Hybrid surface treatment of carbon steel by using a cavitating jet

H. Soyama, M. Asahara, M. Saka

Department of Mechanical Engineering, Tohoku University, Aoba 01, Aramaki, Aoba-ku, Sendai 980-8579, Japan
EMail: soyama@ism.mech.tohoku.ac.jp

Abstract

Cavitation can be used for hybrid surface treatment, that is improvement of the fatigue strength and the corrosion resistance at once. In the present paper, hybrid effects induced by the cavitation were demonstrated experimentally. Cavitation, which normally produces fatal damage on hydraulic machinery, can be used to introduce compressive residual stress in metal surface as the same as shot peening. The cavitation bubble collapse also produces the high temperature spot, which can introduce chemical effect on metal surface. As the cavitation intensity and the cavitating region of high speed submerged water jet can be controlled by the hydraulic parameter such as upstream pressure and the cavitation number, the cavitating jet is useful for surface treatment. In the present test, the upstream pressure of cavitating jet was 15 MPa and the test material was the common carbon steel S45C of Japanese Industrial Standards (JIS). The residual stress was measured by an X-ray diffraction method before and after exposure of the cavitating jet. The cavitating jet such as relatively low injection pressure of 15 MPa changes the residual stress from -250 MPa to -350 MPa, as the cavitation impact was optimized. The corrosion resistance was measured by an electrochemical method. The corrosion potential shifts to noble by the cavitating jet. Namely, the cavitating jet improved the corrosion resistance. It can be concluded that the cavitating jet shows the hybrid effect of the surface treatment, i.e., improvement of the residual stress and the corrosion resistance at the same time.


1 Introduction

Cavitation produces not only high-pressure impacts\(^1\)-\(^3\), which normally make damage on surface of hydraulic machinery, but also high temperature spots\(^4\). These impacts can be used to surface treatment as the same as shot peening, when the cavitation was controlled. The authors have already shown the introduction of compressive stress in metal surface\(^5\) and improvement of fatigue strength by using cavitation\(^6\). The above-mentioned mechanical and thermal effect can improve corrosion resistance on metal surface. The cavitation has a possibility to make hybrid surface treatment, which means the improvement of strength and corrosion resistance on the material surface at the same time.

The advantages in performing the surface treatment by using a cavitating jet are as follows. (1) Since the peening by using the cavitating jet does not need steel balls in the case of shot peening, the running cost is cheaper and the process is clean. (2) The cavitation impact can hit surface within a narrow region such as narrow tubes or even the bottom of a gear tooth. (3) The cavitating jet takes place the cavitation bubbles wherever the cavitation impacts are necessary. (4) The cavitation intensity can be controlled by the hydraulic parameters, such as upstream pressure and downstream pressure of a nozzle\(^7\). (5) Although the water jet in the air can also peen material surface\(^8\),\(^9\), the working pressure of the submerged cavitating jet can be higher than that of the jet in the air at the same pump pressure. Because the cavitation impacts were used at the cavitating jet. (6) The area on the material surface, where the cavitating jet affects, is much wider than that of the water jet in the air\(^10\).

As well known, at the initial stage of the cavitation erosion progress, the only plastic deformation without mass loss takes place on the material surface\(^11\). When the exposure time of the cavitating jet is considered, the surface treatment without damage becomes possible.

In the present paper, the residual stress and corrosion properties on the surface of the carbon steel were experimentally measured before and after exposing to cavitation. The test metal was carbon steel S45C of Japanese Industrial Standards (JIS), which is widely used as materials of machinery components. The residual stress in the surface was measured by an X-ray diffraction method. The corrosion property was investigated by using an electrochemical method. It is noted that this is the first time to evidence the both improvements of residual stress and corrosion resistance at once by using cavitation.

2 Experimental Facilities and Procedures

2.1 Cavitating jet

Figure 1 shows a test section of a cavitating jet apparatus according to the ASTM G134 standard\(^12\). Test water pressurized by a plunger pump, whose maximum
Table 1 Chemical composition of tested carbon steel JIS S45C (weight %)

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</thead>
<tbody>
<tr>
<td>C</td>
<td>Si</td>
<td>Mn</td>
<td>P</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>0.42-0.48</td>
<td>0.15-0.35</td>
<td>0.60-0.90</td>
<td>0.030 less</td>
<td>0.035 less</td>
<td></td>
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Fig. 1 Test section of cavitating jet apparatus

capacity was 20.6 MPa and \(2.2 \times 10^{-4}\) m\(^3\)/s, was injected into a test section filled with the test water through a nozzle. The ion exchanged water was used in the test loop. A target, i.e. a sensor or a specimen, was set perpendicularly to the jet. The nozzle diameter \(d\) and length \(l\) are 0.4 mm and 1.2 mm, respectively. The water temperature \(t_w\) was 303 ± 1 K.

