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Development and Applications of Laser-ultrasonic Testing in Nuclear Industry

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Abstract
A laser-based maintenance system, which includes the laser-ultrasonic testing as a non-destructive testing technology, the laser-peening as a surface stress improvement technology and the laser welding as a repair technology, for the in-service maintenance of nuclear reactor internal components is presented. Regarding the laser-ultrasonic testing, surface acoustic wave generated and detected by lasers is used to detect surface-breaking cracks. As the benefits of broad-band feature of the laser-ultrasonics, this method allows to detect very small cracks having the depth of less than 0.1mm. Also, a frequency response analysis technique of the surface acoustic wave, which propagates through the crack, is developed to size the depth of the crack. The error of this depth measurement method is estimated at less than 0.2 mm through a series of experiments using stress corrosion cracking. A part of the laser-based maintenance system has been already applied to the actual maintenance works in Japanese nuclear power plants. The developed system and its operation are presented. Finally, more recent work to detect and visualize small defects on the weld bead by using leaky-Rayleigh waves is introduced.
Keywords: Laser-ultrasonic testing, laser peening, laser welding, stress corrosion cracking, surface acoustic wave testing, leaky-Rayleigh wave testing, crack depth sizing, nuclear reactor internal component

1. Introduction

In aged nuclear power plants, particularly reactor internal components, initiation of stress corrosion cracking (SCC) is one of the typical deterioration. As countermeasures, it is important to use following technologies properly:

(1) Non-destructive testing (NDT) technology to detect initiation of SCC and to measure detailed information (e.g. depth) of the SCC,
(2) Preventative maintenance technology to prevent initiation of SCC in the future operation,
(3) Repair technology to restore the cracked materials/component.

On the other hand, laser-based technologies in principle feature remote and non-contacting operation and are applicable to narrow space since the laser beams is easily delivered by a fine flexible optical fiber. These are very attractive characteristics for the maintenance technologies of reactor internal components.

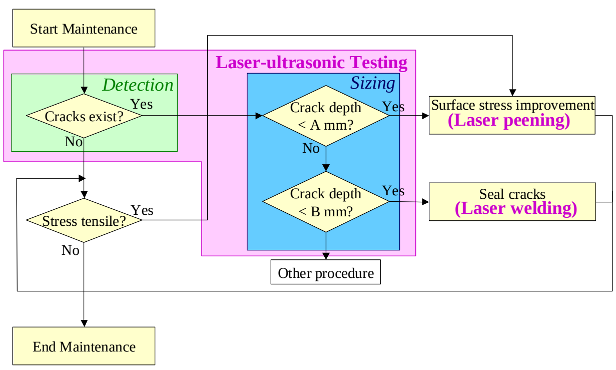


Figure 1. Flow chart of laser-based maintenance for reactor internal components

We established a reactor maintenance strategy based on the laser-based technologies as shown in Fig.1 and firstly developed the

laser peening, which uses pulsed power laser beam to improve surface residual stress of materials to prevent SCC initiation [1].
As the next attempt, we have developed a laser-ultrasonic testing, which realizes NDT of SCC by using laser beams. The laser-ultrasonic uses two lasers, one of which emits short pulse to generate ultrasound in the material and another coupled with an optical interferometer is used to detect ultrasonic signals [2,3]. Using the laser-generated and -detected surface acoustic waves, some pioneer studies to detect surface-breaking cracks in metal have been done from 1980's [4]. Referring these former achievements, we developed an accurate measurement method of crack depth using a frequency response analysis of the surface acoustic waves [5]. To apply this method to the actual industrial reactor internal components, a laser-ultrasonic testing system was developed based on optical fiber delivery function and compact optical head [6,7].
In this paper, we first review the method and performance of the laser-ultrasonic testing. A combined system of the laser-ultrasonic testing and the laser peening, which has already been in practical use in Japan since 2004, is introduced.
Then, as a more recent work, an improved laser-ultrasonic testing method to detect and visualize small defects on the weld bead by using leaky-Rayleigh waves is introduced. This method will be used in the next generation laser-based maintenance system, which includes the laser-ultrasonic testing function, the laser peening function and the laser welding function, in the near future.

