Study on Cavitation Damage Characteristics around a Hollow-Jet Valve

Guoyu WANG**, Shujun LIU***, Masayuki SHINTANI**** and Toshiaki IKOHAGI***

In this paper, to make clear the mechanism of cavitation damage around a hollow-jet valve, cavitation damage test was conducted in a hollow-jet model valve. The eroded surfaces of specimens were observed by Scanning Electron Microscope (SEM) at different times of the test. Cavitation aspects were also observed photographically by a high-speed camera. It was found that the damage occurs in cavitating flows around a hollow-jet valve with two patterns. One is characterized by a big plastic crater, which seems to be generated by one blow event of cavitating vortex collapse near a specimen surface. Another is due to a small brittle irregular pit formed by the cumulative effects of many weaker blows. The former is the main cause to lead serious damage. The high-speed photographic observations of the cavitation aspects showed that more cavitating vortices in middle cavitation number state occur than these in other states. The damage tests also illustrated that the middle state is the most dangerous for cavitation damage around a hollow-jet valve.

Key Words: Cavitation, Damage, Cavitating Vortices, A Hollow-Jet Valve

1. Introduction

In most of industrial systems of fluid and energy transport, various types of control valves are utilized to regulate the flow at various conditions in pressure, temperature, flow rate and fluid properties. The safety operation of these valves is a very important problem which is related not only to the system safety but also to the human life. Among several reasons to induce the valves to become invalid, cavitation, which causes noise, vibration and damage, is one of the most serious problems. Growing interests have been, therefore, focused on the research of cavitation around a valve.

Cavitation researches on the valve have been made by various authors, and are grouped by the following categories: (1) Technique to designate cavitation limits of the incipience, the critical stage and the choking\(^\text{9,10}\). Criteria for the limits contribute directly to cavitation-free or damage-free operations.

\(^*\) Received 9th March, 1999
\(^**\) Graduate School of Tohoku University, Sendai 980-8577, Japan. E-mail: ikohagi@ifs.tohoku.ac.jp
\(^***\) Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan
\(^****\) Sumiyoshi Factory, Kurimoto Ltd., Osaka 559-0021, Japan

JSME International Journal
the formation and the shedding of vortices in the flow immediately before the inception\(^{(16)}\). Kimura et al. measured the vibration around a butterfly valve, and then conducted a frequency analysis of vibration by FFT. They found that the characteristic band of vibration is near 6.3 kHz\(^{(15)}\). Oba et al. studied systematically the cavitation around a butterfly valve. They observed the vortex cavitation around a butterfly valve by mean of a high-speed video camera, measured the velocity of cavitating flow by using the digital-image processing technique, and also measured the impulsive pressure by the pressure-sensitive-film method\(^{(12)}\). However, there still remain various aspects to be studied for a wide variety of valve operations, especially at pressure levels higher than several MPa.

A hollow-jet valve is a kind of new developed type valves which can be used in high pressure flow systems. The cavitation also occurs around the valve, and induces serious damage, noise and vibration\(^{(19)}\). However, the mechanism of the cavitation around this kind of valve has not been known. In this paper, as a part of the researches on the cavitation around a hollow-jet valve\(^{(16)}\), the results of the cavitation damage around a hollow-jet valve are presented.

2. Experimental Setup and Procedures

The present experiment was conducted in an open-type cavitation tunnel in the Institute of Fluid Science, Tohoku University, which has been described elsewhere\(^{(20)}\). Figure 1 shows the test section of the hollow-jet model valve. The key part of the model valve is the needle numbered \(\mathbb{A}\) in the figure which is used to control the flow rate to pass through the valve. A cylinder seal numbered \(\mathbb{B}\) is used to support the needle. There are six splitters which support the cylinder axisymmetrically. The leading edge of the splitters is streamlined to reduce hydraulic loss. The axial stroke of the needle is controlled by a gear through a plunger.

