Effectiveness of Ultrasonic Shot Peening on Stainless Cast Steel SCS6 Containing a Fatigue Crack*1

Jinta Arakawa1, Yoshiichirou Hayashi2, Hiroyuki Akebono1,*2 and Atsushi Sugeta1,*2

1Department of Mechanical Science and Engineering, Hiroshima University, Higashi-hiroshima 739-8527, Japan
2Hydropower Department, Electric Power Development Co., Ltd., Tokyo 104-8165, Japan

In order to investigate the effectiveness of ultrasonic shot peening treatment (USP) as a repairing method for SCS6 material with surficial fatigue crack for hydraulic turbine runner, plane bending fatigue tests were carried out for USP treated SCS6 containing a surface fatigue crack with 1 mm in length and the fatigue crack propagation after USP was observed by a plastic replica method. As a result, the fatigue crack propagation life of SCS6 containing a surface fatigue crack was dramatically improved by USP treatment. Furthermore, the initial effective stress intensity factor ranges were calculated in the USP treated and untreated SCS6 containing a surface fatigue crack, respectively. According to the calculation, it was clear that the surficial fatigue crack could be harmless under the condition that the calculated initial effective stress intensity factor range considering the stress opening a fatigue crack, which was acquired by the unloading elastic compliance method, was less than the threshold of effective stress intensity factor range. Therefore, USP treatment is effective for repairing method of SCS6 containing surficial fatigue crack for hydraulic turbine runner. [doi:10.2320/matertrans.Z-M2020829]

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1. Introduction

Hydropower facilities have many advantages over other power generation methods, including their use of reusable and pure domestic energy sources, extremely low CO2 emissions, and quick response to short-term fluctuations in demand.1-3 Hydroelectric power generation facilities contain a rotating machine called a turbine runner as one of their main operational devices. During operation, high stress acts on one of the blades, called the runner vane, causing the generation of fatigue cracks in the runner vane from long-term use. This phenomenon has been observed in many power stations.2-4 When such fatigue cracks cause the fatigue failure of runner vanes, i.e., the breakage of the water turbine runner, not only is there a huge loss in terms of operability due to the power generation capacity stoppage, but the safety and reliability of the entire hydroelectric power plant are also diminished. Therefore, runners are regularly maintained and replaced as necessary to prevent their breakage in this manner; however, the runners are very large structures that are costly and labor-intensive to construct and maintain.

To address this issue, the authors have previously proposed the use of ultrasonic shot peening USP to improve the fatigue resistance of runner vanes subjected to high stress in order to extend the maintenance interval of the runner material and improve the service life of the runner.5-10 USP treatment is a surface treatment in which the surface of the material is bombarded with shot ejected at a high speed to form a layer on the surface with high hardness and high compressive residual stress. It is characterized by its easy management of materials and its suitability for local treatment such as the construction of hydroelectric power equipment.11-14

In a previous study, we have applied USP treatment to a turbine runner composed of stainless cast steel of grade SCS6 to form a hardened surface layer with high hardness and high compressive residual stress, thereby demonstrating that the crack initiation life could be extended and the crack growth rate reduced in comparison with the untreated case.15 In addition, it was also clarified that the fatigue strength improvement can be quantitatively evaluated from the hardness and compressive residual stress of the hardened layer formed by USP. However, the effectiveness of USP treatment was only examined for runners not subjected to fatigue damage in this previous study, and the effectiveness of USP treatment for runners subjected to fatigue damage due to cyclic loading remains unknown.

Furthermore, in the case of the abovementioned water turbine runner, if a fatigue crack is identified at the time of inspection, the area surrounding the crack is mechanically removed, and a repair process involving welding repair followed by surface smoothing by polishing is undertaken.16 However, in the narrow part of the water turbine runner, which has a complicated shape, performing this type of repair work is difficult and inefficient in terms of workability and working time. As mentioned above, the USP process involves the use of a small shot peening device and is suitable for local treatment in narrow areas, such as that in the water turbine runner. Therefore, if USP treatment can be applied as an alternative to conventional repair work, it would be highly beneficial in terms of cost and time, but there are few cases where USP treatment is applied as a repair method for water turbine runners.

