The Effect of Shot Peening on Residual Stress and Stress Corrosion Cracking for Austenitic Stainless Steel

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Abstract

The water injection type processing machine was developed which could be operated under water, to apply shot peening to in-core components in light water nuclear reactors. The effects of processing parameters on the residual stress depth profiles were examined to get 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 remarkably increased by the shot peening. It was ascertained that shot peening had no detrimental effects to the other material characteristics such as the general corrosion resistance, microstructure. The applicability of the shot peening to in-core components was proven by stress relaxation tests , residual stress measurements using the neutron irradiated specimen and the oxide filming treated specimen.

Keywords

Stainless steel , Stress corrosion cracking , Residual stress , General corrosion , Compressive stress , Irradiation hardening , Light water reactor

1 Introduction

We have developed the preventive maintenance techniques to enhance the reliability of in-core components in light water reactors. Stress corrosion cracking (SCC) might be one of the material degradation of austenitic stainless steel, it is necessary to establish the preventing technique for SCC. Tensile residual stresses formed by welding heat cycle is one of causes for SCC, the stress improvement by shot peening could be effective to suppress the SCC crack initiation. A shot peening has been practically applied in some fields such as repair welds of austenitic stainless steel reactor vessels in chemical plants(1), alloy 600 steam generators in light water rectors(2)(3)(4).

At first we developed the water injection type processing machine which could be operated under water ,and several fundamental experiments were carried out using the processing machine. Austenitic stainless steels in-core region are irradiated by high energy neutrons for long period to have high strength due to irradiation hardening. The test pieces were prepared from 20%

cold worked Type 304 stainless steel which simulated the hardness of the irradiation hardened material. The influence of processing conditions on the residual stress profiles were examined to determine the optimum processing conditions to suppress SCC. The material characteristics of the shot peened materials such as the SCC resistance, general corrosion resistance, microstructure, hardness change were also examined. And the applicability to in-core components were evaluated by stress relaxation tests, stress measurements using neutron irradiated specimen and oxide filming treated specimen.

2 Experimental

2.1 Processing machine

Schematically diagram of the water injection type shot peening processing machine is shown in Fig.1. Shots were injected by high pressured water (3 ~ 10 kgf/cm^2) against test specimens which were fixed under water, shot diameter, water flow rate, the distance between the specimen and the nozzle(injection distance) and nozzle traveling speed were selected as the processing parameters which could be influenced to the stress depth profiles.

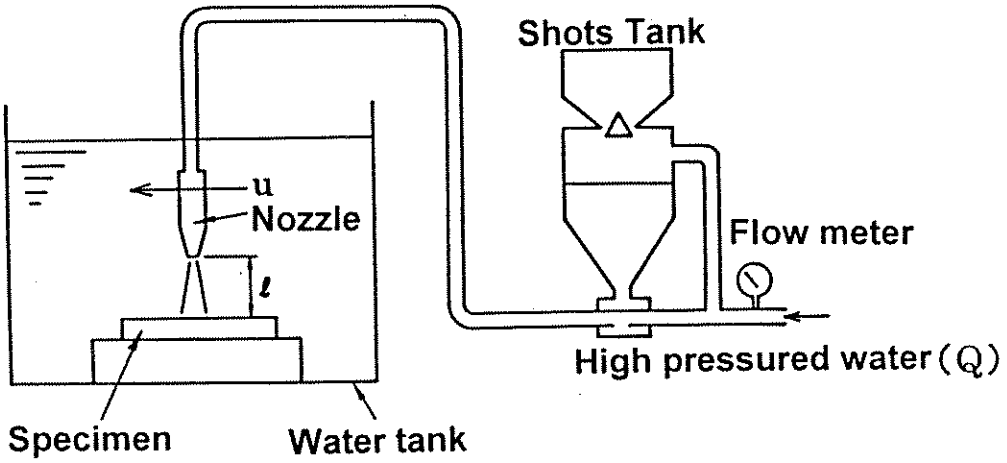

Fig. 1 Schematic diagram of the processing machine

2.2 Specimens and shots

Test specimens(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(1×10^{21} n/cm^2, E>1MeV).
The test pieces for SCC tests were prepared from sensitized heat treated (620℃×24 hours) material followed by 20% cold working. Round type stainless steel shots (diameters:0.6,1.0,1.5 mm) were made from Type 304 SS wire,

were also work hardened during production process to have the Vickers hardness 480～530. Chemical compositions of test specimens and shots are shown in Table 1.

