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Welcome:

X-RAY DIFFRACTION
RESIDUAL STRESS MEASUREMENT OF SHOT PEENED COMPONENTS

ABOUT PROTO

Specializing in in X-ray diffraction systems for over 30 years:

- Residual Stress & Retained Austenite Measurement
- Laue Orientation of Single Crystal Materials
- Powder Diffraction
- X-ray Tubes
- Electropolishers

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Customer Base:

- Over 500 X-ray Diffraction (XRD)systems installed around the world in automotive, aerospace, power generation, marine, military, research & university sectors.

Service Laboratories

- 6 service laboratories with 20 XRD systems available for contract measurement work. Fast turn around time, competitive pricing. (USA, Canada, Japan, India, China, Poland)

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Accreditation:

- ISO/IEC 17025:2005 Residual Stress & Retained Austenite Measurement

Major contributors to following Residual Stress specifications:

- ASTM E915 (major contributor)
- ASTM E1426
- ASTM E2860
- ASM Handbook Vol. 11
- MFN Shot Peening handbook

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Publications:

- Over 70 papers published in peer reviewed journals on residual stress and x-ray diffraction.

Patents:

- Worldwide patents on x-ray diffraction equipment and measurement techniques

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Residual Stress

Finished Component:

- Dimensionally Same
- Alloy / Chemistry Same
- Microstructure Same

Part A : Good

Part B : Fails

Residual Stress Distribution Different

What is residual stress?

• Internal stress distribution locked into a material.

• Present even after all external loading forces have been removed.

• Result of a material obtaining equilibrium after it has undergone plastic deformation.

How does residual stress compare to applied stress?

- **Applied stress** is generated inside a material due to an **external** load. (often measured with a strain gauge).
- **Residual stress** is present **inside** the material regardless of loading.

Units of residual stress?

Force per Unit Area

MPa = Mega Pascals
or
ksi = thousands of pounds per square inch

1 ksi = 6.895 MPa

Stress can be thought of as a kind of pressure

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Defining residual stress at a point.

Stress is a tensor.

Multiple values at a single point

6 independent values.

3 Normal stresses - 3 Shear stresses.

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}$$

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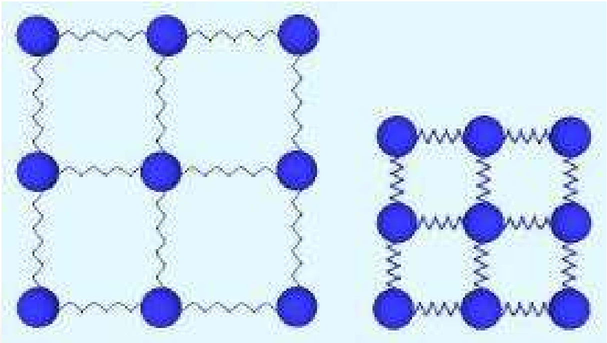
How does residual stress affect a component?

Tensile (+) residual stress or the stress that is causing the material to be stretched or pulled is often detrimental in a component.

Compressive (-) residual stress or the stress that is causing a material to be compacted or pushed together is often beneficial in a component.

Tensile



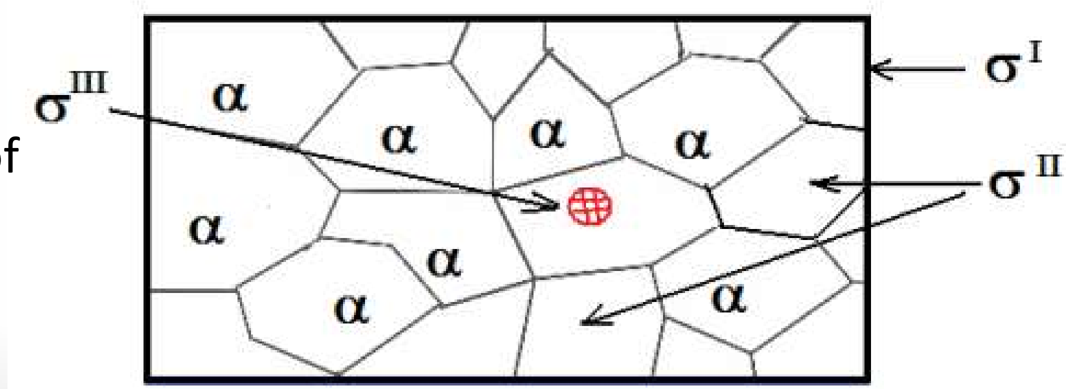
Compressive

Types of Residual stress

Type I (Macro Residual Stresses): are the average over a group of grains in the material, ~mm scale.

Type II (Micro Residual Stresses): residual stress in one grain. It may vary from grain to grain because of the elastic and plastic anisotropy. May also develop in multi-phase materials as a result of the different properties of the different phases example: Titanium (Alpha vs Beta phase).

Type III (Micro Residual Stresses): Exist within a grain essentially as a result of the presence of dislocations and other crystalline defects.



How does residual stress affect a component?

• Net sum of all residual stresses across any cross section is always zero.

• Across any cross section of a component there is typically a residual stress distribution.

• Residual stress distribution affects performance.

How does residual stress affect a component?

•Residual stress sometimes as high as the yield stress of the material.

•Residual stress can often be larger than the applied stresses.

•Typical values of residual stress are anywhere between -1000 and + 1000 Mpa

•Materials with higher yield points will retain higher residual stress.

Are residual stresses real stresses?

- Yes: from a material's point of view there is no difference between residual or applied stress, a material can only take so much stress...

$$\text{Stress}_{\text{total}} = \text{Stress}_{\text{residual}} + \text{Stress}_{\text{applied}}$$

- Atoms don't know the difference between external loads and internal stress.

- High levels of residual stresses can greatly alter the expected performance of a material.

How is residual stress created in a material?

Cause	Example
Mechanical	Plastification of a material during machining.
Thermal	Difference in solidification of the material. (i.e. in a cooling casting)
Phase Changes	Precipitation / Phase transformation resulting in a volume change (i.e. Austenite to Martensite)

Sources of residual stress during manufacturing

- Machining such as grinding, turning, milling
- Welding
- Rolling
- Forging
- Surface enhancements such as peening

What do residual stresses look like from manufacturing processes?

