

Innovative maintenance technology for RPV and RIN of operating nuclear plant

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Abstract. Many nuclear power plants (NPPs) have been successfully operated beyond twenty or thirty years in the world. But there still exist some possibility of unexpected events that affect the integrity of components and cause unscheduled long outage. It is important to confirm and assure the integrity of reactor pressure vessel (RPV) and reactor internals (RIN) in order to maintain NPPs' safe and steady operation. Standard sequence for maintenance and some recent technology and related topics are introduced here.

1. INTRODUCTION

When the maintenance of operating plants' RPV and RIN is considered, stress corrosion cracking (SCC) is a primary subject to be managed. And as for major maintenance technology for RPV and RIN of operating NPPs, there are some categories such as inspection, evaluation, mitigation or preventive maintenance and repair. There is a standard maintenance sequence including and relating those technologies. In this paper, usual maintenance sequence in Japan is explained with some maintenance technology category.

And there are some innovative technologies developed and some of them were applied on actual NPPs. Laser-based technology is considered to be excellent tool for remote operation in NPPs, and particularly beneficial for the work under radiation environment. Accessibility could be drastically improved by a simple handling system owing to the absence of reactive force against laser irradiation. Rapid heating and cooling of the process minimize the heat effect, which extends the applicability to neutron-irradiated material in operating NPPs. In this paper, we describe underwater mitigation technology or laser peening and repair technology or underwater laser beam welding. Those are applicable underwater condition and radiation dose to workers could be significantly reduced compared with conventional procedures that require air surroundings.

As for laser peening, effect of applied stress after laser peening is discussed and some other interesting technical topics is introduced.

And as another plant improvement technology worthy of special mention, integrated reactor internal components replacement work was accomplished for some NPPs in Japan. The main objective of integrated replacement is to replace all RIN susceptible to SCC, such as core shroud, jet pumps and so on. The work can reduce total outage schedule, cost and exposure through the lifetime of NPP.

2. MAINTENANCE SEQUENCE FOR RPV AND RIN OF OPERATING NPPS

Fig.1. shows standard maintenance sequence for Japanese operating NPPs. For the first step, surface inspection is performed by visual testing or other method.

