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SHOT PEENING TECHNIQUE FOR REDUCING RESIDUAL TENSILE STRESS OF CORE SHROUD ON CHEPCO H-1/2

S. Shima*, M. Obata** , K. Sato***, M. Kimura***, A. Sudo***,
H. Hasegawa****, Y. Yamada****
Toshiba Corporation
*Nuclear System Design and Engineering Dept. , ** Heavy Apparatus Engineering Lab.,
*** Nuclear Engineering Lab.,****Nuclear Energy Equipment Manufacturing Dept.,
P.O. Box 235
8,Shinsugita-cho,Isogo-ku,Yokohama,JAPAN

S. Hida
Chubu Electric Power Co., Inc.
Nuclear Power Operation Dept.
P.O. Box 461-91
1,Toushin-cho, Higashi-ku, Nagoya, JAPAN

ABSTRACT

The shot peening technique was practically applied to the core shroud in Hamaoka Nuclear Power Station Unit 1,2 in Chubu Electric Power Co., Inc.(CHEPCO) as a preventive maintenance technique to enhance the resistance for Stress Corrosion Cracking(SCC). The water projection type shot peening technique which was developed to process the core shroud under water, could securely convert the welding induced tensile stress into compressive stress.

Several fundamental experiments were carried out using the shot peening system. The test pieces were prepared from the 20% cold worked Type 304 stainless steel, which simulated the hardness of the irradiation hardened stainless steel by high energy neutron irradiation for a long period. The effects of processing parameters on the stress improvement of the Type 304 stainless steel were examined to determine the optimum processing conditions. And the effectiveness to prevent SCC in hightemperaturewater was evaluated, the other material characteristics such as general corrosion resistance, hardness change, microstructure and thermal relaxation of compressive stress, were also examined. The shot peening technique could certainly prevent SCC of hardened and sensitizing heat treated Type 304 stainless steel, and did not have the detrimental effects to the material characteristics. The effectiveness and the applicability to the practical core shroud were confirmed from the several fundamental experiments.

The stainless steel shots (1.0 mm diameter) were projected by high pressurized water(10 kgf/cm^2) to the weld of the core shroud using the developed head, then the projected shots were completely sucked into the head together with water around it using a high capacity suction pump. The two types of the remote handling robots were applied to Hamaoka Unit 1,2, which had the precise positioning to follow the complicated shape of the core shroud weld line and high processing efficiency to reduce radiation exposure. One was designed and fabricated to process the inner surface of the cylindrical core shroud, which was fixed between the upper grid and the core plate, and the X shaped link arm was employed to access the surface. The other was for processing the outer surface of the core shroud, which was hung on the upper shroud, and could move in the circumferential direction along its edge. We could process the weld on the core shroud of Hamaoka Unit 1,2 with high precision and high efficiency using these robots and the processing system.

INTRODUCTION

SCC is one type of material degradation to which austenitic stainless steel might be subject, and therefore, it is necessary to develop preventive techniques with respect to SCC. Tensile residual stress attributable to the welding heat cycle is one of the causes of SCC, the stress improvement by shot peening could be effective to suppress SCC. Shot peening has been practically applied in some fields, for example, in chemical plants for repairing welds of austenitic stainless steel reactor vessels(1), and in pressurized water nuclear reactors (PWRs) for alloy 600 steam generators(2)(3)(4). Type 304 stainless steel with high carbon content which had the susceptibility for SCC, was employed for the shrouds of early BWR plants, and the occurrence of SCC in core shroud welds has been reported. Shrouds of the early BWRs have been irradiated by high energy neutrons for a long period, and therefore, have high strength due to irradiation hardening. The test pieces for several fundamental experiments were prepared from 20% cold worked Type 304 stainless steel which simulated the hardness of the irradiation hardened material. The influences of processing conditions on the residual stress profiles were examined to determine the optimum processing conditions to suppress SCC using the prototype water projection type processing machine. The material characteristics of the shot peened materials and the applicability to the core shroud were evaluated by several fundamental experiments.

The water projection type shot peening system and remotely driven processing robots were designed and fabricated to process the practical core shroud. It was necessary that the projected shots had to be sucked for repeated use to reduce the radioactive waste and that, the shot peening head had to be driven remotely to access the welds on the shroud inner and outer surfaces under water with precise positioning. It was also necessary to develop some kinds of shot peening heads depending on the shape of processed weld lines, which had the reliable function for the projection and suction of the shots. Especially for processing the shroud outer surface, the thin head which could access the narrow region between the shroud and jet pumps, was developed and applied to the core shroud.

The developed technique was applied to the core shroud on Hamaoka Unit1,2 during one scheduled outage. The processing system was improved to suppress the increase of the radioactivity on the operation floor due to the sucked dusts and scales with radioactivity. For processing shroud inner surface, the remotely driven robot was set after removal of nuclear fuels in core region. It was installed several times at the different peripheral positions in core region to avoid the collision with the in-core monitors.