2. Laser-ultrasonic testing

2.1 Fundamental Process of Laser-Ultrasonic Testing

It is well known that SAW travels only through the surface layer which is as thin as one wavelength of itself. As shown in Fig.2 (a), most energy of SAW having higher frequency (shorter wavelength) is reflected according to the geometry of a small crack. It means that the SAW containing higher frequency components is a suitable tool to detect micro surface-breaking crack. Result of the laser-ultrasonic detection of microcracks having depths of 0.1 and 0.2 mm and lengths of 1 to 3 mm machined on stainless steel plate can be detected. Crack indication is clearly observed even against the smallest cracking (1mm long, 0.1mm deep) on a B-scan image.
The lower frequency SAW (longer wavelength) penetrating deeper layer is not so sensitive to the crack geometry; it therefore travels over cracks to the other side easier (Fig.2 (b)). As a result, the observed frequency components of the transmitted SAW depend on the crack depth. In other words, crack behaves as a low-pass filter for SAW and its frequency

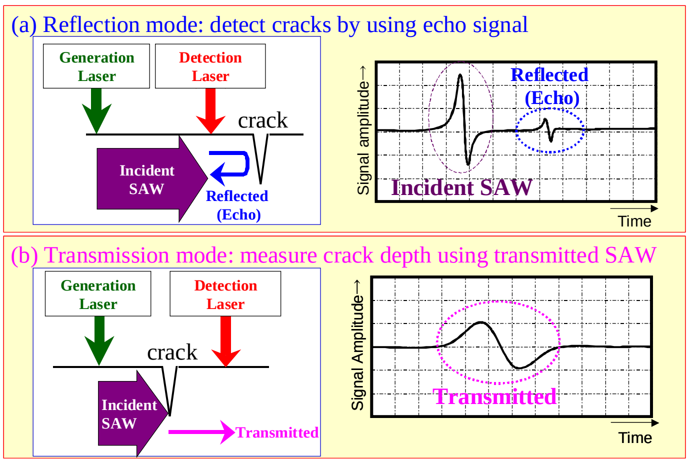


Figure 2. Schematic illustrations of (a) crack detection by using reflection of higher frequency SAW and (b) crack depth measurement by using transmission of lower frequency SAW

response is determined by the crack depth. Based on this principle, a signal analysis process in frequency-domain is developed to obtain the absolute crack depth.

2.2 Performance of Laser-Ultrasonic Testing

To confirm the performance of this crack sizing method, a series of experiments was performed on sample test pieces (T/P). As the basic performance confirmation, 8 machined test pieces, each of which includes 3 electrical discharge machined (EDM) slits having depths of 0.5, 1.0 and 1.5 mm and width of about 0.2 mm, made of stainless steel, welded stainless steel, nickel alloy and welded nickel alloy were prepared. It is noted that 2 types of T/P shape were used: one was flat plate and another was concave shape having a diameter of about 9.0 mm. Also, other 7 cracking test pieces including 14 SCCs were used to verify the performance on actual cracking. The all result of depth measurement is shown in Fig.3. The actual crack depth is measured by the destructive cross-section observation after the experiments. In both cases on EDM slits and SCCs, good agreement with a standard deviation of less than 0.2 mm is achieved between measured and actual crack depth.

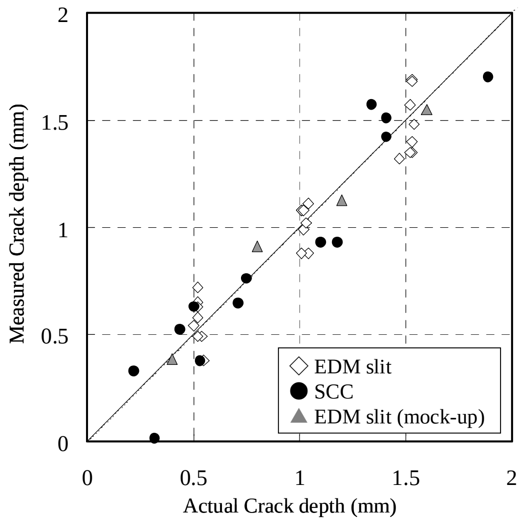


Figure 3. Result of microcrack depth measurement by laser-ultrasonics

3. Application to nuclear reactor internals

3.1 Summary of the application

As an example of the laser-ultrasonic testing, application to the bottom-mounted instrumentation (BMI) in pressurized water reactor (PWR) is introduced. The BMI consists of dozens of tube-shape structures to guide neutron detectors. The tubes are made of Alloy 600 and are welded at the bottom of the reactor vessel. Since inner surface of the each welded part has the potential of SCC initiation, proper inspection and preventive maintenance techniques are expected.