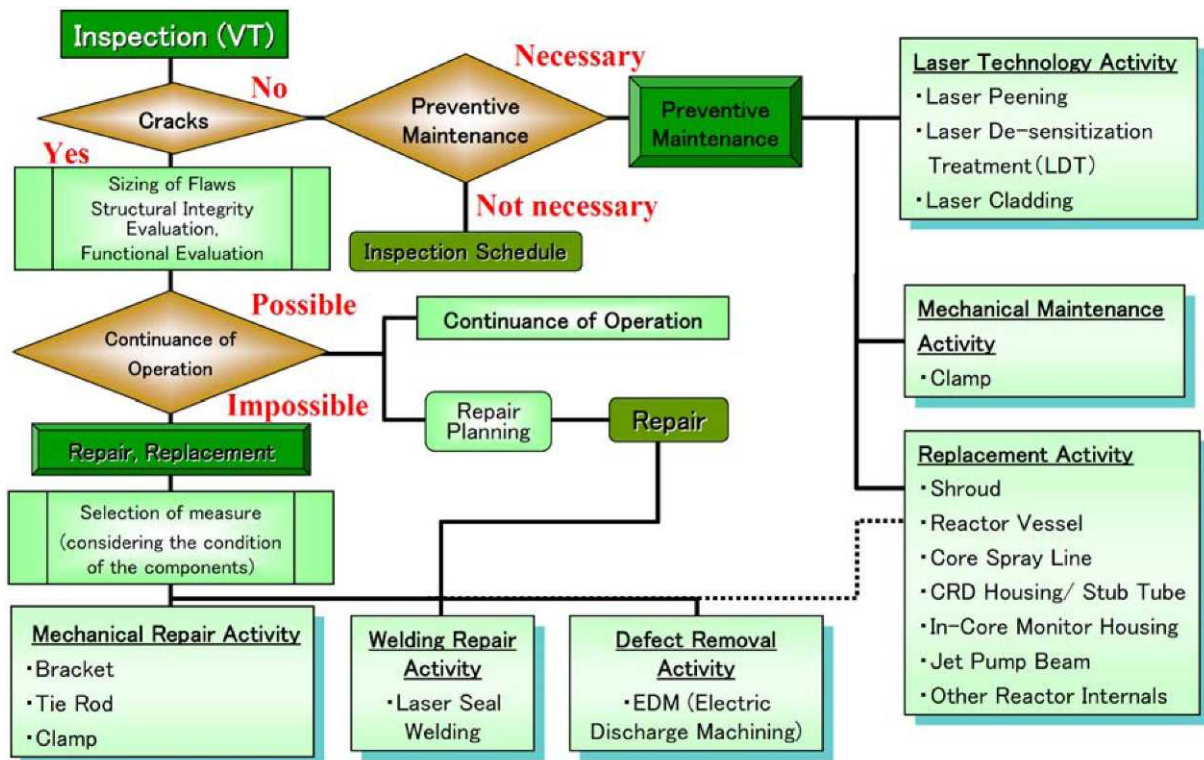


Fig. 1. Standard sequence of RIN maintenance and related technology

If there is no crack observed and it is considered that there is almost no probability of SCC judging from current knowledge on that area, it goes periodical inspection only. In case there is some possibility of SCC occurrence, preventive maintenance work can be implemented. As for preventive maintenance technology, there are some kinds, laser-based technology such as laser peening, mechanical technology such as clamp and replacement technology. If SCC is found on the surface by inspection, sizing of flaw is performed by detail inspection such as ultrasonic testing. And in consideration of the result of crack sizing, evaluation of structural integrity and components' function is performed according to the procedure that is specified in Japanese code endorsed by regulator to judge continuance of operation is possible. If it is possible, there are two selections. One is to continue the operation and another is to plan and implement repair. And if the evaluation results in impossibility of operation continuance, repair or replacement work is to be performed.

As for repair technology, there are also some selection, mechanical repair such as tie rod, welding repair such as underwater laser beam welding, defect removal by EDM and replacement work.

3. INNOVATIVE MAINTENANCE TECHNOLOGY FOR RPV AND RIN

3.1 Laser-based maintenance technology

3.1.1 Underwater laser beam welding

Underwater laser beam welding can be performed in a local dry area made by an argon shield gas flow, which puts surrounding water out of the optical path and welding spot, as shown in Fig. 2. [1]. The optical head is much smaller and simpler than those of conventional ones [2].

A sound and uniform cladding layer without oxidation was obtained by optimizing welding conditions, namely, laser power, welding speed, wire material, wire feed rate, argon shield gas flow rate, etc. No indication was detected in liquid penetrant and side bend testing. [3] Fig.3. [4] shows the results of welding around the inside periphery of pipe. Corrosion-resistant cladding (CRC) layers can be built on degraded or SCC-sensitive surfaces with chromium-rich filler wires. This can be also applied to components with cracks. The resulting layer could isolate crack tips from environment, which would prevent the cracks from further growth. Fig. 4. [3] shows the result of seal welding on crack. And Toshiba confirmed sound weldability of ERNiCrFe-7 weld metal on Alloy 600 base metal.[4]

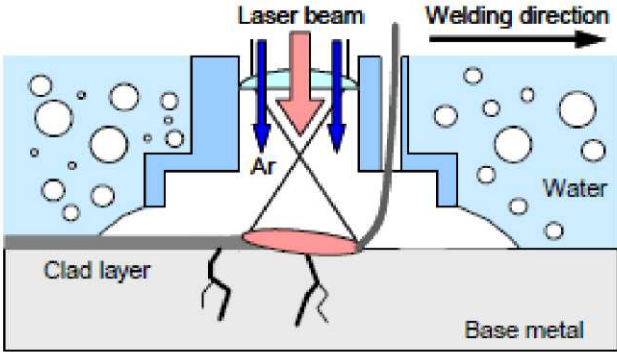
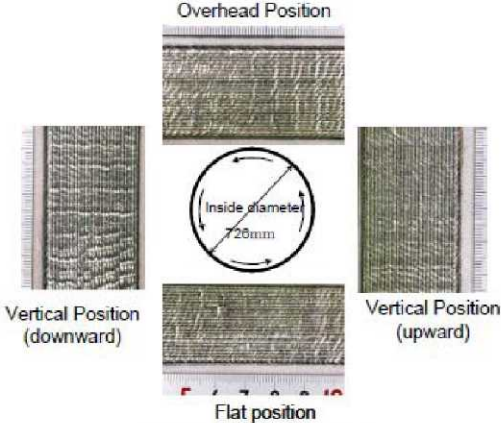


Fig. 2. Underwater laser beam welding



(a) Equipment



(b) Appearance of welding bead

Fig.3. Equipment and the results of welding on inside of the pipe

	Appearance	Cross section
Flat position	• - - - - - ?	
Vertical position (upward)	$r-i$ if	
Vertical position (downward)	\sim T	mm
Overtiead position		1 Tn

Fig. 4. Appearance and cross section of underwater laser beam seal welding

3.1.2. Laser peening

- Fundamental Process and features

Laser peening for RIN is a process to introduce compressive residual stress on metal surface by irradiating laser pulses underwater without any surface preparations.[5] We have already applied it as a preventive maintenance measure against SCC on reactor core components[6,7]. Laser peening utilizes the irradiation of intense laser pulses on a metal surface in water to create compressive residual stress. When a nanoseconds-order laser pulse 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.3.1.2-1. The plasma pressure, which impinges the metal surface, 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 laser pulses throughout the surface to be treated. The surface residual stress becomes compressive in high level magnitude and it is enough to prevent SCC.