MECHANISM FOR COMPRESSIVE STRESS FORMATION

The mechanism for compressive stress formation is illustrated in Figure 1. The accelerated shots projected by highly pressurized water (~1 MPa) which have the kinetic energy, are impinged against the material surface to form the thin plastic deformed region near the surface. The plastic deformed layer is restricted to the near surface region, and the plastic deformation parallel to the material surface is restrained by the elastic material beneath the layer, to form the thin compressive stress layer on the surface. Based on the SCC data(5)(6) for austenitic stainless steels, we determined that 100 μ m from the surface was the preferable thickness of compressive stress layer to suppress SCC.

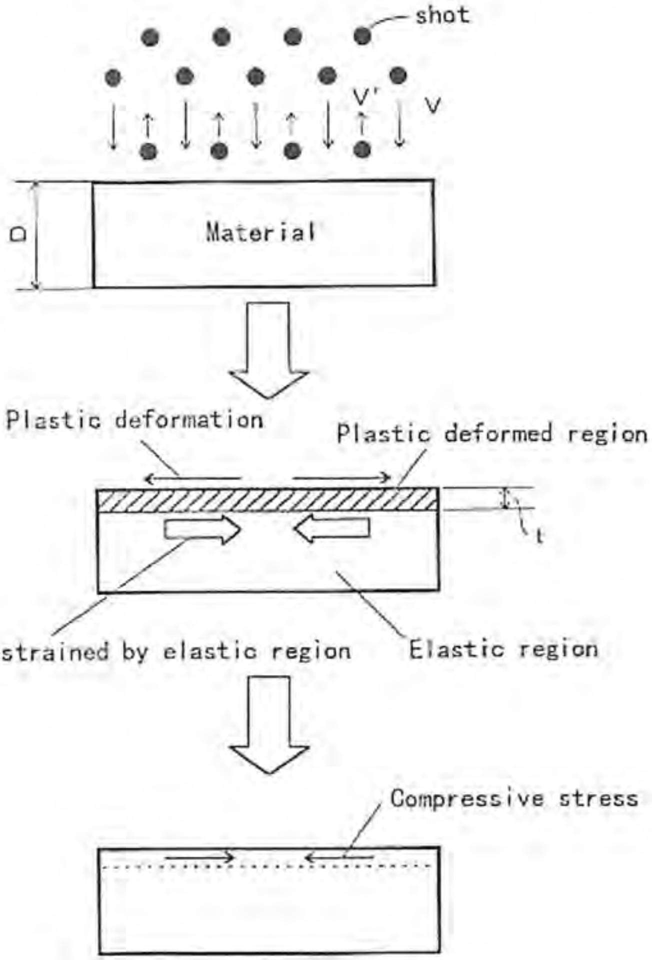


Figure 1 Mechanism for compressive stress formation

RESIDUAL STRESS IMPROVEMENT

Determination of Processing Conditions

The shot peening to the test pieces for fundamental experiments was carried out using the prototype shot peening pump system and water tank (1.5m × 1.2m × 1m depth), which the processing parameters could be changed easily. Shots were projected by highly pressurized water (0.3 ~ 1 MPa) against the test pieces which were fixed under water, and shot diameter, water flow rate, the distance between the specimen and the nozzle(projection distance) and nozzle traveling speed were selected as the processing parameters which could influence the stress depth profiles.

Test pieces (60 × 30× 5t mm) were prepared from 20 % cold worked Type 304 plate (the Vickers hardness was about 340) which simulated the hardness of high energy neutron irradiated material (fluence 1×10^{25} n/m^2, E >1MeV). Round type stainless steel shots (diameters: 0.6,1.0,1.5 mm) were made from Type 304 stainless steel wire, and were also work hardened during the rounding process to have the Vickers hardness of 480 ~ 530. Residual stress was measured using X-ray diffraction technique ($\sin^2 \psi$method).

X-ray source : Mn-k α Diffraction peak : γ (311)

Stress depth profiles were obtained by repeating the surface stress measurement after electrochemical polishing successively. The stress depth profile of each specimen was measured at the center of the shot peened area.

The thickness of the compressive stress layer drastically changed according to shot diameter, nozzle traveling speed and water flow rate, whereas projection distance had little effect on the thickness. One of the obtained results is shown in Figure 2 (the effects of shot diameter). The thickness of the compressive stress layer increased remarkably with increasing shot diameter. From these results the optimum processing conditions, which could certainly form the compressive stress layer having a thickness greater than 100 μ m, were determined. The typical processing conditions of specimens used for evaluating material characteristics are as follows.

Shot diameter : 1.0 mm	Projection distance : 50 mm
Water flow rate : 60 *l* /min (1*l* /s)	Nozzle traveling speed : 500 mm/min(8.3 mm/s)

Stress Improvement of Material with Oxide Film

The stress measurements were also carried out using the oxide pre-filmed specimen, which was formed by immersion in high temperature water (288°C × 500 hours(561K × 1.8 Ms)), to evaluate the effects of the oxide scale of the shroud surface on the stress improvement. The obtained stress depth profile was almost the same as that of the specimen without oxide film, and therefore, it was supposed that the oxide film had little influence on the effectiveness of shot peening.