The cavitation number \(\sigma\) is a key parameter on cavitating flow. The cavitation number \(\sigma\) of such a jet is defined as the ratio of the upstream pressure \(p_1\) and the downstream pressure \(p_2\) as follows:

\[
\sigma = \frac{p_2 - p_v}{p_1 - p_2} = \frac{p_2}{p_1},
\]

where \(p_v\) is the vapor pressure of the test water.

The standoff distance \(s\) was defined as the distance from the upstream corner of the nozzle throat to the surface of specimen. The optimum standoff distance \(s_{opt}\), where the cavitation intensity has maximum, was obtained by erosion test performed with changing the standoff distance using aluminum specimens. The test specimen was made of JIS S45C, whose chemical property was shown in Table 1.
Table 2 Cavitating conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Cavitation number $\sigma$</th>
<th>Upstream pressure $p_1$ MPa</th>
<th>Downstream pressure $p_2$ MPa</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>0.014</td>
<td>15</td>
<td>0.21</td>
</tr>
<tr>
<td>B</td>
<td>0.04</td>
<td>15</td>
<td>0.6</td>
</tr>
<tr>
<td>C</td>
<td>--</td>
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As Soyama reported that the cavitating jet has a maximum intensity at $\sigma = 0.014$ at the constant pressure difference $\Delta p = p_1 - p_2$. Therefore the cavitating condition for the improvement of residual stress was chosen at $\sigma = 0.014$. Optimum standoff distance $s_{\text{opt}}$ was 17 mm for $\sigma = 0.014$. In order to reveal the improvement of the corrosion resistance, experiment was carried out for three different conditions: A (the specimen was exposed to the cavitating jet in the cavitating region), B (the specimen was exposed to the cavitating jet but not in the cavitating region), and C (the specimen was not exposed to the jet). The cavitating condition was shown in Table 2.

2.2 Residual stress measurement

The measurement of the principal stress is important to evaluate the improvement of the residual stress by the cavitating jet. Figure 2 shows a definition of coordinates system $(x, y)$ on the material surface. The normal stresses $\sigma_a$, $\sigma_b$ and $\sigma_c$ in three different directions with $\theta_a$, $\theta_b$ and $\theta_c$ due to the residual stress in the surface were measured by an X-ray diffraction apparatus with changing the exposure time of the cavitating jet. Then, the normal stresses $\sigma_x$, $\sigma_y$ and the shear stress $\tau_{xy}$ were calculated by the following equation;

$$
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
2\tau_{xy}
\end{bmatrix} =
\begin{bmatrix}
\cos^2 \theta_a & \sin^2 \theta_a & \sin \theta_a \cos \theta_a \\
\cos^2 \theta_b & \sin^2 \theta_b & \sin \theta_b \cos \theta_b \\
\cos^2 \theta_c & \sin^2 \theta_c & \sin \theta_c \cos \theta_c
\end{bmatrix}^{-1}
\begin{bmatrix}
\sigma_a \\
\sigma_b \\
\sigma_c
\end{bmatrix}
$$

(2)
Two principal stresses $\sigma_1$ and $\sigma_2$ were obtained from $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ by

$$\frac{\sigma_1}{\sigma_2} = \frac{1}{2}(\sigma_x + \sigma_y) \pm \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2}$$  \hspace{1cm} (3)

Here, $\theta_{\sigma}$, $\theta_{\tau}$, and $\theta_{\psi}$ were chosen as 0, 60 and 120 degrees during the measurement, respectively. The slit diameter of the X-ray was 1 mm. The X-ray tube used was CrK$\alpha$. The intensity of the X-ray was 20 kV and 10 mA. The X-ray was counted for 30 seconds by using a position sensitive proportional counter PSPC at each incidence angle $\varphi_0 = -20, -10, 0, 10, 20$ degrees. The diffractive face was (211) of $\alpha$–Fe, the diffractive angle $2\theta$ was 156.09 degrees and the stress factor of the X-ray diffraction method was $-317.91$ MPa. The diffractive angle was determined by a half value width and the residual stress was calculated by the gradient of $2\theta - \sin^2 \psi$ curve by using the $\sin^2 \psi$ method, where, $\psi$ is the half angle between the X-ray tube and the counter PSPC. The residual stress was measured across the jet center with an interval of 1 mm.

