Newly Undertaken In-situ Inspection for Aged Power Plants

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Some of the Japan's oldest nuclear power plants are now entering their more than 30th year, which is close to their designed lifespan. The Rules on fitness-for-service for nuclear power plants issued in May 2000 allows allowable flaw sizes in operating plant components. In these circumstances, water jet peening against SCC processed on the shroud of many nuclear plants. In such a process, discriminating processed area on the shroud became very important on In-situ work. It was clarified that millimeter wave reflection detection makes cost- and time-effective discriminating tool, compared with X-ray diffraction, sonic velocity measurement and electric resistance measurement.

Key Words: Power plant, SCC, Water jet, Peening, Laser Peening, Millimeter wave

1. Introduction
The Rules on fitness-for-service for nuclear power plants issued in May 2000 allows allowable flaw size and In-situ preventive maintenance. Under such circumstances In-situ preventive maintenance by water jet peening(WJP) have mostly been developed in the nuclear industries. Already the WJP was applied on more than 5 nuclear plants in Japan. As the In-situ work, discriminating method in peening required area was urgent problem and measuring residual stress on substrate surface by X-ray diffraction was already developed. But it spends much detecting time and cost. To realize cost- and time-effective maintenance, the author dared to challenge millimeter wave detection to discriminate WJP required area in specimen.

2. New Rules Realize Cost-Effective Maintenance
The Rules on fitness-for-service for nuclear power plants shown in Fig. 1 updated nuclear plant maintenance policy from not accepting any flaws to allowing flaws within an allowable size and repairing and preventive maintenance guideline was added in 2004. A component that has a flaw within the allowable range can continue operation. The allowable flaw size varies with the material (austenitic stainless and ferric steel), thickness, and flaw configuration and geometrical proportion. That makes WJP to be cost- and time-effective preventive maintenance for Stress Corrosion Cracking(SCC) . WJP prevents SCC keeping surface stress compressive, shown in Fig. 2-3. In our In-situ WJP process, it was very difficult to discriminate peening processed area from not processed area. X-ray diffraction looks like very reasonable, but it takes much money and time. And the author dared to challenge more cost- and time-effective discriminating method.

In our study, to measure surface residual stress, X-ray diffraction, electric resistance and surface sonic velocity measurement were tried. WJP was already applied on core internal components' welded line of several nuclear power plants to prevent SCC.

3. Surface Electric Resistance Measurement
Residual austenite reduction and magnetic permeability increase by WJP, shown in Fig. 4 . Residual austenite reduction causes electric resistance increase and author undertook discriminating WJP processed surface by detecting electric resistance increase . In this trial experiment, surface electric resistance increase should be detected and two detecting electric probe distance settled at very narrow 1.8 mm shown in Fig. 5. But these results were impossible to detect resistance increase. It was because detected resistance depth was much deeper than austenite reduced depth 100μm shown in Fig. 4 and worst reappearance in conductivity came from too narrow 1.8mm detecting probe distance. Workpiece tried in this study is shown in Fig. 7.

4. Experimental Trial on X-Ray Diffraction
Most standard method to measure surface residual stress should be X-ray diffraction . The author tried to detect surface residual stress by conventional X-ray diffraction set up, of which scanning angle was . Scattered X-ray was detected by angle 2θ. Scattered X-ray detected by angle and 2θ shown in Fig. 8. X-ray energy was 30keV and detected stress was very shallow depth, some μm from the surface. Residual stress was given by the gradient 2θ vs. sin 2θ shown in Fig 9 and measured WJP processed stress was from -211MPa to -335MPa but no-processed stress was around 250MPa. It means hard to discriminate by X-ray, which became from too shallow detected depth about 5-10 μm and not-homogenized surface made broad range of residual stress. Peening cavitation offers essentially spotting force, non-homogenized process.
Fig. 1 flow of newly applied maintenance rules

Fig. 2 Water Jet Peening

Fig. 3 Improved stress distribution by WJP
Fig. 4 Residual austenite difference by WJP