Figure 2 is the schematic diagram of experimental facilities. To observe the cavitation aspects, the whole of the model valve is made of transparent acrylic resin. Two cameras were used to photograph the aspects from the direction B and C, respectively. Since the cavitation aspects change very rapidly with time, they were photographed using a xenon flash lamp with an exposure time of 1 µs. To visualize the flow and cavitation patterns in an axisymmetric section of the model valve, a laser light sheet (LLS) beam was employed. The optical system is also shown in Fig. 2. The cavitating flow patterns in LLS were also observed photographically using a high-speed camera.

A test specimen was installed in a splitter position and its shape was machined with the same shape as a splitter. The specimen is made of commercial aluminum with 99.5% purity, whose mechanical properties and chemical compositions are shown in Table 1. All specimen surfaces had been finally polished using \#1500 emery paper. After each test run, the specimen was washed in distilled water, then in acetone solution, dried in a drying oven and weighted by a digital balance with a sensitivity of 0.1 mg. Finally the damage surface was observed by SEM.

The cavitation number \(\sigma\) was defined as follows:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>98 MPa ~ 127 MPa</td>
</tr>
<tr>
<td>Yield Stress</td>
<td>74 MPa</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>6</td>
</tr>
<tr>
<td>Chemical Compositions (%)</td>
<td></td>
</tr>
<tr>
<td>Al 99.50min</td>
<td></td>
</tr>
<tr>
<td>Si 0.25max, Fe 0.40max</td>
<td></td>
</tr>
<tr>
<td>Cu 0.05max</td>
<td></td>
</tr>
<tr>
<td>Mg 0.05max, Zn 0.05max</td>
<td></td>
</tr>
<tr>
<td>Ti 0.03max, Others 0.03max</td>
<td></td>
</tr>
<tr>
<td>Heat Treatment Condition</td>
<td>Annealed Temperature</td>
</tr>
<tr>
<td></td>
<td>340~410 °C</td>
</tr>
</tbody>
</table>

Fig. 1 Test section

Fig. 2 Schematic diagram of experimental facility

Series B, Vol. 42, No. 4, 1999

JSME International Journal
\( \sigma = 2(P_2 - P_0)/\rho V^2 \), where \( P_2 \) is the downstream pressure of the model valve, \( P_0 \) is the saturated vapor pressure, \( V \) is the mean flow velocity at needle seal in valve section, and \( \rho \) is the density of water. In this paper, we use \( \beta \), the percentage of the valve stroke, to express the opening of the valve.

3. Results and Discussions

In the developing process of cavitation damage, chemical corrosion is an important factor in some cases. In this paper, therefore, the term "cavitation damage" is used to represent the result of a mixture of erosion and corrosion induced by cavitation.

3.1 Experimental results of damage

The damage test was conducted under 4 different cavitation states. For each damage test run, the test duration is 80 hours. It should be pointed out that all the cavitation states tested are in the so-called sub-cavitation stage judging from the analysis of the vibration induced by cavitation around the model valve\(^{230} \).

The cavitation damage data for different experiment conditions are plotted as mass loss versus time in Fig. 3. The mass loss rate curves obtained from the mass loss data are shown in Fig. 4. From the mass loss results, we can find that the effect of the valve opening is not so strong as the cavitation number is. The cavitation state, where the cavitation can leads to the large damage loss, is not small cavitation number state \( (\sigma = 0.56) \), but the middle cavitation number states \( (\sigma = 0.74 \text{, and } \sigma = 0.90) \). As shown in Fig. 4, it takes about 50 hours for the damage process in the small cavitation number state to reach the final steady damage phase\(^{231} \). However, in the middle cavitation number state, the time is only about 20 hours. Indeed, in the steady damage phase, the damage mass loss rate in the middle cavitation number state is about two times larger than that in small cavitation number state.

The damage appearances of the specimen surfaces which have been exposed for 80 hours in cavitation flows of different cavitation states are shown in Fig. 5. It can be found that cavitation damages have seriously occurred on the specimen surfaces. For the small cavitation number state \( (\sigma = 0.56) \), the relatively small damage pits mainly distribute in the downstream region of the surface. For the middle cavitation number states \( (\sigma = 0.90 \text{ and } \sigma = 0.74) \), there are two damage regions on the surface. One is in the downstream region which is similar to that in the

![Image of graphs showing mass loss versus time and mass loss rate versus time for different cavitation states and valve openings]
small cavitation number state. Another is in the central part of the surface with a more serious damage. There is no remarkable difference which can be found in the damage appearances at different openings. To explain the results mentioned above, we carefully observed the microscopic damage appearances by SEM and cavitation aspects by high-speed photographs.