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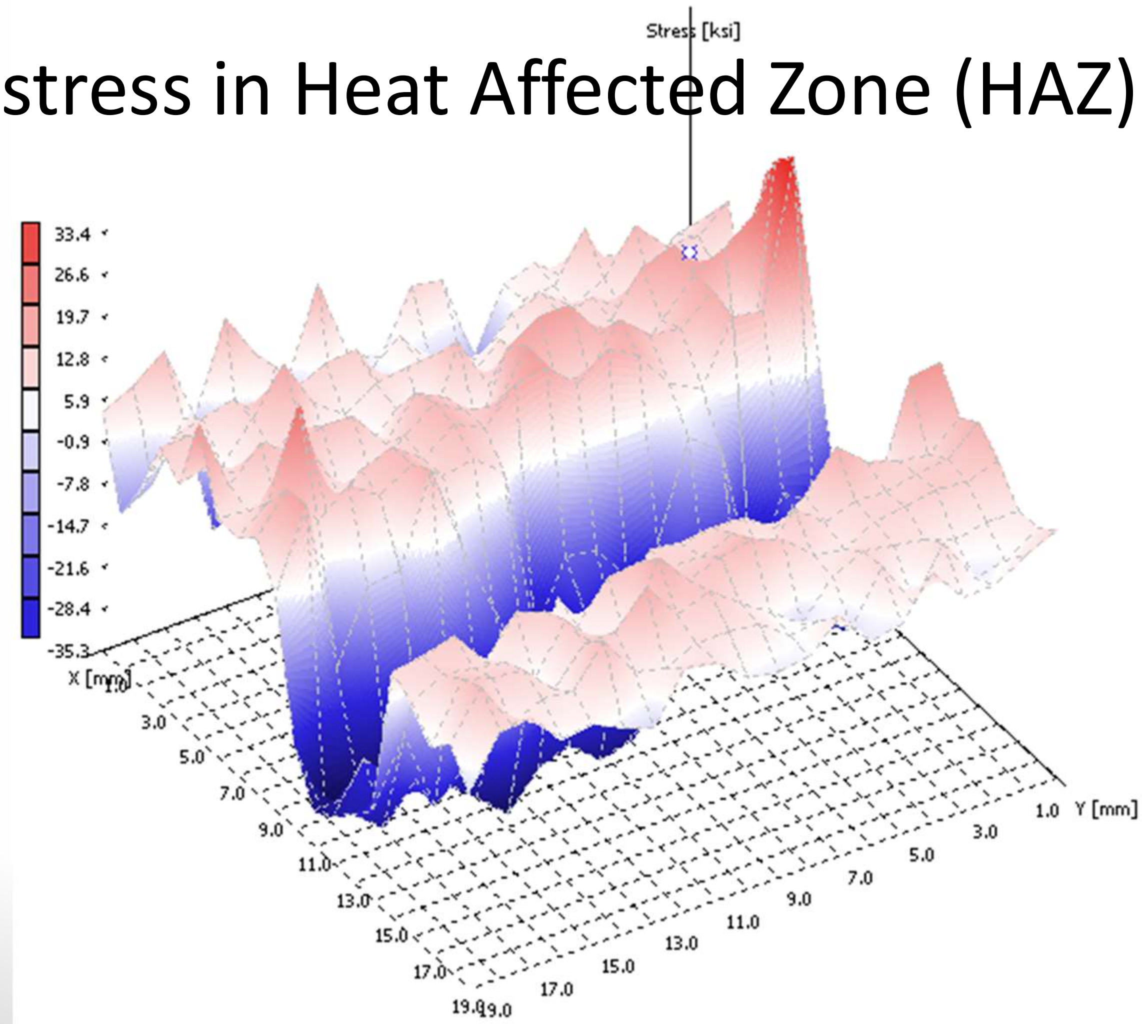
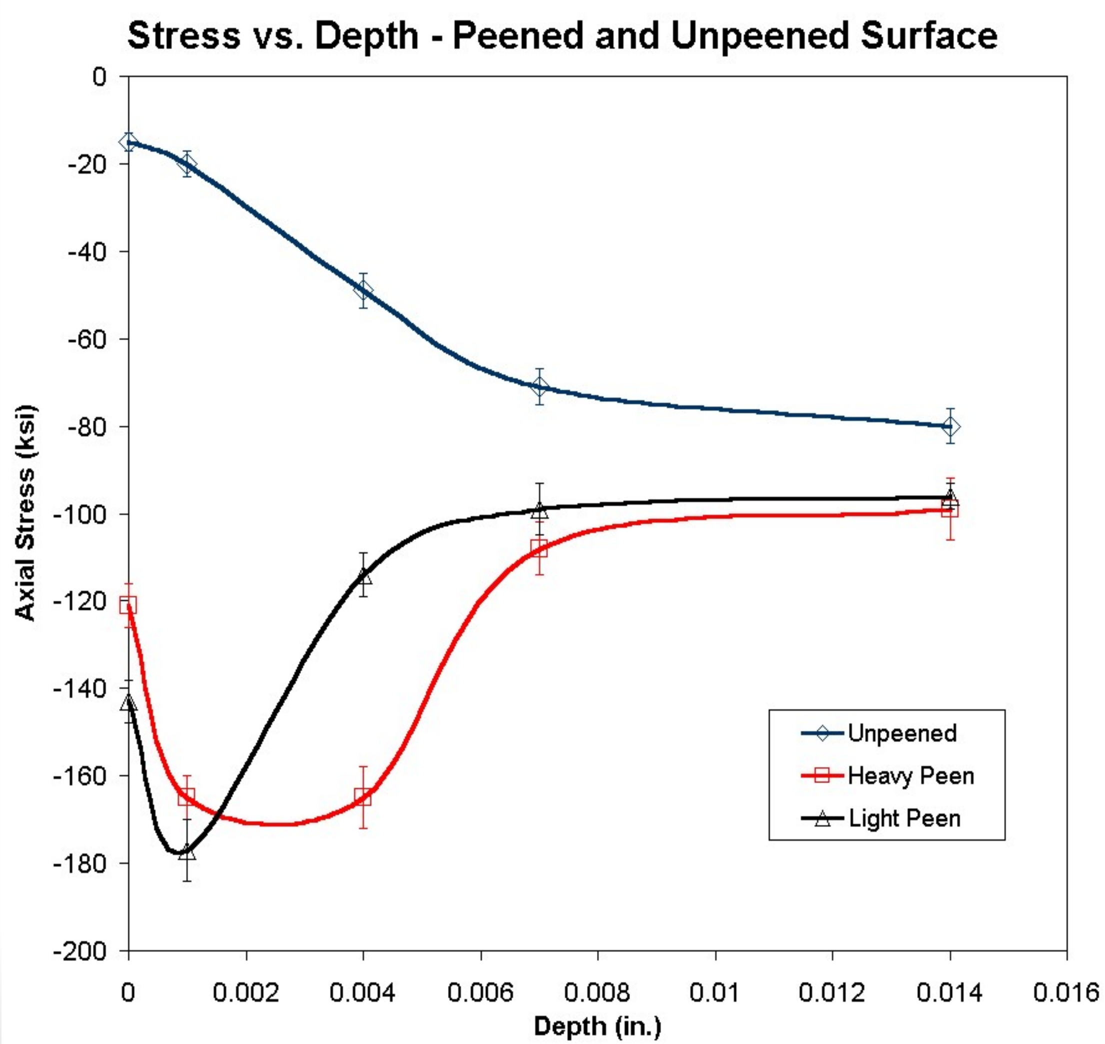
Weld Stresses :

Tensile residual stress in Heat Affected Zone (HAZ)



Evaluate Surface Treatments: Shot Peening



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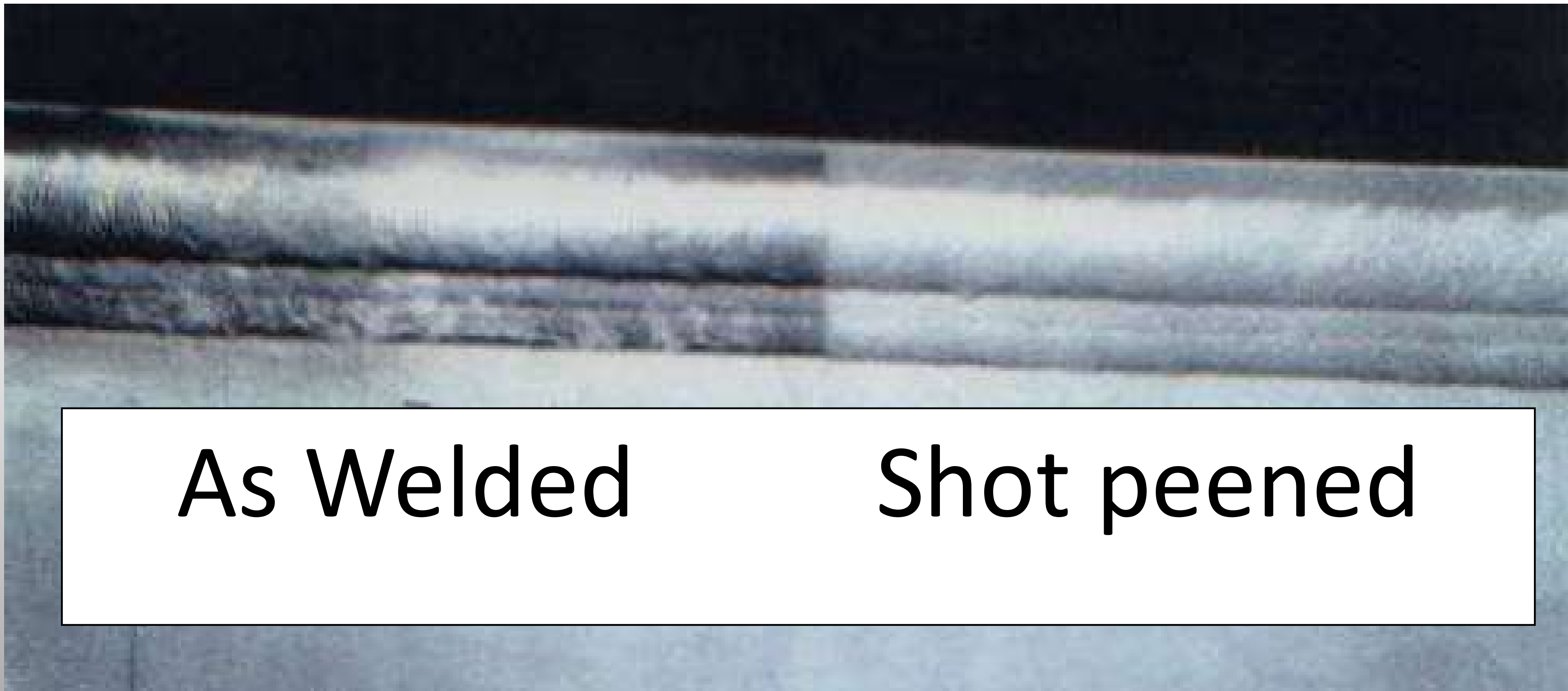