In the present study, USP treatment was applied to specimens composed of SCS6, the abovementioned material commonly used for water turbine runners. Fatigue cracks were generated in these specimens, and the fatigue crack propagation behavior was observed in detail to determine the effectiveness of the USP treatment of this material. In addition, the effect of USP treatment on the fatigue cracks

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*2Corresponding authors, E-mail: akebono@hiroshima-u.ac.jp, asugeta@hiroshima-u.ac.jp
was quantitatively evaluated with a fracture mechanics approach considering the crack opening and closing.

2. Specimens and Experimental Procedure

2.1 Specimens

In this study, we focused on a section of cast stainless steel of grade SCS6 that had been used for 27 years as a water turbine runner for hydroelectric power generation. This material has a martensitic structure, as shown in Fig. 1, and Tables 1 and 2 respectively give its chemical composition and mechanical properties. From the same section of material, two types of test pieces were cut out by electric discharge machining, and the center of each test piece was polished to a mirror surface with emery paper (#600–#2000) and alumina powder (CR 3.0 to CR 1.0). These test pieces are shown in Fig. 2(a) and (b) and were respectively used for plane bending fatigue testing and to measure the crack opening point. In addition, to set the location of the cracks in the specimens, an elliptical notch was made in the center of the fatigue test specimen, and a notch with a diameter of 0.3 mm and a depth of 0.2 mm was made in the center of the crack opening point measurement specimen.

2.2 Experimental procedure

2.2.1 Plane bending fatigue tests

Fatigue testing was performed using a plane bending fatigue test machine at a frequency of \( f = 20 \text{ Hz} \), a stress ratio of \( R = -1 \), and room temperature. An initial crack was produced in the plane bending fatigue test specimen according to the procedure described below, the center part of the test piece was then subjected to USP treatment under the conditions listed in Table 3, and the fatigue test was carried out once more after treatment. The crack propagation behavior was observed in detail by the replica method.

1. A fatigue test was conducted under a stress amplitude of \( \sigma_a = 570 \text{ MPa} \), and the test was stopped when a fatigue crack of approximately 1 mm in length was identified.
2. USP treatment was performed on both sides of the central part of the test piece.

Table 1 Chemical composition of SCS6 [mass%].

| Element | C | Si | Mn | P | S | Ni |
|---------|----|----|----|---|---|----|
|         | 0.049 | 0.50 | 0.83 | 0.040 | 0.004 | 3.62 |

Table 2 Mechanical properties of SCS6.

| Test | HV | \( \sigma_y \) [MPa] | \( \sigma_b \) [MPa] |
|------|----|-------------------|-------------------|
|      | 280 | 594 | 829 |

Fig. 1 Microstructure observation by an optical microscope.

Fig. 2 Schematic illustrations of specimens.
The fatigue test was again conducted under stress amplitudes of \( \sigma_a = 600, 550, 500, \) and \( 450 \) MPa and the propagation behavior of the fatigue crack was observed.

The specimen was said to fracture when the crack length reached 2 mm, at which point the test was concluded.

The depth distributions of the hardness and residual stress of the hardened layer that formed on the surface of the test piece as a result of the USP treatment adopted in this study are shown in Fig. 3. 15)

### 2.2.2 Measurement of a stress opening fatigue crack

In this study, to quantitatively evaluate the effectiveness of the USP treatment in preventing crack formation, a fracture mechanics approach was applied in consideration of the crack opening and closing behavior. A hydraulic servo pulsar was used for the test, and the unloading elastic compliance method was used to measure the crack opening point. The method of measuring the crack opening point stress is described below.

1. A fatigue test was conducted under a stress amplitude of \( \sigma_a = 400 \) MPa, a frequency of \( f = 5 - 8 \) Hz, and a stress ratio of \( R = -1 \). The total length of all fatigue cracks generated from defects, including artificial defects, was measured, and the test was stopped when this cumulative length reached 1 mm.