And there are some features in this technology. Depth of compressive stress is about 1mm or more that is deeper than conventional peening such as shot peening. During the implementation of laser peening, there is no influence by vibration on surrounding structure, and reactor water can be kept clean without raising crud in reactor. Ability to prevent SCC by laser peening is tested and confirmed enough.[3,8]

- Experience

From 1999 Toshiba has applied laser peening on Japanese actual plants, both BWR and PWR. Fig. 5. [8] shows the target location for laser peening application for BWR. As for PWR plant, ID and OD of BMI nozzles, ID of primary water inlet nozzles and ID of safety injection nozzles were applied.

Toshiba has performed laser peening implementation at 8 BWR plants and 2 PWR plants.

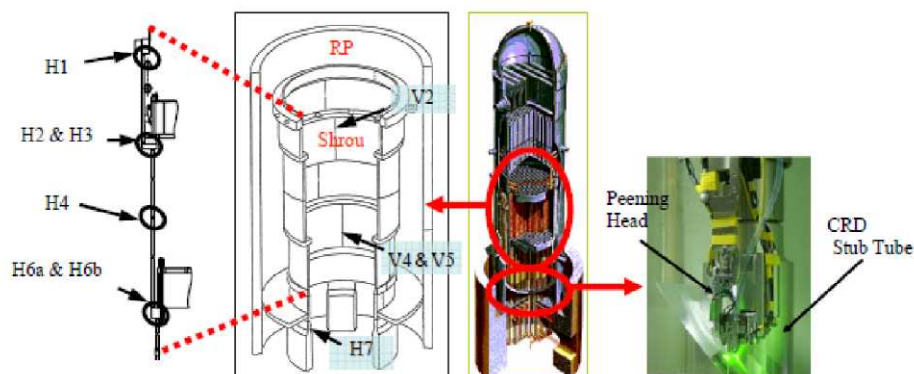


Fig. 5. Application for Japanese BWR

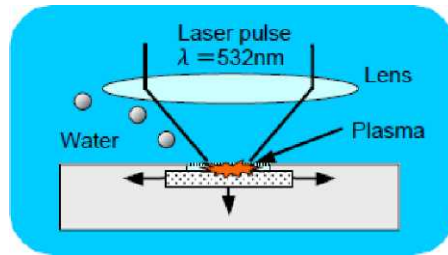


Fig. 6. Fundamental process of laser peening



Fig. 7. PLP system for BWR bottom

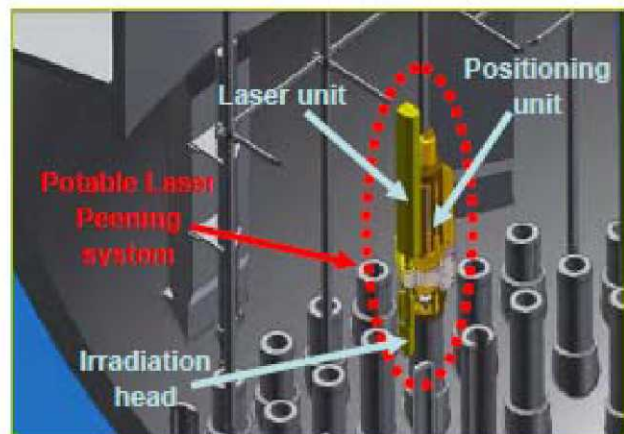


Fig. 8. Concept of peening application for BWR bottom by PLP system

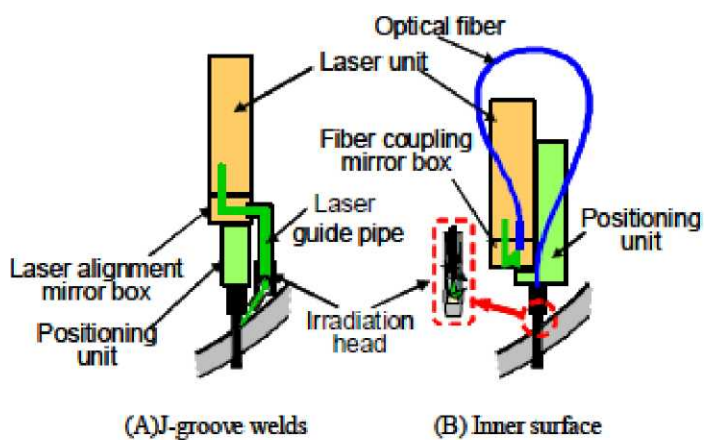


Fig. 9. Schematic figure of application for OD and ID of BMI nozzles

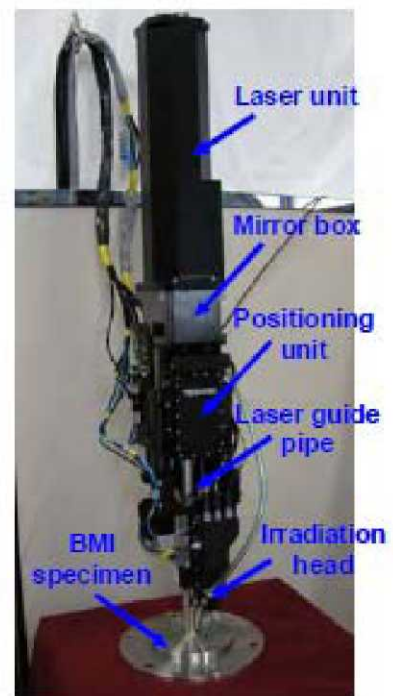


Fig. 10. PLP system for outside J-groove welds of BMI nozzles

- **Development of portable laser peening system**

A new concept of portable laser peening system (PLP system) was developed to enhance the usability and reliability of the laser peening technology. By integrating the laser oscillator into the positioning unit, total volume of the system was drastically reduced and handling ability was improved. Fig. 7. shows PLP system for BWR bottoms. Fig. 8. shows the concept of peening application for BWR bottom by PLP system. Weight of the system is only 30kg [9]. Fig. 9. [9] shows schematic figure of application for OD and ID of BMI nozzles. Fig. 10. [9] shows PLP system for outside J-groove welds of BMI nozzles.

3.1.3. Reliability and application of laser peening

- Effect of applied stress on the compressive residual stress after laser peening

