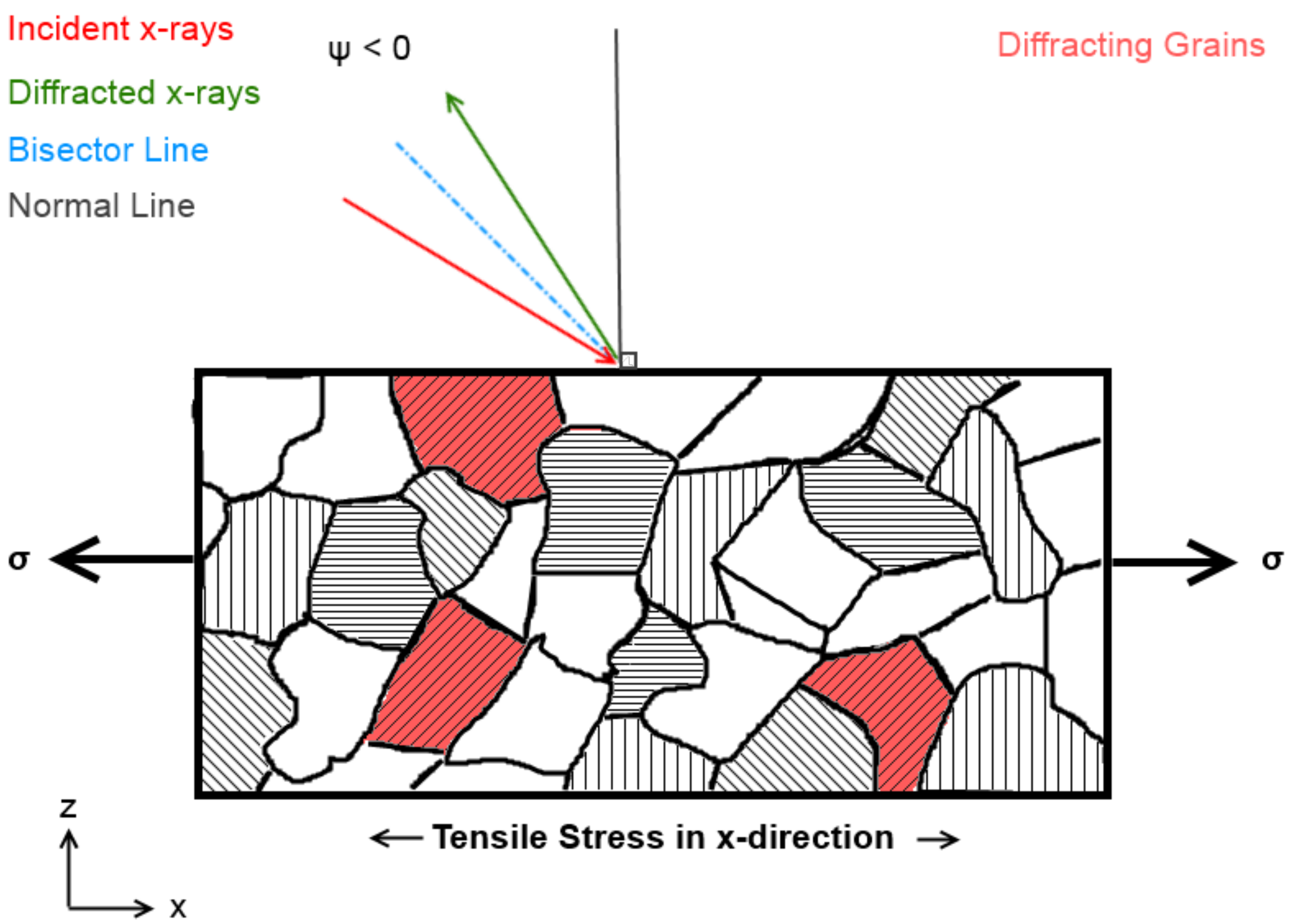
Cross Section of Material

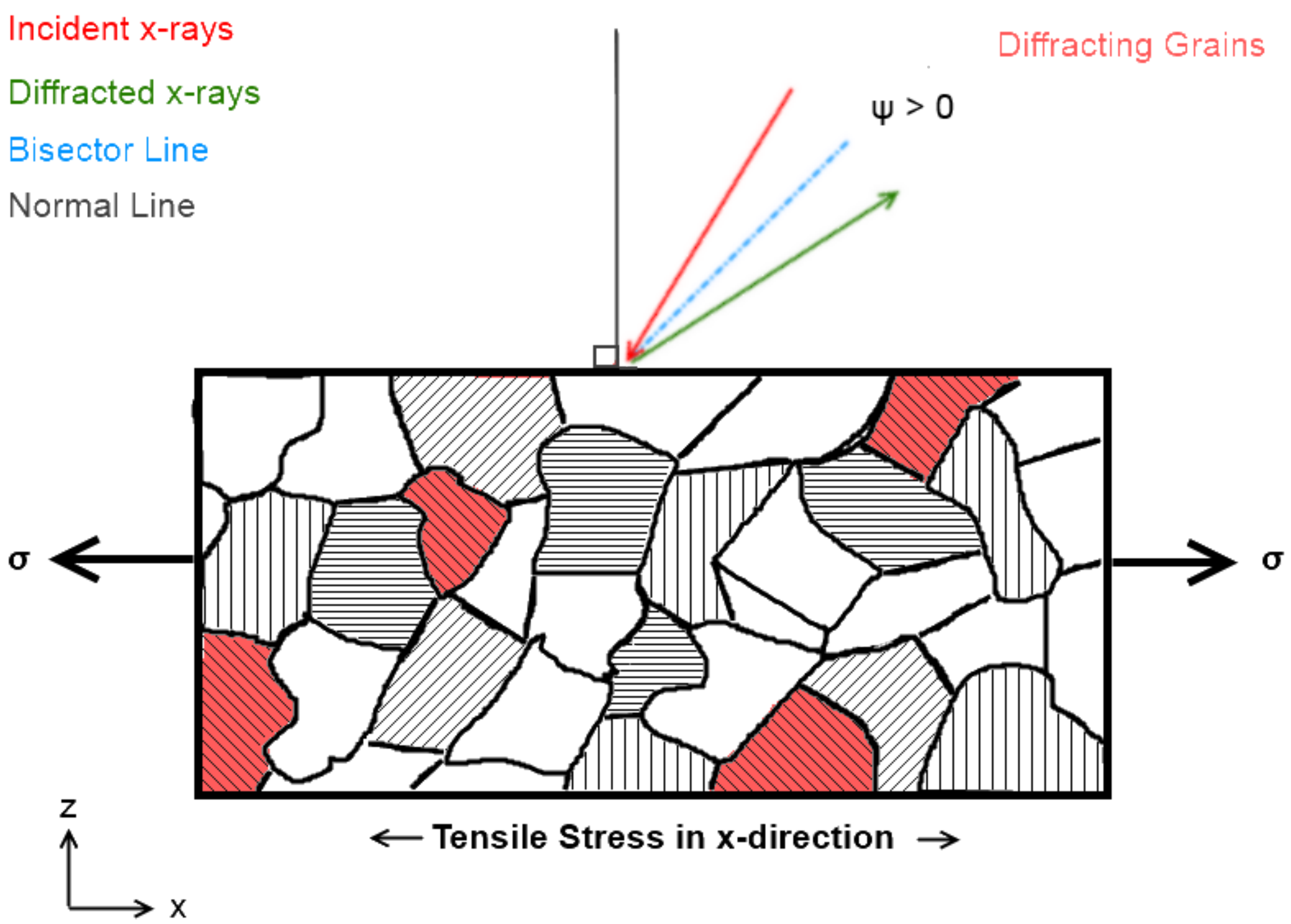



More affected by
stress in x-direction
Least affected by
stress in x-direction
σ
σ
Tensile Stress in x-direction
z
x

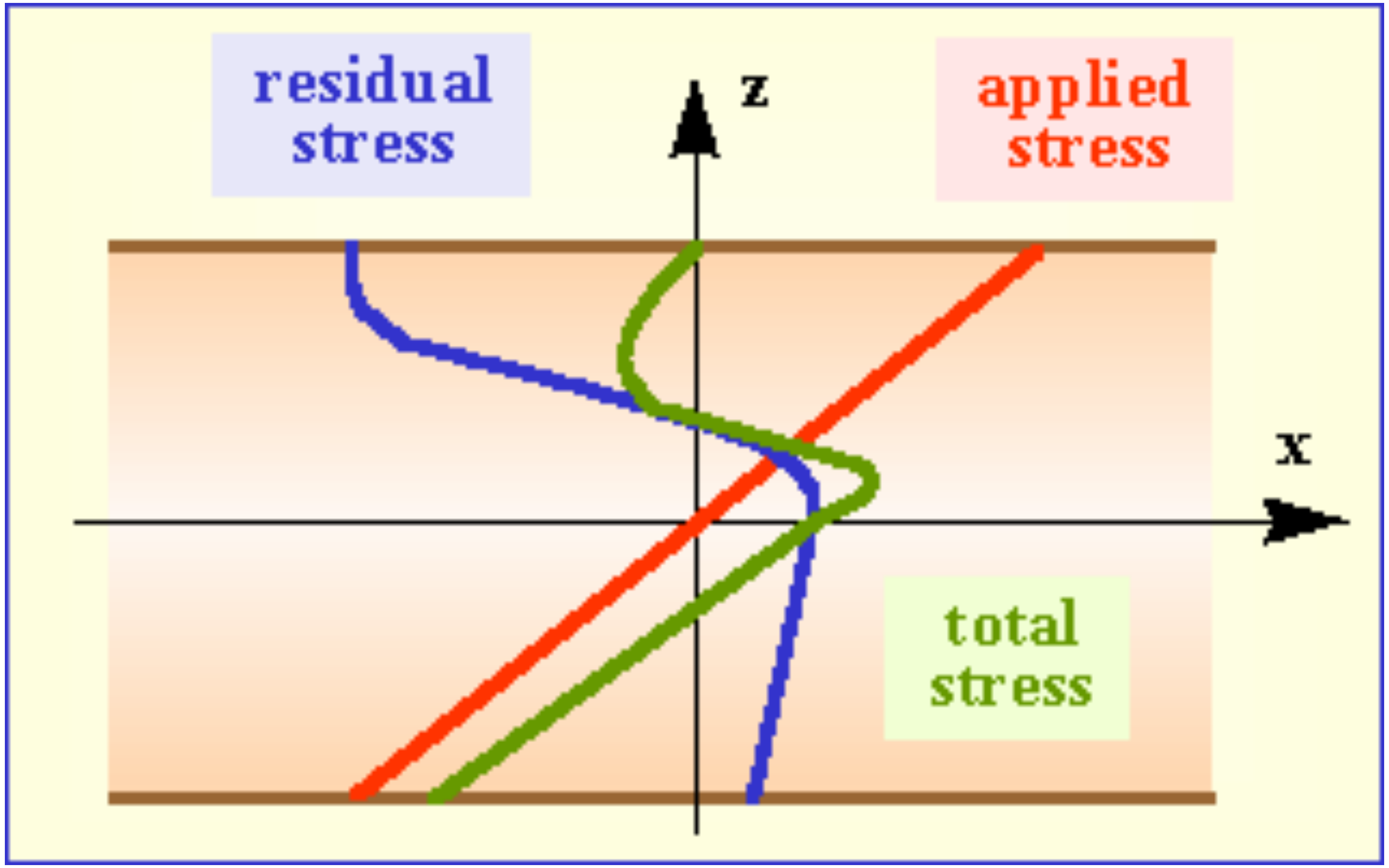

Incident x-rays
Diffracted x-rays
Bisector Line
Normal Line
Diffracting Grains
σ
σ
Tensile Stress in x-direction
z
x


Incident x-rays
Diffracted x-rays
Bisector Line
Normal Line
ψ = 0
Diffracting Grains
σ
σ
Tensile Stress in x-direction
z
x


Incident x-rays
Diffracted x-rays
Bisector Line
Normal Line
ψ < 0
Diffracting Grains
σ
σ
Tensile Stress in x-direction
z
x


Incident x-rays
Diffracted x-rays
Bisector Line
Normal Line
Diffracting Grains
ψ > 0
σ
σ
Tensile Stress in x-direction
z
x

