Preventive Effect of Shot Peening on Stress Corrosion Cracking

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Abstract: The effect of shot peening (SP) on stress corrosion cracking (SCC) prevention was evaluated from the viewpoints of crack initiation and propagation. It was found that the residual stress in a Type-304 stainless-steel specimen is changed—from tensile of 300 MPa to compressive of -800 MPa—by shot peening, and the effective SP depth is 0.35 mm. It was also found that the crack initiation and propagation were prevented by shot peening. The mechanism by which the shot peening prevents these phenomena is explained according to the theory of superposition and loading history. That is, the prevention of crack initiation and propagation results from the fact that the compressive residual stress caused by SP decreases the applied load on the crack surface and prevents rupturing of the oxide film on the surface. Moreover, the effects of SCC prevention were shown to be valid when cyclic loading is applied after peening.

Key words: Stress corrosion cracking, Shot peening, Residual stress, Stress relaxation, Crack initiation and propagation

1. INTRODUCTION

Shot peening (SP) deforms and hardens a metal surface plastically with particles of metal or glass. As a result, compressive residual stress appears and the surface properties are improved. This method has been used in industrial fields, since it can improve fatigue strength, stress corrosion cracking (SCC), and delayed fracture [1]. SP has recently been used to prevent SCC in nuclear power plants as well as to improve the fatigue strength of springs, automobile parts [2], and gears [3]. The peening methods used in nuclear power plants to keep the reliabilities use highly pressurized cavitations [4], which is called water-jet peening (WJP), or laser pulse [5] instead of metal or glass shots because of their conveniences. There are two main reasons behind the tendency to use the above two peening methods: SCC was reported to occur in the weldment of the shroud of several aging nuclear power plants [6-8], and the number of nuclear power plant in age will increase in the future. The objective of using SP in nuclear power plants is to prevent SCC by means of decreasing the tensile residual stress which causes the SCC. The conditions and effects of these peening methods for nuclear power plants have been investigated widely and it has been reported that the value of the residual stress at the surface after peening varies from -400 to -700 MPa [4,5].

Cracks, not only those caused by SCC, in compressive residual stress fields are difficult to propagate unless an external load is applied. The cracks on the peened material, consequently, will not propagate without the external load. However, the effects of peening may be decreased by the plant operation temperature and cyclic loading during start up and shut down of a nuclear power plant [9]. It is thus necessary to evaluate the time dependency of residual stress change of the peened material in order to maintain the SP effect.

The main conditions for shot-peening procedures are material hardness and particle size of shots as well as peening velocity and time for shot peening per unit area. An equation that predicts the influence of these conditions on the effects of residual stress has been studied by many researches [10]. Also the dependencies of residual stress on temperature and time have been discussed. However, the effects of SCC prevention on these dependencies have not been discussed [9]. Accordingly, in the present report, the effects of SCC prevention from the viewpoints of SCC crack initiation and propagation are investigated.

2. EXPERIMENTAL METHOD

2.1. Specimen Preparation

The materials used in this research were stainless steel, Type-304, and a nickel-based alloy, Inconel 182. The chemical composition and mechanical properties of each material are listed in Tables 1 and 2. The heat histories of both materials are also listed in Table 2. The Type-304 stainless-steel specimen was extended to 2.5% strain and heated (for sensitizing) at 650°C for 2 hours and at 550°C for 24 hours. The Inconel 182 specimen was welded, and then heated at 621°C for 24 hours and at 500°C for 24 hours. Both heat-treated specimens were then machined.

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Table 1. Chemical composition of specimens. 

<table>
<thead>
<tr>
<th>Type-304</th>
<th>Inconel 182</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.07</td>
</tr>
<tr>
<td>Si</td>
<td>0.44</td>
</tr>
<tr>
<td>Mn</td>
<td>1.18</td>
</tr>
<tr>
<td>P</td>
<td>0.032</td>
</tr>
<tr>
<td>S</td>
<td>0.01</td>
</tr>
<tr>
<td>Cr</td>
<td>18.26</td>
</tr>
<tr>
<td>Ni</td>
<td>8.32</td>
</tr>
<tr>
<td>Fe</td>
<td>Bal.</td>
</tr>
<tr>
<td>Nb + Ta</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties and heat treatment histories of specimens.