The cyclic stress is loaded by using the round bar specimen subjected to LP of the austenitic stainless steel and the nickel base alloy. The influence of the applied stress and the number of cyclic loads on the surface compressive stress is evaluated [10]. Fig. 11. [10] shows the round bar specimen of 8mm in the diameter. LP is constructed to the shaded portion. First of all, the residual stress on the LP construction surface is measured by the X-ray diffraction method. Afterwards, the applied stress is loaded axially of the test specimen with a fatigue testing machine. The magnitude of the applied stress is decided S_y and $1.5S_y$ in the tensile stress, $-S_y$ and $-1.5S_y$ in the compressive stress based on design yield stress S_y of Type 316L and NCF600(Inconel 600). The cyclic stress is loaded up to 600 times under load control. The stress ratio is 0.1. After 1, 3, 5, 10, 50, 100 and 600 cyclic loads, the surface residual stress is measured. To confirm the temperature influence, the stress load examination of Type 316L is executed at room temperature and $288^\circ\text{C}(=561\text{K})$ that is the BWR operating temperature. Fig. 12. [10] shows a relation between the applied stress and the measured surface residual stress by the room temperature and $288^\circ\text{C}(=561\text{K})$ of Type 316L. These are the residual stresses after constructing LP(=before loading) and after 1 cycle loading. A residual stress axially of the test specimen is measured. Moreover, Fig. 13. [10] shows the test results at the room temperature of NCF600. A horizontal axis is a value in which the applied stress is divided in 0.2% proof strength of each material and each temperature. In each test results, a small relaxation occurs for the tensile stress of $1.5S_y$. However, the compressive residual stress is maintained. There is no change under the surface compressive residual stress when the applied stress doesn't exceed 0.2% proof strength of each material.

Fig. 14. [10] shows the relation between the number of cyclic loads and the surface residual stress after the cyclic loads. The applied stress is $1.5S_y$. In each test results, the surface residual stress changes at the early stage of the cyclic loading, and it changes a little afterwards. However, it hardly changes in the cyclic loading since the tenth times. The cyclic applied stress on the surface compression stress caused by the LP construction was evaluated for Type 316L and NCF600 used in the BWR plant. It is confirmed that the surface stress keeps compressive when applying stress is 0.2% proof strength.