Total Stress = Residual + Applied



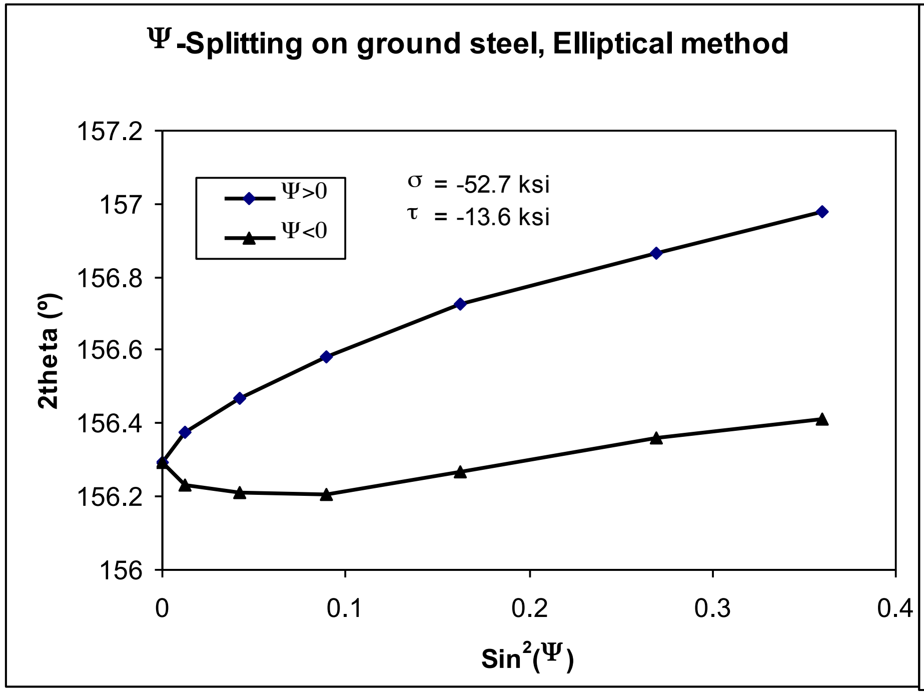
Validation: Standards & Guidelines

- SAE HS784 – RS measurement
- ASTM E2860 – RS measurement
- ASTM E915 – RS Instrument Alignment
- ASTM E1426 – 4 pt bend to determine XEC
- ASM Handbook Vol.11 – General guidelines

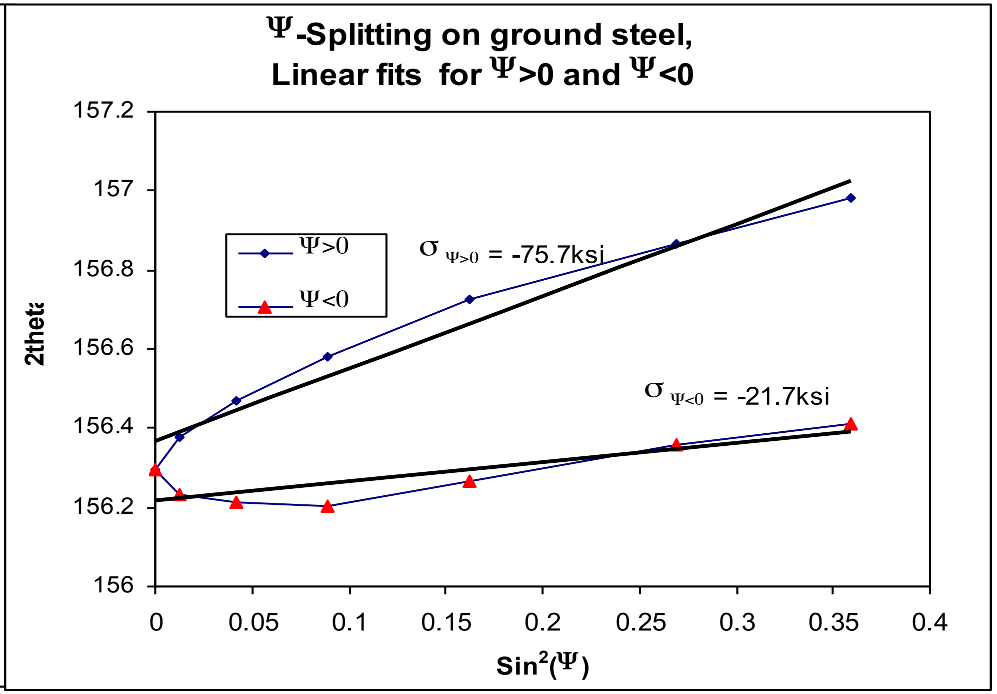
5 Steps to Data Confidence

1. Alignment of XRD instrument ASTM E915.
2. X-ray elastic constant determination ASTM E1426.
3. Surface condition evaluation.
4. Collection parameter selection (optimization).
5. Repeatability and reproducibility determination.