<table>
<thead>
<tr>
<th>Type-304</th>
<th>Inconel 182</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength (MPa)</td>
<td>287</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>640</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>58</td>
</tr>
<tr>
<td>Heat treatment</td>
<td>2.5% tensile → 650°C x 2h, FC → 550°C x 24h, FC*</td>
</tr>
<tr>
<td></td>
<td>621°C x 24h, FC* → 500°C x 24h, FC*</td>
</tr>
</tbody>
</table>

2.2. Stress Corrosion Cracking (SCC) Initiation Test

The procedures for the SCC initiation test on the Type-304 and Inconel 182 specimens are shown in Fig. 1. The specimens were 10 mm wide, 50 mm long, and 3 mm thick. They were ground to produce a tensile residual stress on their surfaces, and then some of them were peened under the conditions listed in Table 3 in order to confirm the effect of SCC prevention by SP. The specimens were extended under a strain range from 0.15% to 0.4%, whose strain was more conservative than that of actual plant. The maximum strain of 0.4% contains the 4 times of engineering design. These specimens then soaked in an autoclave for 500 hours, at a temperature of 289°C, in which the concentration of dissolved oxygen was 8 ppm and the electric conductivity of water was 1 μS/cm. The specimens were cut along the perpendicular direction to the cracks after the autoclave soaking. After polishing the cut surface of the specimens, the number and length of cracks were measured by penetration test (PT) and optical microscope.

2.3. SCC Propagation Test

The procedures in the SCC propagation test are also shown in Fig. 1. Only the Type-304 specimens were used in the SCC propagation test. The SCC specimen was 20 mm wide, 120 mm long, and 8 mm thick. As in the SCC initiation test, the specimens were ground to produce tensile residual stress at their surface. The specimens were soaked in a MgCl₂ bath for a standard time in order to produce transgranular cracks as the pre-crack for the SCC propagation test, then they were shot peened under the conditions listed in Table 3. In order to occur the SCC propagation, the machined specimens were extended under a strain range from 0.15% to 0.4% and soaked in the autoclave for 500 hours. They were then machined and treated in the same way as the SCC initial test, and then the number and length of cracks and their lengths were measured.

2.4. Residual Stress Measurement

The residual stress was measured by X-ray diffraction using the Cr-Kα radiation for the Type-304 specimens and the Cu-Kα radiation for the Inconel 182 specimens. The size of incident X-ray beam was 4 x 4 mm². The residual stress was evaluated by the sin² φ method. The specimens were polished electrically to the arbitrary

Table 3. Conditions of shot peening.

| Distance (mm) | 190 |
| Projecting pressure (MPa) | 0.5 |
| Projecting volume (g/sec) | 58 |
| Shot velocity (mm/sec) | 400 |
| Projecting angle (degree) | 90 |
| Shot diameter (mm) | 0.4 |

*FC : Furnace Cooling

Fig. 1. Procedures of SCC initiation and progress test.
2.5. Relaxation of Residual Stress

Tests on the relaxation of residual stress by cyclic loading were carried out on the Inconel 182 specimens. The shape of the specimens used for relaxation test is shown in Fig. 2. Two slits were machined in each specimen in order to divide the specimen’s test section into three pillars, and then the central pillar was bead welded. Both ends of the pillars were compressed by rolling in the thickness direction in order to apply tensile residual stress at the central pillar. The central pillar was then peened by shot under the conditions listed Table 3, and loaded for 30 cycles (at maximum) under a range of load amplitude from 150 to 380 MPa. The residual stress at the surface and at 200-μm depth from the surface were measured after the cyclic loading.

3. RESULTS

3.1. Change of Residual Stress Before and After Shot Peening

The residual stress in four specimens of each material was measured in order to confirm the effects of SP and are listed in Table 4. In the case of the Type-304 specimens, the dispersion of residual stress is in the range from 148 to 386 MPa even though the specimens were in the same ground condition. A similar tendency applies to the Inconel 182 specimens, which show a dispersion range of residual stress from 470 to 769 MPa. This dispersion range was significantly reduced after SP. Namely, the residual stress after SP of the Type-304 specimens was in range from −771 to −879 MPa; that of the Inconel 182 specimens was in range from −562 to −675 MPa. The depth profile of residual stress after SP of a Type-304 specimen is shown in Fig. 3. This figure shows that the tensile residual stress of 300 MPa before SP was reduced by the SP to a compressive residual stress of −700 MPa. It can thus be concluded that the SP reduced the residual stress to a depth of 0.35 mm.

3.2. SCC Initiation Test

The results of surface observation of the Type-304 and Inconel 182 specimens after soaking in an autoclave for 500 hours are listed in Table 5. In both materials,
SCC was observed on the ground specimens under all strain conditions. On the other hand, no cracks were observed in the shot-peened specimens under strain below 0.4%.

The propagation length of cracks caused by SCC was observed in the shot-peened specimens under strain below 0.4%, measured in detail (Figs. 4 and 5). These results were obtained by measuring the maximum crack length in 2 mm long, 3 mm wide sections along the longitudinal direction of the specimens. In the case of the ground specimens in both materials, it is clear that the crack length increases with increasing strain. In the case of the ground and peened specimen, the crack propagation in depth did not occurred.