2. After the USP treatment was applied to both sides of the center of the test piece under the conditions listed in Table 3, a strain gauge was attached to the specimen as shown in Fig. 4. At this time, to prevent the strain gauge breaking as a result of the opening of the fatigue crack, a Teflon film was stuck around the crack opening region, and the strain gauge was attached to the Teflon film. In addition, as shown in Fig. 4, a strain gauge for load measurement was attached separately, and a load signal not affected by the crack opening and closing was obtained.

3. A hysteresis loop describing the stress–strain relationship was obtained under the conditions of \( f = 0.02 \) Hz, \( \sigma_a = 400 \) MPa, and \( R = -1 \). From this, the stress at the opening of the fatigue crack was estimated based on the change in the slope of the stress–strain curve at the time of fatigue crack opening.

In addition, for comparison, an initial crack was also introduced to a similar material that was not subjected to USP treatment (virgin material), and the open point measurement was conducted in the same manner as for the USP material.

Furthermore, it was confirmed that the test specimens for the bending fatigue test and crack opening point measurement showed similar compressive residual stress on the surface after USP treatment. There was no significant difference in the compressive residual stress distributions of the two specimens after USP treatment.

### 2.3 Simulation of fatigue crack growth

In this study, the effect of USP treatment on fatigue crack is examined by applying USP treatment to SCS6 material with fatigue crack and acquiring fatigue crack growth behavior and propagation life experimentally. In order to do this, in this study, the effect of USP treatment on fatigue crack behavior was examined by applying USP treatment to SCS6 specimens with fatigue cracks and experimentally observing their growth behavior and propagation life. To properly evaluate the observed behavior, it is necessary to accurately determine the fatigue crack growth life in similar specimens not subjected to USP treatment; in this study, this was achieved by performing fatigue crack growth simulation. The fatigue crack growth was simulated using Paris’ law with parameters obtained from the fatigue crack growth characterizations.

![Vickers hardness and residual stress distribution generated by USP treatment.](image)

![Schematic illustration of fatigue crack initiation site.](image)
istics (Fig. 5) of the same material obtained in a previous report. The obtained formula is given by

$$\frac{da}{dN} = \left(6.0 \times 10^{-12}\right)(\Delta K_{\text{eff}})^{3.3}$$

where $a$ is the crack length, $N$ is the number of load cycles, and $\Delta K_{\text{eff}}$ is the effective stress intensity factor range. From eq. (1), it is possible to calculate the increase $da$ in the length of the fatigue crack for a given number of load cycles $dN$. The fatigue crack length was calculated for every $dN = 1000$ cycles, and the number of cycles at which the crack length reached 2 mm was defined as the number of cycles to failure. In addition, the weighting function method considering the stress gradient was applied to the calculation of the maximum stress intensity factor $K_{\text{max}}$.

3. Experimental Results

3.1 Fatigue crack propagation in plane bending tests

3.1.1 Observation of initial fatigue crack

USP treatment was applied to five bending fatigue test pieces with an initial crack length of approximately 1 mm. These five specimens are hereafter referred to as USP1 to USP5. As a representative example of the fatigue crack observation results before and after USP treatment, Fig. 6 shows the results for USP5. As shown in this figure, there was no significant change in the apparent shape and crack length of fatigue cracks observed in the surface of the specimen before and after USP treatment. In addition, to measure the aspect ratio of the fatigue crack after USP treatment, heat treatment (873 K, 2 h) was applied to USP5 using an electric furnace, and the crack cross section was oxidized and colored and then broken for observation. The aspect ratio of the fatigue crack after USP treatment was then calculated from this specimen. An image of the crack cross section and a schematic illustrating the aspect ratio calculation are shown in Fig. 7. The fatigue crack aspect ratio $\lambda$ was approximately 0.7. This value was used in the fracture mechanics evaluation described in Section 3.2.