In the presence of shear stress the elliptical method **must** be used



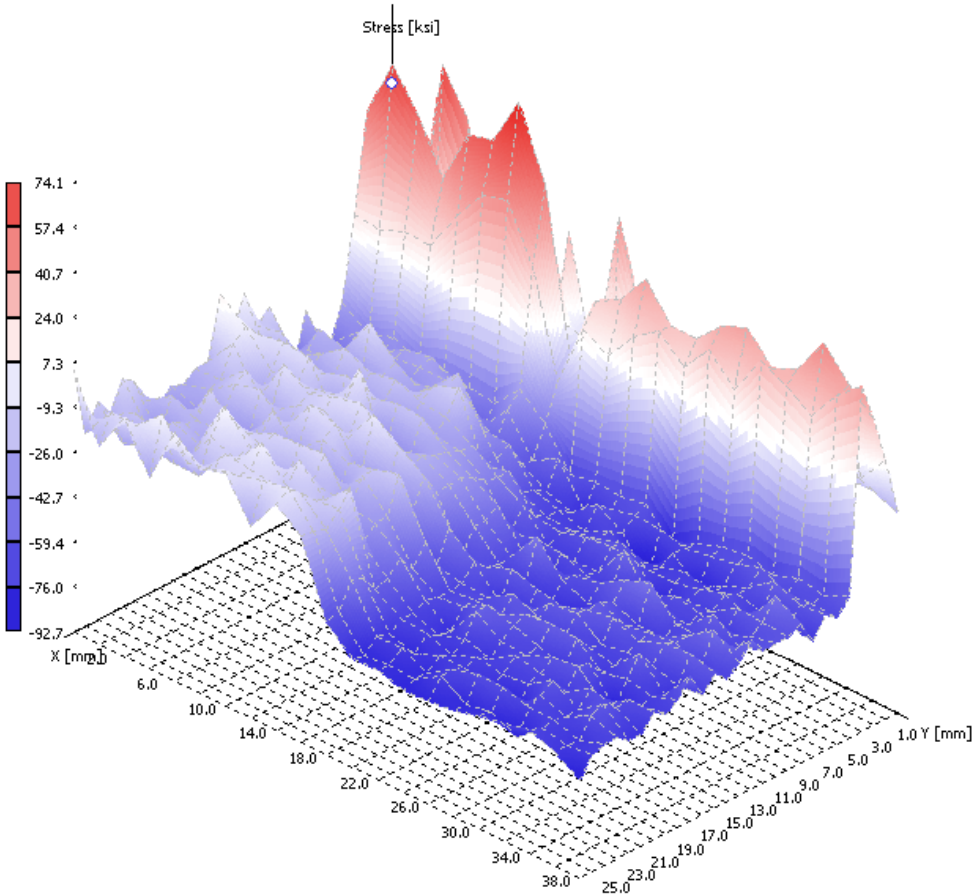
Correct

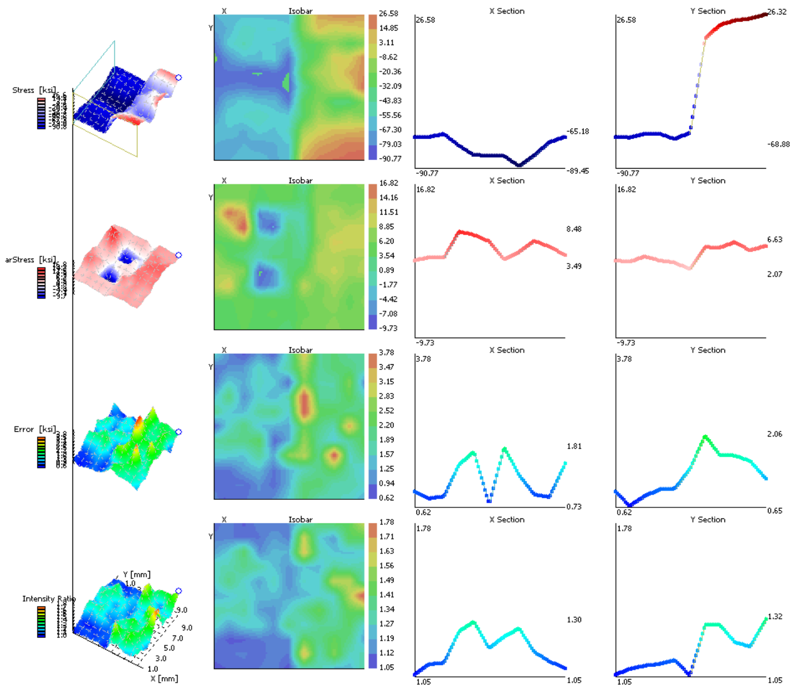


Incorrect

Automated Stress Mapping

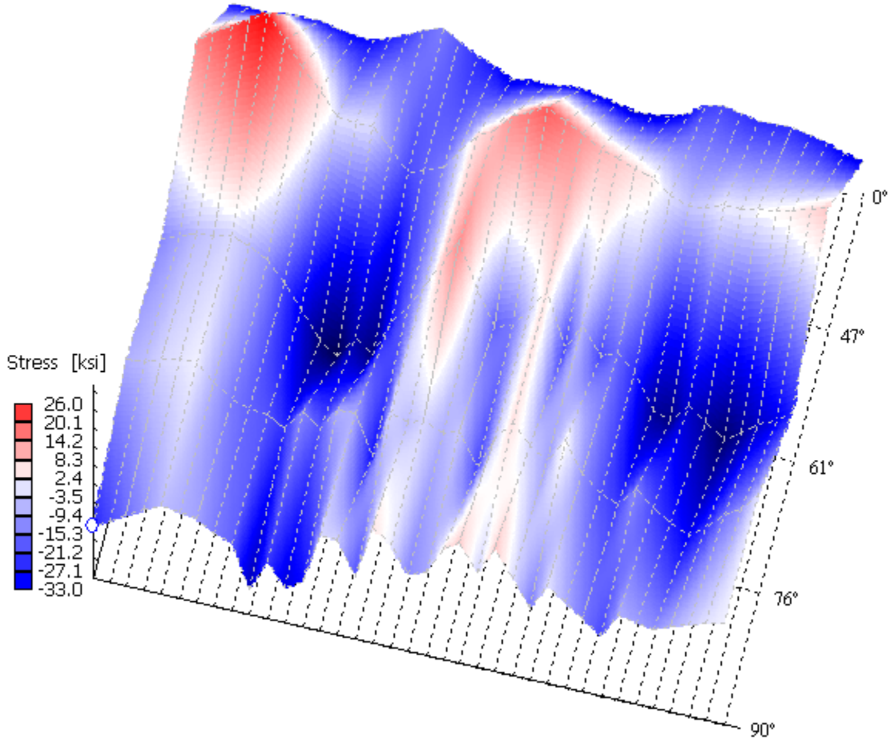
Multiple Map Analysis

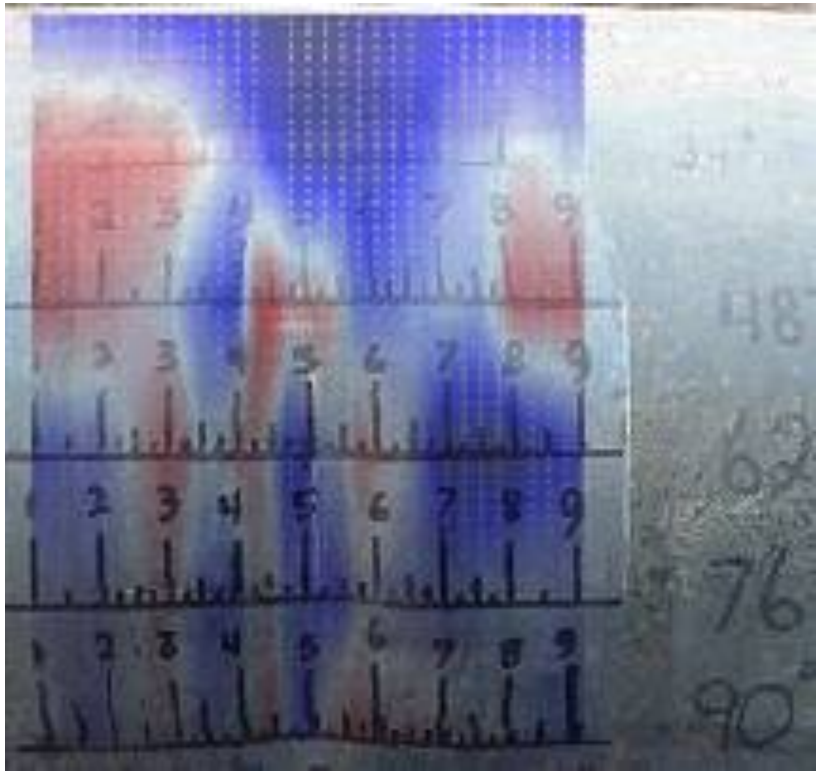




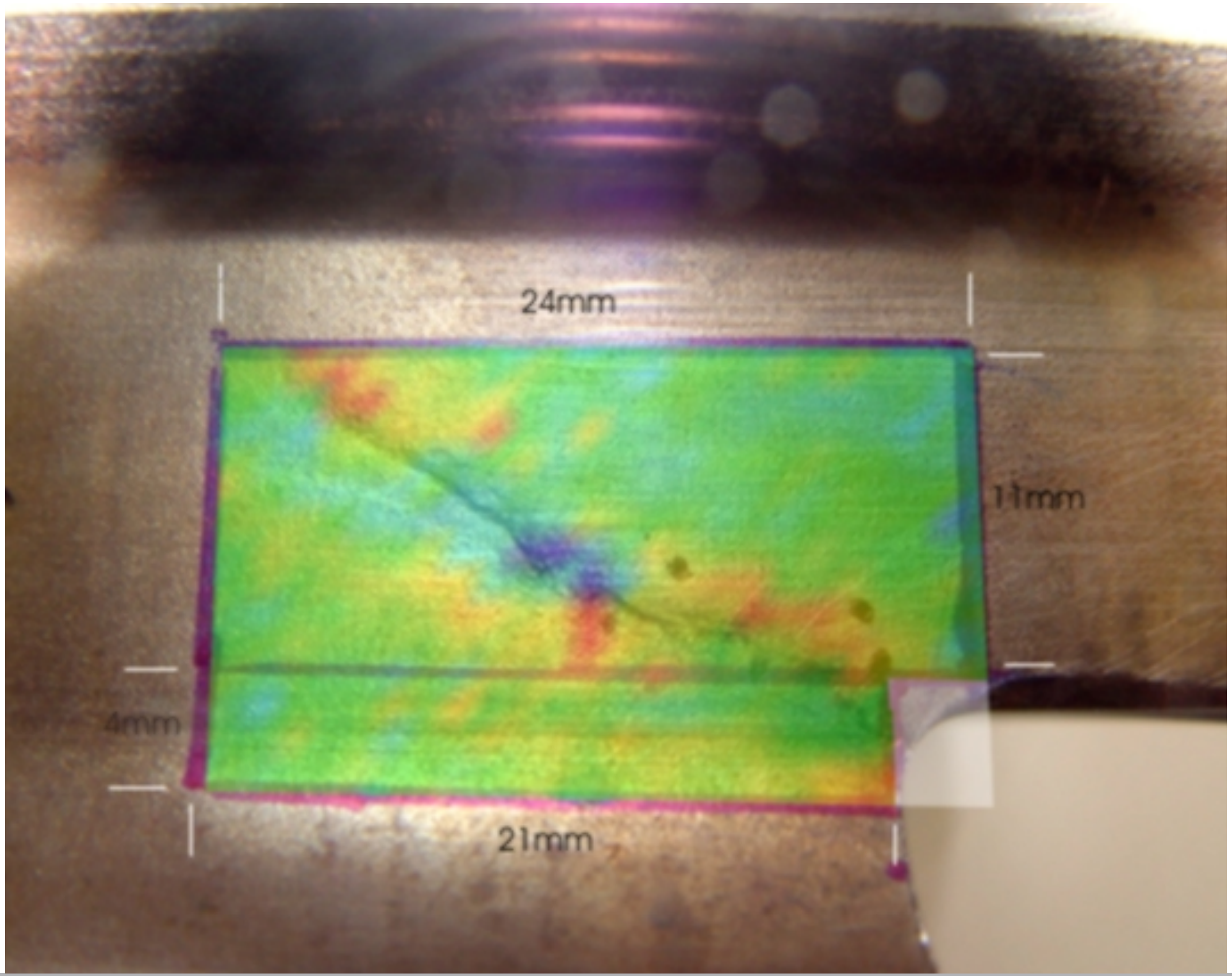
Surface Bending - Stress Mapping

- Compressive stresses shown in blue
