Fundamental Studies of Cavitation Erosion*
(In the Case of Low Cavitation Intensity)

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Previously, the authors reported on the severe erosion where the pit was made by a single blow of cavitation pressure. The present paper deals with the erosion of mild steel under cavitation of comparatively low intensity. Under the test conditions, the incubation period is found in early stage of damage progress, where slips and plastic deformations occur in ferritic crystals but not in pearlitic crystals. From these, the blow intensity of the cavitation is known to be tens of thousands of atm. Cracks are made by the accumulation of plastic deformations and they propagate to a falling off of large particles. Neither residual stresses nor cold worked layers are found in the damaged portions under this progressing stage. This may be one of the characters of erosion under low cavitation intensities.

1. Introduction

The mechanism of cavitation erosion is not yet fully understood because of the difficulty to observe accurately the phenomena since cavitation bubbles are very small and their behaviors are very fast. The phenomena are further complicated under the combined effects of mechanical stresses and chemical attacks.

Previously, the authors(1) have reported on the mechanism of erosion under severe cavitation by observing the formation of pits on test surface in the early stage and the progress of erosion damage in the stationary stage. Impact pressures produced by collapses of cavitation bubbles are calculated to be as high as tens or hundreds of thousands of atm.(2)(3). Such an intense blow produces a high rate stress whose distribution is similar to the Hertzian stress. Because of its extremely high rate, a conical pit of 90° apex is made on the surface of steel, whilst a depression is made on the surface of aluminium which is insensitive to the strain rate.

The impact made by cavitation has some distributions in intensity and the resulting damage of materials depends on their mechanical properties. In the previous paper(1), the relation between the rate of pit formation and the hardness of materials is discussed by using the cumulative frequency curve (a) in Fig. 1. In the case of high cavitation intensity, the blows higher than \( W_p \) which depends on the hardness or fracture energy of the materials are the causes of pits. Since the blow \( W_f \) for fatigue failure is lower than \( W_p \), the fatigue failures take place in the surface after a given time and big particles caused by fatigue cracks fall off, the erosion damages progressing rapidly. Consequently, no incubation period appears in early stage of run.

However, under low intensity of cavitation whose cumulative frequency curve is shown as curve (b) in Fig. 1, all the blows are lower than \( W_p \), and the fatigue failure with no pit formation may be generated on the surface. In this case, the incubation period is considered to present in

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Fig. 1 Cumulative frequency curve of blow impact under high cavitation intensity (a) and low cavitation intensity (b)

\( W_p \): impact for pit formation by a single blow
\( W_f \): impact for fatigue failure by repeated blows
early stage though some corrosion effects may exist. Even if no corrosion attack exists, the mechanism of fatigue failure under cavitation has been hardly known, and various discussions have been made on the correlation between the mechanical properties and erosion resistance of materials.

From the reasons above mentioned, the present paper deals with the mechanism of cavitation erosion under low cavitation intensity and in the environment of weak corrosion attack. Tests are carried out by vibrating a disc oscillator close to the test pieces in deionized water. The effects of corrosion attack will be studied in near future.

2. Test procedures

The testing apparatus is shown in Fig. 2 whose details are described elsewhere. An oscillating disc of 20mm in diameter and 6mm in thickness which is made of 18-8 stainless steel is screwed in the free end of a magnetostrictive horn. The surface of the disc is finished by emery paper No. 120. The test pieces shown in Fig. 3 are fixed at a small parallel distance from the disc surface. The distance $h$ is measured by using a dial gage which shows the height of the horn over the test piece. The contact of both surfaces is found with the electric resistance.

Test pieces are made of a mild steel whose chemical compositions are shown in Table 1. Test pieces machined after annealing 1 hr in 890°C are polished with diamond paste, and again annealed 1 hr in vacuum of 650°C.

The disc is vibrated at a frequency of 22.1 kc/sec, with an amplitude (half value) of 20 μm, and at a depth of 10mm. The deionized water is used as a testing liquid to prevent corrosion attack. The water is circulated through a cooling bath and its temperature is kept at 26 ± 1°C.