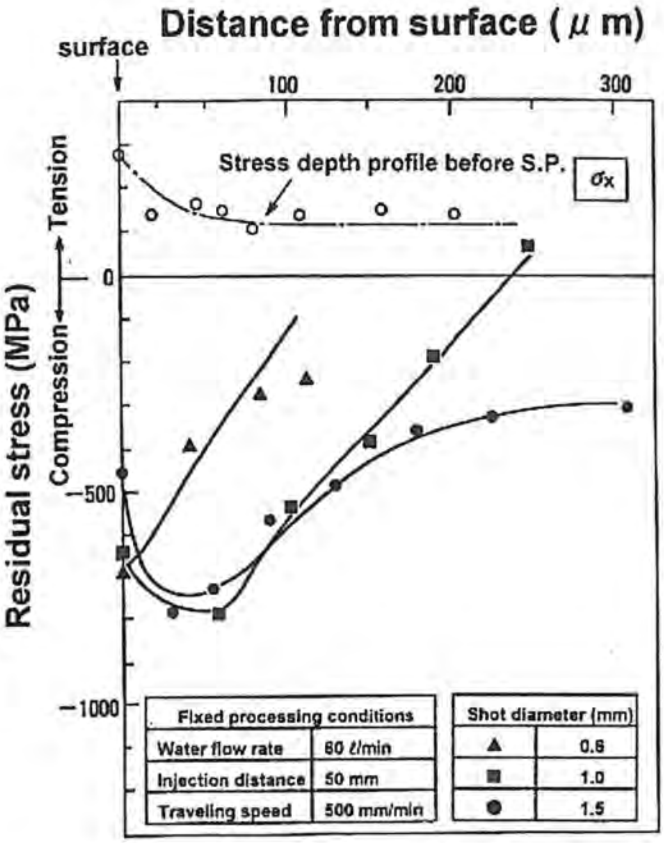


Figure 2 Effects of shot diameters on the residual stress depth profiles

Stress Improvement of Neutron Irradiated Material

The high intensity γ ray emitted from the neutron irradiated material makes X-ray stress measurement impossible. Therefore we tried to obtain stress depth profiles by neutron diffraction technique in the thin layer beneath the shot peened surface using the neutron diffraction facility of DR-3 reactor in Riso National Laboratory (Denmark). The specimen was prepared from Type 304 stainless steel plates (1×10^{25} n/m^2) irradiated in a practical BWR in-core and shot peened under water. The stress depth profile of the shot peened neutron irradiated (1×10^{25}n/m^2 specimen (Figure 3) was similar to that of the unirradiated 20 % cold worked specimen. It was quantitatively confirmed that stress improvement for the irradiated Type 304 stainless steel could be simulated by the evaluation using the cold worked specimen.

MATERIAL CHARACTERISTICS OF SHOT PEENED STAINLESS STEEL

Stress Corrosion Cracking Resistance

The SCC resistance of the shot peened Type 304 stainless steel was investigated by CBB type SCC tests. The test pieces for SCC tests were prepared from sensitized heat treated (620°C × 24 hours) material followed by 20% cold working. The specimens were bent to form 1% tensile

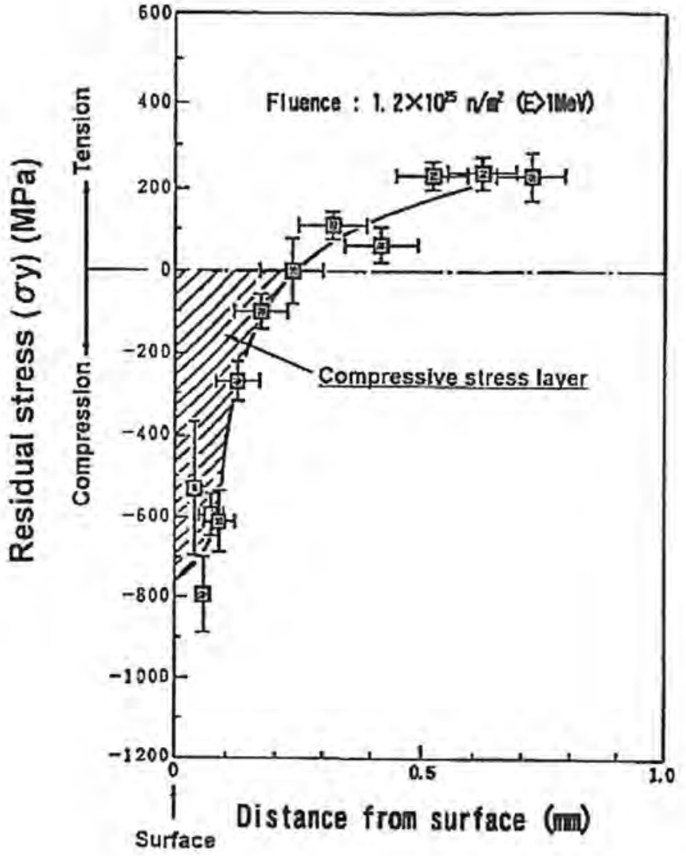
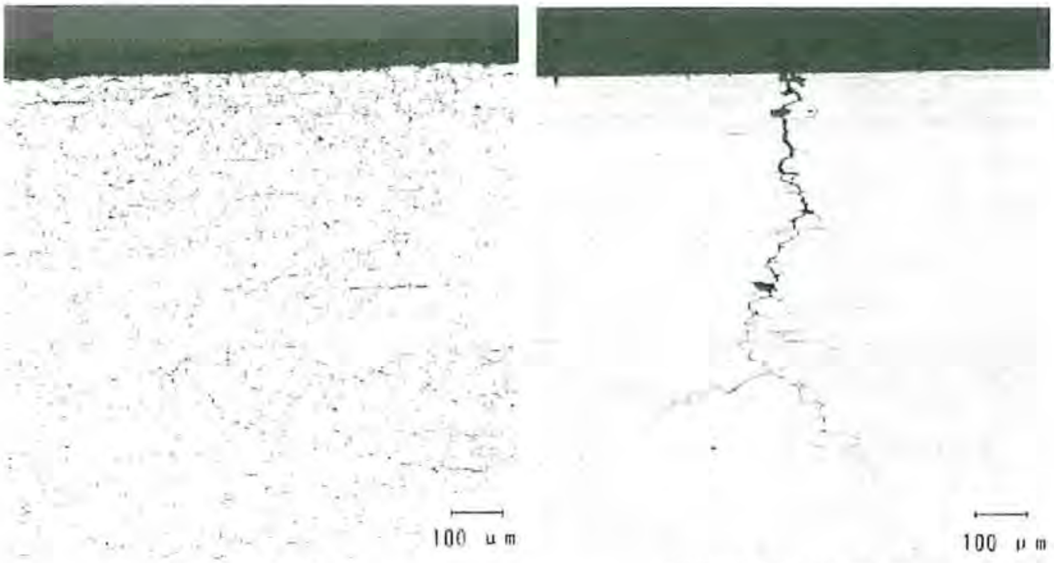


