Development of Multifunction Laser Welding Head as Maintenance Technologies against Stress Corrosion Cracking for Nuclear Power Reactors


ABSTRACT

Multifunction laser welding head, which performs repairing, preventive maintenance and inspection in one head, had developed. As a function of repairing, underwater laser welding is achieved for sealing cracks. Preventive maintenance is achieved by laser peening for improving residual stress from tensile to compressive. For inspection, we have been developing a new method of visualized weld defects in water by laser-ultrasonics. To detect and visualize a surface of weld metal with welding bead, we have developed a new detection method by leaky wave induced by interaction with surface acoustic waves and defects. Furthermore, developing Synthetic Aperture Focus Technique (SAFT) for visualized inspection surface 2-dementionally, we achieve the inspection result alike Penetrant Testing (PT) despite underwater environment. We confirmed all functions mentioned above work well by developed multifunction laser welding head.

INTRODUCTION

Stress corrosion cracking (SCC) is to reduce the reliability of aged nuclear reactor internal components. To prevent internal components from generating or growing SCC, we have been developing various laser-based maintenance technologies and already applied them in practical [1][2][3].

Laser-based technology is considered to be the best tool for remote processing in nuclear power plants, and particularly so for the maintenance and repair of reactor internal components. Accessibility could be drastically improved by a simple handling system due to no-reactive force against laser irradiation and the flexible optical fiber.

Recently, we have developed the multifunction laser welding head, which is able to perform not only underwater laser welding as repair, but also laser peening as preventive maintenance and laser ultrasonic testing as inspection. In this paper, various laser-based technologies being developed at Toshiba and development of multifunction laser welding head are described.

PRINCIPLE OF LASER TECHNOLOGIES

Underwater Laser Welding

Underwater laser welding which we has been developing is a technique to weld metal onto a surface by feeding filler wire, where local dry area is formed and laser beam is irradiated, as shown in Fig.1. Underwater laser welding without draining reactor water contributes to short outage and low exposure of radiation by shielding of water. Underwater laser welding can be applied to both cladding and seal
welding. Cladding is effective to improve the corrosion resistance and seal welding can isolate the crack from corrosive water environment.

Figure 2 shows the bead appearances and typical cross-sectional micrographs of underwater laser cladding and seal welding. No weld defect such as crack or porosity was observed and excellent weld bead was formed on the base metal, even though laser welding was performed underwater.

<table>
<thead>
<tr>
<th>Bead appearance</th>
<th>Cross-sectional macrograph</th>
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</thead>
<tbody>
<tr>
<td>Clad weld</td>
<td><img src="image1" alt="Clad weld macrograph" /></td>
</tr>
<tr>
<td>Seal weld</td>
<td><img src="image2" alt="Seal weld macrograph" /></td>
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</tbody>
</table>

Figure 2 - Bead appearance and cross-sectional macrograph of underwater laser welding

**Laser Peening**

Laser peening is a process to change stress condition from tensile residual stress to compressive one on metal surface by irradiating pulsed laser underwater without any surface preparations. We have already applied the technique as a preventive maintenance against generating SCC on reactor internal components [3][4].

When a nanoseconds-order pulsed laser is focused on a water-immersed metal surface, laser energy is absorbed on its surface and the metal plasma is generated through the ablative interaction. The inertia of water acts to confine the metal plasma and prevents it from expanding rapidly. As a result, high-pressure plasma forms on the metal surface shown in Fig.3. The plasma pressure reaches several GPa and exceeds the yield strength of metal material. The surrounding metal material contains the strained region and forms the compressive stress in the metal. The residual compressive stress can be introduced in the metal surface layer by scanning the pulsed laser throughout the surface to be treated. The surface residual stress becomes compressive, almost equivalent to yield stress, by increasing the number of irradiating laser pulses.
Laser Ultrasonic Testing

Irradiating pulsed laser with a few ns pulse duration to surface induces ablation plasma. The plasma generates not only compressive residual stress but also Shock Wave (SW) in water and Surface Acoustic Wave (SAW) on inspection surface by counteraction of plasma. Propagating SAW concentrically, Leaky Surface Acoustic Wave (LSAW) is generated by leaking a part of SAW’s energy in water by critical angle derived from Snell’s law. When there are cracks on propagating path of SAW, interaction between SAW and cracks generates a Leaky Waves (LW). Sound pressure of LW is identified as dilatational change, therefore change of index of refraction is occurred [5]. As refraction index change is equivalent to optical path length change, laser interferometer can detect LW.

