Developing Stages of Ultrasonically Produced Cavitation Erosion and Corresponding Surface Roughness*

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Vibratory-erosion tests on a typical erosion-resistant material made of 304 stainless steel were carried out. We carefully observed the erosion patterns and the surface roughness aspects with respect to test time, under a specified condition of uniform nuclei-size distribution, by a scanning electron microscope and a profilometer. The eroded surface is classified into three stages from surface topography and roughness profile. In the first stage, the surface is plastically deformed and its roughness rapidly increases. In the second stage, the surface becomes more hardened, so that cracks initiate and propagate; after that, local removal of material occurs. In addition, the roughness doubles and then increases slightly. In the third stage, almost all the virgin surface is removed and the roughness doubles again. It is found that skewness has, respectively, a positive and a negative value before and after the material removal, while the kurtosis is always positive.

Key Words: Cavitation, Erosion, Bubble, Ultrasonic Cavitation, Cavitation Nuclei, Surface Roughness, Stainless Steel

1. Introduction

With the rapid growth in use of hydraulic machinery in the field, the possibility of fatal cavitation erosion increases. A burgeoning interest has, therefore, been shown in finding feasible and practical methods to predict probable erosion rates in machinery.

As is well known, there are several types of cavitation with their own aspects and behavior as well as occurrence zones. Most of them are nonerosive, but some are erosive⁽¹⁾⁽²⁾. Thus, contrary to the expectations of machine designers, destructive erosion often results in hydraulic machinery in the field, especially when the cavitation nuclei⁽³⁾⁻⁽⁵⁾ are quite different from the expected ones. At the present stage, therefore, it is quite necessary to predict precisely the stages of erosion⁽⁶⁾⁽⁷⁾ such as the incubation, accelera-

tion, deceleration and steady stages in the field. For such precise predictions, detailed information on eroded surfaces is essential. However, no useful literature detailing such erosion investigations, in which the cavitation nuclei and their dominant factors are clearly shown is known to us.

In the present paper, as the first step of such studies, the authors made vibratory-erosion tests on a typical erosion-resistant material made of 304 stainless steel conforming to ASTM Standards⁽⁸⁾. We carefully observed the erosion patterns and the surface roughness aspects, under a specified condition of uniform cavitation-nuclei-size distribution⁽⁹⁾, by a scanning electron microscope and a profilometer. It is shown that the change in roughness corresponds well to the change in the eroded surface, i.e., the stage of the erosion.

2. Definition of Surface Roughness

Let us first define the roughness of the eroded surface for the convenience of the following discussion. Let y be the distance along the mean line of the roughness profile, $f(y)$ the height departure of the profile measured from the mean line, L the length of

* Received 11th May, 1989. Paper No. 88-0574A

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the profile, $f_{\max}$ and $f_{\min}$ the maximum and the minimum values of $f(y)$ within the distance L , respectively, and $P\{f(y)\}$ the amplitude distribution of $f(y)$. Then the average roughness R_a , the root mean square roughness R_{rms} , the maximum peak-to-valley height roughness R_{max} , the skewness S_k and the kurtosis K_u are defined by

$$R_a = \frac{1}{L} \int_0^L |f(y)| dy, \quad R_{\text{rms}} = \frac{1}{L} \left\{ \int_0^L f^2(y) dy \right\}^{1/2},$$

$$R_{\text{max}} = f_{\max} - f_{\min},$$

$$S_k = \frac{1}{R_{\text{rms}}^3} \int_0^L f^3(y) P\{f(y)\} df(y),$$

$$K_u = \frac{1}{R_{\text{rms}}^4} \int_0^L f^4(y) P\{f(y)\} df(y),$$

and their digitalized expressions are

$$R_a = \frac{1}{N} \sum_{i=1}^N |f(y_i)|, \quad R_{\text{rms}} = \frac{1}{N} \left\{ \sum_{i=1}^N f^2(y_i) \right\}^{1/2},$$

$$S_k = \frac{1}{NR_{\text{rms}}^3} \sum_{i=1}^N f^3(y_i), \quad K_u = \frac{1}{NR_{\text{rms}}^4} \sum_{i=1}^N f^4(y_i).$$

The third and the fourth moments of the amplitude distribution $P\{f(y)\}$, S_k and K_u , provide⁽¹⁰⁾ information regarding the shape of the profile, as shown in Fig. 1.

3. Experimental Facilities and Procedures

In order to keep the cavitation nuclei of test water as uniform as possible throughout the present experiments, sufficiently clean test water was allowed to settle for 24 hours in a large clean plastic tank, so that air bubbles in the water could be released. As described previously⁽⁹⁾, the nuclei-size distribution scarcely changes with time t . Figure 2 illustrates the typical nuclei distributions. The present erosion experiments were carried out in a vibratory apparatus as shown in Fig. 3, conforming precisely to ASTM standards; oscillation frequency of the test specimen $f = 19.5$ kHz, peak-to-peak displacement amplitude $a = 50 \mu\text{m}$, and output of the ultrasonic transducer was 1200 W. The flat-disc test specimens made of 304

stainless steel are 15.9 mm in diameter, and 11 mm high, also conforming to ASTM standards. Further details of the apparatus, the test specimens and the test procedures are described elsewhere⁽⁹⁾.

