DEVELOPMENT OF AN UNDERWATER SHOT PEENING SYSTEM TO PREVENT STRESS CORROSION CRACKING OF REACTOR INTERNALS

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ABSTRACT

The water projection type shot peening system and remotely driven robots were developed to be operated under water, in order to apply shot peening to reactor internals (shroud) in boiling water reactors (BWRs). The effects of processing parameters on the residual stress depth profiles were examined to obtain the optimum processing conditions to suppress stress corrosion cracking (SCC). Creviced bent beam (CBB) type stress corrosion tests showed that the SCC resistance in Type 304 stainless steel was remarkable increased by the shot peening. It was ascertained by several fundamental experiments that the shot peening had no detrimental effects on the other material characteristics and had sufficient applicability to the practical shroud. The reliable processing system which the accelerated shots by the pressurized water could be supplied, completely sucked and repeatedly used in order to reduce radioactive waste was developed. Two types of remote handling robots were also developed to positioning to follow the complicated shape of the core shroud welds, and for processing efficiency by reducing radiation exposure , one for processing the inner surface of the cylindrical core shroud, and the other for processing the outer surface in the narrow annulus region. The system and robots were successfully applied to the core shrouds of Hamaoka Unit-1 and Unit-2 of Chubu Electric Power Co., Ltd.

1. 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 respecting SCC. Tensile residual stresses attributable to the welding heat cycle are one of the causes of SCC and stress improvement by shot peening could be an effective way to suppress SCC. Shot peening has been practically applied in some fields, for example, in chemical plants for repair welds of austenitic stainless steel reactor vessels(1), and in pressurized water reactors (PWRs) for alloy 600 steam generators(2)(3)(4). Type 304 stainless steel with high carbon content susceptible to 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 long periods, 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 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 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. 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.

2. DETERMINATION OF PROCESSING CONDITIONS

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 the compressive stress layer to securely suppress SCC.

2.1 Processing Parameters

Shot peening the test pieces for fundamental experiments was carried out using the prototype shot peening pump system and water tank (1.5m x 1.2m x 1m depth), allowed the processing parameters to 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 travelling speed were selected as the processing parameters which could influence the stress depth profiles.

2.2 Specimens and Shots

Test pieces (60 x 30 x 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.

2.3 Residual Stress Measurement

Residual stress was measured using X-ray diffraction technique ($\sin^2 \mu$ method).

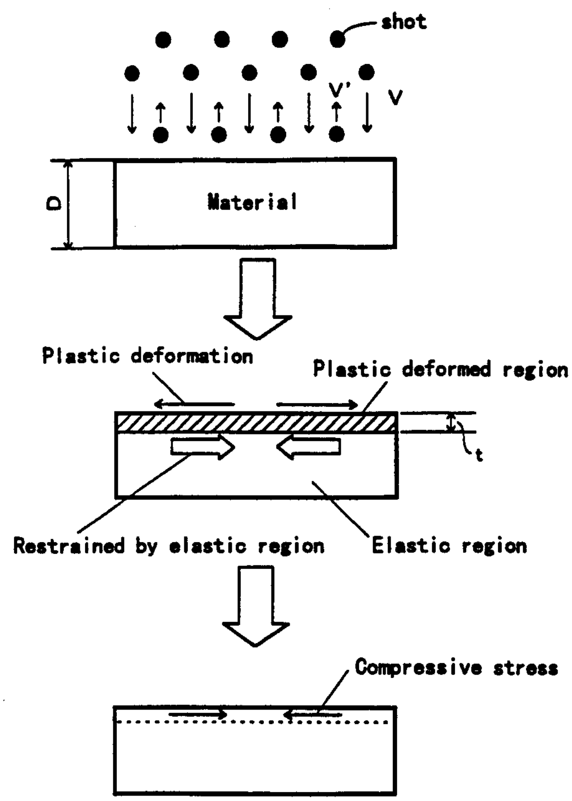
X-ray source: Mn-k *a* Diffraction peak: *r* (311)

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

2.4 Results of Stress Measurements

The thickness of the compressive stress layer drastically changed according to shot diameter, nozzle travelling 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 the 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 travelling speed:	500 mm/min (8.3 mm/s)