2.3 Corrosion property measurement

In order to reveal the improvement of the corrosion resistance by the cavitating jet, the corrosion potential was measured experimentally for three different conditions as shown in Table 2. The polarization on the specimen surface was also investigated for condition A and C.

Figure 3 shows a sensor to measure corrosion potential. The sensor has an insulated pin made of JIS S45C, 2 mm in diameter and 4 mm in length. The pin was set at a distance of 3 mm from the jet center, where the cavitation intensity on the surface reaches its maximum value. The surface of JIS S45C was polished by emery paper No. 1500 and buffed before exposing it to the jet at each condition. Figure 4 illustrates a schematic diagram of the electrochemical method to measure corrosion potential. The area under test on the surface of the sensor was connected through a stainless steel tube and a salt bridge to a reference electrode of AgCl with saturated KCl. The potential was described by a standard hydrogen electrode SHE in this paper.

The polarization on the specimen was measured by a controlled potential method. The sweep speed of the potential was 0.5 mV/s. The current density was obtained from the current measured by the potentiostat divided by the tested area. The tested area is calculated by the diameter of the tested carbon steel S45C without taking the roughness of the surface into account.

![Diagram of sensor to measure corrosion potential](image-url)

Fig. 3 Sensor having a tested carbon steel to measure corrosion potential
3 Results

3.1 Improvement of residual stress

Figure 5 shows the residual stress in the surface as a function of the distance.
Surface Treatment

Figure 6 illustrates the averaged maximum and minimum residual stress \( \sigma_{1ave}, \sigma_{2ave} \) calculated from 5 measuring points as a function of the exposure time. The compressive residual stress increased within 10 seconds by the cavitating jet and it seemed to be saturated. The cavitating jet of the relative low upstream pressure such as 15 MPa can introduce compressive residual stress, as the cavitating condition was optimized.

### 3.2 Improvement of corrosion potential

In order to demonstrate the improvement of corrosion resistance, the corrosion potential was measured at both cavitating and non-cavitating conditions. Figure 7 illustrates the potential \( E \) changing with time \( t \). The sensor was exposed to the jet for 1 minute. The time \( t \) is the duration after the cession of the jet. In order to reveal repeatability, two sets of data for each of the conditions A, B and C are plotted in Fig. 7. In both cases of conditions A and B, the potential increased towards more noble potentials with time, until they reached saturation. After the exposing to the cavitating jet, i.e. condition A, the saturation potential 205 mV is more noble than that for condition B (155 mV) and for the non-cavitating condition C (110 mV). Hence it will be concluded that the corrosion...
Fig. 7  Shift of the corrosion potential of carbon steel (JIS S45C) to a more noble potential after exposure to a cavitating jet

Fig. 8  Electrochemical polarization curve
potential of S45C in ion-exchanged water shifts towards more noble potentials after exposure to a cavitating jet. Therefore the cavitating jet improves the corrosion resistance of test carbon steel.

Figure 8 shows the electrochemical polarization for conditions A and C. The injection time of the cavitating jet was 5 minutes. For condition A, it was measured just after cession of the cavitating jet. The anodic polarization curve for condition A is lower than that for condition C. It is shown that the corrosion current density decreases by the cavitating jet. The corrosion current density is, of course, directly related to the corrosion rate through Faraday’s Law. Therefore, the cavitating jet improves the corrosion resistance.

4 Conclusions

In order to demonstrate the hybrid effects of the surface modification by the cavitating jet. The hybrid effects mean that the cavitating jet improves both of the mechanical and chemical properties of the common carbon steel JIS S45C at the same time. The obtained summarized results are follows;
(1) The introducing the compressive residual stress in the surface of the tested carbon steel by the cavitating jet was revealed, even though the upstream pressure was relatively low pressure such as 15 MPa.
(2) The corrosion potential of the tested carbon steel shifts toward noble by the cavitating jet. Namely, the cavitating jet can improve the corrosion resistance.

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References