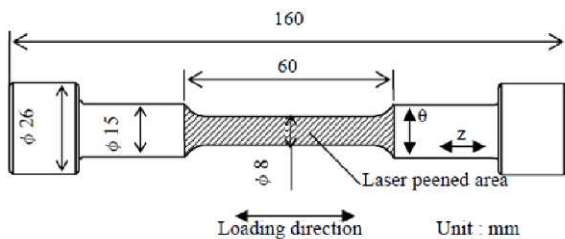


Fig. 11. Test specimen

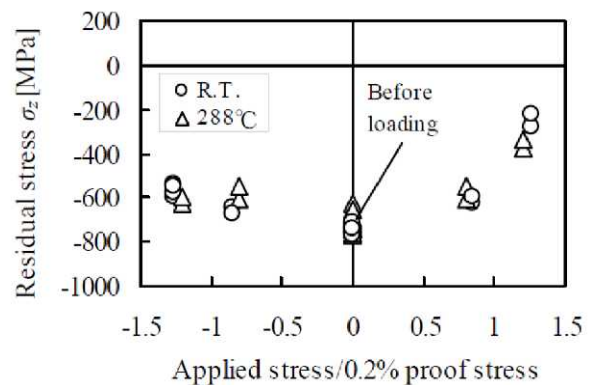


Fig. 12. The effect of applied stress on the residual stress (Type 316L, RT and 288 degrees C (=561K))

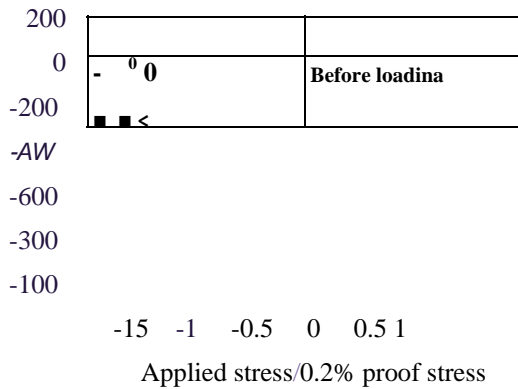


Fig. 13. The effect of applied stress on the residual stress (Ni base alloy ,R.T.)

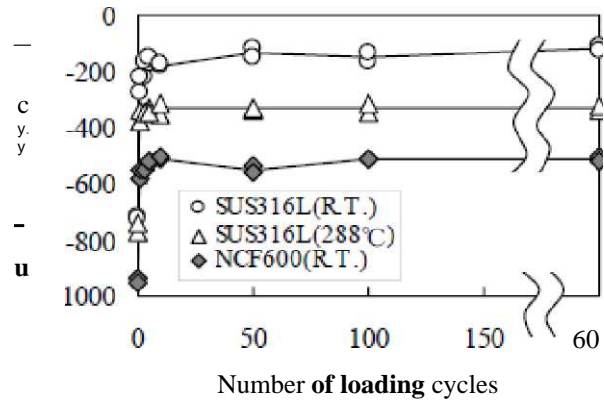


Fig. 14. The effect of number of loading cycles on the residual stress (Applied stress =1.5Sy)

- Application of laser peening to component including cracks

Laser peening process can change surface tensile residual stress into compressive. At the laser peened area where there was significant tensile stress before peening, the residual stress change into compressive as deep as 1mm or a little more from the surface but residual stress remains tensile as before in deeper region. When surface crack growth from unpeened area reaches the front of laser peened area, or when SCC exists in laser peened area, crack could propagate in the peened area even if crack growth rate may become slower.

When we apply laser peening to component including existing SCC, we must do some evaluation beforehand, and based on it, implementation should be planned.

Imaging BWR core shroud as an component example, author recommends the way of consideration.

- Assumption

There is a circumferential weld line that has already SCC within limited area.

By applying laser peening to the weldline, it is desired to assure the component's integrity through the plant lifetime.

SCC that already exists can propagate even in the peened area.

- Consideration

Attention to be paid is that new crack does not occur in the laser peened area. Evaluation should be performed to confirm the minimum required area (or length) for this weldline to keep the structural integrity. Evaluation is considered to be better if it is done according to the method regulator admit. For example, as for U.S. it is recommendable by applying limit analysis specified in ASME code, as for Japan by same method specified in Japanese maintenance code.

After understanding the minimum required area evaluated above, adjacent peening area (or length) is to be decided. Adjacent peened area should be decided in consideration of SCC growth of required period as plant's lifetime after laser peening performance. (As for this required period, there can be some alternate such as 'inspection free period' according to case.) SCC crack growth can be evaluated using the published knowledge or code. For example, recent published PVP paper describes $1.6\text{mm} \times 10^{-7}$ mm/s [11]. (corresponds to 5.1mm/year) Fig. 15. shows the schematic concept for peening needed area. Through above evaluation peening area can be decided. Considering this peening needed area requirement and actual plant's crack distribution, actual implementation area can be planned.