- Tensile stresses shown in red





Stress gradients <u>must</u> be mapped

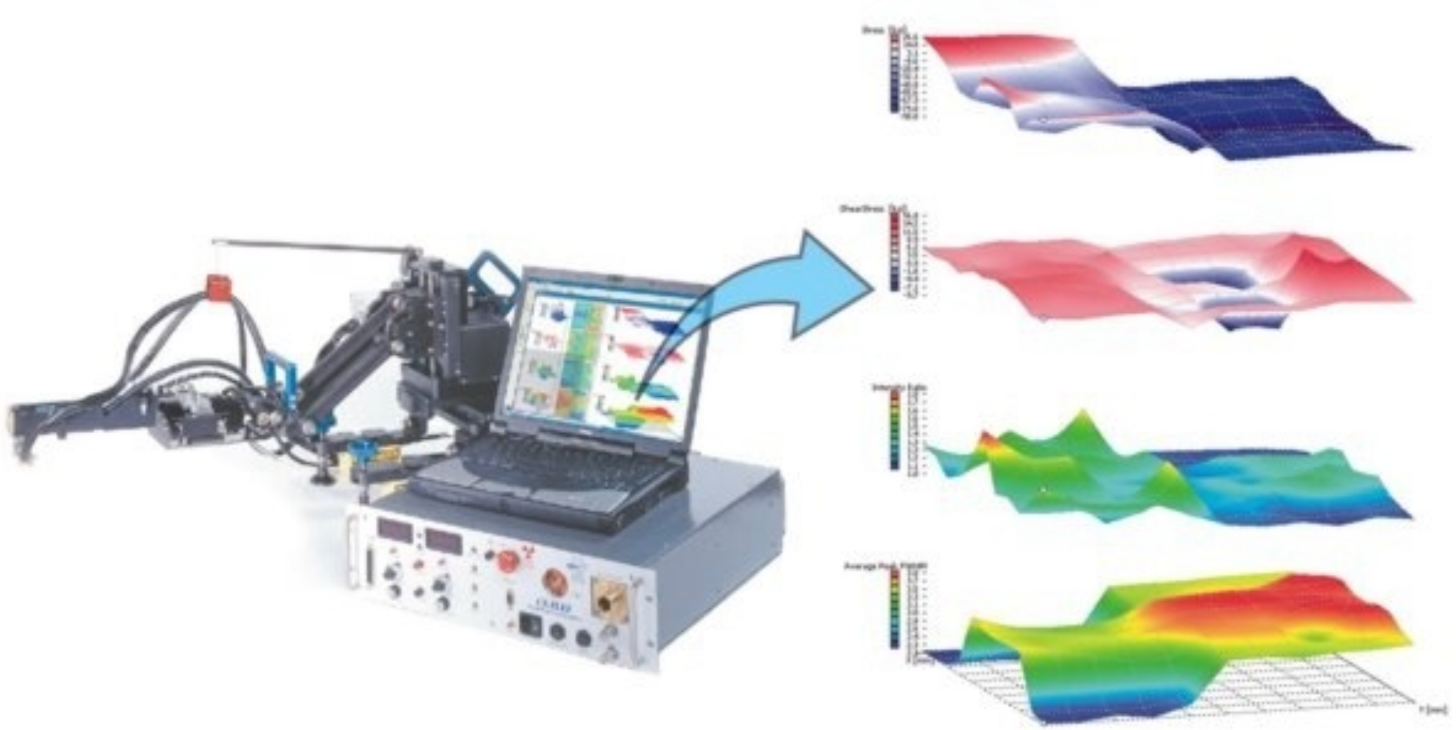


The Equipment

The instrument <u>must</u> suit the job

MG2000		High power x-ray tube system for high speed measurements.
MGR40P		Phi rotation for measuring residual stress in multiple directions without rotating part.
MG15P		To measure inside a 90 mm bore.
MGBH40L		To measure inside small diameter holes.

