X-ray Residual Stress Analyzer

- Typically 『90secs/point measurement』 for Ferritic samples.
- 『360°』FWHM, retained austenite measurement
- Truly portable x-ray analyzer
μ-X360: Standard System

Outline specification
- X-ray Tube: Standard Cr • 30kV • 1mA
- Collimator size: Φ 1.0mm (φ0.04inch)
- (Illuminated surface Approx. Φ2mm (0.08inch))
μ-X360: Sensor Unit

Uses a single incident angle measurement

『cosα method』
μ-X360: Safety Cabinet: Standard Set

- Standard Safety cabinet
  - Material: Polyvinyl chloride / thickness [inch]
  - D/W/H: 24/24/32 [inch]
  - Weight: 75 [lbs] (Only safety cabinet)
Compact & Portable for ‘On-site’ Analysis

Sensor unit
4.0kg (8.8lbs)

Tripod & Arm
Approx. 10kg (22lbs)

Main power supply

Control PC

Battery
2.5 kg (5.5lbs)

Typical battery power operation: 6 hours life enabling around 100 individual point measurements
μ-X360 Key features

● Easy setup - Sample position tolerance ±5mm
  (in-built marker & CCD camera to assist the sample positioning)

● Fast – 90 secs / measurement (typical)

● Reliable - Acquires the complete Debye diffraction rings
  (Data reveals: grain orientation (texture) & grain coarsening, etc.)

● Low price - Around 50% less than alternative systems.

● On site analysis - Made practical due to the compactness, light-weight and ease of setting up at sample’s location

● Accuracy - The 2D detector captures the complete Debye rings; which improves the measurement accuracy of multiple data acquisitions

● Eco & Safe - High sensitivity of detector requires low power X-rays emission

● Compact & light - The 5 kg (11lbs) sensor unit is easily setup on a tripod or arm on-site

● Low electric power - Only 75W during measurement and 30W in standby mode. (battery power available)
What is stress analysis by XRD?

Steel material

When external force applied

Tensile Compressive

External force

Shot(small spherical media)

Residual stresses remain in the material after all external loads are removed.

Residual stresses are often generated from processes such as Grinding, Machining, Welding, Shot Peening and Surface treatment.

Possible to evaluate the stress condition within the surface regions by X-ray diffraction.
About X-ray diffraction

- Bragg’s law

Bragg’s law (Diffraction the x-ray scattering from plane of lattice that satisfy the Bragg conditions.)

\[ n\lambda = 2dsin\theta \]

\( n \) (an integer) is the "order" of reflection, \( \lambda \) is the wavelength of the incident X-rays, \( d \) is the interplanar spacing of the crystal and \( \theta \) is the angle of incidence that equals the angle of scattering (diffraction angle).
Crystal grains of polycrystalline material such as iron (Fe) have various orientations. X-rays reflected from various orientations of crystal grains because x-ray illuminated spot size is much bigger than the average crystal grain.
X-ray diffraction occurs from the various orientation of the grain crystals that satisfy Bragg’s law. The diffracted X-ray form as a cone around the incident x-ray axis because of the variation in crystal’s orientation.
The $\sin^2\psi$ Method

- **Outline of $\sin^2\psi$ method**

In the $\sin^2\psi$ method the variation of the lattice interplanar distance is detected by changing the angle of incident X-rays ($\psi_0$). (In the standard XRD measurement, 7 different angular measurement is recommended.)
The $\text{Sin}^2\psi$ Measurement Method

- $\text{Xray}(\psi_0)$
- $\text{Xray}(\psi_20)$
- $\text{Xray}(\psi_40)$

- Strain(0)
- Strain(20)
- Strain(40)
The $\sin^2 \psi$ Measurement Method

When the stress is applied, X-ray incident angle $\psi_0$ is large, Compressive stress apply $\rightarrow$ strain’s change results $\rightarrow$ d become smaller $\rightarrow$ $\theta$ increases $\quad n\lambda = 2d \sin \theta$

Calculate the stress from the change of diffraction normal angle $\psi$. 
Calculation of $\sin^2\psi$ Method

There is a linear relationship exhibited when plotting strain angle (deg) on the vertical axis, and $\sin^2\psi$ on horizontal axis. The slope gives the stress value; this is the basis of the $\sin^2\psi$ method.