Figure 3 Residual depth profile obtained by neutron diffraction technique for neutron irradiated specimen (E>1MeV, 110^{25} n/m^2)

strain at the specimen surface, and this was followed by shot peening under selected conditions. Peened and unpeened (reference) specimens (five pieces for each) were immersed in high temperature water as follows, which accelerated SCC initiation and propagation.

Temperature : 288 °C (561K)	Dissolved oxygen : 8 ppm
Conductivity : 1 μ S/cm	Immersion duration : 500 h (1.8 Ms)

The typical stress corrosion cracking occurred in all test specimens without shot peening, whereas there was no SCC in shot peened specimens (Figure 4). It was confirmed that the shot peening completely suppressed SCC in the sensitized cold worked Type 304 stainless steel.



shot peened specimen

unpeened (reference) specimen

Figure 4 Microstructure of shot peened and unpeened specimens examined by creviced bent beam (CBB) tests

General Corrosion Resistance

The resistance to general corrosion was also evaluated by immersion tests in high temperature water which were under the same condition as for CBB tests. The degree of general corrosion was evaluated by the weight gain of the test pieces after immersion tests. There was little difference between the weight gains of test pieces with and without shot peening. The shot peening does not accelerate general corrosion in Type 304 stainless steel.

Hardness and Microstructure

The hardness depth profiles were obtained using a Knoop hardness tester by measuring the hardness at 20 ~ 50 μ m intervals from the shot peened surface. The microstructure at the cross section of shot peened specimens was observed after electrochemical polishing in 10 % oxalic acid. The work hardened layer was induced by shot peening beneath the surface, though the microstructure was only slightly changed by the shot peening.

Thermal Stress Relaxation

The magnitude of thermal stress relaxation of high compressive stress was evaluated by measuring the stress depth profile after heat treatment 450°C × 800 hours (723K × 2.88 Ms) which corresponded to 40 years at 288°C (561K). The high compressive stress at the region near the surface considerably relaxed, though the compressive stress was kept above 100 μ m without converting to tensile stress after thermal relaxation.

PROCESSING SYSTEM AND ROBOTS

Processing System

The efficient shot peening processing system which consisted of a projection head, a reservoir tank, a projection pump and a suction pump, was developed for processing core shroud welds. The schematic diagram is shown in Figure 5. The stainless steel shots with the diameter 1.0 mm are transported from the reservoir tank to the head, and projected through the nozzle with diffuser to the core shroud surface by highly pressurized water (about 1 MPa). The projected shots are completely sucked into the head together with water around it using a high capacity suction pump. The sucked water flux (about 300 *l* /min (5 *l* /s)) was about five times as much as the projected water flux (about 60 *l* /min (1 *l* /s)). A sensor or a limit switch is installed at the tip of the head to keep a definite distance between the shroud surface and the head. The projection pump is interlocked with the signal from it, and the shots cannot be projected without keeping the definite distance. The sucked dusts and oxide scales are removed in the separator, and the sucked shots are used repeatedly to reduce the radioactive waste to a minimum.

