Development of the residual stress measuring technique for irradiated materials by X-ray diffraction

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Residual stress after welding is one of the factors causing SCC.

It is known that the residual stress is relaxed by neutron irradiation.

It is important to know the state of residual stress after long-term operation for crack growth evaluation.

1) Ishiyama et al. 11th EDM (2003)
Background(2)

- X-ray diffraction method is a commonly used technique to measure residual stress non-destructively.

- However, measuring the stress of highly irradiated materials is difficult because radioactivity of them increases the background noise.
Objective

- Development of an X-ray diffraction apparatus that reduces the influence of radioactivity to measure residual stress in irradiated materials.
Mechanism of residual stress measurement by X-ray diffraction method (1)

- From Bragg’s equation \((2d \sin \theta = n\lambda)\), diffraction angle “\(\theta\)" changes as lattice spacing “\(d\)" changes since wave length of character X-ray “\(\lambda\)" is constant.

Fig. Diffraction of X-rays (Bragg condition) ¹).

Mechanism of residual stress measurement by X-ray diffraction method (2)

- Assuming compressive residual stress parallel to the specimen surface, “d” becomes smaller as “ψ” becomes higher.
  
  \[ d: \text{lattice spacing} \]
  \[ ψ: \text{angle between specimen surface and diffraction plane} \]

direction normal to specimen surface

direction normal to diffraction plane

incident X-rays

diffracted X-rays

\( d \eta \)

\( 2\theta \)

\( ψ = 0° \)

\( ψ = 45° \)

Fig. A schematic drawing showing the mechanism of residual stress measurement by X-ray diffraction method.
Mechanism of residual stress measurement by X-ray diffraction method (3)

- Residual stress is denoted by “\( \sigma = K \cdot \frac{\partial (2\theta \psi)}{\partial (\sin^2 \psi)} \) [MPa]”.

- In other words, residual stress is evaluated from a gradient on a graph of \( \sin^2 \psi - 2\theta \), “\( M \)”.

- Since stress constant “\( K \)” is denoted by “\( K = -\frac{E}{2(1+\nu)} \frac{\pi}{180} \cot \theta_0 \) [MPa/deg]”, we can find compressive residual stress when the gradient “\( M \)” is positive, and tensile residual stress when that is negative.
Development of the apparatus(1)

Major factors which increase background noise during measurement of irradiated materials are

- γ-rays from the irradiated materials.
- Secondary X-rays produced by the γ-rays irradiating the metal parts.

Fig. A schematic drawing showing elevation of background because of radioactivity.

Fig. Layout of the developed apparatus.
In order to reduce the influence of radioactivity,

- Shielding was increased by placing lead blocks around the detector.
- Few metal parts were used for the detector and the monochromator.
S/N ratio was significantly improved in the case of the developed apparatus.

Fig. Comparison of S/N ratio of the standard type and the developed apparatuses.
Some noises were included in the detected X-ray profile. The intended region of diffracted X-ray was extracted by MCA*.

Fig. An example of a screen view on the PC.

MCA

Intensity
data region
corresponding to X-ray energy
diffracted X-ray profile

Intensity
corresponding to angle (2θ)

measuring conditions

* MCA: multi-channel-analyzer
Experimental

Austenitic stainless steel with different stress levels (powdered, emery polished, shot-peened, carburized)

- The residual stress of specimens was previously measured with the standard type apparatus without radiation field.
- Then, the stress was measured with the developed apparatus with irradiated materials (1 TBq and 2 TBq in $^{60}$Co equivalent) near the specimen as background sources.

Table: Conditions of residual stress measurement with the developed apparatus.

<table>
<thead>
<tr>
<th>Characteristic X-ray</th>
<th>CrKα</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>30 kV, 40 mA</td>
</tr>
<tr>
<td>Entrance slit</td>
<td>2 $\times$ 10 mm</td>
</tr>
<tr>
<td>Detector</td>
<td>PR gas flow type proportional counter</td>
</tr>
<tr>
<td>Step range</td>
<td>0.1°</td>
</tr>
<tr>
<td>Incident angle</td>
<td>$\Psi = 0, 18, 27, 33, 39, 45°$ (6 conditions)</td>
</tr>
</tbody>
</table>

Fig. Location of background source.
Result(1)

Measured specimen
- Powdered stainless steel

Background sources
- 0 TBq, 1 TBq, 2 TBq
  (assuming $1 \times 10^{25} \text{n/m}^2$ at the maximum)

Obvious peaks of diffracted X-ray were obtained in each case.
Almost the same values were obtained with the developed apparatus as those previously measured with the standard type apparatus without radiation field.

Confidence intervals were about ±130 MPa at the maximum.

There was no significant difference between the two radiation fields.
Summary

- In order to measure residual stress of irradiated materials, the X-ray diffraction apparatus was developed with reduced influence from radioactivity of specimens.

- Residual stress of four types of specimens which had been prepared to get different stress levels was measured by the standard type apparatus without a radiation field and the developed apparatus with irradiated materials as background sources (radioactivity of 1 TBq or 2 TBq in $^{60}$Co equivalent).
Summary

- Almost the same values were obtained by the developed apparatus as those previously measured by the standard type apparatus without the radiation field. Confidence intervals were about ±130 MPa at the maximum.

- The developed apparatus can provide residual stress measurements of irradiated materials, with radioactivity of up to 2 TBq in $^{60}$Co equivalent, with an accuracy of ±130 MPa.
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