A laser-based maintenance system, which works as both the laser-ultrasonic testing system and the laser peening system, is developed to perform both inspection and preventive maintenance on the inner surface of BMI tubes. The generation laser in the laser-ultrasonic testing system can be identical to the laser source of the laser peening. As an example operation of the laser-based maintenance system, the laser-based maintenance system firstly works as the laser-ultrasonic NDT mode and tests the inner surface of the BMI tube. If no cracks are detected, the laser-based maintenance system then changes its work mode to the laser peening and improves surface stress to prevent SCC initiation in future operation.

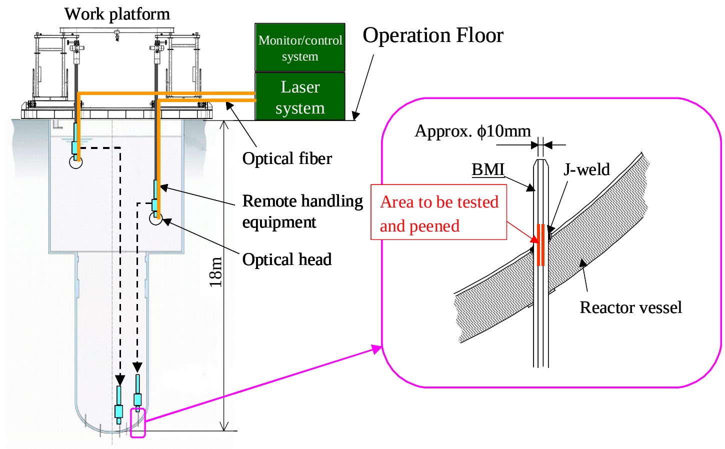


Figure 4. Laser-based maintenance system for inner surface of BMI

3.2 Laser-Based Maintenance System for BMI

The laser-based maintenance system is composed of laser system, beam delivery system (optical fibers), optical head, remote handling equipment, work platform and control system as shown in Fig.4. The laser system and the control system are placed on the operation floor. The laser beams are delivered by the optical fiber having a length of about 40 m. The remote handling equipment is hanged under the work platform and is fixed on the top of the BMI tube. The optical head is inserted into the BMI tube and is scanned helically with irradiating inner surface. The axial scan rate was about 8 sec/mm in this experiment. Since the inner diameter of the BMI is very narrow, 10mm-ID for example, a small optical head is required. The developed optical head equips with two mirrors in one housing; one reflects and collects detection laser to detect ultrasonic signals and another is used to irradiate generation laser to the tested surface, as shown in Fig.5. The generation laser and the detection laser are split at the first mirror (dichroic mirror) by their wavelengths. It is noted that the most of these components are shared between the laser-ultrasonic NDT and the laser peening.

The first laser-based maintenance system is produced and tested its performance through full-scale mock-up facility. Four EDM slits, having depths of 0.4 mm, 0.8 mm, 1.2 mm and 1.6 mm respectively, are introduced on the inner surface of a BMI tube mounted on the full-scale test piece. Crack depths measured with the laser-based maintenance system are plotted in Fig.3 as grey triangles. As a result, it is confirmed that the laser-ultrasonic testing system detects micro cracking on the inner surface of BMI tube and the depth of the cracks are successfully measured using the suggested signal processing on the transmitted SAW.

In December 2004, we started to use the system in the actual reactor maintenance work in Japanese nuclear power plants.

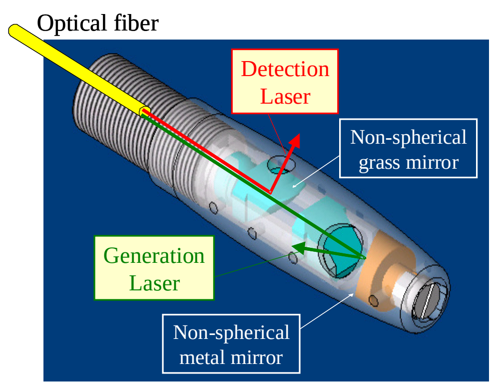


Figure 5. Concept of optical head used for laser-based maintenance on inner surface of BMI

4. Multifunction laser welding system

As a recent work, we attempt to install the laser welding function into the laser-based maintenance system. In this case, the laser-ultrasonic testing is required to perform small weld defects detection on the rough surface as laser weld bead.

4.1 Improved Process of Laser-Ultrasonic Testing

Irradiation of the generation laser induces ablation plasma. The plasma induces shock wave (SW) in water and surface acoustic wave (SAW) on inspection surface. Also, leaky surface acoustic wave (LSAW) appears due to leakage a part of SAW's energy in water by critical angle derived from Snell's law. When cracks exist on the propagating path of SAW, interaction between SAW and cracks generates leaky waves (LW). The detection laser irradiates to a reflector with finished surface in water. When the LW travels through the 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.