Fig. 5 Experimental schematic apparatus

Fig. 6 Experimental set up

Fig. 7 Experimental workpiece
5. Experimental Trial by Vz Method

Hardness increased by WJP shown in Fig. 10. Hardness increase caused by compression stress, which makes acoustic velocity faster point several %. At the time stress given as following equation (1).

$$\Delta V/V = C_s \sigma$$  \hspace{1cm} (1)

where \quad \sigma: \text{Acoustoelectric coefficient} \\
\quad C_s: \text{Loaded stress}

Residual stress measured by surface acoustic wave velocity increase called Vz method. Applied ultrasonic frequency was 18MHz by ultrasonic microscope shown in Fig. 11. Vz method principle schematics are shown in Fig. 12.

Reflected sonic wave was interfered by leaked Rayleigh wave in Z-axis shown in Fig. 13. From this interfered curve cycle, surface sonic wave velocity was given from 2800m/sec to 2855m/sec. But there is no valid difference in leaked Rayleigh wave velocity. This became from Rayleigh wave traveling path increase canceled out velocity increase by surface roughness.

![Hardness distribution in depth](image)

Fig. 10 Hardness distribution in depth

![Experimental set up](image)

Fig. 11 Experimental set up

![Experimental Vz method schematics](image)

Fig. 12 Experimental Vz method schematics
6. Experiments on Millimeter wave reflection

The author's final trial gave up to measure surface residual stress. WJP process makes material surface a little rough and localized electric resistance increase by water cavitation. Rough surface and localized resistance increase makes random millimeter wave reflection. The author undertook discriminate from the difference in random radar cross-section $\sigma$, sometimes larger and sometimes smaller. Power density reached at a target is given as following Equation (2).

$$ S = \frac{P_r G_t}{(4 \pi R^2)} $$

(2)

where

- $P_r$: Power of antenna
- $G_t$: Gain of antenna

Scattered millimeter wave received by the antenna is given as following Equation (3) using radar cross-section $\sigma$.

$$ P_r = (P_t G_t / (4 \pi R^2)) (1/4 \pi R^2) \sigma A_r $$

(3)

where

- $A_r$: Receiving area of antenna
- $\sigma$: Radar cross-section

Material surface roughness makes the radar cross-section broaden coefficient. Random reflection makes larger standard deviation in reflected millimeter wave strength ratio $P_r / S$ in [dB]. 110GHz millimeter wave of which wavelength was about 3mm was used in this trial experiments shown in Fig. 14-15. Working distance was settled at 100$\mu$m and scanning pitch was 40$\mu$m. Experimental results in millimeter wave reflection is shown in Table 1 using open-ended coaxial line sensor, upper data are standard deviation in not-processed areas and bottom data are standard deviation in WJP processed area. Longitudinal distribution in reflected millimeter wave is shown in Fig. 16-17.

Fig. 14 Schematic electromagnetic wave detection

Fig. 15 Experimental sensor set up

Fig. 16 Millimeter wave longitudinal reflection from the workpiece

Fig. 17 Millimeter wave reflection distribution in 2D
Table 1 Averaged standard deviation in millimeter wave reflection ratio [dB]

<table>
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<th>process</th>
<th>case1</th>
<th>case2</th>
<th>case3</th>
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From Table 1 WIP processed surface standard deviation in reflection strength are more than 10% larger than not processed one. It means that standard deviation increase in millimeter wave reflection inform us WIP processed or not by remote millimeter wave tooling.

7. Conclusions

To discriminate peening processed surface, millimeter wave reflection method was most useful compared with other three tried methods, electric resistance measurement, residual stress measurement by X-ray diffraction, and Rayleigh wave velocity increase.

a. It was impossible to discriminate peening processed surface by electric resistance measurement by electric probes, of which detecting probes distance 1.8mm was too smaller to get stable conductivity.

b. It was impossible to discriminate peening processed surface by X-ray diffraction, which measured too shallower depth residual stress compared with WIP processed depth and X-ray diffraction much disturbed by surface roughness.

c. It was impossible to discriminate peening processed surface by Vz method using Rayleigh wave, of which traveling path stretched by WJP rough surface.

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