This slope is stress.

On the assumption that the stress condition is on plane surface, stress $\sigma_x$ is calculated from the following formula.

$$\sigma_x = \frac{E}{1+\nu} \cdot \frac{\partial(\varepsilon_\psi)}{\partial(\sin^2\psi)} = -\frac{E}{2(1+\nu)} \cdot \cot \theta_0 \cdot \frac{\partial(2\theta_\psi)}{\partial(\sin^2\psi)} \cdot \frac{\pi}{180} \text{ [MPa]}$$
The Cos $\alpha$ Method (μ-X360)

- Outline of the cos$\alpha$ method

Acquire full Debye-Scherrer ring; by a single short duration X-ray exposure. Determination of the residual stress achieved by accurately measuring the position of the Debye-Scherrer rings; their positions are a direct measure of strain.
Principal of the Cosa Method

X-ray

Debye-Scherrer ring

2 D detector
Green face - the lattice planes are orientated close to the stress direction and the crystal lattice spacing become smaller in response to the applied stress, therefore $\theta$ increases.

Blue face - the lattice planes are orientated close the direction parallel to the stress direction. The interval of the crystal lattice increases (Poisson’s ratio) crystal lattice spacing increases and $\theta$ becomes smaller.
The Cos $\alpha$ Calculation Formulae

- **Residual stress calculation** ($\sigma$) by the Cos$\alpha$ method

Acquire the full Debye-Sherrer ring. The magnitude of strain is determined from the detected position of the Debye-Scherrer ring. Calculate using the following formula.

\[ \varepsilon_{\alpha 1} = \frac{1}{2} \left\{ (\varepsilon_{\alpha} - \varepsilon_{\pi} + \alpha) + (\varepsilon - \alpha - \varepsilon_{\pi} - \alpha) \right\} \]

\[ \varepsilon_{\alpha 2} = \frac{1}{2} \left\{ (\varepsilon_{\alpha} - \varepsilon_{\pi} + \alpha) - (\varepsilon - \alpha - \varepsilon_{\pi} - \alpha) \right\} \]

\[ \sigma_{\alpha} = -\frac{E}{1+\nu} \cdot \frac{1}{\sin 2\eta} \cdot \frac{1}{\sin 2\psi_0} \cdot \left( \frac{\partial \varepsilon_{\alpha 1}}{\partial \cos \alpha} \right) \]

Elastic constant $K$

Slope $M$

\[ \tau_{xy} = \frac{E}{2(1+\nu)} \cdot \frac{1}{\sin 2\eta} \cdot \frac{1}{\sin \psi_0} \cdot \left( \frac{\partial \varepsilon_{\alpha 2}}{\partial \sin \alpha} \right) \]
The Cos $\alpha$ Method

Horizontal axis is $\cos \alpha$ [$\alpha$ is the Azimuth angle of Debye-Sherrer ring], vertical axis is $\epsilon \alpha 1$ calculated using the formulae in the previous slide. As with the $\sin^2 \psi$ method, the slope of the line gives the stress value. This is the cos $\alpha$ method.

This slope is stress.
The Cos α & Sin²ψ Methods compared

Comparison between the Sin²ψ and Cos α techniques – the Cos α requires only a single angular measurement for complete analysis.