The instrument must suit the job



The instrument must suit the job

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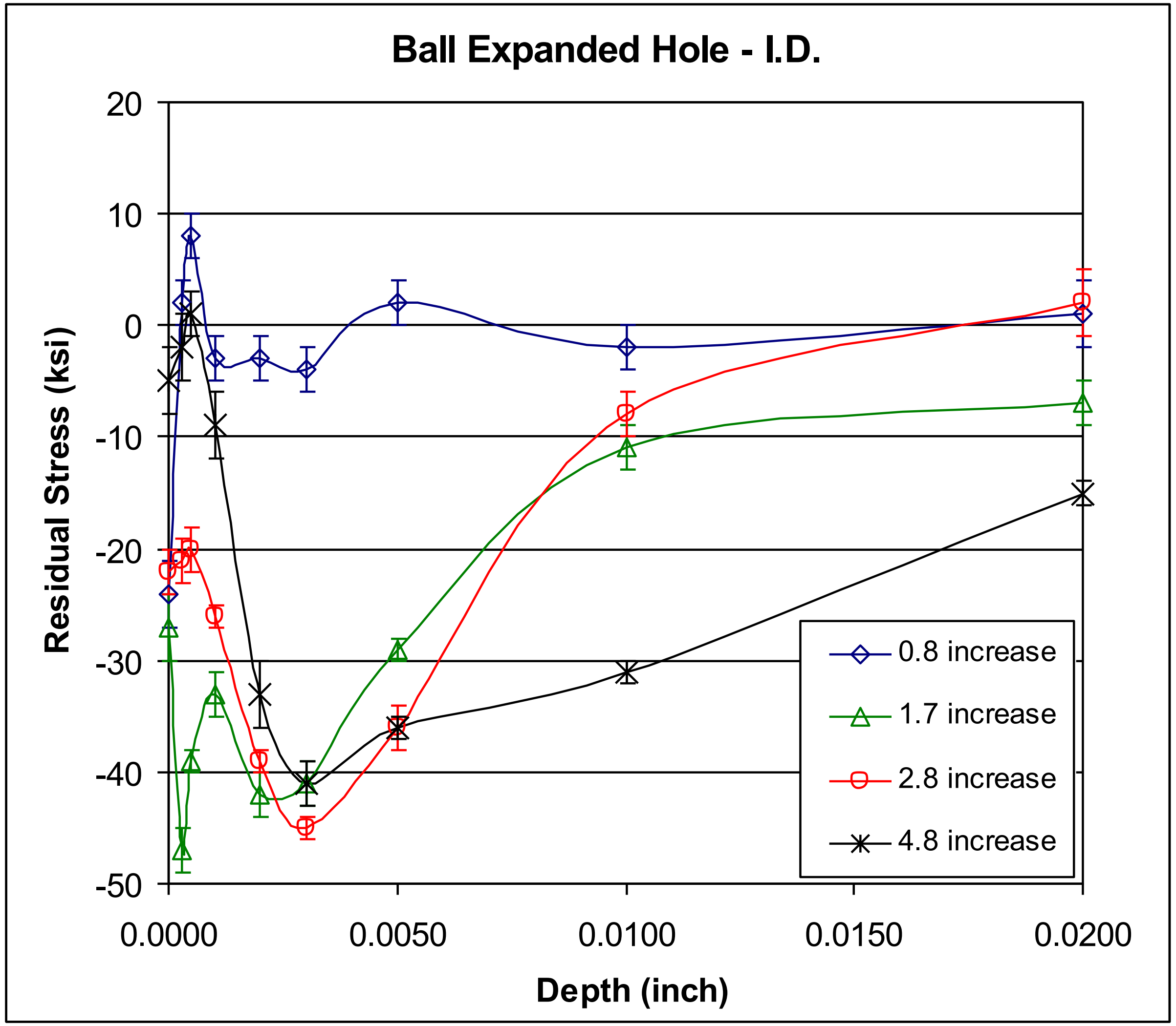
Automotive Applications

Ball Expanded Bolt Hole

Purpose:

- Determine the residual stresses as a result of cold expanding the i.d. of a bolt hole.
- Optimize compressive stress layer by increasing ball diameter.

Ball Expanded Bolt Hole



Ball Expanded Bolt Hole

Conclusions:

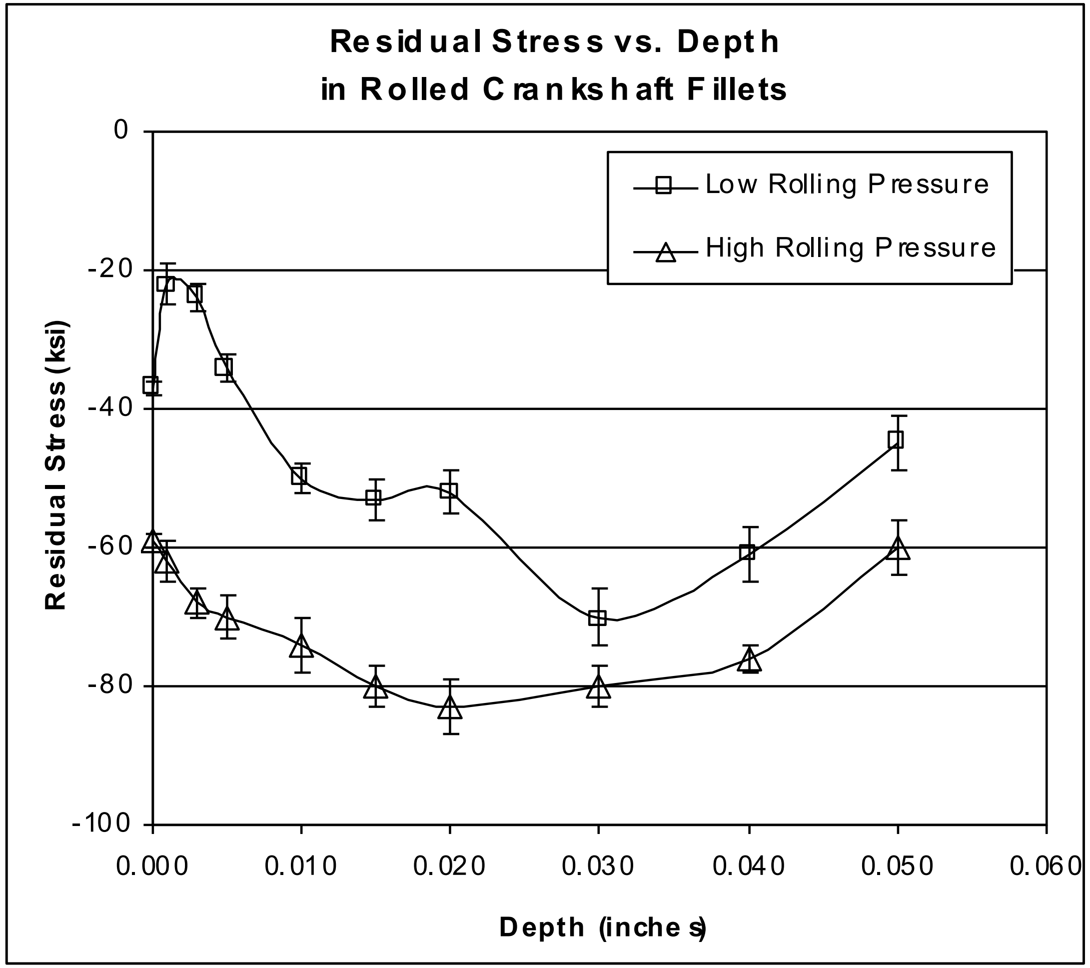
- Stress relief cycle results in low residual stresses.
- 0.8 increase has minimal effect.
- 1.7 increase introduces significant compressive layer.
- 4.8 increase introduces deepest compressive layer and tensile stresses at the surface.