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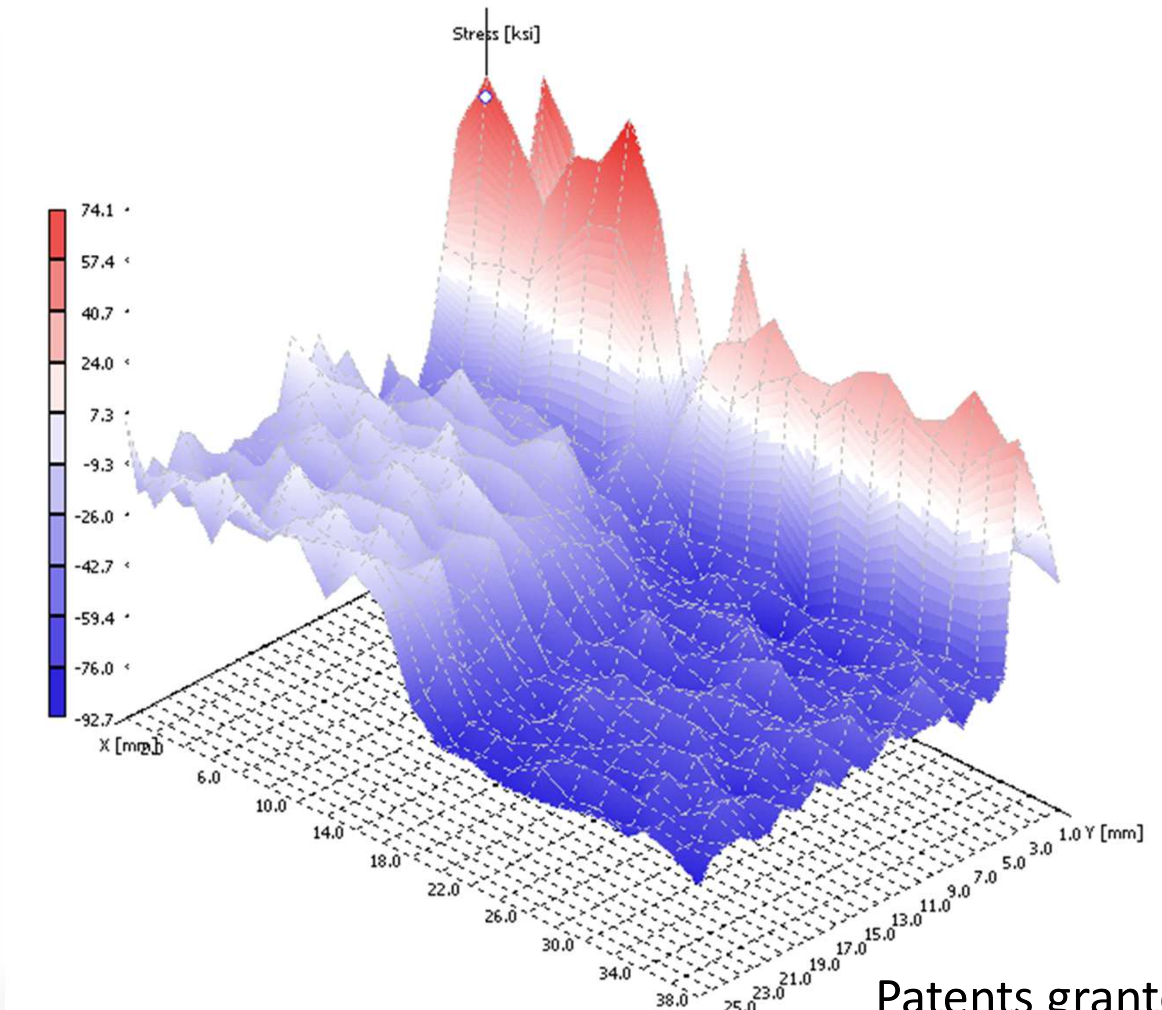
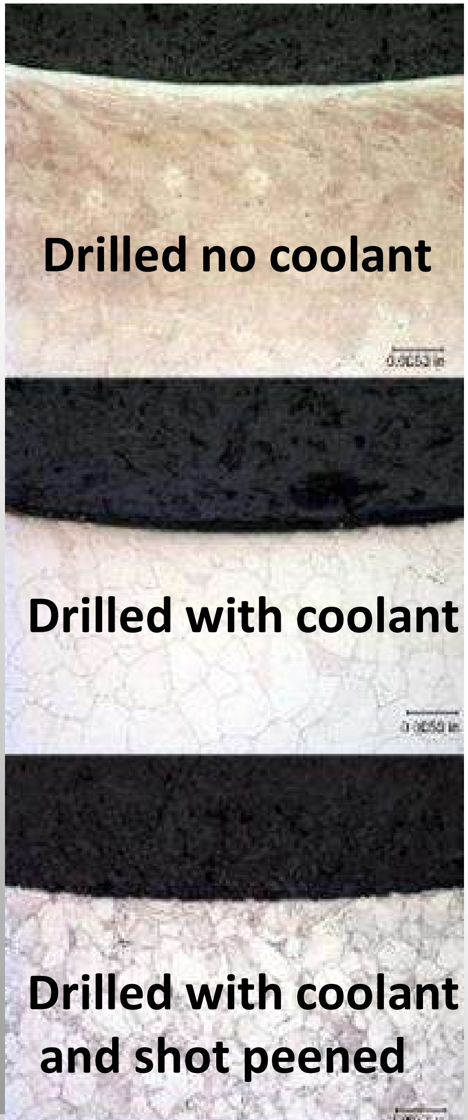
Evaluate Surface Treatments: Shot Peening



Patents granted and/or pending

Understand effects of mechanical working processes such as machining, grinding, rolling, forging, extruding