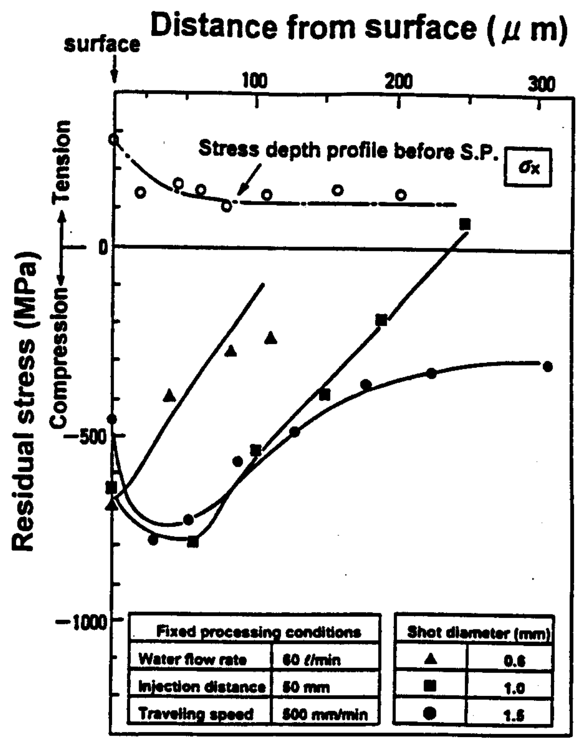


Figure 1: Mechanism for the Formation of Compressive Stress Along the Left Margin

Figure 2: Effects of Shot Diameters on the Residual Stress Depth Profiles Along the Right Margin

3. INFLUENCE ON MATERIAL CHARACTERISTICS

3.1 Stress Corrosion Cracking Resistance

The test pieces for SCC tests prepared from sensitized heat treated (620^{0}C x 24 hours (893K x 86,4 ks)) material followed by 20% cold working. The SCC resistance of shot peened type 304 stainless steel was investigated by CBB type SCC tests. The specimens were bent to form 1% tensile 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 which accelerated SCC initiation and propagation, as follows.

Temperature: 288 ^{0}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. It was confirmed that the shot peening completely suppressed SCC in sensitized cold worked Type 304 stainless steel.

3.2 General Corrosion Resistance

The resistance to general corrosion was also evaluated by immersion tests in high temperature water under immersion conditions which were the same 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.

3.3 Hardness and Microstructure

The hardness depth profiles were obtained using the 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 were 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.

3.4 Sealing Effect for Microcracks

The influence on the propagation of microcracks on the metal surface was examined using the specimens with narrow and shallow cracks prepared by immersion in $MgC1_2$ solution. The specimens prepared from sensitized heat-treated Type 304 stainless steel were bent to form 0.3% tensile strain on the surface and immersed in boiling 35% $MgCl_2$ solution for 24 hours (86.4 ks) to make cracks with the width of 10 ~ 20 μ m and the maximum depth of about 250 μ m. Half the area of the specimen was shot peened and the other half was unpeened, and the specimen was then immersed in boiling 42% $MgCl_2$ solution for 24 hours (86.4 ks) to evaluate the effects of shot peening on the propagation of the microcracks. After the immersion test the cross section of the specimens were observed in order to measure the crack depth, it was seen that several microcracks on the unpeened area further propagated to reach the maximum depth 2000 μ m, whereas the depth of microcracks on the peened area did not increase at all. The thin plastic flow on the shot peened surface had sealing effect against the corrosive environment, thereby retarding further propagation of the pre-existing microcracks.

4. APPLICABILITY FOR PRACTICAL SHROUD

4.1 Stress improvement of material with oxide film

The stress measurements were carried out using the oxide pre-filmed specimen, which was formed by immersion in high temperature water (288^0C x 500 hours (561K x 1.8 Ms)), to evaluate the effects of the oxide film 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.

4.2 Stress Improvement of neutron irradiated material

The high intensity *r* ray emitted from neutron irradiated material makes X-ray stress measurement impossible. Therefore we tried to obtain stress depth profiles by a 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 x 10^{25} n/m^2) irradiated in a practical BWR incore and shot peened under water. The stress depth profile of the shot peened neutron irradiated (1 x 10^{25} n/m^2) specimen was similar to that of the unirradiated 20% cold worked specimen. It was quantitatively confirmed that stress improvement for irradiated Type 304 stainless steel could be simulated according to the evaluation using the cold worked specimen.