Crankshaft - Rolled fillet radius

Purpose:

- Determine the RS as a result of rolling journal fillet undercut to inhibit the initiation and propagation of fatigue cracks.
- Characterize RS gradients as a function of depth.
- Measure RS at different angles around the circumference to compare rolling pressure variations.

Crankshaft - Rolled fillet radius



Crankshaft - Rolled fillet radius

Conclusions:

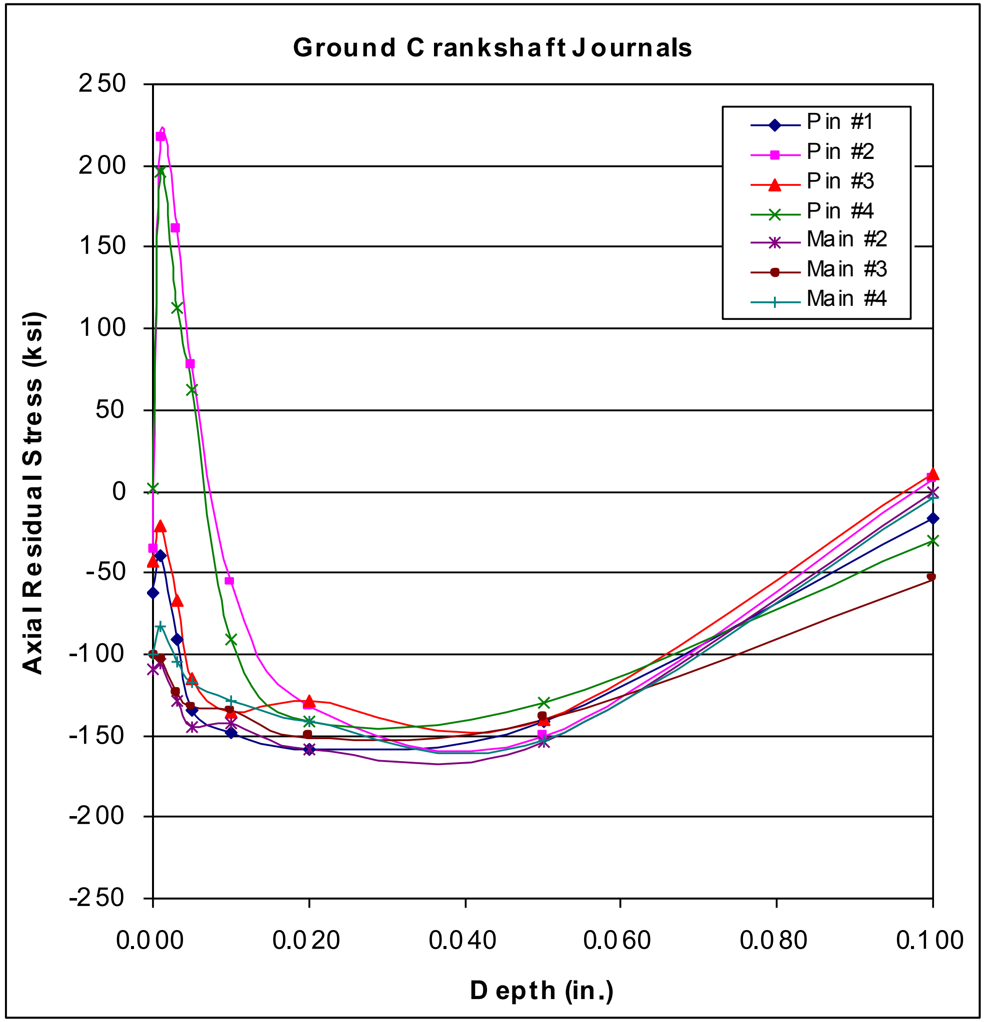
- Rolling can introduce a very deep compressive residual stress layer.
- The magnitude of RS layer varies with rolling pressure.
- The SCF in a concentration geometry can be determined experimentally

Crankshaft - Journal

Purpose:

- Measure RS as a result of final grind to detect grinder burn.
- Characterize RS gradient as a function of depth.
- Measure RS at different angles around the circumference to find variations.
- Optimize grinding parameters

Crankshaft - Journal



Crankshaft - Journal

Conclusions:

- Grinding can introduce very high tensile RS near the surface (grinder burn).

- The RS layer varies with grinding parameters (wheel type, feed, speed, coolant etc…)