3.1.2 Fatigue crack growth behavior

Figure 8 shows the fatigue crack growth behavior after USP treatment for a fatigue crack of approximately 1 mm in length. The stress amplitudes were $\sigma_a = 600, 550, 500,$ and $450$ MPa for USP1 to USP4, respectively. In Fig. 8, the crack length is plotted against the number of cycles to failure in the USP-treated specimens, $N_{\text{USP}}$, normalized with respect to the number of cycles to failure calculated from the estimated fracture life when USP is not applied to the initial crack, $N_{\text{f Virgin}}$. The results clearly demonstrate that the fatigue life can be greatly improved by applying USP treatment to the initial crack. For USP1 to USP3, the numbers of cycles to failure $N_{\text{USP}}$ were respectively 15.2, 23.9, and 100.0 times that $N_{\text{f Virgin}}$ for the virgin material. In addition, in the USP4 series, the test was continued for $1 \times 10^7$ cycles, but the growth of the initial crack was not observed, and the fatigue crack was considered harmless under the given loading conditions.

3.2 Evaluation by using fracture mechanics parameter $K$

The mechanism underlying the improvement of the fatigue life by USP treatment was then examined using the fracture mechanics parameter $K$. The parameter $K$ was calculated according to eq. (2) using the weighting function method. As shown in Fig. 3(b), although the USP treatment resulted in a
compressive residual stress of 450 MPa at the surface of the test piece, the stress decreased with fatigue load, and in the early stage, it is known that the compressive residual stress is saturated. Therefore, in eq. (2), the release compressive residual stress saturation value of 241 MPa experimentally obtained in a previous study was used to calculate the parameter $K_R$, which indicates the change in the stress intensity factor due to the residual stress. In addition, although the release compressive residual stress was measured at various stress levels, it was consistently measured as the abovementioned value of 241 MPa. In addition, the aspect ratio of the USP-processed material was calculated using $\frac{\sigma}{C_1K_{eff}} = 0.7$, as obtained from USP5 (see Section 3.1.1).

$$\Delta K_{eff} = K_{max} - K_{op} + K_R$$  (2)

### 3.2.1 $\Delta K_{eff}$ at zero opening point stress

The simple case in which the stress at the opening point is assumed to be $\sigma_{op} = 0$ MPa was then examined. From eq. (2), the initial effective stress intensity factor range ($\Delta K_{eff}$)$_{ini}$ can be expressed as the sum of the maximum stress intensity factor $K_{max}$ and the reduction $K_R$ in the $K$ value due to compressive residual stress. Table 4 gives the results of the initial effective stress intensity factor range ($\Delta K_{eff}$)$_{ini}$ calculated from $K_{max}$ and $K_R$ using the weighting function method. In Table 4, in addition to the initial effective stress intensity factor range ($\Delta K_{eff}$)$_{ini}$ of the USP-treated material, the values for the virgin material are given for comparison. A comparison of the ($\Delta K_{eff}$)$_{ini}$ values of the USP-treated and virgin materials reveals that the ($\Delta K_{eff}$)$_{ini}$ value is greatly reduced by the USP treatment. This is a result of reflecting the effect of the compressive residual stress in the calculation of the stress intensity factor, and the introduction of compressive residual stress by the USP treatment reduces ($\Delta K_{eff}$)$_{ini}$. The results demonstrate that USP is an effective method for improving the lifetime of SCS6. However, for USP4, the initial effective stress intensity factor range was 3.9 MPa·m$^{1/2}$, which is higher than the threshold of the effective stress intensity factor range (3.0 MPa·m$^{1/2}$) for this material shown in Fig. 5. Thus, the results given in Table 4 are not consistent with the “fatigue crack arrest” phenomenon observed in the experimental results. This is considered to be caused by the overestimation of the initial effective stress intensity factor ($\Delta K_{eff}$)$_{ini}$ of the crack tip by simply assuming the opening point stress to be 0 MPa. The initial effective stress intensity factor range ($\Delta K_{eff}$)$_{ini}$ was calculated from eq. (2) based on the measured values obtained by accurately measuring the crack opening stress.