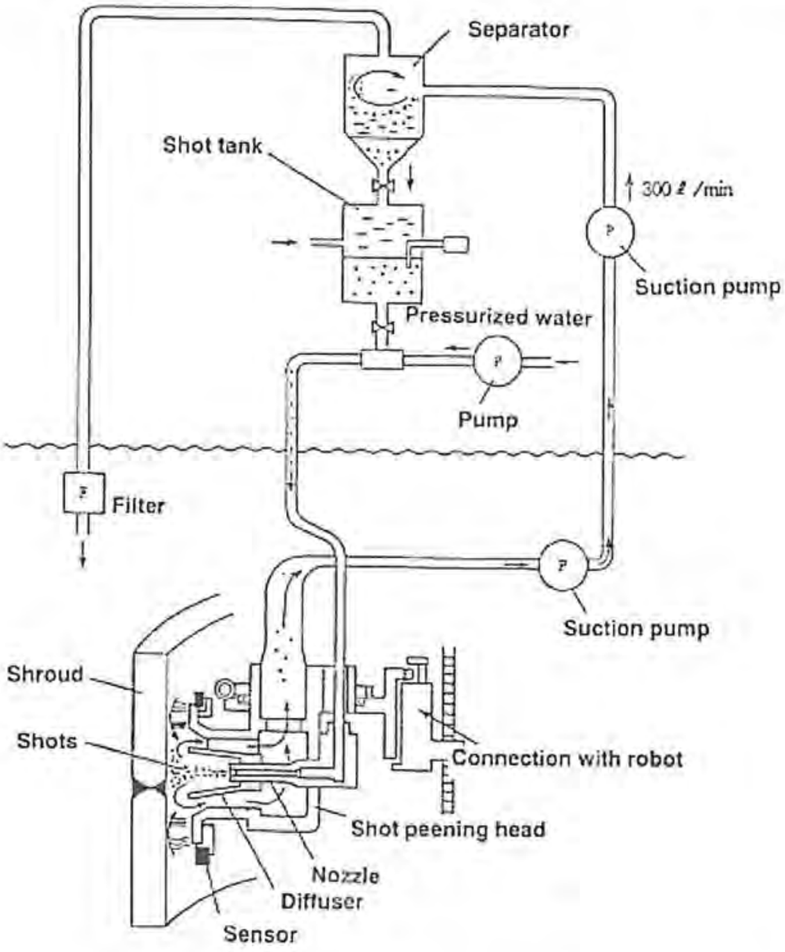


Figure 5 Schematic diagram of the shot peening system

Robot for the Shroud Inner Surface

The multipurpose maintenance robot (MMR) was designed and fabricated for the application to various tasks in the core region. The MMR consists of a housing frame, a driving mechanism, a X-shaped link arm and an elevation guide, and it is fixed between the upper grid and the core plate (Figure 6,7), The MMR has three degrees of freedom (extension, rotation and elevation) to access the shroud inner surface with precise positioning. Several tasks are carried out due to exchanging different tools on the tip of a X-shaped link arm. The MMR has a handling capacity of 120 kg, reaction force of 350 N along horizontal direction and positioning accuracy within ±1mm required for ultrasonic inspection. It can be fixed not only at the center of the core but also at the peripheral grid to avoid the collision with in-core monitors. In case of fixing at the peripheral position, one more degree of freedom corresponding to the rotation freedom of the tool, is necessary to direct the tool perpendicular against the shroud surface.

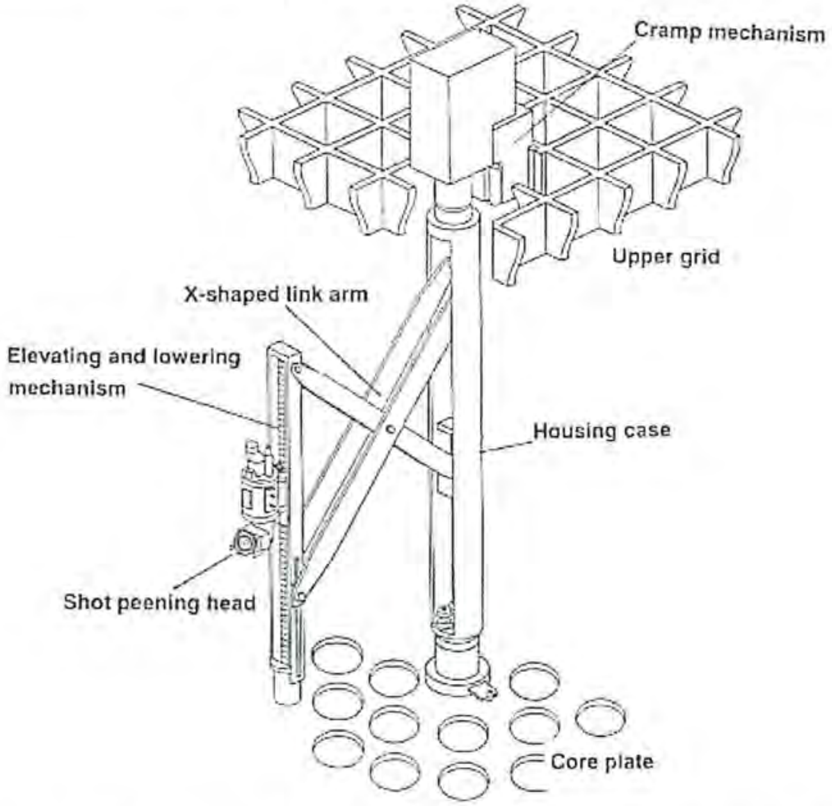


Figure 6 Remotely driven robot for processing shroud inner surface

The MMR was applied to Hamaoka Unit-1 and Unit-2 of CHEPCO to apply shot peening to the shrouds after several functional tests under water and full size mockup tests simulating the practical internals. The MMR passed through the upper grid, with the X-shaped link arm housed in the main frame, and was fixed between the upper grid and the core plate at various peripheral positions, and then the arm was extended to connect the shot peening head with the tool holder on the elevation guide in the core region. The shot peening head was precisely driven according to the four degrees of freedom along the vertical and transversal weld lines.