3.2 SEM observation results

Figure 6 shows a series of SEM photographs which represent the general aspects of damage development process from a virgin surface to markedly eroded ones in a middle cavitation number state ($\sigma=0.90, \beta=66.7\%$). The SEM observed area is in the central part of the specimen surface. At different times, the same area was observed to verify the damage development process. It should be noted that many parallel fine tracks can be seen in these photographs, especially in the virgin one, which are polishing tracks formed by #1500 emery paper. The pits generated by the cavitation are randomly distributed on the observed surface, indicating that such very small roughness as tracks on the specimen surface seems to have no effects on the pit formation.

As can be seen from the photographs, serious damage has been observed on the surface exposed in the cavitating flow for 7.5 hours. With increase in testing time, the damage becomes more serious. There are two kinds of damage patterns found on the surface. The first kind consists of some craters with dimension of about 100 $\mu$m, one of which is labeled as A in the figure. Also we can find some of them having a fan-shaped wake, labeled as C in the photographs. A number of observations shows that the shape and the size of craters and wakes, do not change for most situation during the subsequent testing for sufficiently long time once they have been observed, and that no process for the crater formation can be found. It seems that the whole of a crater and its following wake is generated instantaneously. Then, the crater must be formed in a single blow event$^{(25)}$. The observations on different specimens also indicate that the craters are mainly occurred in the central part of a specimen surface in middle cavitation number states, which leads serious damage as illustrated in Fig. 5. The second kind appears as white pits with irregular shapes in the SEM photographs. One of the pits is labeled as B in the photographs. The pits can be observed for any different cavitation number states, especially in the small cavitation number state. The damage in the downstream region of a specimen surface illustrated in Fig. 5 is mainly composed by this kind of pits.

Figure 7(a) shows two high-magnification SEM photographs of the first kind of crater which is labeled as A in Fig. 6. Other two photographs of this kind of a crater with a fan-shaped wake are shown in Fig. 7(b), which was taken in other cavitation state ($\sigma=0.90, \beta=100\%$). The photographs show that both the crater and wake appear as the same plastic deformation. The craters have their rims which show material ductile displacement and material loss$^{(25)}$. Many of
Fig. 6 SEM photographs of damage development process ($\sigma=0.90$, $\beta=66.7\%$)

(a) Crater A in Fig. 6 ($\sigma=0.90$, $\beta=66.7\%$)  
(b) Crater with a fan shaped wake ($\sigma=0.90$, $\beta=100\%$)

Fig. 7 SEM photographs of the first kind of crater
the observations on this kind of craters evidently show that the direction of a wake is not related to the flow direction. Therefore, it seems that the wake is also formed by the same blow event as the formation of the crater.

Figure 8 shows two SEM photographs of the same area in a specimen surface at different time, where the second kind of pit is formed. In Fig. 6, this area is labeled as B. In this particular area as shown in Fig. 8(a), after 7.5 hours of testing, the surface becomes some small loosened slabs with irregular contours. This means that the area has been subjected to impulsive force induced by a cavity collapse. However, as the action is not so strong to form a pit, only the surface becomes loosened slabs. After 15 hours of testing, all of the loosened slabs have been peeled off, and a pit is formed as shown in Fig. 8(b). This kind of pit is different from the first kind of crater by the following characteristics: (1) The microstructure of the pit suggests that the rupture strength of the material has been locally exceeded, because the pit appears as brittle rupture and the pit outline seems to follow the material grain boundaries. (2) The pit has an entirely irregular contour. (3) The dimension of the pit is only about 50 μm, which is smaller than the first kind of crater. (4) The formation of this kind of pit needs much long time. Figure 9 shows a series of photographs which recorded a pit formation process of the second kind of damage patterns. At 50