Laser-ultrasonics is using two lasers for generating and detecting ultrasonic waves [6]. It is known as a distinctive technology having high spatial resolution, so it has a potential to be used as surface inspection substitute for PT. However conventional Laser-ultrasonics is that detection laser irradiates inspection surface directly, and thus sensitivity of detection is highly depend on surface condition of asperity, roughness and reflectivity. Therefore we propose a new robust detection method, which detection laser doesn’t irradiate inspection surface directly.

Put a reflector with mirror finished surface on in water, and detection laser irradiates to surface of reflector shown in Fig. 4. When LW generated by defects pass through laser beam path, laser interferometer detects LW signals as the changing of laser path length. As a result, proposed method can detect ultrasonic in water without effect of inspection surface conditions.

To confirm detectability of proposed method, we tested visualized performance by using artificial holes having diameter of 1.0mm and depth of 1.0mm. Four holes were drilled on type304 stainless steel apart from 5mm each other (shown in Fig. 5(a)). Inspection area (40x40mm) was scanned at 0.2mm intervals. In order to visualize inspection result as similar as PT, acquired ultrasonic data should transform to 2-dimentional surface information by signal processing. SAW generated by generation laser is nondirectional ultrasonic source, therefore it is suitable to adapt SAFT algorm. So
as to reconstruct objects images from ultrasonic signals, SAFT is common technique [7] and uses in
many fields. Several studies were applying to laser-ultrasonics [8]. However SAFT for 2-dimentional
surface reconstruction technique is not common, therefore we developed SAFT for 2-dimentional
surface working under combining SAW and water velocity.

The result is shown in Fig. 5(b). It visualizes four indications caused by holes. Therefore
proposed method and SAFT for 2-dimentional are applicable to visualize surface inspection substitute
for PT [9].

![Image](image.png)

(a) Top view of specimen    (b) Visualized result

Figure 5 - Visualized result of laser ultrasonic testing

**Development of Multifunction Laser Welding Head**

As mentioned above, we have already developed several kinds of laser-based maintenance
technologies, such as underwater laser welding, laser peening and laser ultrasonic testing. Though
individual irradiation head is necessary on each process, each laser beams irradiated from different
laser oscillators can be transmitted through the optical fibers. We therefore propose the new concept of
integrating mentioned above laser technologies and developed multifunction laser welding head
involving all function mentioned above.

In case of underwater laser welding, a high power fiber laser oscillator with wavelength of
1060nm is used, and defocused laser beam with continuous wave mode is irradiated so as to feed filler
wire into the molten pool. In addition, laser beam is irradiated in the local dry area, so laser welding is
performed in air even though irradiation head is set underwater.

On the other hand, laser peening is a process that focused pulse laser beam with wavelength of
532nm by YAG laser oscillator is irradiated on the material surface underwater.

In order to develop multifunction laser welding head, optical path for both underwater laser
welding and laser peening was designed as shown in Fig.6.

For underwater laser welding, when a continuous wave laser beam with wavelength of
1060nm is irradiated in air, a defocused beam with ideal spot size is irradiated on the material surface
as shown in Fig.6 (a).

In case of laser peening, when a laser beam with wavelength of 532nm is irradiated from
YAG laser oscillator through the lens into water, focusing length is getting longer compared to the
case of underwater laser welding by the effect of optical refraction index n=1.33 as shown in Fig.6 (b).
Therefore, it is possible to irradiate laser beams with different wavelength through the same optical
paths with different ideal spot sizes on each process as shown in Fig.6.
Based on the concept mentioned above, multifunction laser welding head was designed as shown in Fig. 7. In case of underwater laser welding, shielding gas is blown from the inlet and local dry area is formed in the head. In case of laser peening and laser ultrasonic testing, the head is filled with water by pouring water from the same inlet. In addition, inspection unit for laser ultrasonic testing is equipped in the head. Therefore, three different processes can be performed with the one head.