The surface of the test piece is subjected to erosion damage due to cavitation which is generated by the opposite surface of the vibrating disc. So the damage is affected by the distance between two surfaces. Under the extremely small distance the damage is due to the surface shearing fatigue by squeezed film, but in general the damage is cavitation erosion and its intensity can be controlled by the distance in wide range.

3. Test results and considerations

The temperature distributions of the liquid film between the testing surface and the vibrating surface are shown in Fig. 4. The damage on testing surface is limited to within the circle

<p>| Table 1 Chemical compositions of mild steel |</p>
<table>
<thead>
<tr>
<th>C%</th>
<th>Si%</th>
<th>Mn%</th>
<th>P%</th>
<th>S%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.29</td>
<td>0.56</td>
<td>0.015</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Fig. 2 Schematic view of testing apparatus

![Fig. 2 Schematic view of testing apparatus](image)

![Fig. 3 Shape of test piece](image)

![Fig. 4 Temperature distribution of water film at various film thicknesses h](image)
whose radius is nearly equal to the radius of the vibrating disc, i.e. 10mm. So the temperature distribution of the liquid film is found nearly constant except in periphery portion of damaged area.

3.1 Damage in early stage

Weight loss of the test piece is shown in Fig. 5 with progress of the test. The rate of damage is maximum when the distance \( h \) is 0.5mm. It decreases with a smaller \( h \) where bubbles between the two surfaces become hard to disperse and play a role of cushion, and decreases again with a larger \( h \) where impacts by bubbles produced on the vibrating surface decrease to arrive at the test surface \( h \). Hereafter, the distance \( h \) is kept at 1mm in general to obtain the low intensity cavitation for the purpose of the present study. Figure 6 is a magnified figure of the early stage in Fig. 5. The sensibility of the balance is 0.01 mg. In the figure, dotted lines show the variation of surface roughness \( h_{CLA} \) which is the average value of five points near the center of damaged area. A slight weight loss occurs for several minutes after the beginning of tests, and then the weight loss ceases to increase. The slight weight loss may be due to a falling off of local weak points of the test surface which will be referred to later. The damage progresses markedly after a given period which is the so-called incubation period. As mentioned in the introduction, the impact pressure produced by cavitation bubbles has some distributions in intensity, and the impacts more intense than a given value \( W_p \) make pits on the material surfaces. In this case, the weight loss, though it may be slight, should be observed progressively. Consequently, the most intense impact in the present cavitational tests is known to be lower than \( W_p \).

The surface roughness increases linearly from...
the beginning of the test and shows no incubation period, unlike the weight loss. The increase of surface roughness with no increase of weight loss shows that the test surface is subjected to severe deformation during the run, after which the erosion appears with a progressive weight loss.

Figure 7 shows optical microscopic photographs of the test surface under the early stage damage which is etched with 4% Nital. In the figure, (a) shows a fresh surface before the test. The surface is mirror-like smooth, slant fine lines are buff finish scratches. In (b), which shows the surface after 30min run, unevennesses and wrinkles are clearly found in ferritic crystals. They increase in degree with duration of tests, especially on crystal boundaries, as is seen in Fig. 7 (c). The unevennesses and wrinkles confirm plastic deformation on the surface layer of the test piece.

Since the surface of test piece finished by buffing has some worked layers, tests are carried out with the test pieces polished electrolytically. The optical microscopic photographs are shown in Fig. 8. In Fig. 8 (a) which shows a fresh surface, white portions are ferritic crystals and black portions are pearlitic crystals. On the surface after 30min test, as is shown in (b), slip lines and unevennesses are observed in ferritic crystals. The direction of slip lines is characteristic of crystal grains. Sometimes, slip lines are found in two or three directions in a unit grain as is shown in Fig. 8 (c). This is because the area under impacts by cavitation blow is small, the resulting maximum shearing stresses are in various directions in the same crystals, and the slip lines are made on slip planes which most coincide with the plane of the maximum shearing stresses. Slip lines and twin deformations have been observed on

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Fig. 8 Slip lines on ferritic crystals in early stage of damage (on electrolytically polished surface)

Fig. 9 Damaged surface of pearlitic crystals in early stage (scanning electron micro-photographs)
a single crystal of cobalt under impingement attack. This may be for the same reason as mentioned above. In the present tests, twin deformations are not found in consequence with different crystal lattices.