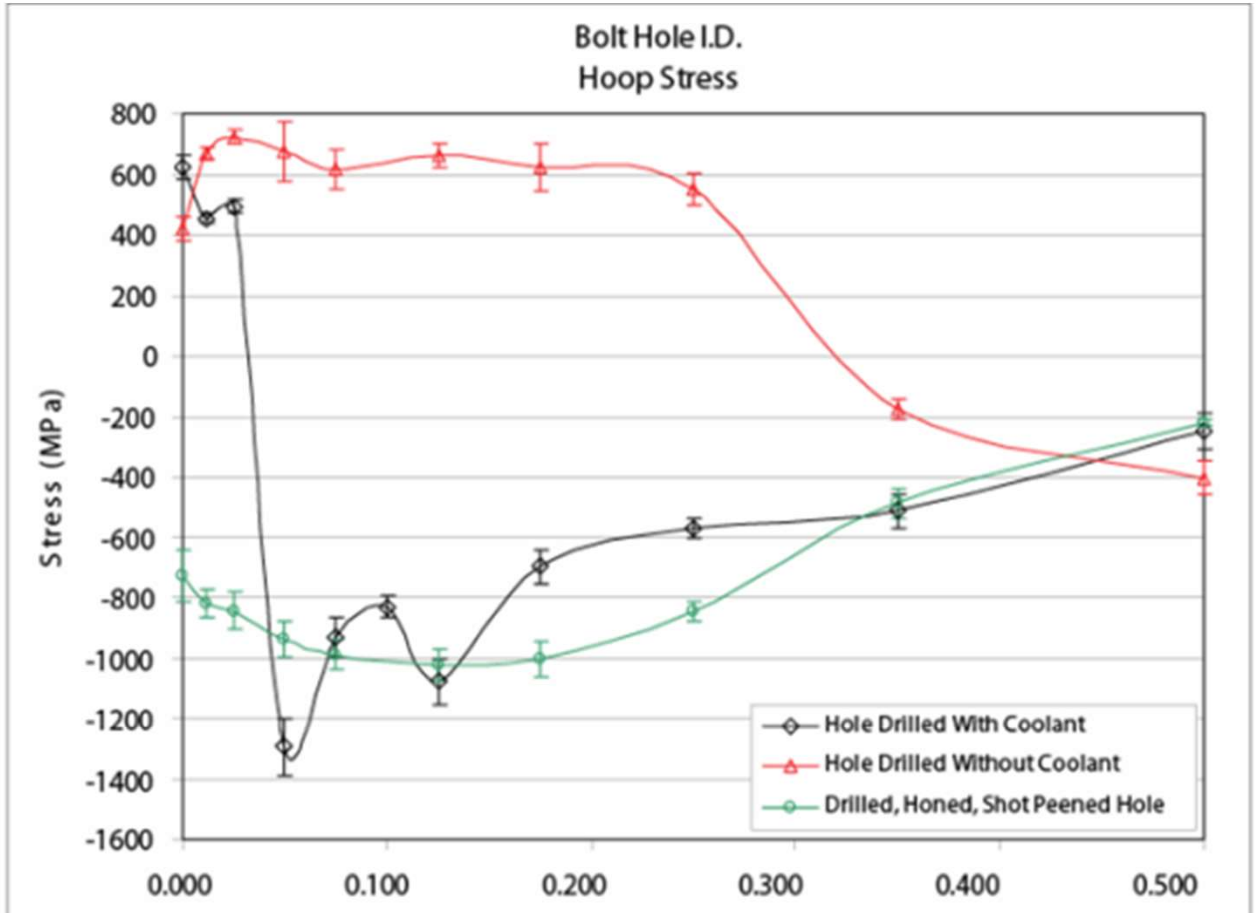
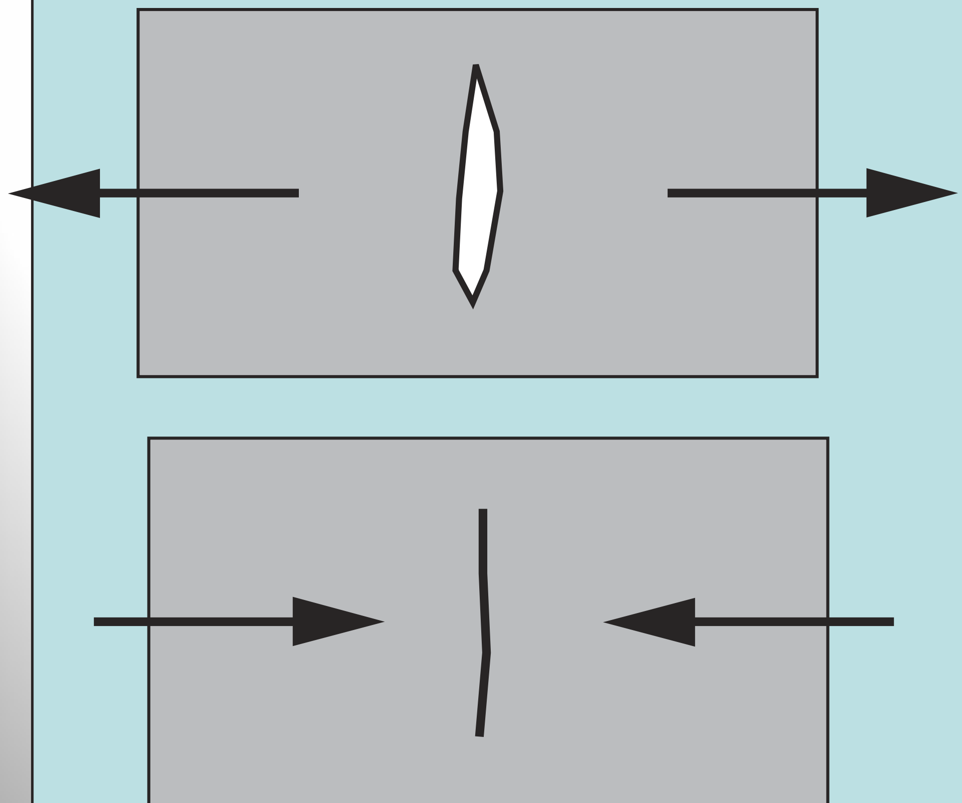


Figure b)

Crack Initiation and Propagation

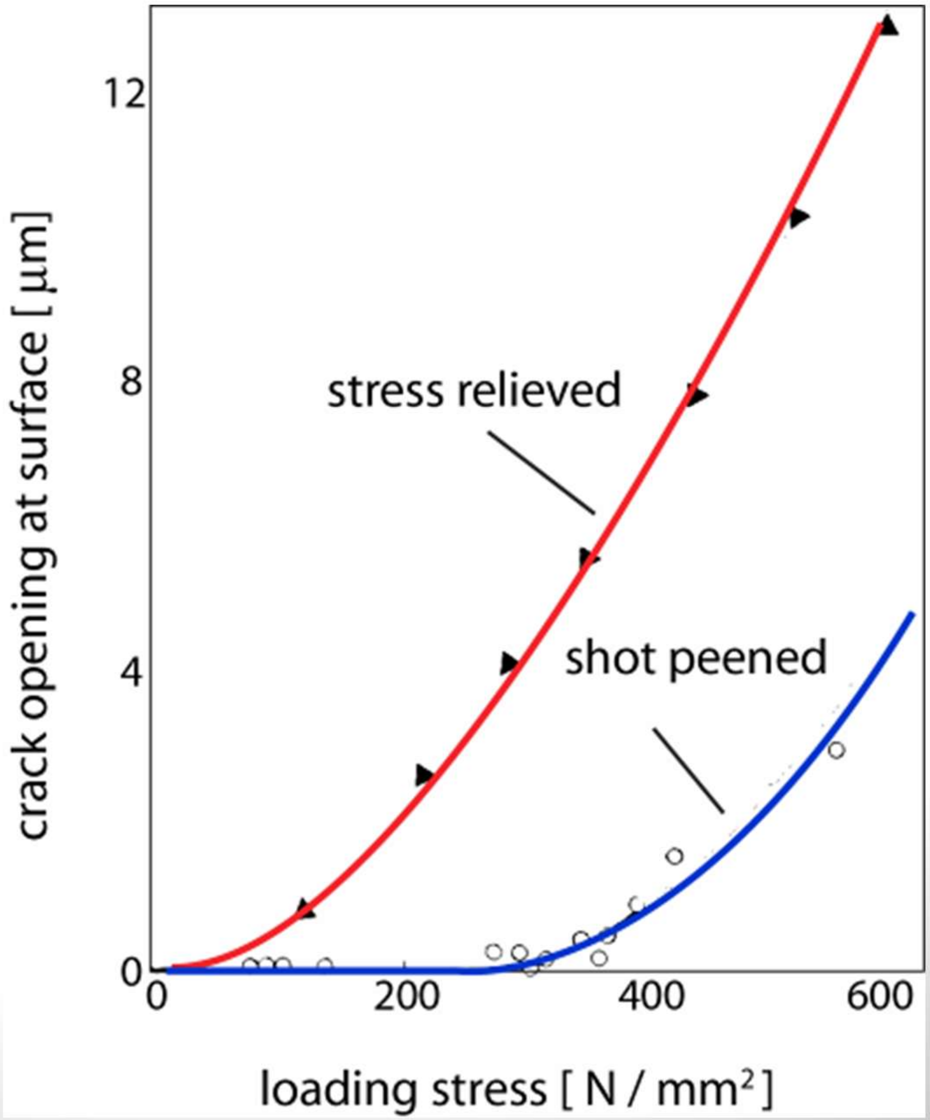
Residual Stress - Effect on Cracks



Tensile residual stress opens crack and increases crack propagation

Compressive residual stress closes crack and slows crack propagation

Crack Initiation and Propagation



Crack Initiation and Propagation

Crack initiation phase: NDT can not detect yet
(Time in this phase highly dependent on residual stress)

↓

Crack propagation phase: NDT can usually detect

↓

Failure

What techniques are available to measure residual stress?