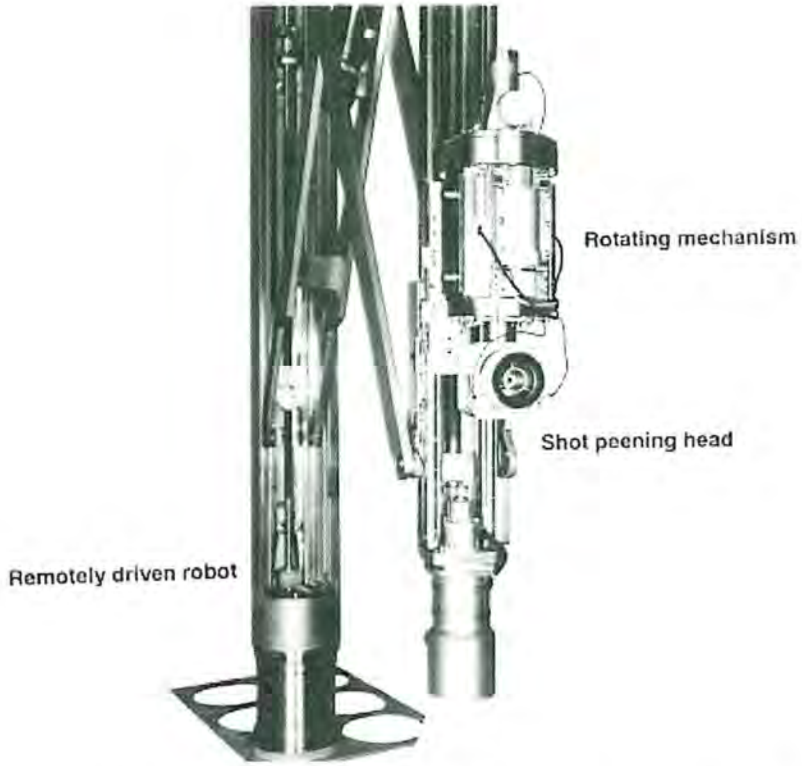


Figure 7 Remotely driven robot for processing shroud inner surface

Robot for the Shroud Outer Surface

A remotely driven robot for annulus region was developed to apply the shot peening to the shroud outer surface, which can insert the head fixed on its elastic arm into the crevice between jet pumps and a shroud. The robot consists of a rotation axis fixed on the center of the upper grid, a rotation frame with wheels which can be moved in the circumferential direction on the edge of a upper shroud , the main frame with a tilt mechanism which holds the folding arm for its setting(Figure 8). The folding arms have three joints which connect an elevating and lowering mechanism, an approaching mechanism to the shroud surface, and an extension mechanism in the circumferential direction and a scanning mechanism of the head in the vertical and transversal directions. These mechanisms allow the specially designed thin shot peening head, which can be inserted into a narrow region, descend over the overhang of the upper shroud and pass through the jet pumps to reach the shroud surface.

APPLICATION TO THE CORE SHROUD ON CHEPCO H-1/2

Processed Weld Lines

The developed water projection type shot peening system was applied using the remotely driven robots to the shroud welds of Hamaoka Unit-1 and Unit-2 of CHEPCO. The system and the remotely driven robots were sufficiently reliable to perform underwater processing of the

