Errata

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Improvement of the corrosion resistance of a carbon steel surface by a cavitating jet by H. Soyama and M. Asahara is reprinted here with color in figure 1.

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Improvement of the corrosion resistance of a carbon steel surface by a cavitating jet

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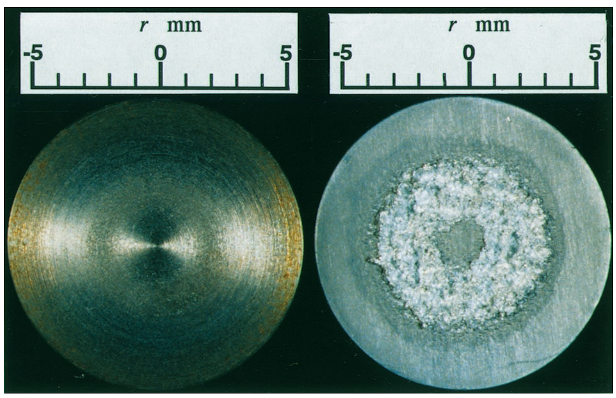
Collapse of the cavitation bubble produces not only mechanical impact, which normally results in cavitation erosion in fluid machinery, but also high temperature spots [1]. Recently cavitation impacts have been applied in surface modification such as peening [2–4], and the high temperature effect has also been used for making amorphous powder [5]. These mechanical and thermal effects can improve the corrosion resistance of a material.

The authors found that the region attacked by cavitation on carbon steel JIS S45C is brighter than the surrounding region as shown in Fig. 1a. Cavitation around a high-speed submerged water jet attacks a ring region ($|r| \cong 1 \sim 3$ mm) shown typically by the damage to a soft aluminum specimen in Fig. 1b. The region on the carbon steel corresponding to the damaged region on the soft aluminum specimen is the brighter part of the specimen. In the outer region of the bright region in Fig. 1a, the color of the specimen was brown and rusted. There are two possible reasons why the bright and rusted regions are produced. One of them is that corrosion within the rusted area is accelerated by the cavitating flow. The other is that the corrosion resistance of carbon steel is increased by cavitation impact in the bright region. In this paper, the effects of the cavitating jet on the corrosion resistance of carbon steel are discussed. The results indicate that an improvement in the corrosion resistance is achieved using cavitation and it should be noted that this is the first report of such evidence.

It is well-known that there is an incubation period without loss of any mass in the initial stage of exposure to cavitation [6]. It might be possible to improve the corrosion resistance of a metal surface without damage by taking the exposure time to cavitation into account. Watanabe *et al.* investigated the erosion-corrosion damage caused by a gas-liquid jet flow using an electrochemical method, and revealed passivity and pitting in the passive region [7]. The cavitating flow is also a high-speed multiphase flow, however, it produces the mechanical and thermal effects mentioned above. These effects significantly influence corrosion and they may be used to improve the corrosion resistance of metals. A high-speed submerged water jet with cavitation bubbles around the jet, was used as a source of cavitation. The cavitating region and its intensity can be controlled by the upstream and downstream pressures of a nozzle [8].

In order to demonstrate the improvement of the corrosion resistance by the cavitating jet, the corrosion property of carbon steel (JIS S45C) was evaluated experimentally by measuring the corrosion potential 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).

Fig. 2 shows a section through the test area of the cavitating jet apparatus and a schematic diagram of the electrochemical method to measure corrosion potential. Water pressurized by a plunger pump was injected through a nozzle into the test area which was filled with water. The nozzle throat diameter d was 0.4 mm. Ion-exchanged water was used in the test loop. A sensor having an insulated pin made of common carbon steel (JIS S45C), 2 mm in diameter (see Fig. 3) was set perpendicularly to the jet. 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 the carbon steel was polished by emery paper No. 1500 and buffed before exposing it to the jet at each condition. Table I shows the chemical composition of JIS S45C. 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. In this work the potential was described by a standard hydrogen electrode SHE. The standoff distance s at which the sensor was set, where the cavitation intensity takes its maximum value [9], was obtained by



(a) Carbon steel (b) Aluminum alloy

Figure 1 Optical photographs of (a) the bright region on carbon steel (JIS S45C) induced by the cavitating jet ($\sigma = 0.014$, $p_1 = 15$ MPa, $p_2 = 0.21$ MPa), and (b) area of attack of the cavitating jet shown by erosion area on soft aluminum alloy (JIS A1050P).