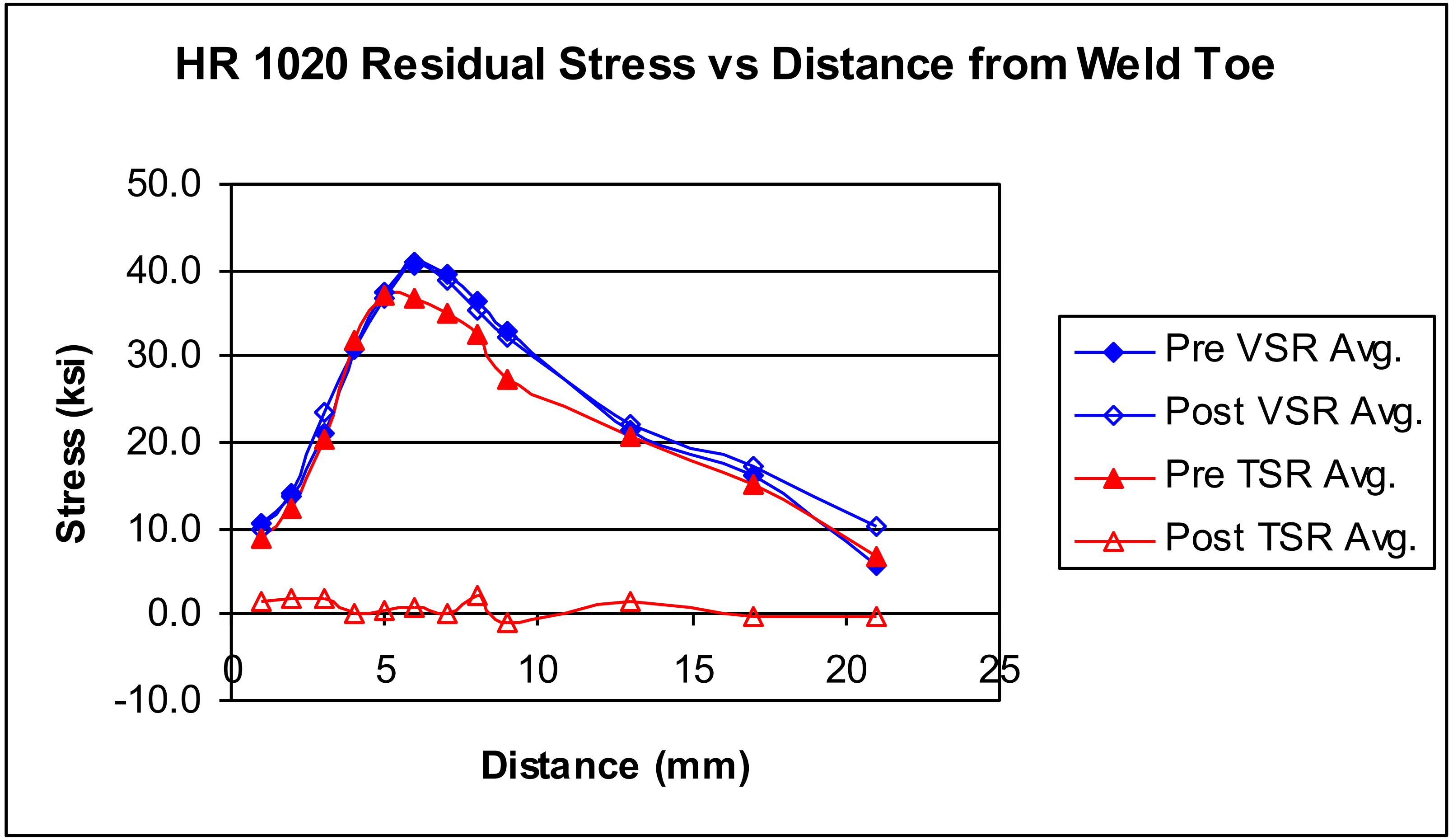
Weldments

Purpose:

- Determine residual stresses introduced by the welding process.

- Evaluate thermal and vibratory stress relief

Compare Effects of TSR and VSR



Weldments

Conclusions:

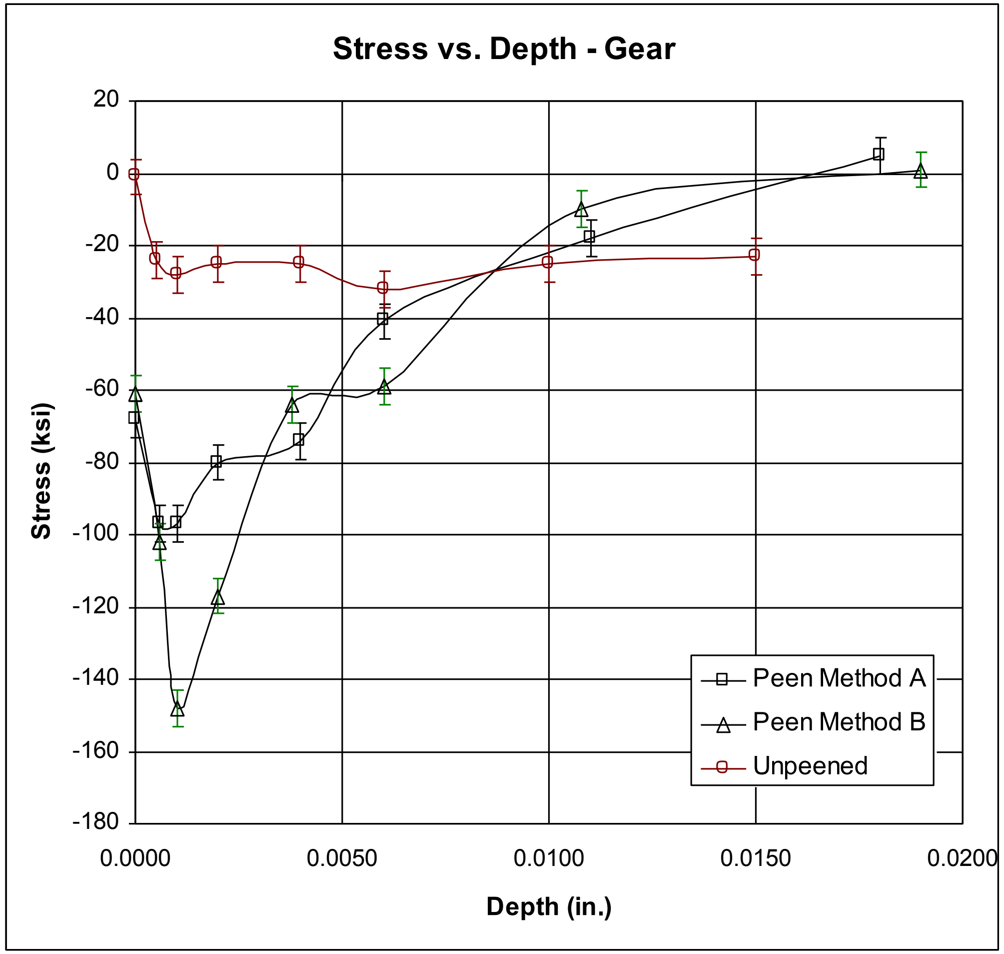
- The welding process introduced significant tensile residual stress in the weld HAZ.
- The thermal stress relief cycle was successful in relaxing tensile residual stresses due to welding.
- The vibratory stress relief did nothing.

Gears - Effects of Peening

Purpose:

- Determine the RS as a result processing prior to peening.
- Characterize RS gradients as a function of depth.
- Compare the RS due to different levels of peening and prior processing.

Gears - Effects of Peening



Gears - Effects of Peening

Conclusions:

- Peening can introduce a deep compressive residual stress layer.

- The magnitude of RS layer varies with peening parameters.

- The effect of peening can be compared to the baseline.

Summary - What can I do with XRD?

- XRD can be used to measure residual stress in automotive components
- Verify the root cause of failures
- Characterize corrective actions applied
- Enhance FEM designs
- Incorporate mean stress in fatigue predictions
- Incorporate RS in fracture mechanics
- Develop optimum processing
- Implement quality assurance strategy