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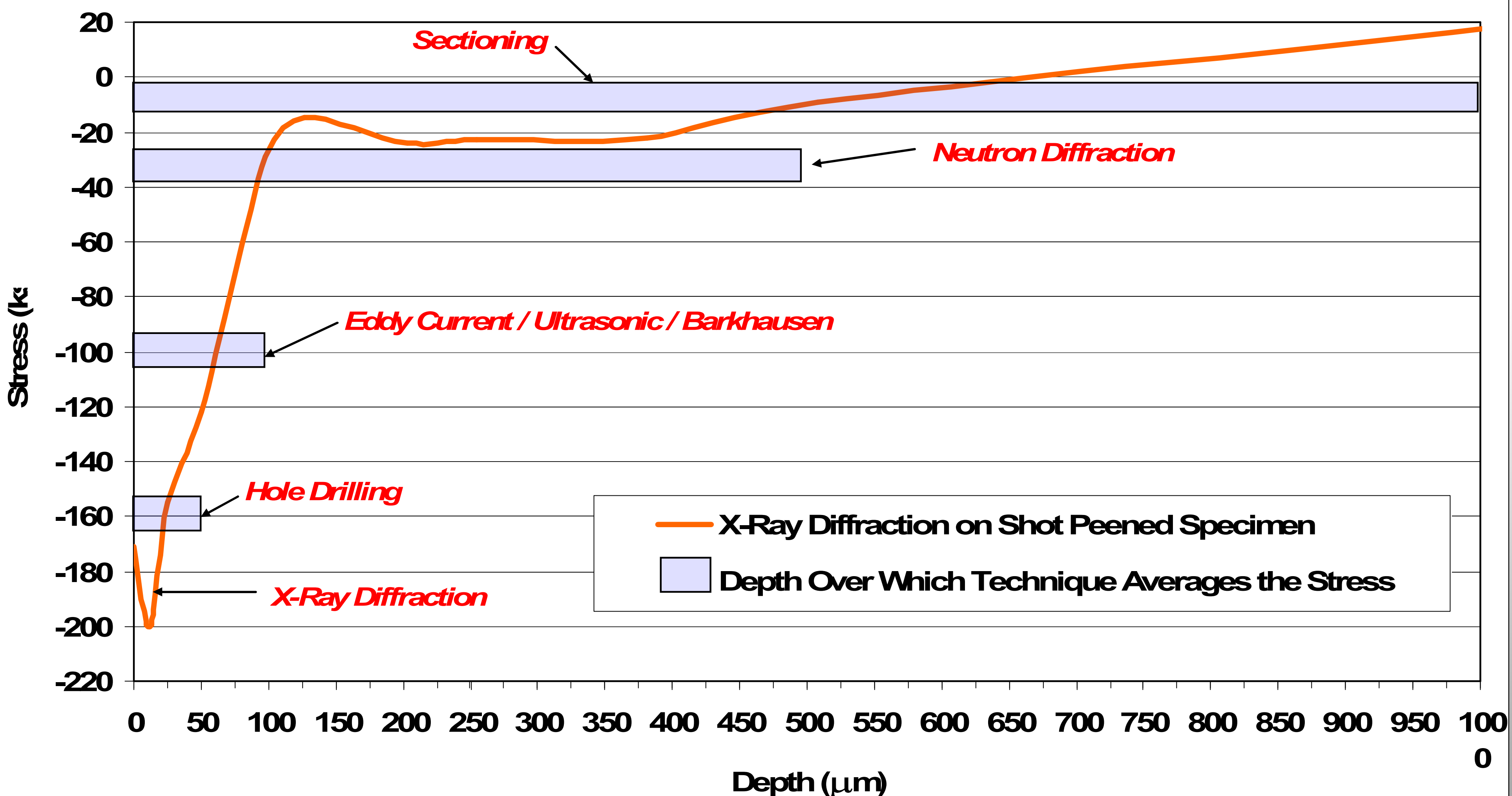
Technique	*Time for One Measurement*	*Spatial Resolution*	*Depth of measurement*	*Best Accuracy (MPa)*	Limitations	Calibration
Ultrasonic	5 to 20 min	0.1 to 30 mm^2	60 to 300 μm	10 to 20	Microstructure effects Qualitative	Required
Barkhausen	1 sec to10 min	1 mm^2	0.1 to 1 mm	10 to 20	Non-ferromagnetic materials & microstructure effects Qualitative	Required
Eddy Current	1 sec to10 min	1 mm^2	60 to 200 μm	Unknown	Limited materials Material & microstructure effects Qualitative	Required
Neutron diffraction	5 min to 2 hrs	1 mm^3	70um to 30 cm in Al, 3 cm Steel	10 to 20	Depths greater than 1mm, texture and coarse grain size	Not Required
X-ray diffraction	0.5 sec to 2 hrs	0.5 mm^2 or less	5 to 30 μm	5 to 10	Texture and coarse grain size increase measurement error	Not Required
Sectioning	40 min to >5 hrs	100 mm^2	1 to 2 mm	10	Partial Measurement of RS, parts must be cut or machined	Not Required
Hole drilling	40 min to 2 hrs	0.5 mm^2	50 μm	35	Geometry, high residual stresses, and high stress gradients	Not Required

Residual Stress Results for Various Methods on Shot Peened Gear



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Why we prefer X-ray Diffraction (XRD).

- Excellent spatial resolution.
- Can measure in complex geometries such as a gear root.
- Fast 2 to 3 minutes per measurement
- Nondestructive.
- Measures residual stress quantitatively.
- Applicable for metals and ceramics.