TABLE I Chemical composition of the tested carbon steel JIS S45C (weight %)

C	Si	Mn	P	S
0.42–0.48	0.15–0.35	0.60–0.90	0.030 less	0.035 less

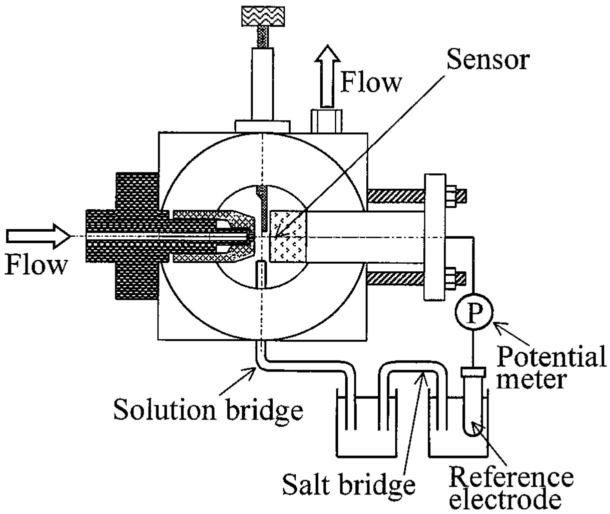


Figure 2 Cavitating jet apparatus and schematic circuitry for corrosion potential.

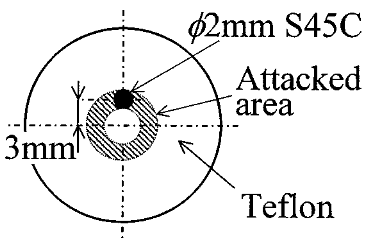


Figure 3 Carbon steel sensor to measure corrosion potential.

changing the standoff distance in erosion tests on soft aluminum specimens.

The cavitation number σ of such a jet is defined in terms of the upstream pressure p_1, the downstream pressure p_2 and the vapor pressure of the test water p_v as

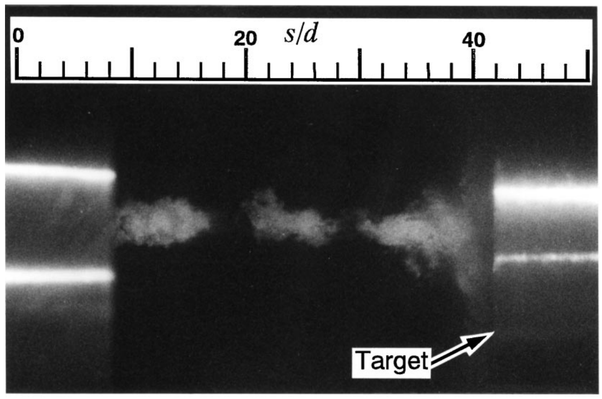
$$\sigma = (p_2 - p_v)/(p_1 - p_2) \cong p_2/p_1 \tag{1}$$

because $p_1 \gg p_2 \gg p_v$. When the cavitation number decreases, the cavitating region develops.

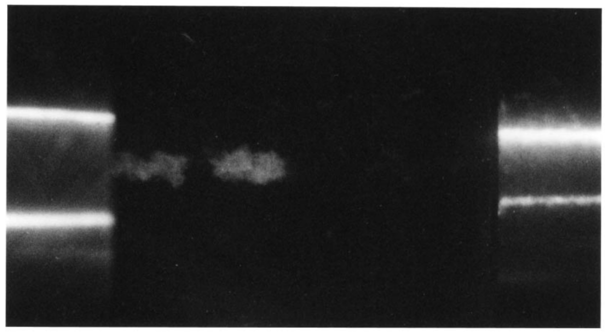
In order to investigate the effects of a cavitating jet on the corrosion potential, tests were performed under the three conditions listed in Table II. The water temperature t_w was 303 ± 1 K. At condition A, the specimen was exposed to the cavitating jet in the cavitating region, and the corresponding cavitation number was 0.014. On the other hand, under condition B, the specimen was exposed to the cavitating jet but not in the cavitating region in order to examine the effects of jet flow in the area surrounding the test section. The jet velocity in each case was the same. Under each condition A and B, the upstream pressure p_1 was 15 MPa and the normalized standoff distance s/d was 42, as this was the optimum standoff distance under condition A. Under condition C, the sensor was put into the test water without a jet.