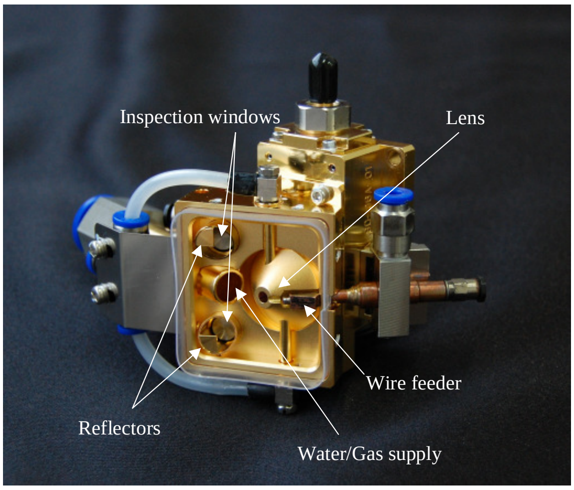
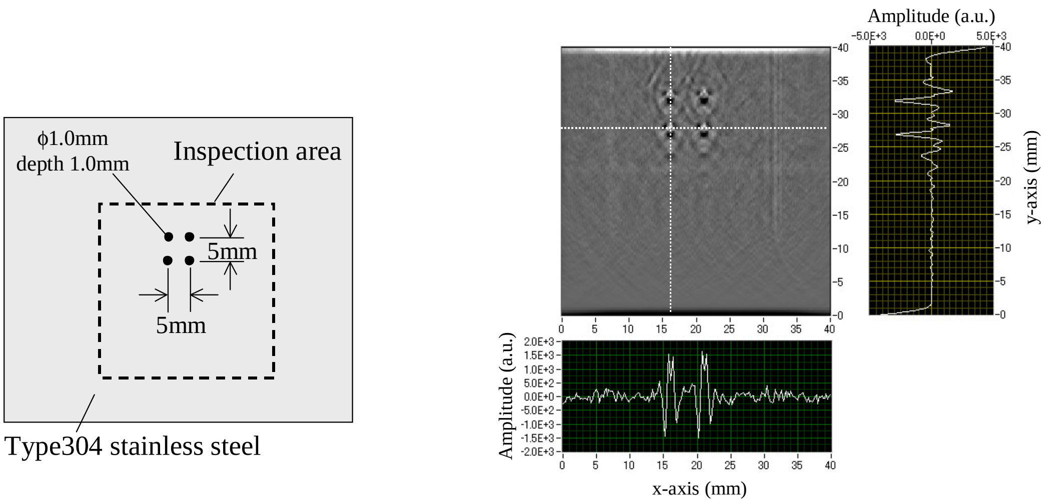


Figure 6. Appearance of the multifunction laser welding head

4.2 Summary of multifunction laser welding head

A multifunction laser welding head, which works as the improved laser-ultrasonic testing system, the laser peening system and the laser welding system, is developed to



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

Figure 7. Result of feasibility study by drill holes

perform all aspect of maintenance tasks listed in the first section. The appearance of the head is shown in Fig.6.
To confirm detectability of the improved method, we visualized artificial 4 holes having diameter of φ1.0mm and depth of 1.0mm. The holes were drilled on type304 stainless steel apart from 5mm each other (shown in Fig. 7 (a)). Inspection area (40x40mm) was scanned at 0.2mm intervals. In order to visualize the inspection result, acquired ultrasonic data is reconstructed to 2-dimensional surface information by signal processing. The SAFT processing is well-known technique and several studies have been attempted with laser-ultrasonics, too [8,9]. However, in our case, the SAFT processing should be implemented on 2-dimentional surface under combining SAW and water velocity. As a result, four indications are successfully visualized shown in Fig. 7 (b).

5. Conclusions

Laser-ultrasonic testing technologies developed as NDT tools for nuclear power plants are introduced. We have reported that the laser-ultrasonic testing is capable of providing very accurate depth of micro cracks including SCCs. Also, the laser-ultrasonic testing system for the inner surface of BMI tubes is developed and its performance is verified through some feasible tests and full-scale mock-up experiments. The system has been already industrially used in Japanese nuclear power plants. As more recent work, the improved laser-ultrasonic testing technique, performance of which is more robust against the surface condition, is suggested.

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