The pearlitic crystals show no appearance of plastic deformation or unevenness in Fig. 8. However, the lamellar structure becomes a little more clear by cavitation. Figure 9 shows the photographs by a scanning electron microscope. The pearlitic crystals after 30 min tests in Fig. 9 (b) show lamellar structure more clearly than those of the fresh surface in Fig. 9 (a). The cementite layers are embossed, the ferrite layers in the pearlite being lost away. Micro cracks are also found at the boundaries of ferritic and pearlitic grains as is shown by arrow mark in Fig. 9 (b).

The reason why those damages appear in ferrite layer within the pearlite lamellar structure at the early stage where only plastic deformations are produced but not falling off in ferritic crystals is considered to be either local cell action or restraint of deformation. And this may be one of the main causes of slight weight loss in the beginning of tests shown in Fig. 6.

The hardness of ferritic grains is measured under indentation load of 5g for 30 sec, by using Haneman Micro Hardness Tester. The crystal structures are distinguished by etching the normal section of the test piece polished carefully with diamond paste. The hardness distribution in ferritic structures at the early stage of the damage is shown in Fig. 10. The depth of the worked layer is known to be about 20 μm. The hardness of pearlitic grains is also measured under 100g, 30 sec. The mean value of 20 measuring points is 240 for the fresh surface, and is 236.5 for the surface after 30 min testing. Variation by the testing is hardly observed. This is because pearlitic grains are not subjected to plastic deformation as mentioned before and the embossed cementite lamellar supports about all the indenting load.

3.2 Estimation of impact pressure due to cavitation

Impact pressures due to cavitation bubbles are difficult to measure, and are calculated in some cases with the analysis of fluid dynamics. The present paper deals with the possibility to presume the pressures by means of materials behaviors.

As mentioned in the previous section, the plastic deformation which is predominant in the damage of early stage is due to the metal flow by local high pressure. The local pressure is considered to make stresses similar to the Hertzian stress on materials surfaces, though the pressure is explained to be due to the shock wave by bubble collapse, or to stream jet by collapse of semispherical bubbles adhering to the materials surfaces, and or to the shock wave by volumetric vibration of bubbles. Consequently, the pressure to make such a plastic deformation is concluded to be the flow pressure, that is the hardness of materials.

The ferritic grain of the fresh surface has Vicker's hardness $H_v=120$, the flow pressure being 120 kg/mm², as is shown in Fig. 10. The surface of ferritic grain is known to flow under the pressure of about 12000 atm according to the theory of metal contact. Similarly, the surface of pearlitic grain flows under pressure of 24000 atm. Since the plastic deformation in the early stage is found only in ferritic crystals but not in pearlitic crystals, the cavitation pressure may be in the range from 12000 atm to 24000 atm, when converted to the static flow pressure of the materials. The actual pressure is considered a little higher than the values, because the deformation of mild steel is reduced by its high rate. Taking into consideration the velocity dependence, however, the pressure may be tens of thousands of atm, being nearly equal to the values calculated by Plesset and Hammitt, and to the value of 14000 atm measured by Sutton in his photo-elastic experiments. It should be noted that the pressure above mentioned is made under the condition of low cavitation intensity and, as a matter of course, the pressures lower than the value are made by a number of bubbles because of their distributions.

3.3 Damage in stationary stage

Figure 11 illustrates the variation of roughness of damaged surfaces from early stage to stationary atage recorded by Talymsurf. In the figure, the magnifying force is varied and the horizontal
line shown in its left portion gives the level of the surface undamaged. In early stage of the damage (a), the plastic deformation makes a piling up and sinking in, both of which are nearly equal in volume. With the progress of tests, (b), the surface roughness increases in the same manner as (a). After a given test duration, (c) (d), the peak of the damaged surface becomes lower than the undamaged surface, and the damage is known due to falling off of metal particles. The test duration of (c) corresponds to that after which the rate of weight loss becomes high as shown in Fig. 5.