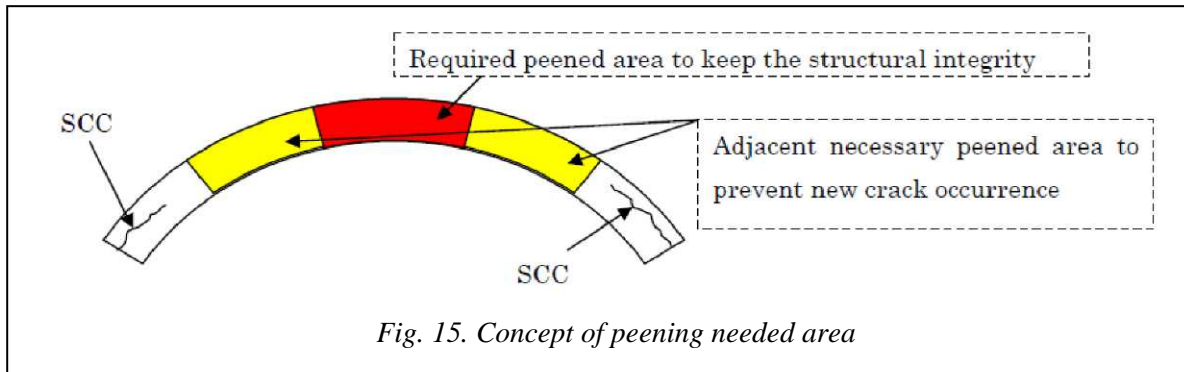


Fig. 15. Concept of peening needed area

- Affect to the existing crack by laser peening

In the laser peening construction, it irradiates it while making the laser pulse on the metal material for component overlap by moving the enforcement device. The compressive residual stress is formed on the surface as an accumulation result of energy by the repetition. The SCC crack that exists on the component also repeatedly receives the laser irradiation. The residual stress is analyzed by the LP construction for the BWR shroud support ring weld [12]. The re-distribution of the stress by having generated the compressive stress on the surface occurs. The influence on the crack when the laser peening to the component with the crack is constructed is examined. In this paper, J -integral by the residual stress distribution after LP is evaluated. It thinks J -integral to be crack extension force that considers the effect of the accumulation of the laser peening. J -integral is evaluated from the residual stress distribution before and after the laser peening. In addition, the extension of the crack by the laser peening is evaluated compared with J -value of the J -R curve that shows the crack extension resistance of the material.

The circumferential surface crack depth of 360 degree is assumed to be 1mm by using the residual stress distribution before and after the laser peening for the shroud support ring weld, and J -value is calculated. J -value before the laser peening is 1.6(kN/m). J -value after the laser peening is 0.08(kN/m). Therefore, J -value as the crack extension force in the laser peening is evaluated as from 0.08 to 1.6(kN/m).

The toughness of base metal and HAZ of Type 304 are so high. J_{IC} can not be determined for such materials. J_{IC} is obtained for weld metal since the toughness is relatively low. J_{IC} of the weld metal is about 200(kN/m) from room temperature to 289°C(=562K) of BWR operating temperature[13]. In addition, the toughness is high and J_{IC} is not obtained by the nickel base alloy weld metal (Inconel 182). The value evaluated with J_Q is about 300(kN/m) at room temperature and is about 800(kN/m) at 300°C(=573K) [14]. Thus, the fracture toughness (ductile crack initiation) of the material of the austenitic stainless steel weld metal and the nickel base alloy weld metal is very high by the laser peening to the crack whose depth is 1mm compared with J -value.

The sensitized austenitic stainless steel Type 304 is soaked in 42% boiling $MgCl_2$ solution. A lot of small cracks are introduced into the surface of the specimen. And the laser peening is constructed to the surface of specimen. The laser peening construction is executed by the maximum and the standard energy within the range of the conditions of performance. Fig. 16. shows the cross-sectional micrograph of SUS304 after laser peening. The crack close when LP is constructed on both conditions, and the crack blunting is not observed at crack tip. Therefore, a new crack doesn't propagate by the laser peening.