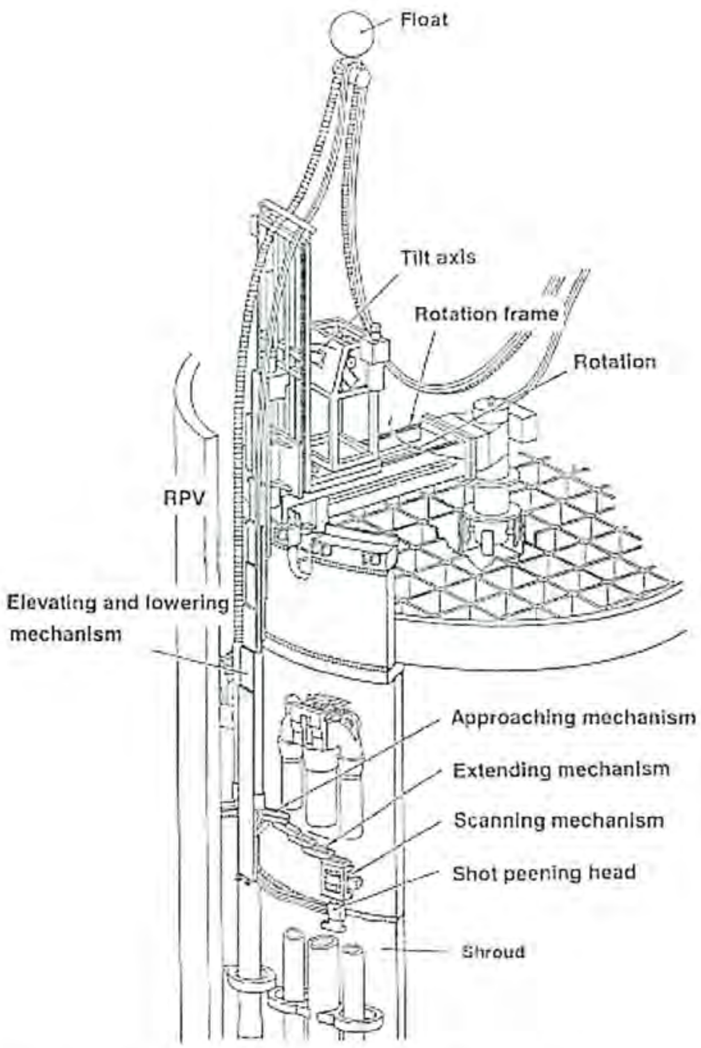


Figure 8 Remotely driven robot for processing shroud outer surface

shrouds in different size of plants (Unit-1 : 500MWe class, Unit-2 : 800MWe class). The susceptibility to SCC depends on the material of core shroud, sensitization by welding heat cycle, neutron irradiation fluence and water chemistry. The shroud of Unit-1 is made of Type 304 stainless steel, and that of Unit-2 is made of Type 304L stainless steel which is less susceptible to SCC than Type 304 stainless steel, and the other factors which enhance the susceptibility of the material depend on the weld line and its position for each plant. The welds which should be processed preferentially were selected according to the analysis of these factors for each plant. The vertical and transversal weld lines on the middle shroud inner surface, the transversal weld line between the upper ring and the middle shroud on the inner surface in Unit-1 and Unit-2, and the transversal weld line on the upper shroud outer surface in Unit-1, which were evaluated to have the potential for SCC, were shot peened during one scheduled outage for each plant.

The area over 10 mm from weld metal on its both sides was peened, in which both welding induced tensile stress field and thermal sensitization might be remained to enhance the susceptibility for the occurrence of SCC.

Arrangement of Robot and Instruments

The shot tank, a projection pump unit, a control system for the remotely driven robots and a monitoring system were set on the operation floor. The shots were transported from the shot tank to the shot peening head held on the arm of robots. The sucked shots were collected in the shot tank with the cyclone separator set under water, the sucked dusts and scales were separated from the shots, and collected using the filter in order to avoid the increase of radioactivity on the operation floor. The shots with less radioactivity were intermittently transported back to the shot tank on the operation floor, and were used for processing repeatedly (Figure 9). The conditions of a shot peening head and the movement of the robots were continuously monitored using underwater cameras.