Table 1 Chemical compositions

	Cr	Ni	Mn	Si	P	S	C
Specimen (Type304)	18.14	8.21	1.13	0.42	0.034	0.002	0.063
Shots (Type304)	18.10	10.10	0.81	0.30	0.034	0.002	0.04

(wt %)

2.3 Residual stress measurement

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.

2.4 Evaluation of material characteristics

The resistance to stress corrosion cracking was evaluated by CBB(Creviced Bent Beam) type tests which immersion tests conditions were as follows.

Temperature : 288 ℃ Dissolved oxygen : 8 ppm

Conductivity : 1 μ S/cm Immersion duration : 500 h

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

The hardness depth profiles were obtained using Knoop hardness tester by measuring the hardness at 20 ～ 50 μ m intervals from the shot peened surface.

The changes of stress depth profiles by thermal relaxation were evaluated by measuring the stress after heat treatment(450℃×800h) which attributed to 40 years at the temperature in-core (288 ℃). The microstructure of near surface region, the surface roughness after shot peening ware evaluated, and the effects of injection angle, surface oxide film on the stress depth profiles were also examined.

2.5 Irradiated specimen test

The emitted high intensity γ ray from neutron irradiated material makes a X-ray stress measurement impossible. Therefore we tried to get 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^{21} n/cm^2) irradiated in a practical light water reactor and shot peened under water.

3 Results and discussion

3.1 Effects of processing parameters on the residual stress depth profiles

We established the aim for the thickness of compressive stress layer to suppress SCC securely, which was above 100 μ m. The stress depth profiles of shot peened specimens were measured at the center of shot peened area, the effects of shot diameter, nozzle traveling speed, water flow rate and injection distance are shown in Fig.2,3,4 and 5. The thickness of the compressive stress layer drastically changed according to shot diameter, nozzle traveling speed and water flow rate, on the other hand injection distance had little effect to the thickness. From these results the optimum processing conditions which could