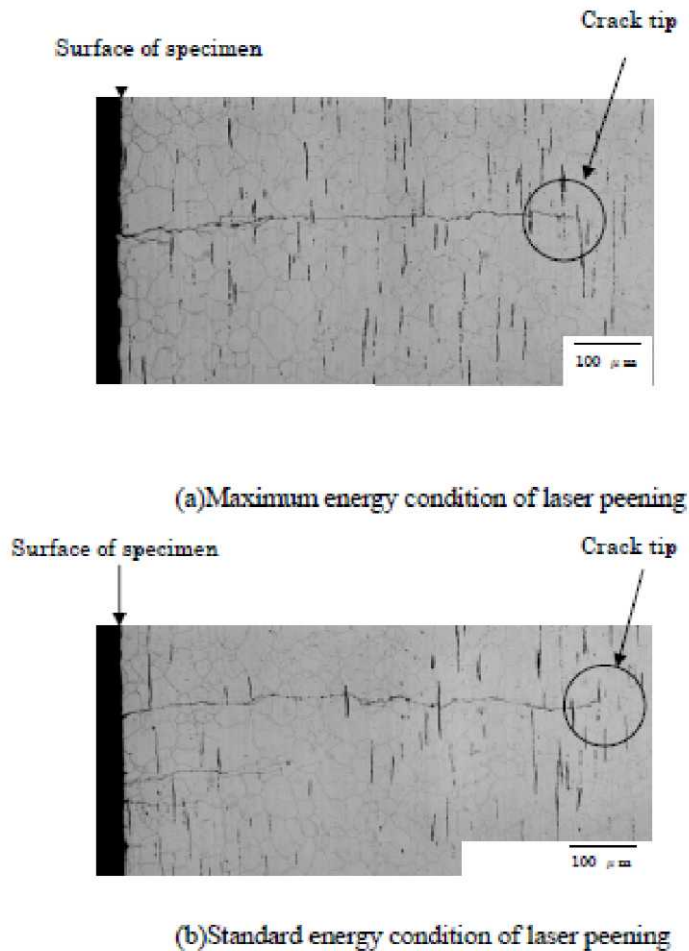


Fig. 16. Cross-sectional micrograph of Type 304 after laser peening

3.2 Integrated reactor internal component replacement technology for BWR [15]

SCC on the core shroud of WR was first found in the 1990s in several countries (Germany, Japan, Sweden, USA, etc.). Since the shroud is typically welded to the RPV and other parts of core internals, mechanical repair, brackets, or tie rod devices have been applied to reinforce the shroud with respect to cracking, under regulatory approval. A method of replacement of the core shroud together with other internal components such as jet pumps was developed jointly by Japanese BWR owners and fabricators and applied to several Japanese plants.

In these replacement works for welded reactor internal components, there are several basic policies to follow to perform the work efficiently. They are as follows,

- The possibility to work on the reactor bottom during a certain period of the replacement work greatly assists performing complex and difficult work.
- To gain access to the bottom, chemical decontamination should be performed.
- To gain access to the bottom, effective shields should be installed during certain periods of the replacement work.
- Removal of the old reactor components should be performed remotely in order to reduce the radiation exposure.
- New core shroud weld edge is a narrow groove employed to reduce residual stress and minimize the welding time.

The main objective of integrated replacement is to replace immediately all components susceptible to SCC, such as core shroud, jet pumps and so on, thereby reducing total schedule, cost and radiation

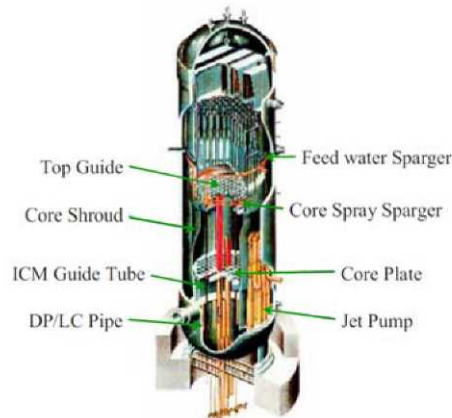


Fig. 17. Outline of replacement target components in integrated replacement work

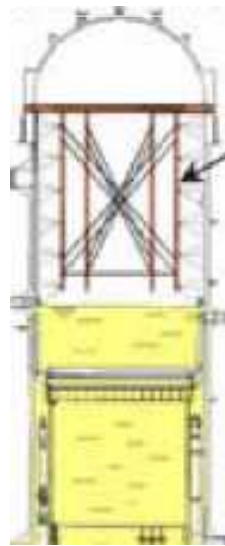
exposure. Several components were replaced at the same time, they are as follows, Fig. 17. shows the explanation.

- Core shroud;
- Top guide;
- Core plate;
- Core spray spargers;
- Feedwater spargers;
- Jet pumps;
- Differential pressure liquid control piping;
- In-core monitor guide tubes;
- Internal piping and nozzle safe ends connected to these components.