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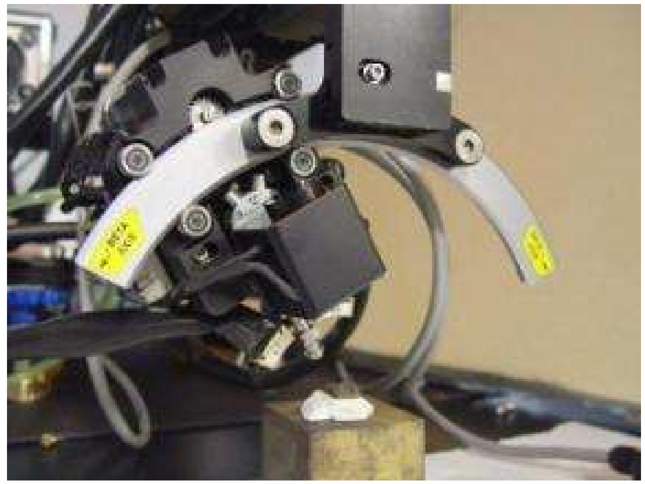
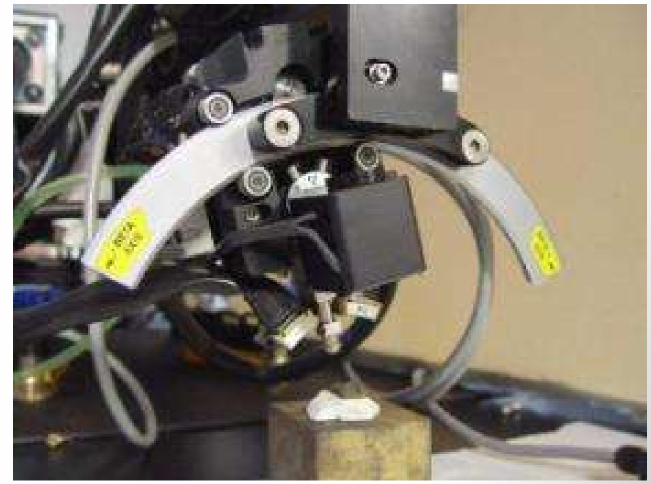
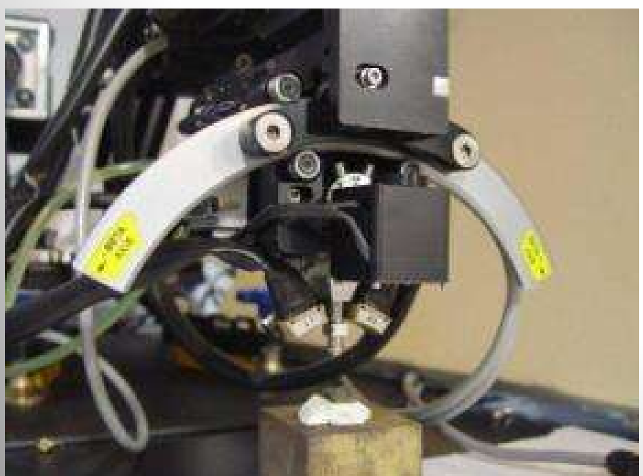
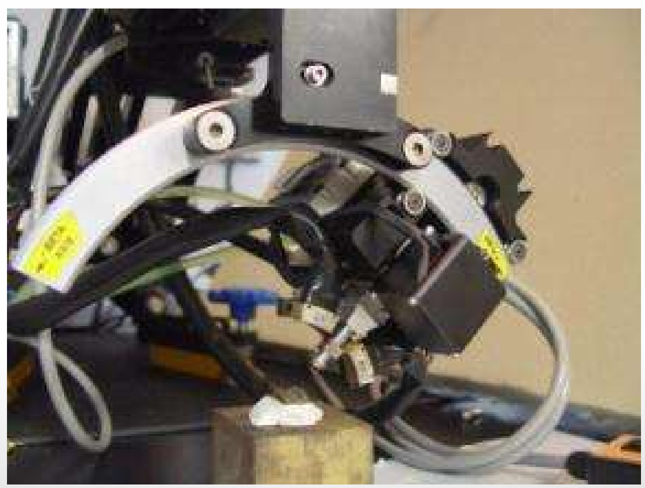
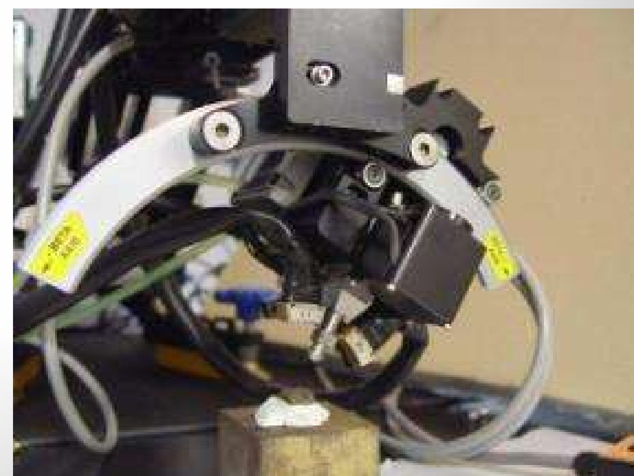
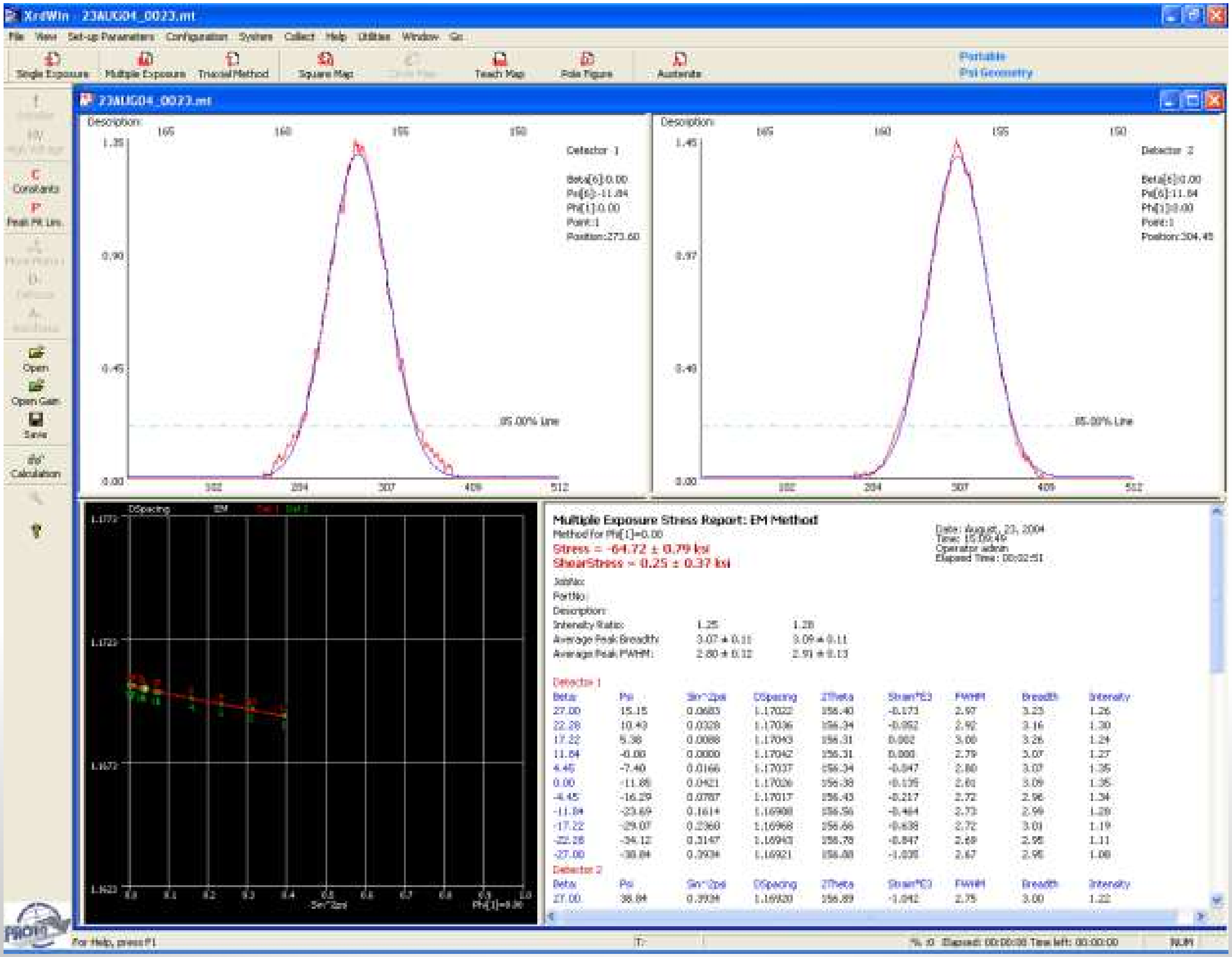
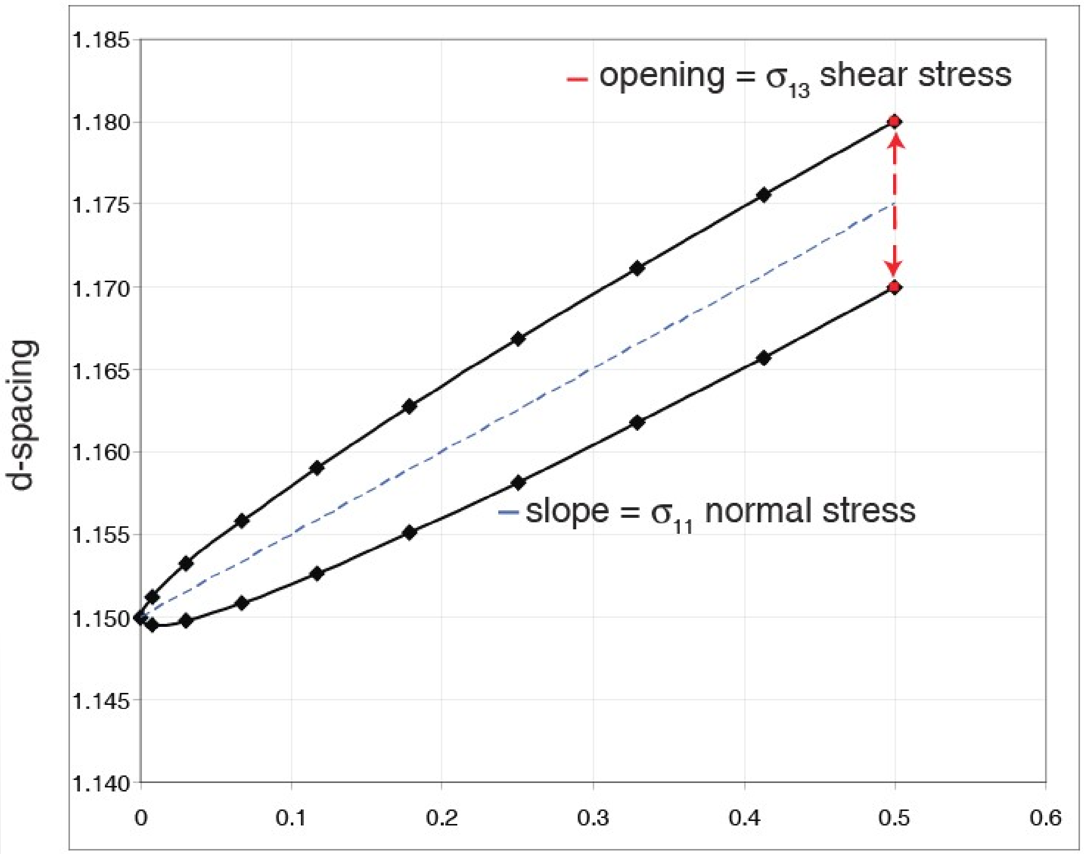
XRD in action.

XRDWIN 2.0 Software- Sample Screen Shot



d vs. $\sin^2\psi$ plot



$\sin^2\psi$

$$\varepsilon = \frac{d - d_0}{d_0} = \frac{\Delta d}{d}$$

$$d_{\phi\psi} = \frac{1}{2} S_2(\sigma_{11}) d_{\psi=0} \sin^2\psi + \frac{1}{2} S_2(\sigma_{13}) d_{\psi=0} \sin 2\psi + S_1 d_{\psi=0}(\sigma_{11} + \sigma_{22} + \sigma_{33}) + d_{\psi=0}$$

- **Measurements of atomic spacing will give the strain of the material.** $\varepsilon_{\varphi\psi} = \frac{d_{\varphi\psi} - d_0}{d_0}$

- **Strain is converted to stress via Hook's Law:** $\varepsilon = \frac{\sigma}{E}$

$$\varepsilon_{\varphi\psi} = \frac{d_{\varphi\psi} - d_0}{d_0} = \frac{1}{2} S_2 \sigma_{11} \sin^2 \psi + \frac{1}{2} S_2 \sigma_{13} \sin 2\psi - S_1 (\sigma_{11} + \sigma_{22} + \sigma_{33})$$

Where: ε = measured strain from Bragg's Law
σ = stress in sample
ψ and ϕ = measurement direction

Converting from strain to stress.