3.3. SCC Propagation Test

The length of crack propagation produced by soaking in the autoclave was measured by cross-sectional observation (Fig. 6). It is clear from these figures that the propagation of the pre-cracks whose strain range was 0.15 and 0.2% was arrested by SP. In the case of 0.3% strain range, pre-cracks length exceeded 0.7 mm propagated by SCC even if they were peened or not. In the case of 0.4% strain range, moreover, if the pre-crack length exceeded 0.5 mm, cracks produced by SCC propagated.

4. DISCUSSION

The results described in the previous sections lead to the conclusion that SP prevents SCC initiation when the strain is less than 0.4% (as shown in Table 5). The prevention of the SCC initiation and propagation and the time dependency of these effects are discussed below.

The effects of SP on prevention of SCC initiation and propagation are considered to result from the compressive residual stress at the surface. There are many theories to explain the mechanism of SCC initiation, but the most appropriate theory is that rupture of the oxide film on the specimen surface in local areas produces SCC [11]. Such rupture of the oxide film will be produced
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Fig. 7. Evaluation of crack propagation under compressive residual stress (based on superposed theory).

The crack propagation behavior in the depth and surface crack propagation direction under a compressive residual stress field was evaluated according to the principle of superposition (Fig. 7) [12]. In this evaluation, it was supposed that the target component regarding crack extension was a wall with a thickness of 35 mm and containing a crack of 3 mm deep and 15 mm long. The effective SP depth was assumed to be 1 mm from the peened surface. Under this assumption, the residual stress was changed by SP from tensile of 200 MPa to compressive of −200 MPa at the surface, while the internal stress stayed constant at 200 MPa. The depth profile of residual stress was determined by approximating these values. The SP decreased the crack growth rate by half in the depth direction. Moreover, the SP arrested the crack propagation direction on the surface because of the compressive residual stress on the surface. According to the principle of superposition, the load on the crack surface controls the stress intensity factor $K$ at the crack tip. The sum of load on the crack surface and $K$ decreases if a compressive residual stress exists at the surface. As the result, the crack growth rate in the depth direction will decrease. The prevention effect of crack propagation on the surface is greater than that in depth direction since the compressive residual stress will prevent the crack from opening. As the result, crack propagation on the surface was arrested.

Compressive residual stress at the peened surface prevents SCC initiation and propagation as explained above. Consequently, evaluating the time dependency of the change in compressive residual stress is equivalent to evaluating the effects of SCC prevention. In the case of Inconel 182, the cyclic load dependency of compressive residual stress under the condition of stress amplitude of 370 MPa was evaluated as shown in Fig. 8. The residual stress changed from −1000 to −800 MPa under three-cycle loading. Under over-10 cycle loading, the residual stress changed slightly, i.e., from −600 to −550 MPa. Since the cyclic dependency disappeared over 10-cycle loading, the stress amplitude dependency under the condition of 30-cycle loading was also evaluated, as shown in Fig. 9. The residual stress was measured by X-ray diffraction at the surface and at a depth 0.2 mm below it. These measurements showed that the residual stress at

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the surface changed slightly with increasing stress amplitude. By applying cyclic loading under a stress amplitude of 400 MPa, the residual stress was reduced from −800 MPa to −600 MPa. As in the case of surface residual stress, the residual stress at a 0.2 mm depth reduced slightly with increasing stress amplitude. These results indicate that compressive residual stress is retained; that is, SCC is prevented by SP. An actual plant is operated within a 0.1% strain condition on the basis of an engineering design to prevent SCC. In the case of Inconel 182, 0.1% strain is equivalent to a stress of 200 MPa. It is thus expected from our results that SCC will be prevented if surface residual stress is compressive. Therefore, it is concluded that the cyclic loading dependency on the residual stress change by SP is very small and can be neglected.

It will be possible to occur a crack initiation and propagation under a large strain condition. In the case of Type-304, stress-strain curve which obtained from FEM analysis is used for evaluating the loading histories by 1.0% strain, and are explained as follows (Fig. 10). The strain produced by SP was assumed to be 0.5%. This strain was determined by the residual stress after SP. In the case of 0.1% strain, the stress was −350 MPa. Therefore, SP prevents SCC initiation and propagation since the residual stress is still compressive. The residual stress changes from compressive to tensile when the applied strain exceeds 0.35%. When the 0.6% strain was applied, the specimen was deformed plastically. On this stage, compressive residual stress disappeared and the peening surface was extended; that is, the effect of SP also disappeared. However, it should be noted that this 0.3% strain condition, under which residual stress changed from compressive to tensile, is considerably larger than the engineering design value in the case of an actual plant construction used under an SCC environment.

4. CONCLUSION
The effects of shot peening (SP) on stress corrosion cracking (SCC) initiation and propagation were investigated. It was found that SP prevents SCC initiation and propagation. These effects result from the fact that the compressive residual stress caused by SP decreases the applied loads at the crack surface and prevents rupturing of the oxide film at the surface. Moreover, it was also found that these two effects of SCC prevention are maintained when cyclic loading is applied to the peened specimens.

REFERENCES