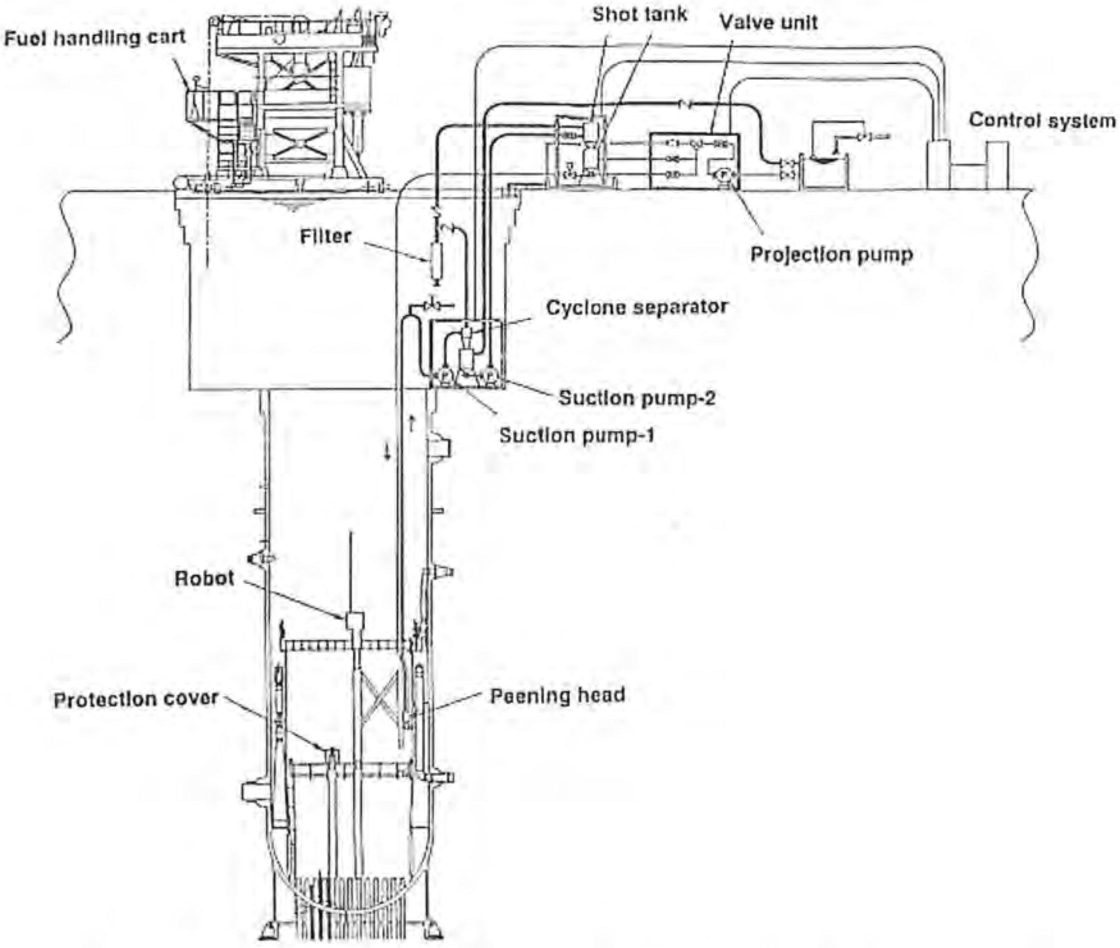


Figure 9 Arrangement of the remotely driven robot and the instruments for the shot peening process

Figure 10 shows the installed positions of remotely driven robot for processing the shroud inner surface in the case of Unit-2. The robot was installed for 7 times in the different peripheral positions in order to avoid the collision with in-core monitors. The main frame was tightly clamped on the upper grid using a pair of legs on its both sides, the arm was extended to connect with the shot peening head which was put into the core region though the neighbor grid. For transversal weld lines, the processed region for one installed position was divided into two or three regions depending on the installed position due to the limit of the rotation freedom of the head to direct it perpendicular against the shroud surface. For vertical weld lines, the shot peening head was driven along the guide at the tip of the arm by the elevating and lowering mechanism.

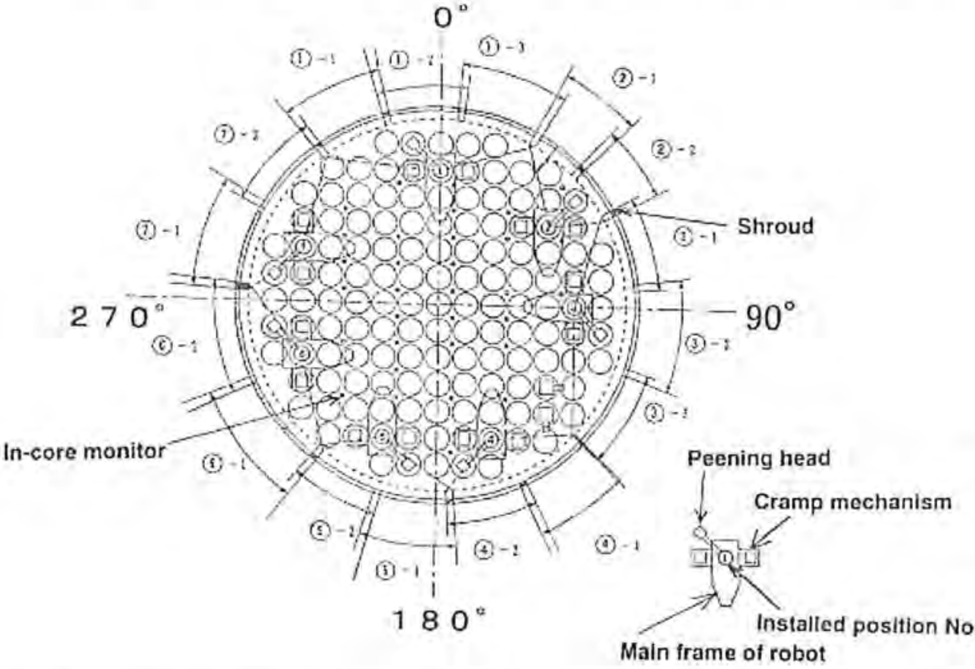


Figure 10 Installed positions of the remotely driven robot for processing shroud inner surface (CHEPCO Hamaoka Unit 2)

In the case of processing the shroud outer surface, the remotely driven robot was fixed on the center of the upper grid, and the shot peening head could be driven along the weld line in the circumferential direction by rotating the main frame.

SUMMARY

The effectiveness and applicability of water projection type shot peening as a preventive maintenance technique for the core shroud in BWRs was examined. It was confirmed that the shot peening remarkably enhanced the resistance of irradiation hardened Type 304 stainless steel to IGSCC and had no detrimental influence on other material characteristics. The water projection type shot peening system and two types of remotely driven robots for inner and outer shroud surfaces were developed, and it was ascertained on the basis of sufficient functional tests and full size mockup tests that its performance and controllability is sufficient for application to the internals in nuclear power plants. The shot peening was practically applied to the core shrouds on CHEPCO Hamaoka Unit-1 and Unit-2 plants.

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