4.3 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^{0}C x 800 hours (723K x 2.88 Ms) which corresponded to 40 years at 288^{0}C (561K). The high compressive stress at the region near the surface considerably relaxed, though the thickness of the compressive stress above 100 μ m was kept without converting the compressive stress to tensile stress after thermal relaxation.

5. PROCESSING SYSTEM AND ROBOTS

5.1 Processing System

The efficient shot peening processing system which consisted of projection head, reservoir tank, projection pump and suction pump, was developed for processing core shroud welds. The schematic diagram is shown in Figure 3. The stainless steel shots with the diameter 1.0 mm are transported from the reservoir tank to the head and projected by highly pressurized water (about 1 MPa) through the nozzle. The projected shots are completely sucked into the head, together with the water around it using a high capacity suction pump. The sucked water flux (about 300 *I* /min (5 *I* /s)) was about five times as much as the projected water flux (about 60 *I* /min (1 *I* /s)). A sensor or 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 the sensor or limit switch, 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.

5.2 Robot for Shroud Inner Surface

The multipurpose maintenance robot (MMR) was designed and fabricated for application to various tasks in the core region. The MMR consists of a housing case, driving mechanism, X-shaped link arm and elevation guide, and it is fixed between upper grid and core plate (shown in Figure 4), 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 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 $\pm$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 a collision with the in-core monitor. 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.

The MMR was used at Hamaoka Unit-1 and Unit-2 of Chubu Electric Co., Ltd. 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 case, and was fixed between 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.