- XEC can be determined for an alloy using a 4- point bend apparatus.
- XEC is known for most common alloys.

Standards & Guidelines

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

Accuracy of XRD for residual stress

- Measurement error can be as low as ± 10 MPa.
- X-ray beam can be sized from 0.040 mm to 5 mm to analyze features.
- Measurement time is 2 to 5 minutes per location. (MET). A few seconds for (SET)
- Works on highly ordered polycrystalline materials only (i.e. metals and ceramics.)

Common XRD measurement geometries (detector and beam arrangement) for RS

- $\sin^2\psi$ Multiple Exposure
- $\sin^2\psi$ Single Exposure
- $\sin^2\chi$ Multiple Exposure
- $\sin^2\chi$ modified Multiple Exposure
- $\sin^2\chi$ Single Exposure
- $\cos\alpha$

Each has its own advantages and disadvantages

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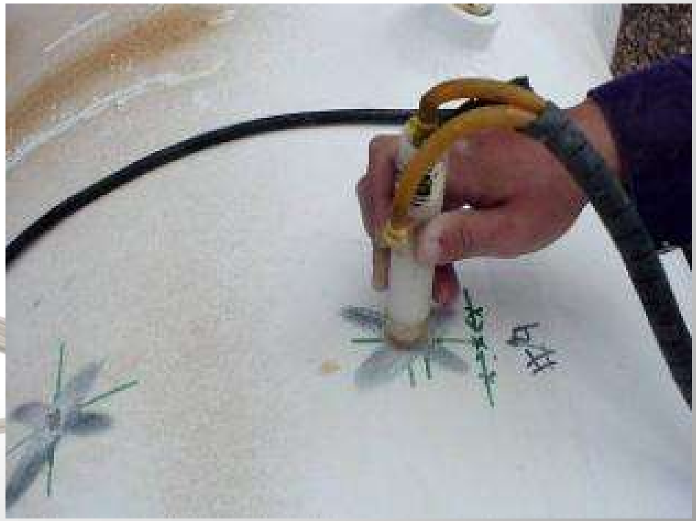
Residual Stress Measurement Examples

Stress profiling through a part.

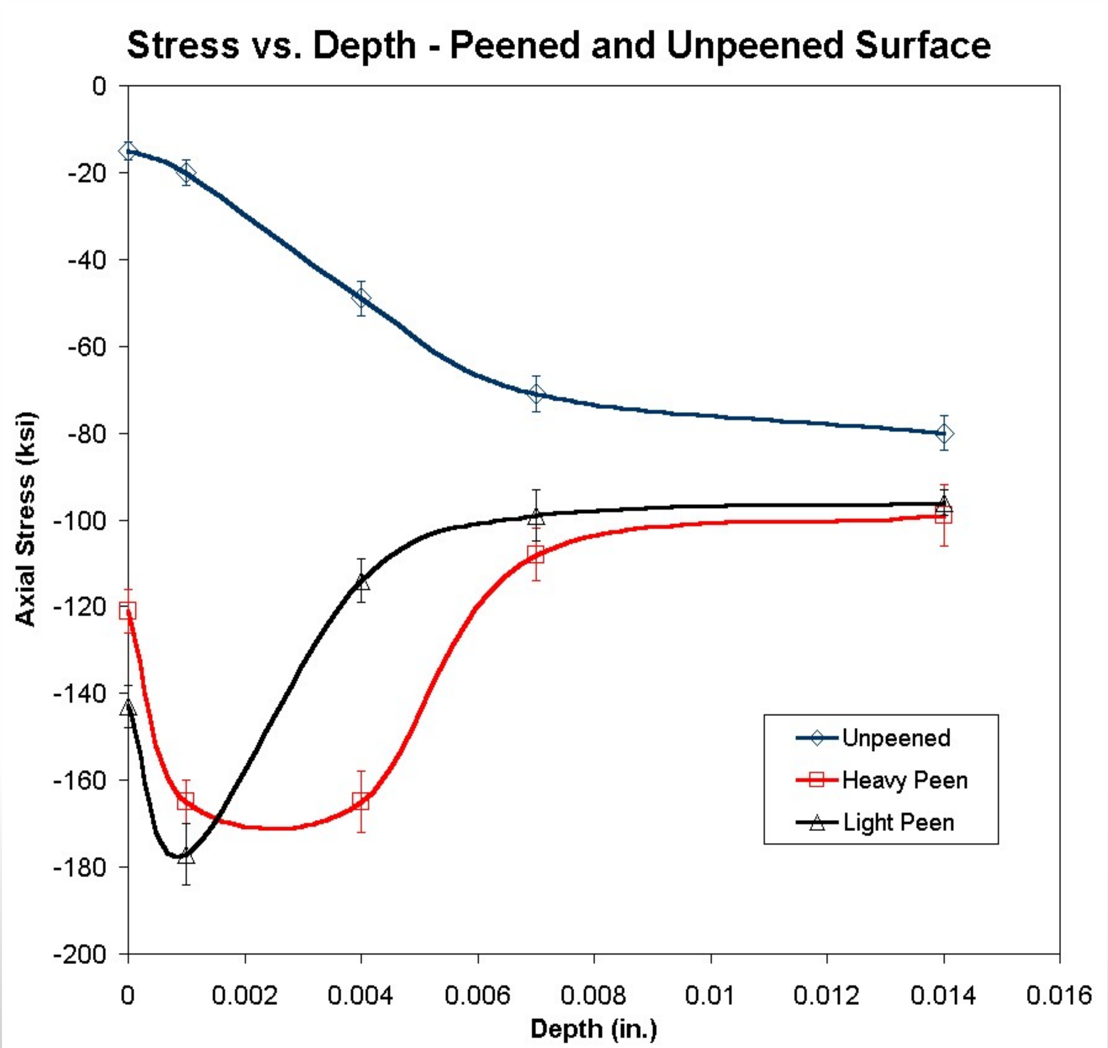
- XRD is a surface techniques. X-ray beam only penetrates 5 to 10 microns into the material.

- Electropolish to remove layers to generate stress vs. depth curves.



Electropolishing Spot

Stress profiling through a component



Quality Control of a Peened Spring

- Compare the residual stress in vintage springs, current production with increased field failure incidence and improved peening process.

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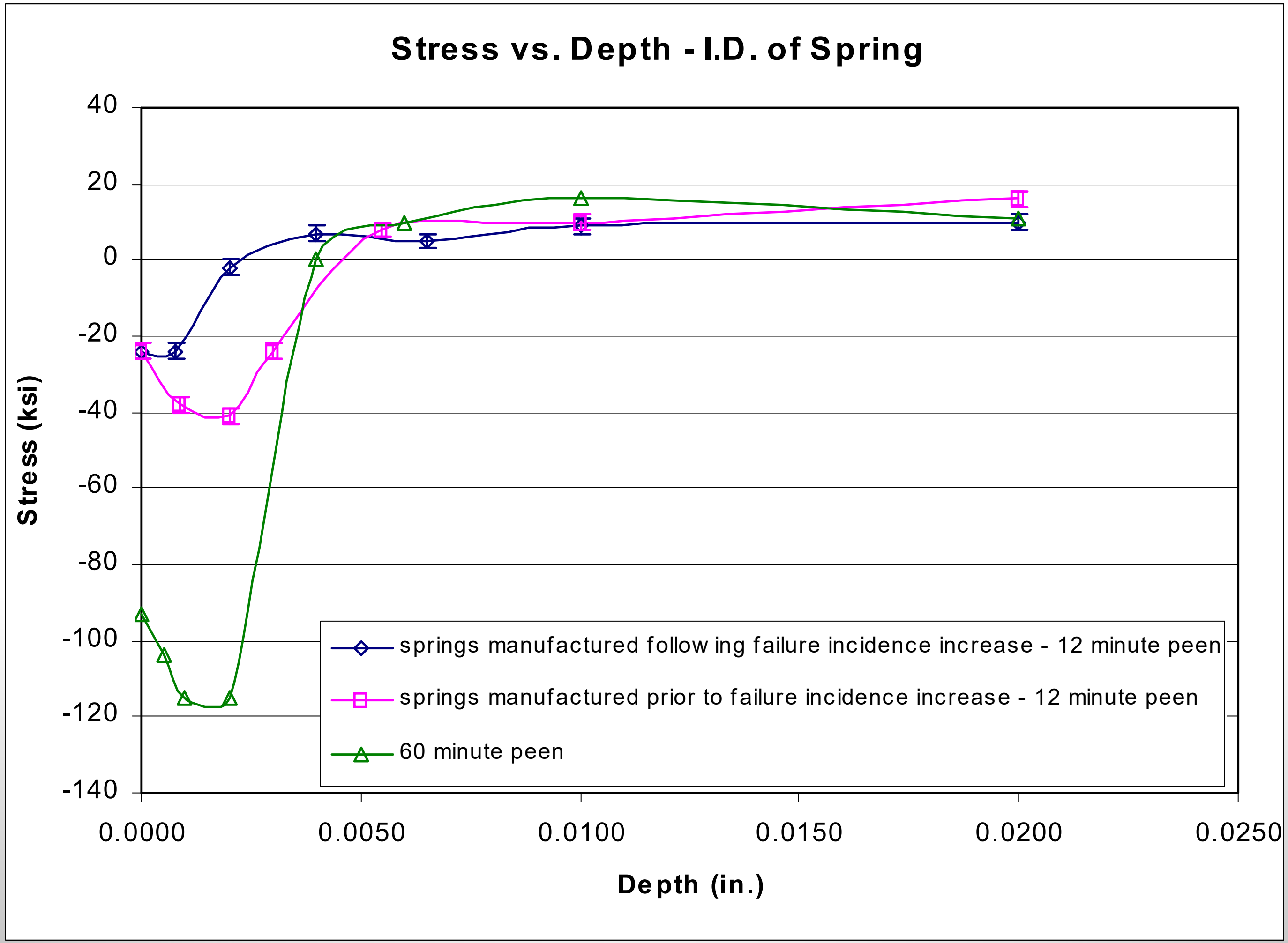
Quality Control of a Peened Spring