Fig. 18. [15] shows the explanation of the replacement target components and Fig. 19. [15] shows the outline of the replacement sequence.

4. SUMMARY

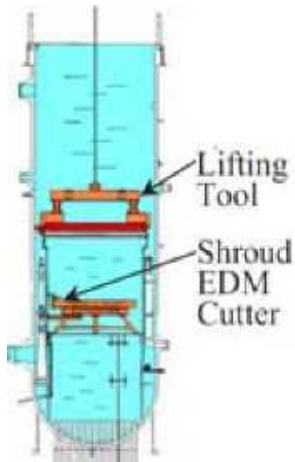
The underwater laser processing is considered to be one of the most beneficial tools for the maintenance and repair of components in nuclear power plants (NPPs). In line with the idea, the authors have developed the underwater laser beam welding and laser peening technologies to prevent or repair SCC. Each technology has unique and outstanding features as a remote processing. As for laser peening, authors introduced some technical topics that has been studied up to this point. They are effect by cyclic loading to laser peened area, consideration to apply laser peening to components including SCC and affect to the existing crack by laser peening. Considering those studies, application scope of laser peening can be extended than ever. And integrated reactor internal component replacement technology for BWR is also introduced. It is a profitable implementation considering through plant's lifetime and it will be implemented to more NPPs with successive improvement of work procedure in future.



Spray ring

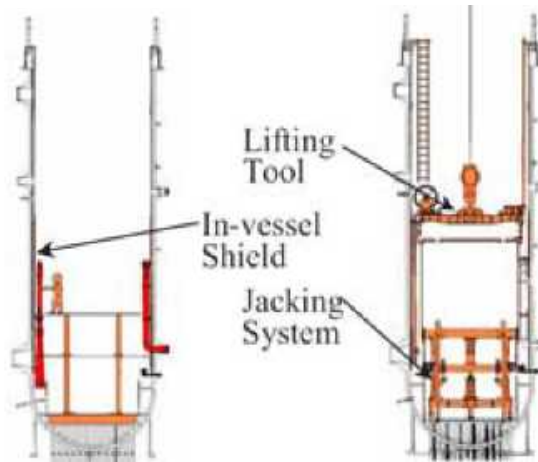
(1) Chemical Decontamination

(2) Core Shroud and other internals cutting



Lifting Tool
Shroud EDM Cutter

(3) Jey Pump Installation



Lifting Tool
In-vessel Shield
Jacking System

(4) New Core Shroud Installation

Fig. 18.

(5) New Core Shroud
Welding

(6) Core Plate Top
Guide Installation

(7) Restore Internals
Components

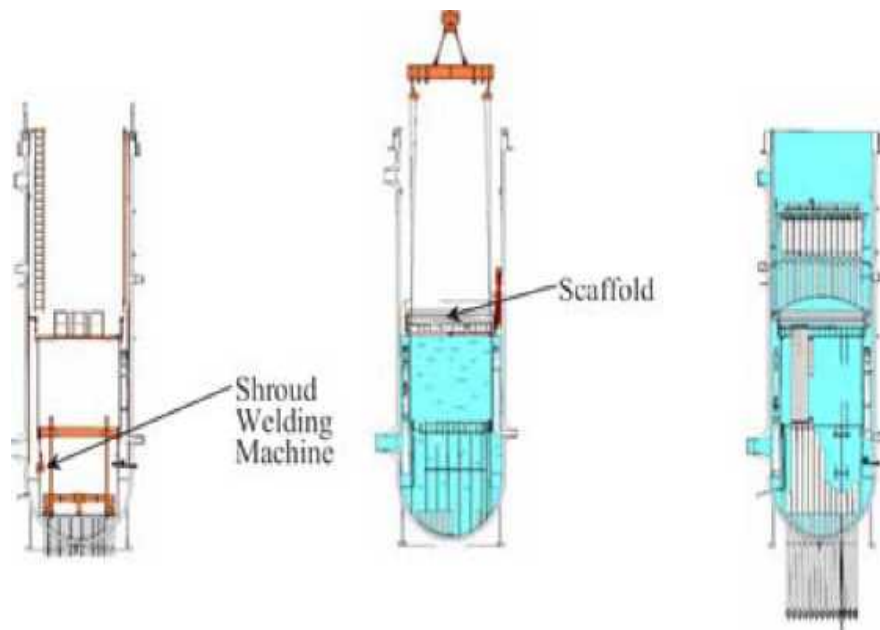


Fig. 19. Replacement sequence of reactor internal components.

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