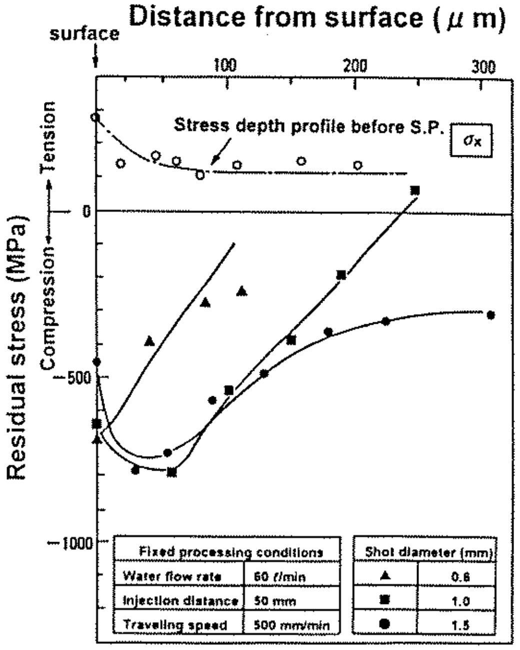

Fig. 2 Effects of shot diameters on the residual stress depth profiles

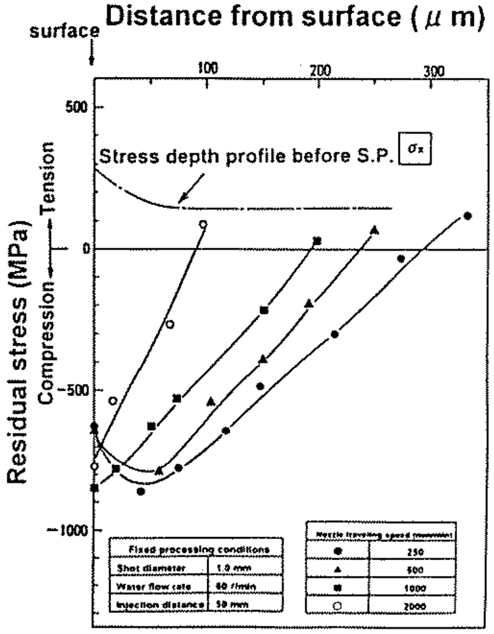

Fig. 3 Effects of traveling speeds on the residual stress depth profiles

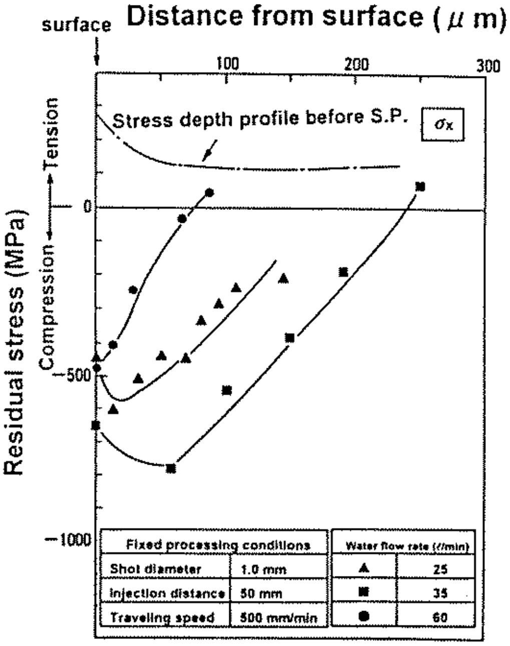

Fig. 4 Effects of water flow rates on the residual stress depth profiles

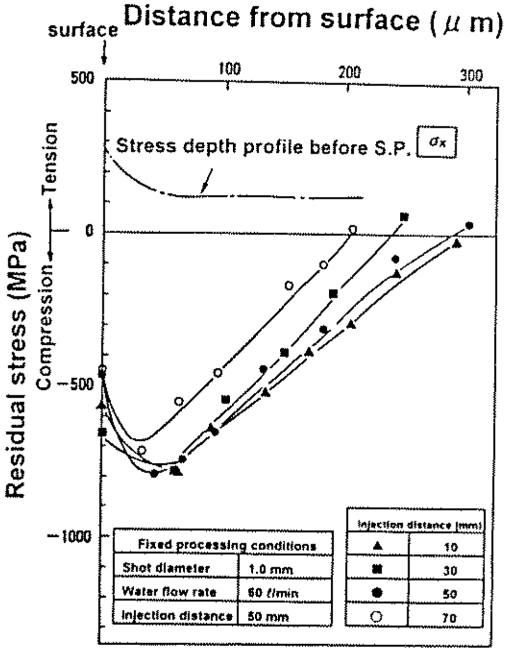

Fig. 5 Effects of injection distances on the residual stress depth profiles

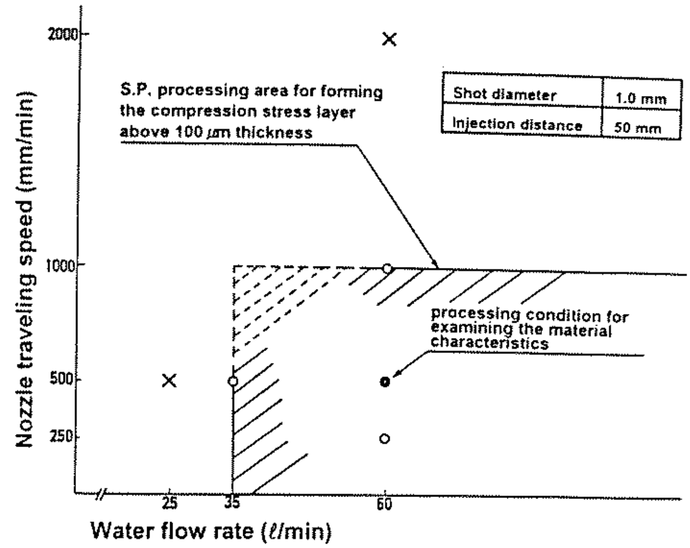

Fig. 6 Shot peening processing conditions (Nozzle traveling speed vs Water flow rate)