The residual surface stresses measured by X ray diffraction vary with the test duration as shown in Fig. 12. Tests of a few minutes give very high compressive residual stresses which remain constant during the incubation period. However, the residual stress decreases rapidly after the incubation period, and settles down to a low value in the stationary stage. The high compressive stress in the early stage results from the plastic deformation of the surface layer due to the cavitation pressures. Micro cracks produced by the repetition of the plastic deformation release the residual stresses. And then, the falling off of particles removes the worked surface layer, and makes the residual stresses very low. The effects of surface roughness in the present experiments on the magnitude of residual stresses measured by X ray diffraction were ignored as a result of inquiry.

The surfaces in stationary stage of damage are observed with a scanning electron microscope.

![Fig. 11 Damage of surface profile](image1)

![Fig. 12 Variation of residual stresses in damaged surfaces](image2)

![Fig. 13 Scanning electron micro-photographs of damaged surfaces in progressing stage of damage](image3)
Figure 13 (a) shows the test surface after 1 hr, that is, in the later part of incubation period in Fig. 6. Most micro cracks are observed at the boundary of ferrite and pearlite. (b) shows the surface after 2 hr. Only ferritic grains fall off, pearlitic grains remaining on the surface. But the pearlitic grain is constructed of layers of cementite crystal, ferritic layers being absent. (c) shows the surface in stationary stage of damage, \( t = 5 \text{ hr} \). Pearlitic grains are falling off too, and are not distinguished from ferritic grains. Though the appearance of the surface is very complex, remarkable cracks are observed.

Figure 14 is a photograph of a section of the test piece under stationary stage of damage. Surface profile is very complex and many fine cracks are found together with transcristalline macro cracks. The cracks propagate through crystal grains, meet with the others, and make particles fall off. Particles have a very complex shape like the surface profile and are sometimes as large as 100 \( \mu \text{m} \). In this stage where the crack propagation is predominant for the erosion damage, the impact pressure by cavitation bubbles is mostly spent in the crack propagation. This may be understood from the hardness distribution of ferritic crystals in the section of a test piece under stationary stage where no work hardening is found as is shown in Fig. 15 which is obtained with the same method as Fig. 10, and from the low residual stresses of damaged surface layer shown in Fig. 12.

The reason why no work hardening and low residual stresses are found after the removal of the work hardened layer made in the early stage is considered that the damage in the stationary stage is due to the propagation of cracks without slips because of the high strain rate under cavitation. This may be affirmed by the following

Fig. 14 Section of surface layer in stationary stage

![Fig. 14](image)

Fig. 15 Distribution of hardness of ferritic grains in normal section in stage of crack propagation

![Fig. 15](image)

Fig. 16 Surface profile in progressing stage of damage

![Fig. 16](image)

Fig. 17 Variations of surface roughness

![Fig. 17](image)
facts. In low carbon steel and commercially pure iron under supersonic fatigue testing, formation of slip bands and crack initiation from them which are familiar in usual fatigue tests hardly take place, and fatigue cracks initiate and grow at the boundary between ferrite and pearlite without any slip bands. Moreover, the hardness of pure iron fractured by supersonic fatigue tests is nearly equal to that before testing, work hardening being hardly found. Some slip bands are found close to cracks only under a considerably high stress. Consequently, it may be reasonable to be consider that the surface layer is work hardened under more severe cavitation than the present test conditions.

The stationary stage of damage represents the period of constant rate of weight loss as shown in Fig. 5, but in this period a constant surface roughness is not yet attained. Surface profiles of test pieces under the stage are shown in Fig. 16, where the roughness is increasing with test duration and a few pits of very big size are found after long time. The maximum roughness increases linearly with test duration in the range of the present test and its scatter is also widening as is shown in Fig. 17.