Sin²ψ technique (existing) (Multi-positions of detector)

COS α technique (µ-X360) (Single position of detector)
Comparison between $\sin^2\psi$ & $\cos \alpha$ Methods

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2\psi$ method (Conventional)</th>
<th>$\cos \alpha$ method ($\mu$-X360)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray tube</td>
<td>40 kV &amp; 40 mA (typical)</td>
<td>30 kV &amp; 1 mA (Safety &amp; Ecology)</td>
</tr>
<tr>
<td>X-ray detector</td>
<td>Point, 1D and part 2D</td>
<td>Full 2 D (visual analysis)</td>
</tr>
<tr>
<td>Precision mech.</td>
<td>Mandatory</td>
<td>Not necessary</td>
</tr>
<tr>
<td>Data</td>
<td>5-7 point</td>
<td>Max 125 point (Debye-Scherrer ring)</td>
</tr>
<tr>
<td>Permissible range</td>
<td>±50 µm (complicated setting)</td>
<td>±5 mm (easy setting)</td>
</tr>
<tr>
<td>Measurement time</td>
<td>5-20 min.</td>
<td>90 sec.</td>
</tr>
<tr>
<td>Cost</td>
<td>250,000 (USD)</td>
<td>125,000 (USD)</td>
</tr>
<tr>
<td>FWHM repeatability</td>
<td></td>
<td>◎</td>
</tr>
<tr>
<td>On-site</td>
<td>×</td>
<td>◎</td>
</tr>
<tr>
<td>Portable</td>
<td>Water cooling &amp; Goniometer stage</td>
<td>Air cooling, Goniometer not required</td>
</tr>
</tbody>
</table>

- △: Better
- ×: Worse
- ◎: Equivalent
- ○: Not applicable
Application Software – key points to making a measurement

Procedure

Sample positioning
(Captured by CCD camera)

Measurement
(X-ray incidence & detection)

Calculation
(Residual stress)

Data output
(Residual stress & FWHM)

① Display diffraction ring, residual stress
② Measurement log: easy and fast to retrieve past data
③ Captured by the CCD camera: confirms sample position and recorded image stored for future reference
μ-X360 Various Analysis Images

- Display the various Debye-Scherrer rings
- Display the diagram of residual stress & FWHM

Calculate the stress from the slope

Create New Value
Create New Value
Create New Value
Create New Value
Advantage of the Full 2D detection

- Advantage 2D Full data of Debye-Scherrer ring (500 points)
  → High repeatability and reliability because of max. 500 points data

① Debye-Scherrer ring
  2D sensor intensity distribution

② Result (Example)

③ Cos α line
  125 points
A key advantage of the Full 2D detection – immediate results

**Grain coarsening**
e.g. Bead on Plate of stainless steel weld

**Grain orientation**
*(texture)*
e.g. Influence of rolling direction

Easy & quick visual analysis
Standard Type and Narrow space Type

- **μ-X360 [Standard]**
- **μ-X360n [Narrow space]**

Suitable for measuring in narrow spaces such as fillet welding joints.
μ -X360n: Narrow Space Type

PC(USB)  
Sensor unit  
Approx. 4kg (8.8lbs)  
(Z height stage)  
Power supply unit  
Approx. 6kg (13.2lbs)

Outline specification

- Tube: Standard Cr • 30kV • 1mA
- Collimator size: Φ1.0mm (φ0.04inch)
- (Illuminated surface Approx. Φ2mm (φ0.08inch))
μ-X360n Narrow Space Measurement

Standard measurement

*Possible to measure fillet welded joints.

μ-X360n

センサユニット 4.0kg

Create New Value

Create New Value Create New Value

Create New Value
① Safety Cabinet (Optional)

0.2inch thickness polyvinyl chloride safety cabinet can protect against radiation leakage. Possible to design the customized safety cabinet.

Standard safety cabinet
24×24×32inch : 25kg(55lbs)

Door open

Customized safety cabinet

Doors opened
② Accessories

Possible to design the customized accessories.
③ Retained Austenite Analysis

Displays the percentage of the retained austenite that has not transformed even at ambient temperature.