be certainly built the compressive stress layer above 100 μ m ,were determined(Fig.6). The typical processing conditions of specimens used for evaluating material characteristics are as follows.

Shot diameter	: 1.0 mm	Injection distance	: 50 mm
Water flow rate	: 60l/min	Nozzle traveling speed	: 500 mm/min

3.2 Evaluation of material characteristics

Fig.7 shows the results of CBB tests for the specimens with and without shot peening. Typical stress corrosion cracking occurred in all test specimens(5 test pieces) without shot peening, on the other hand there was no SCC in shot peened specimens. It was confirmed that shot peening completely suppress SCC in sensitized cold worked Type 304 stainless steel

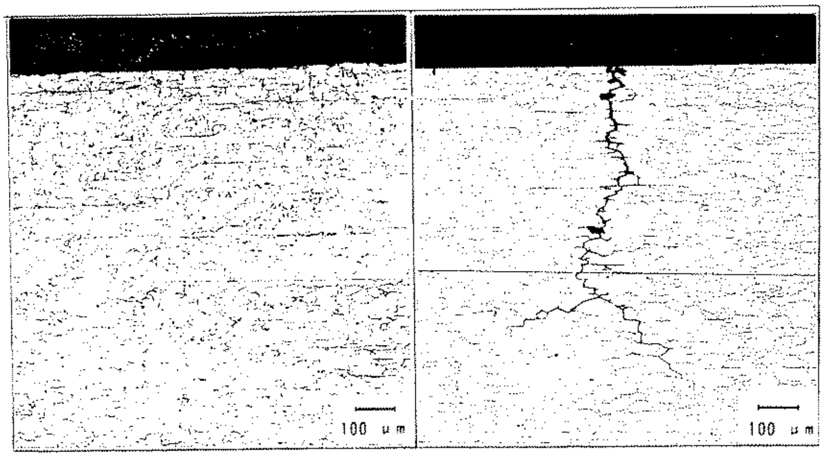

Fig. 7 The results of metallographic examination after stress corrosion cracking tests (CBB tests)

The results of hardness depth profiles measurements are shown in Fig.8. Although the shot peening induced work hardened layer beneath the surface, it had little effect to the microstructure and surface roughness.

Fig.9 shows the weight gain of the test pieces after general corrosion tests. There was no difference between specimens with and without shot peening. The shot peening does not accelerate general corrosion in Type 304 stainless steel.

3.3 Evaluation of practical applicability

Fig.10 shows the injection angle dependence of stress depth profiles. The sufficient stress improvement (the thickness of compressive stress layer > 100 μ m) to suppress SCC was obtained even at the injection angle 30 degree.