This severe local erosion is remarkable under cavitation in a thick liquid film such as $h = 1.0 \text{mm}$ as is shown by broken lines in Fig. 17 though the dependence of the increasing rate of surface roughness on film thickness $h$ corresponds to that of weight loss on $h$ shown in Fig. 5. When a very thin film becomes a thick one, the surface roughness becomes larger due to the increased facility of bubble growth and to the increased intensity of impact pressure. The damaged surface was observed to be more rough with water-drop of larger diameter in the impingement tests. For a still greater thickness of liquid film, however, surface roughness together with weight loss decreases because of decrease of impact pressure arriving at the test surface, while local pits become large in their size because of increase of crack growth before breaking in accordance with the decrease of particles falling off.

It may not always be adequate to evaluate the erosion resistance merely from weight loss or mean depth of damaged surface since a few large local pits grow under low cavitation intensity as mentioned above.

4. Conclusions

The erosion damage was studied under cavitation intensity as high as to make a pit by a single blow in the previous paper, while it is studied under low cavitation intensity in the present paper. Tests are carried out by vibrating a disc oscillator close to the test piece of a mild steel in deionized water. The cavitation intensity is controlled by the distance between the two surfaces. Results obtained under low cavitation intensity are as follows.

1. In early stage of tests, no weight loss is observed. In this incubation period ferritic crystals are subjected to plastic deformation with slip bands.

2. The plastic deformation is not found in pearlitic crystals, but the ferrite layer in pearlite lamellar is lost away.

3. Ferritic crystals are work hardened by plastic deformation, but not pearlitic crystals. From this, impact pressures are estimated to be as high as tens of thousands of atm under cavitation intensity of the present tests.

4. Propagation of micro cracks produced by the repetition of the plastic deformation results in a falling off of pearlite as well as ferrite, removing the work hardened layer made in the early stage.

5. Hereafter, the damage is due to a crack propagation and neither residual stress nor work hardened layer is observed near the damaged surface. A few local pits are made larger in size by low intensity cavitation rather than by high intensity cavitation.

The present paper deals with the damage due to mechanical stresses, the chemical attack being removed as much as possible. The effects of corrosion will be reported in near future. Thanks are due to Japan Electron Optics Laboratory Co. for the scanning electron micro photographs in the paper.

References

Discussion

J. Hoshiba (The Japanese Marine Corporation): 
(1) Concerning Fig. 13, I request your opinion. In the stage of progressing damage, roughening and weight loss are considered to increase at the same time because of selective corrosion at the depressions of surface profile. If the peaks of surface profile are eroded just as under electrolytic polishing, the surface should become smooth. How do you think about the mechanism to explain the erosion damage being concentrated at the depressions of roughened surfaces?

(2) Several seepages of etching reagent are found at the boundaries of ferritic crystals in Fig. 14. May we consider these are due to intercrystalline cracks? Dark portion at the tip of macro crack is found in the right side of Fig. 14. Is this due to the seeping of etching reagent or to corrosion during the tests?

Authors' closure

(1) In the present study, erosion in the stationary stage of damage is not due to selective corrosion at the depression of roughened surface because of the very poor corrosion attack, but due to crack propagation from the depression root resulting in a falling off of large particles as is mentioned in the paper. A model[*1] is proposed to explain the high stress given at the depression root by cavitation impacts, but this does not fully explain the propagation of fatigue cracks. Depressions of roughened surfaces are likely to generate bubble nuclei and enclose shock waves from the bubbles. These are considered the causes of acceleration of initiation and propagation of cracks together with the stress concentration due to depressions and cracks. A similar model is proposed for water drop impingement[*2].

(2) Seeping traces at the boundaries of ferritic crystals and other portions found in Fig. 14 are due to the fault of etching technique, and are not intercrystalline cracks beneath the test surface. Cracks are usually transcryalline. Dark portion in the right side of the figure is pearlitic crystal whose lamellar structure is confirmed by magnified observations.