In order to eliminate unfavorable roughness effects on the erosion, which have not yet been solved sufficiently, the test surfaces of all the specimens were very smoothly polished by 3 000 emery paper. Very low initial surface roughness of $0.025 \mu\text{m}$ or less was detected on the surfaces by a profilometer, so that R_{max} was $0.025 \mu\text{m}$. The height departure $f(y)$ was measured from the roughness profile drawn by the profilometer with a very sharply pointed needle $2.5 \mu\text{m}$ in radius, whose magnification ranged from 100 to 100 000, and the several kinds of roughness mentioned

Fig. 2 Changes in nuclei-size distributions with respect to test time t

Fig. 1 Surface profiles with their associated height distribution characteristics

Fig. 3 Schematic of vibratory test apparatus

above were digitally calculated. To insure sampling from the same population, all the test specimens were cut from a single large block of 304 stainless steel of sufficiently uniform composition. Table 1 shows the composition and the mechanical properties at room temperature. Mass loss caused by erosion, Δm , was precisely measured by a digital balance with a sensitivity of 0.01 mg. Local material destructions and their development were carefully observed by a scanning electron microscope.

Since the cavitation aspects change very rapidly with time, they were photographed using a xenon flash lamp with a very short exposure time of 1 μ s. The cavitation nuclei and the air content rate α/α_s in the test water were measured by means of a Coulter counter⁽¹¹⁾ and a kind of van Slyke apparatus⁽¹²⁾, where α is the total air content and α_s is the saturated air content at the same water temperature T_w .

4. Results

Most existing vibratory-erosion tests rarely show such instantaneous photographs of cavitation aspects around the test surface which are considered to affect the erosion greatly. After all, none of the previous reports clarified how uniformly the cavitation developed throughout the experiments or what types of cavitation arose. In view of this, it is perhaps understandable that several contradictions exist between the results obtained by different investigators. In the following experiments, we investigate vibratory erosion under the specified condition that the cavitation nuclei, the most powerful factor of cavitation, scarcely changes throughout the experiments.

4.1 General aspects of eroded surface

For the basic data of the present experiments, the roughness profile of the eroded surface was first inspected for various test times, $t=0, 4, 20, 30, 60, 90$, and 120 minutes, where time is measured from the beginning of the vibrations. The results are shown in Fig. 4. The mean line y lies horizontally. In the cases of $t > 90$ min where the roughness rapidly increases

with time in the accelerated stage of erosion, the ordinate $f(y)$ is reduced by 2/5. For comparison, scanning electron micrographs (SEM) of the eroded surfaces were systematically taken. Typical micrographs are shown in Fig. 5. In Fig. 5(a), numerous diagonally parallel fine tracks are seen. These are not erosion tracks but polishing tracks formed by 3 000 emery paper sliding on the test surface and are 0.025 μ m in maximum height.

Clearly, from Figs. 4 and 5, observation of the eroded surfaces are quite different for the following three stages: stage I for $t < \text{about } 20$ min; stage II for about 30 min $< t < \text{about } 50$ min; stage III for about 60 min $< t$. In stage I, as seen in Fig. 5(a), a number of circular erosion pits, which probably resulted from microjets accompanying very high local pressure pulses of 1 500 MPa or more, are distributed randomly on the surface and are in the order of μ m in diameter⁽¹³⁾. More specifically, these pits were somewhat concentrated along the material grain boundaries where the destructive crack lines develop in stage III, as discussed later, so that the strength of the material may be very low there. Along the grain boundaries, we can observe a number of wavy tracks which probably resulted from the accumulation of a huge number of local plastic deformations caused by medium pressure pulses. The lengths of the deformations and the distances between them are almost the same size as

Fig. 4 Eroded surface profiles

Table 1 Mechanical properties and composition of the 304 stainless steel tested

Density	8027 kg/m ³
Yield stress	517 MPa
Tensile strength	758 MPa
Elastic modulus	193 × 10 ³ MPa
Hardness, Bhn	240
Elongation percent	60
Nominal chemical composition %	C 0.08 max, Mn 2 max Si 1 max, P 0.045 max S 0.03 max, Cr 18–20 Ni 8–12

Fig. 5 Scanning electron micrographs of the eroded surface with test times of (a) 20 min, (b) 30 min, (c) 50 min, (d) 90 min

those of the average grain size of SUS 304 stainless steel (several tens of μm). Thus, profiles of the roughness consist of two components: the plastically formed component several μm in wavelength, and the pit component several μm in wavelength. The height of the roughness remains fairly low, within $1\sim 4\ \mu\text{m}$.