Fig.11 shows the results of stress measurements using the oxide pre-filmed

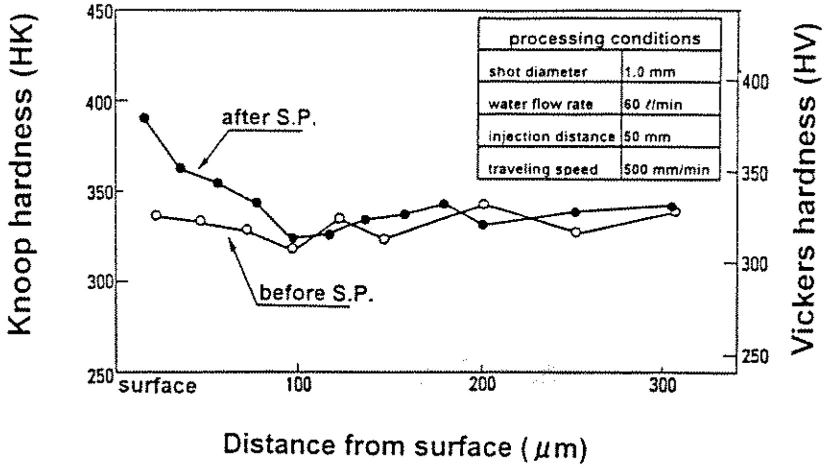

Fig. 8 Hardness depth profiles beneath the specimen surface

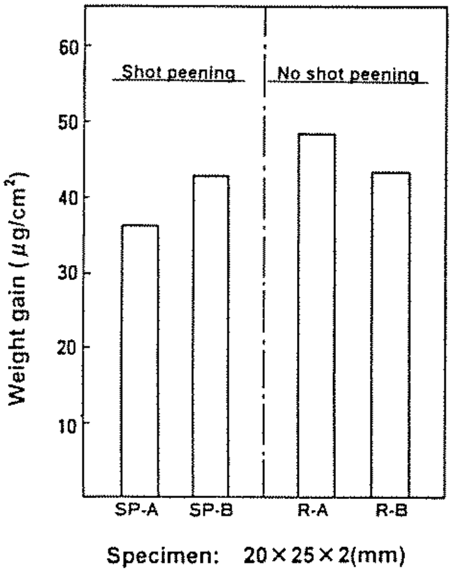

Fig. 9 Weight gain of the specimens due to immersion in high temperature water (general corrosion tests)