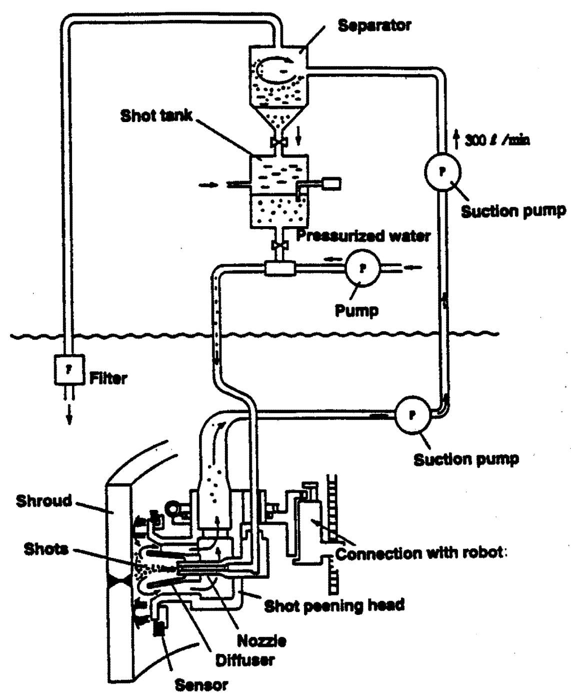


Figure 3

Schematic diagram of water projection type shot peening system

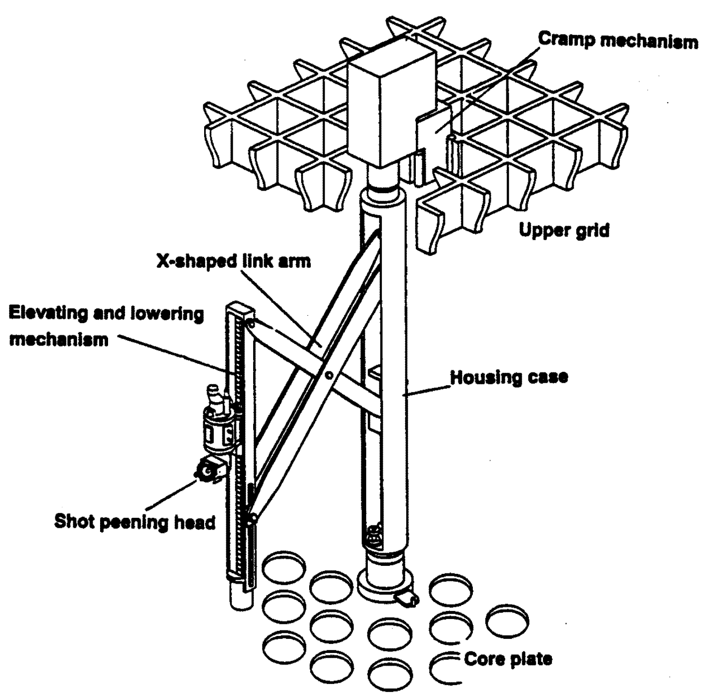


Figure 4

The remotely driven robot for processing the shroud inner surface

5.3 Robot For Shroud Outer Surface

A remotely driven robot for the annulus region was designed and fabricated to apply the shot peening to the shroud outer surface, which can insert the head installed on its elastic arm into the crevice between the jet pump and the shroud. The robot consists of a rotation axis fixed on the center of the upper grid, rotation frame with wheels which can be moved in the circumferential direction on the edge of upper shroud, the main frame with tilt mechanism which holds the folding arm for its setting (Figure 5). The folding arms have three joints which connect the elevating and lowering mechanism, the approaching mechanism to the shroud surface, the extension mechanism in the circumferential direction, and the 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, to descend over the overhang of the upper shroud and pass through the jet pumps to reach the shroud surface.

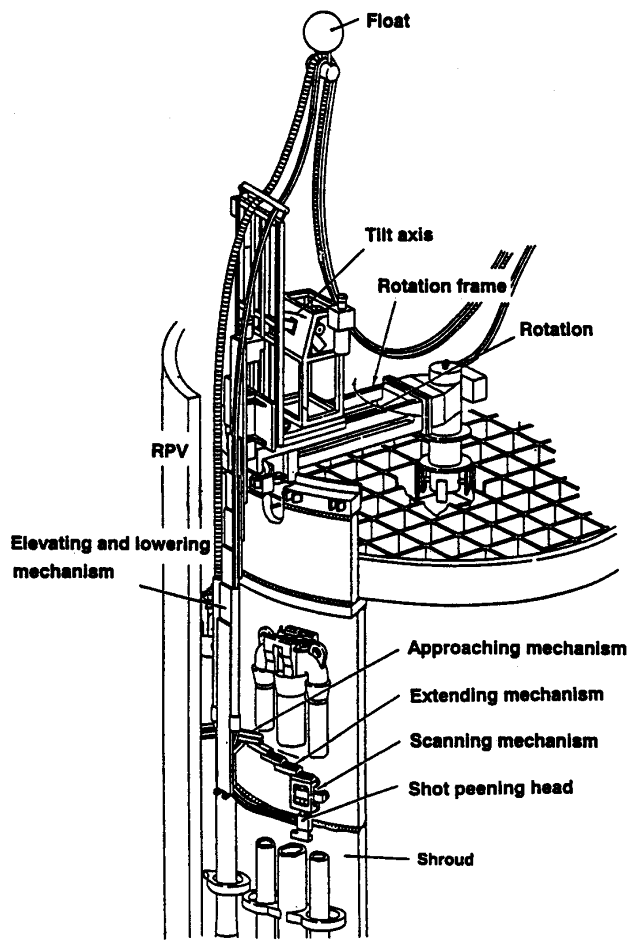


Figure 5
The remotely driven robot for processing the shroud outer surface

6. APPLICATION TO THE PRACTICAL SHROUD

The developed water projection type shot peening system was applied using the two types

of remotely driven robots to he shroud welds of Hamaoka Unit-1 and Unit-2 of Chubu Electrical Power Co., Inc. The system and the remotely driven robots were sufficiently reliable to perform underwater processing of the shrouds in different size plants (Unit-1: 500 MWe class, Unit-2: 800 MWe class). The susceptibility to SCC depends on the material of the core shroud, irradiation fluence, sensitization by welding heat cycle and water chemistry. The shroud of Unit-1 is made of Type 304 stainless steel, and that of Unit-2 is made of Type 204L stainless steel which is less susceptible to SCC than Type 304 stainless steel. 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 analysis of these factors for each plant. The vertical and transversal weld lines on the middle shroud inner surface, the transversal weld line of 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 tank for shots, the projection pump unit, the control system for the remotely driven robots and the 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 transported back to the shot tank on the operation floor, and were used repeatedly for processing. The conditions of the shot peening head and the movement of the robots were continuously monitored using cameras.

7. SUMMARY

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

8. REFERENCES

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9. KEY WORDS

Core shroud, maintenance, Austenitic stainless steel, Stress corrosion cracking, Residual stress, Compressive stress, Shot peening, Remotely driven