$\gamma R = 19.2\%$

$\alpha (\text{Max data}) = 341.28\deg$

$\alpha (\text{Min data}) = 272.16\deg$

$\gamma 220$

$\alpha 211$
④ X & Y Stage – stress mapping

- Stress mapping by controlling X & Y axis stage.
 『Stress mapping come true.』

*Measure 25mm (1 inch) by 1mm (0.04 inch) Step.
 26p × 26p = 676 points

Mapping result

* 2 axis stage (X/Y) + Application software

Weld bead

Create New Value
Create New Value
Create New Value

PULSTEC
Create New Value
⑤ Electropolishing (Under development)

Electropolishing machine, μ-X360 & μ-X360n Accessories
Current control and Timer function

① Top part (electropolishing part)
It takes 5 mins to electropolish
□ 7mm size to 100um depth

② Controller weight: Approx. 3lbs
Size: WHD: 7 /2.7/ 10.2 inch

③ Electropolishing liquid: TBD

*This image may be different from actual product because it is under development.
6 Positioning tool using a Microscope (under development)

Optional items to improve the positioning accuracy
Positioning accuracy: 50µm

① Position setting
  Sample setting by checking through microscope
  Angle setting by angular auto-collimator

② Measurement
  Once measurement point is fixed, move the sensor unit and measure.

*This image may be different from actual product because it is under development.
Measurement Example: Automobile parts

① Gear
② Wheel
③ Crankshaft
④ Exhaust manifold
⑤ Suspension
⑥ Bearing
⑦ Conrod
⑧ Chassis
⑨ Screw
⑩ Ball screw
⑪ Muffler
Measurement Example : Shot-Peening

① Before shotpeening - 141 MPa  ② After shotpeening - 459 MPa
Measurement Example: On-site measurements

- Plant maintenance
  Welds & Shot-peening effect
  Check aging degradation

- Tank
  Welds, Tempering effect

- Tube
  Welds & Heat treatment
Measurement Example: On-site measurements

① Railway
② Road construction
③ Water plant
④ Bridge
Measurement Example

① Medical instruments
② Added value product
③ Teeth of saw
Thank you very much for your attention.

In some cases, additional information is needed, please ask separately!
Appendix 1) Repeatability and Compatibility

100 measurement repeatability and 3 machines compatibility

Number of measurement

Residual stress [MPa]

0 20 40 60 80 100

0

-100

-200

-300

-400

-500

-600

-700

-800
Annex 2) Correlation with strain gauge; by 4 point

Data comparison between “Strain gauge” & “u-X360” using stress-free sample piece.
(sample piece : SS400, Gauge : KYOWAKFG-2-120-C1-11L30C2R)
Annex 3. Radiation dose leakage operating when using the safety cabinet

Inside the safety cabinet

- Radiation dose leakage 0.1µSv/h or less (minimum measure unit: 0.1µSv/h)
- Survey Dosimeter ICS-331BV1 (Hitachi-Aloka)

5mm thickness polyvinyl chloride safety cabinet can protect against radiation leakage.
Annex 4. Radiation dose leakage operating without the safety cabinet

Without the shielding cabinet e.g. On-site measurements

- Radiation dose leakage
  0.0 uSv/h (@2000mm) (minimum measure unit: 0.1 uSv/h)

- Survey Dosimeter
  ICS-331BV1 (Hitachi-Aloka)

Operating outside the shielding cabinet, Pulstec has confirmed the radiation dose leakage is 0.0 uSv/h, at a distance of over 2 meters or more.
Annex 4) Correlation with a $\sin^2\psi$ based analyzer

\[ y = 1.087x - 65.319 \]

\[ R^2 = 0.998 \]

(sample : Ferrous test piece)
Annex 5) Research study  FWHM and grain size

Grain size 3～5um

- FWHM: 6.71 deg
- (6.54 - 6.87 deg)
- \( \alpha_{\text{Max data}} = 141.12 \, \text{deg} \)
- \( \alpha_{\text{Min data}} = 69.12 \, \text{deg} \)

Grain size 5～10um

- FWHM: 2.62 deg
- (2.50 - 2.75 deg)
- \( \alpha_{\text{Max data}} = 0.00 \, \text{deg} \)
- \( \alpha_{\text{Min data}} = 181.44 \, \text{deg} \)
If the type of the steel is same, the relationship between HRC (Rockwell ‘C’ scale) and FWHM may be same.