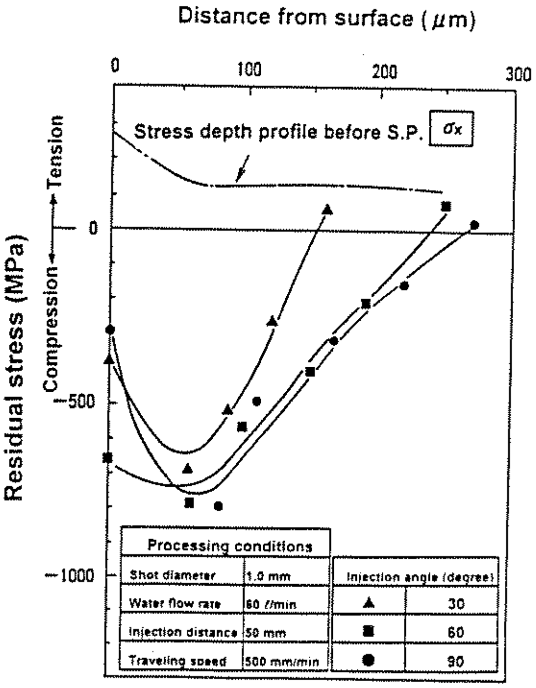

Fig. 10 Effects of injection angles on the residual stress depth profiles

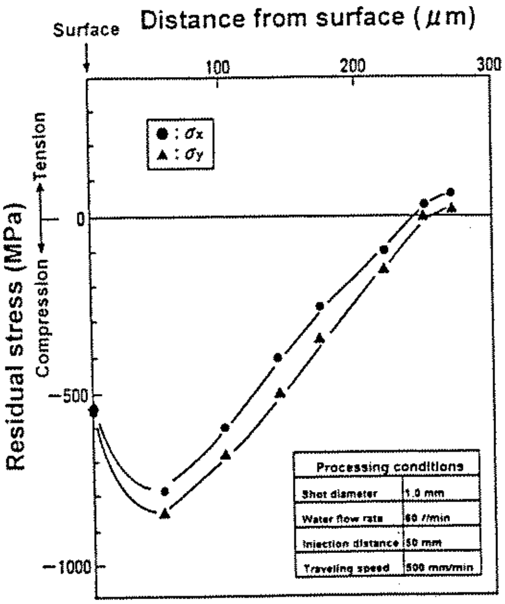

Fig. 11 Effects of oxide film on the residual stress depth profiles

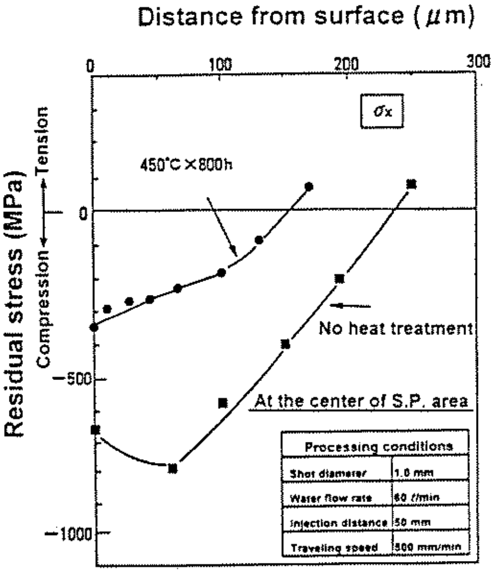

Fig. 12 Effects of thermal relaxation on the residual stress depth profiles

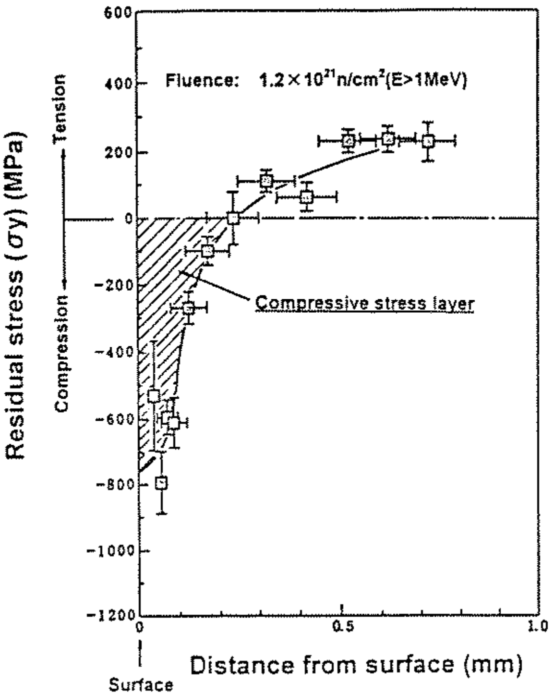

Fig. 13 Residual stress depth profiles in neutron irradiated specimen measured by neutron diffraction technique

specimen which was formed by immersion in high temperature water(288℃ × 500 hours), to evaluate the effects of the oxide film on the in -core components to the stress improvement. The profile was almost same with the specimen without oxide film, it was expected that the oxide film had no effect to the stress improvement.

Fig.12 shows the stress depth profiles after thermal relaxation heat treatment. Although the high compressive stress near surface region considerably relaxed, the thickness of the compressive stress above 100 μ m was kept after thermal history which attributed to 40 years at 288℃.

Fig.13 shows the stress depth profile of the shot peened neutron irradiated ($1 \times 10^{21} n/cm^2$) specimen which was obtained using neutron diffraction technique. It was quantitatively confirmed that the stress depth profile similar to the unirradiated specimens could be built in irradiated Type 304 stainless steel.

4 Summary

The effectiveness and the applicability of water injection type shot peening were examined as the preventive maintenance technique of in-core components in light water reactors. The obtained results are summarized as follows.

1. The effects of processing parameters to the thickness of the compressive stress layer were examined, and determined the optimum processing condi tions to suppress SCC securely.
2. It was ascertained that shot peening effectively suppress SCC in sensitized Type 304 stainless steel, and there were no detrimental effects to general corrosion, microstructure, hardness and surface roughness.
3. Stress relaxation by thermal history ,the effects of oxide film and injection angle on stress depth profiles were evaluated to be applicable to the practical in-core components.
4. The neutron diffraction technique showed that the almost same stress depth profiles with the unirradiated specimens were obtained to the neutron irradiated material.

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