TABLE II Cavitating conditions

Condition	Upstream pressure p_1 (MPa)	Downstream pressure p_2 (MPa)	Cavitation number σ	Standoff distance s/d	Exposure time t_{jet} (min)
A	15	0.21	0.014	42	1
B	15	0.6	0.04	42	1
C (No jet)	—	—	—	42	0



(a)



(b)

Figure 4 Profiles of the cavitating region of a cavitating jet taken by moment photography with 1.1 μs flash lamp. (a) Condition A ($\sigma = 0.014$, $p_1 = 15$ MPa, $p_2 = 0.21$ MPa, $s/d = 42$); (b) Condition B ($\sigma = 0.04$, $p_1 = 15$ MPa, $p_2 = 0.6$ MPa, $s/d = 42$).

Fig. 4 shows typical profiles of cavitation observed using a xenon flash lamp with exposure time 1.1 μs. The jet flows from left to right. The cavitating region is shown white, since it is the cavitation bubbles that reflect the light. Because the cavitating region changes with time, the photographs of the longest cavitating jets were chosen [10]. The many fine cavitation bubbles formed a vortex and a cloud. The cloud cavitation shed periodically from the nozzle [10], even though the jet flow was continuous. The cavitating region reached the surface of the specimen with condition A ($\sigma = 0.014$). Under this condition, the cavitation produced the high-pressure impacts on the specimen [8], which caused plastic deformation and then erosion (see Fig. 1b). When the downstream pressure was increased at constant upstream pressure, the cavitation number also increases and the cavitating length decreases. At condition B ($\sigma = 0.04$), the cavitating region does not reach the surface of the target and there is no cavitation bubble on the specimen.

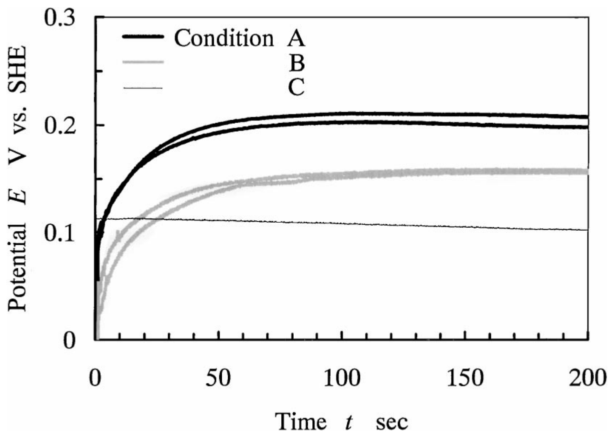


Figure 5 Shift of the corrosion potential of carbon steel (JIS S45C) to a more noble potential after exposure to a cavitating jet.

Fig. 5 illustrates the potential *E* changing with time *t* obtained at both cavitating and non-cavitating conditions. Two sets of data for each of the conditions A and B are plotted to show repeatability. The time *t* is measured from the cession of the jet, after the sensor was exposed to the jet for 1 min. The potential under conditions A and B increased towards more noble potentials with time, until they reached saturation. The saturation potential for the cavitating condition A (205 mV) is more noble than that for condition B (155 mV) and for the non-cavitating condition C (110 mV). Hence it can be concluded that the corrosion potential of S45C in ion-exchanged water shifts towards more noble potentials after exposure to a cavitating jet. Therefore this shows that the cavitating jet improves the corrosion resistance of this carbon steel.

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