#### 3.2.2 Measurement for stress opening crack $\sigma_{op}$

The hysteresis loops of the virgin and USP-treated specimens are shown in Fig. 9(a) and (b), respectively. Additionally, in the figure, because the fatigue crack opening is not clear, the strain was obtained from the unloading elastic line. The stress was calculated using the least squares method from a plot in the $\sigma_{detected}$ range of 300 to 400 MPa to determine the unloading elastic line. The difference between the strain obtained from this unloading elastic line and the experimentally obtained strain is denoted $\Delta \varepsilon$ to clarify the

Table 4 The initial values of $\Delta K_{eff}$ ($\sigma_{op} = 0$ [MPa]).

| $\sigma_a$ [MPa·m$^{1/2}$] | USP | Virgin |
|---------------------------|-----|--------|
| $\sigma_a=600$           | 6.1 | 12.1   |
| $\sigma_a=550$           | 6.5 | 12.6   |
| $\sigma_a=500$           | 5.3 | 11.2   |
| $\sigma_a=450$           | 3.9 | 10.2   |
crack opening point. The results are shown in Fig. 10(a) and (b). From this, it was found that the fatigue crack opening stresses of the virgin and USP materials are approximately 60 and 90 MPa, respectively, and that this stress was shifted to the tensile side as a result of the USP treatment. This is considered to be largely influenced by the compressive residual stress introduced by the USP treatment, implying that the resistance to the fatigue crack opening is increased by applying USP treatment. Therefore, it is possible to reduce the effective stress intensity factor range $\Delta K_{\text{eff}}$ of the crack tip by applying USP treatment to the fatigue crack formed by the fatigue load.

3.2.3 ($\Delta K_{\text{eff}}$)$_{\text{ini}}$ considering fatigue crack opening point

Recalculation of ($\Delta K_{\text{eff}}$)$_{\text{ini}}$ was performed based on the stress at the opening point of the fatigue crack obtained in the previous section. Table 5 gives the calculation results. From this, ($\Delta K_{\text{eff}}$)$_{\text{ini}}$ was found to be 2.2 MPa-m$^{1/2}$ for USP4. Because this value is lower than the threshold for the effective stress intensity factor range of ($\Delta K_{\text{eff}}$)$_{\text{ini}}$ = 3.0 MPa-m$^{1/2}$, this result is consistent with the “fatigue crack arrest” of USP4 observed in the experimental results. It can be seen that whether the fatigue crack grew after USP treatment can be quantitatively evaluated by the effective stress intensity factor range taking into account the opening point stress.

The above results indicate that it is possible to reduce the initial effective stress intensity factor range and extend the fatigue crack growth life by applying USP processing to SCS6 in which a fatigue crack is generated by the fatigue load. In addition, the results demonstrate that in the initial stage under stress conditions in which the effective stress intensity factor range falls below the threshold effective stress intensity factor range, the phenomenon of fatigue crack arrest may occur, where the fatigue crack is rendered harmless.

4. Conclusion

In this study, to clarify the effectiveness of USP treatment
in increasing the lifespan of fatigue-damaged stainless cast steel (SCS6), USP treatment was applied to specimens with initial fatigue cracks, and the crack propagation behavior was observed in detail. Furthermore, the effect of USP treatment was quantitatively assessed by fracture mechanics evaluation considering the crack opening and closing. The main conclusions reached in this study are as follows.

1. Applying USP treatment to SCS6 material with fatigue crack can significantly extend the fatigue crack growth life because the compressive residual stress introduced by USP treatment significantly reduces the effective stress intensity factor range of the crack tip.

2. In USP-treated specimens, the initial fatigue crack did not progress and remained in an applied stress condition where the effective stress intensity factor range, taking into account the opening point stress, was lower than the threshold of the effective stress intensity factor range by USP treatment; therefore, it is possible to render fatigue cracks harmless by applying this treatment.

3. The USP treatment considered in this study shows promise as an extremely effective method for repairing a water turbine runner that has been fatigue-damaged.

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