Figure 8 shows the developed multifunction laser welding head. The size of the developed head is a height of around 85mm, a width of around 85mm, and a depth of around 45mm. A small size of the developed head make possible to access to narrow areas in the reactor components.

Experimental results

Underwater Laser Welding

To confirm the applicability on each process, we verified developed multifunction laser welding head by experimentally.

Figure 9 shows the experimental setup. A specimen of Type 316L stainless steel with slit was set underwater and seal welding was performed with laser power of 1100W, welding speed of 40cm/min and with filler wire of Alloy 82. The slit simulated SCC was fabricated by Electric Discharge Machining (EDM) with opening width of 0.3mm, length of 10mm and depth of 3mm.
specimen was set in a water tank and laser beam was transmitted through the optical fiber to the multifunction laser welding head. The head position was scanned by Numerical Control (NC) machine and weld beads were formed on the specimen by irradiating laser beam, feeding filler wire and blowing Ar gas of 50 l/min.

Figure 10 shows the appearance of underwater seal welding with multifunction laser welding head. Excellent weld bead without oxidation was formed on the material surface and EDM slit was sealed with the weld beads.

**Laser Peening**

Figure 11 shows the experimental setup for laser peening with multifunction laser welding head. Conditions of laser peening were shown in Table 1.

Specimens of both Type 304 stainless steel and Alloy 600 were set in a water tank and laser beam was transmitted through the optical fiber to the multifunction laser welding head. The head position was scanned by NC machine and laser peening was performed by irradiating the laser beam as shown in Fig. 11. Residual stress was measured by X-ray diffraction so as to confirm the effect of laser peening.

Figure 12 shows the results of residual stress measurement by X-ray diffraction. Secure compressive residual stress on the peened surface with both Type 304 stainless steel and Alloy 600 was confirmed.
Optical fiber
Multifunction laser welding head
NC machine
Water
Nd:YAG Laser oscillator
Irradiation spot
Specimen
Beam tracking pattern
Figure 11 - Experimental setup of Laser peening

Table 1: Conditions of laser peening

<table>
<thead>
<tr>
<th>Material</th>
<th>Type 304 Stainless steel</th>
<th>Alloy 600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot diameter</td>
<td>0.7mm</td>
<td>0.7mm</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>70mJ</td>
<td>70mJ</td>
</tr>
<tr>
<td>Pulse number density</td>
<td>7000 pulse/cm²</td>
<td>4500 pulse/cm²</td>
</tr>
</tbody>
</table>

Figure 12 - Results of residual stress measurement

Laser Ultrasonic Testing

Figure 13 shows the experimental setup and appearance of laser ultrasonic testing with multifunction laser welding head. A pulse laser beam, whose wavelength and pulse energy were respectively 1064nm and 45mJ/pulse, was transmitted through the optical fiber. To detect LW, another laser beam, whose wavelength was 1064nm, irradiates surface of reflector. Signal of LW was detected with Fabry-Perot interferometer having frequency response from 0.5MHz to 50MHz. Specimen of laser welding with defects was prepared as shown in Fig.14. Scanning area was 40x40mm by 0.2mm pitch, and detected ultrasonic signals were calculated by 2-dimensional SAFT.

Figure 15 shows the result of surface inspection with multifunction laser welding head. Surface morphology of weld bead was visualized and indication caused by weld defect was observed on the weld bead.

Therefore, the proposed and developed method has the performance of visualizing inspection surface in underwater environment and has possibility of substitute for conventional penetrant test.
CONCLUSION

As a new concept applying underwater laser welding technology to nuclear reactor components, multifunction laser welding head was developed and applicability on each process was confirmed. In future work, practical application devices will be developed.

REFERENCES

3) I. Chida et al., Laser based maintenance technology for PWR power plants, Proceedings of 13th International Conference on Nuclear Engineering, ICONE13-50334, 2005
4) M. Yoda et al., Laser-based maintenance and repair technologies for reactor components, Proceedings of 12th International Conference on Nuclear Engineering, ICONE12-49238, 2004