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The future for residual stress in component manufacturing.

- Improved quality control of manufacturing processes.
- Increase fatigue life of critical components.
- Use of residual stress as a gauge of the health of in-service components.
- Decrease costs by using lower cost materials with designed in residual stress to enhance the performance of the material.

The Equipment

iXRD – MG40 Goniometer and Field Stand #2

Residual Stress & Retained Austenite

Features	
Control unit	iXRD
Power	300 Watts
Goniometer	MG40
Geometry	iso, modified-χ
Field Stand	#2
Travel	100 or 200 mm Z axis, Cobra Arm

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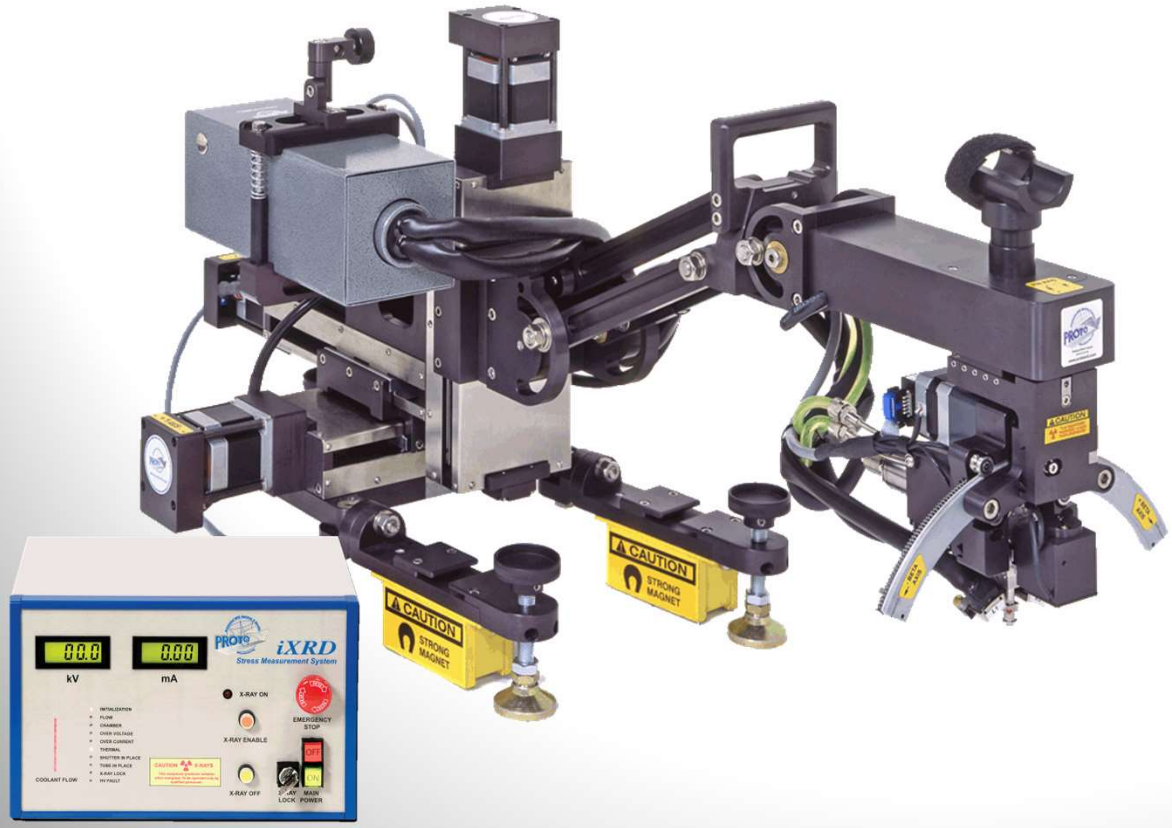
PRODUCT OVERVIEW

iXRD - MGR40 Goniometer and Field Stand #4

Residual Stress Mapping &
Retained Austenite



Features	
Control unit	iXRD
Power	300 Watts
Goniometer	MGR40
Geometry	iso, modified-χ
Field Stand	#4
Travel	100 mm X,Y Z axis Cobra Arm

iXRD Floor Stand - MGR40
Goniometer and Field Stand #4

Residual Stress Mapping &
Retained Austenite

Features	
Control unit	iXRD
Power	300 Watts
Goniometer	MGR40
Geometry	iso, modified-χ
Field Stand	#4
Travel	100 mm X,Y Z axis Cobra Arm
Floor Stand	920 mm Z-axis and 560 mm Y-axis.

iXRD Combo

Residual Stress & Retained Austenite

Features	
Control unit	iXRD
Power	300 Watts
Goniometer	MG40
Geometry	Iso, modified-χ
Sample Positioning	200 mm X,Y Z axis Phi rotation stage Cobra Arm
Cabinet Dimensions	1.6 x 1.1 x 1.8 m

iXRD Gantry

Residual Stress & Retained Austenite

Features	
Control unit	iXRD
Power	300 Watts
Travel	760 mm Z axis 2100 x 650 mm XY axis 360° ϕ rotation
Goniometer	MGR40
Geometry	iso, modified-χ
Cabinet Dimensions	2700 x 1100 x 2600 mm

LXRD

Residual Stress & Retained Austenite

Features	
Control unit	LXRD
Power	1200 Watts
Travel	500 mm Z axis 200 mm X,Y stage 360° ϕ rotation stage
Goniometer	MG2000
Sample Positioning	Mapping Stages
Geometry	Iso, modified-χ
Cabinet Dimensions	1.1 x 0.7 x 1.9 m

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PRODUCT OVERVIEW

LXRD **Widebody**

Residual Stress & Retained Austenite

Features	
Control unit	LXRD
Power	1200 Watts
Travel	700 mm Z axis 300 mm X,Y stage 360° ϕ rotation stage
Goniometer	MG2000
Geometry	Iso, modified-χ
Cabinet Dimensions	1.1 x 1.1 x 1.9 m

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LXRD **Microarea**

Residual Stress & Retained Austenite

Features	
Control unit	LXRD
Power	3000 Watts
Travel	300 mm Z axis 100 mm X,Y stage 360° ϕ rotation -45° to +51° χ axis
Goniometer	MG2000+Chi axis
Geometry	Iso, side inclination, modified-χ
Cabinet Dimensions	1.1 x 0.8 x 1.9 m

mXRD **Ultraportable**

Residual Stress

Features	
Control unit	mXRD
Power	40 Watts
Travel	50 mm Z axis
Goniometer	MG15
Geometry	iso

LXRD Modular Mapping

Residual Stress & Retained Austenite

Features	
Control unit	LXRD
Power	3000 Watts
Travel	500 mm Z axis 200 mm X,Y stage 360° ϕ rotation
Goniometer	MG2000
Geometry	Iso, modified-χ
Cabinet Dimensions	2.5 x 1.9 x 2.0 m

LXRD Gantry

Residual Stress & Retained Austenite

Features	
Control unit	LXRD
Power	3000 Watts
Travel	800 mm Z axis 2500 mm X,Y axis 360° ϕ rotation
Goniometer	MGR2000
Sample Positioning	Gantry System
Geometry	Iso, modified-χ
Dimensions	3.8 x 3.6 x 4.0 m

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Thank You