Fig. 8 SEM photographs of pit B in Fig. 6

Fig. 9 Formation process of a second kind of damage pattern (σ=0.90, β=100%, tₜ=50 hours)
hours of testing, some corrosion products are observed on a specimen surface. After 1 hours of testing, that is 51 hours of testing shown in the figure, no remarkable difference can be found in the same area. After 2 hours of subsequent testing, only a part of the product has been peeled off resulting in some loosened slabs. After 5 hours of subsequent testing, the second kind of damage pattern is formed. It is clear that this kind of pattern is formed by the cumulative effects of many weaker blows (fatigue failure). It should be pointed out here that the material of the specimen is homogeneous. Figure 10 shows the X-ray diffraction results in the different areas of the specimen surface. The results indicate that the material in the different areas keep almost the same compositions as main Al and remains of very small amount of Si and Fe, suggesting that the difference between two kind of damage patterns is due to the behavior of cavity collapse. The observation of cavitation aspects should be able to help us to make it more clearly.

3.3 Observation of cavitation aspects

When cavitation occurs around the valve, the cavities first appear as individual spherical bubbles in the seal of the valve needle and then form a circumferential bubble ring structure behind the needle as shown in Fig. 11, where the instantaneous cavitation aspects were taken. The rings contain more and more bubbles with decrease in cavitation number. Both the experimental visualization and the numerical simulation of the flow field around the valve indicate that there is a series of shedding vortices formed in a separated shear layer behind the needle. Some of the bubbles are trapped by the vortices and form cavitating vortices. Figure 12 shows an appearance of cavitating vortices in a LLS-formed axial section of the model valve. In the cavitating flow behind the needle, there are two kinds of cavities. One is the individual travelling bubbles. Another is cavitating vortices. The damage of the specimen surface is induced by the collapses of these two kinds of cavities. The first kind of crater damage should be caused by a collapse of a cavitating vortex near the surface. And the formation of the second kind of pit is related to the impulsive pressure induced by the collapses of individual travelling bubbles or the cavitating vortices.

![Fig. 10 X-ray diffraction results of the specimen material](image)

![Fig. 11 Cavitation aspects around the needle (β=66.7%)](image)
Fig. 12  Appearances of cavitating vortices in a LLS section
\((\beta=33.3\%,  \ (a) \ \ \sigma=0.74, \ (b) \ \ \sigma=0.56)\)

Fig. 13  Cavitation aspects between splitters

relatively far from the specimen surface. Figure 13 shows the cavitation aspects in different cavitation states between the splitters. The aspects strongly depend on the cavitation number. For large cavitation number, most of the cavities appear as the cavitating vortex, while the number of individual travelling bubbles is relative small. In middle cavitation number states, more cavitating vortices and individual bubbles appear. As we have mentioned above, large mass loss is induced, and the number of the first kind of crater is also large. However, with decreasing the cavitation number, in small cavitation number state, there are so many cavitation bubbles generated behind the needle that the structure of the vortex is strongly affected. Most of the cavities, therefore, appear as individual bubbles as shown in Fig. 13. Then the damage should be mainly induced by the collapses of the individual travelling bubbles, resulting in the second kind of pit. Since the pit size is smaller, and their formation needs more time, the mass loss becomes smaller than that in middle cavitation number state.

4. Conclusions

Cavitation damage phenomena are studied around a hollow-jet valve, and the conclusions are summarized as follows:

(1) The damage occurred in the cavitating flow around a hollow-jet valve has two patterns. One is accompanied by a big plastic crater with a fan-shaped wake in the middle cavitation state, which seems to be formed by one blow event of a cavitating vortex collapse near the specimen surface. Another pattern is caused as a irregular brittle pit by cumulative effects of many weaker blows.

(2) Comparing the two kinds of damage, the first kind of crater is more erosive because it has large size and can be formed instantaneously.

(3) In the middle cavitation number states, there exist more cavitating vortices in the flow than other states. It can be said that these states are the most dangerous for the cavitation damage around a hollow-jet valve.

References


(3) Tullis, J.P. and Marschner, B.W., Review of