In stage II (see Fig. 5(b)), in addition to the further growth of pits and plastic deformation mentioned above, we can clearly see a number of crack lines developing along the wavy tracks and very local material removal from the weaker parts along the tracks. In the central part of Fig. 5 (b), we can see the typical picture of such removal, where the material is just beginning to be removed in triangular flakes. In the following, we will call such a local crack a "triangular crack". It is, at most, $10\ \mu\text{m}$ in length, so that the mass loss of the test specimen must be negligible. Since a number of pits fall on the crack line, and sharp-edged cracks begin to propagate from some of pits, the pits may play an important role in crack development. Thus, the roughness profiles are superposed by a component of medium wavelength corresponding to the triangular cracks, and the profile height becomes at least double that in stage I.

Close observation of Fig. 5(c), however, shows that some crack lines clearly propagate along the polishing tracks. This suggests that even a small

roughness of $0.025\ \mu\text{m}$ or less can affect erosion. In future studies on erosion, therefore, we should carefully consider the effects of such initial surface roughness.

In stage III, shown in Fig. 5(d), several portions of the surface, thin layers of several tens of grains, are rapidly removed from the original surface, and results in a remarkable increase in mass loss Δm , and erosion enters the accelerated stage. As time passes, the original surface is completely removed, and the tracks extend into the layer below the original surface. Thus, the roughness profiles are added to by a characteristic long-wave component corresponding to the mass removal, and the height is again doubled at $t=90\ \text{min}$, resulting in a very roughened surface.

4.2 Roughness aspects and the stages of erosion

Hydraulic engineers often have to judge when currently slowly developing erosion changes to rapidly developing erosion, resulting in dangerous destruction of hydraulic machinery. For such judgments, it is absolutely necessary to know how to correlate the erosion stages to a highly erosion-dependent phenomenon which must be very easily detectable or observable in the field. In the following, we try to correlate erosion stages to surface roughness easily observable in the field.

Figure 6 compares the results of the average

roughness R_a , the root mean square roughness R_{rms} , the maximum roughness R_{max} and the mean depth of penetration MDP for various test times t . MDP is defined⁽¹³⁾ as V/A , where V is the volume loss from the specimen and A is the area of eroded surface. I, II, III refer to the above-mentioned stages I, II, and III, respectively. In the present experiments, since we have no data points in the transient regions of I→II and II→III, we roughly connect them by dotted lines. It should be noted here that the most technically important accelerated stage begins at the end of stage II. The end of the incubation stage is customarily defined as the intersection between the extension of the erosion curve in the accelerated stage and the abscissa, thus it is at $t=60$ min. In consequence, stages I and II must be included in the incubation stage.

In order to specify the roughness more precisely, in Fig. 7, the relationships among R_a , R_{rms} , R_{max} and t are plotted on a log-log chart. Clearly, R_a , R_{rms} and R_{max} all increase monotonously with t in stage I. They rapidly increase and double in the transient region I-II, and remain almost constant within stage II, approaching the end of the incubation stage. Vyas and Preece⁽¹⁴⁾ also reported two such stages within the incubation stage. With a further increase in

t , R_a , R_{rms} , R_{max} and MDP or the mass loss rapidly increase again in the transient region II-III and change very slowly in stage III. Thus, it is clear that the change in the roughness corresponds well to the change in the eroded surface, that is, the stage of erosion. The present results can be applied to indicate the erosion stage of hydraulic machinery blades, especially at the beginning of the accelerated stage.

For precise judgment of the erosion stage in practice, R_a and R_{rms} are more suitable than R_{max} , while R_{max} is a more sensitive indicator for describing the change of erosion, especially in the accelerated stage where erosion becomes significant.

4.3 Skewness S_k and kurtosis K_u

To further clarify the shape of the roughness profile, the skewness S_k and the kurtosis K_u are digitally calculated for various test times t and are presented in Table 2. During stages I and II, i.e., the incubation stage, the profile has a positive skewness value and is thus said to be dominated by peaky protuberances. In other words, the wavy tracks which are formed plastically and the triangular cracks are more dominant than the pits which are formed very concentrically, so that the former must have a typically negative influence on S_k . Conversely, as shown in Fig. 4, during stage III, i.e., in the acceleration stage, S_k is a negative, clearly showing that the valleys, the traces of mass removal, predominantly arise there. In short, the skewness S_k is consistent with the mass removal which is the most important mechanism of erosion.

The kurtosis K_u is always positive throughout the present experiments on 304 stainless steel and is almost limited to within a range from 2.8 to 3.0. The

Fig. 6 Change of mass loss MDP, average R_a , RMS roughness R_{rms} , and maximum roughness R_{max} with test time t

Fig. 7 Average, RMS and maximum roughness with test time t

Table 2 Skewness S_k & kurtosis K_u

t min	4	8	12	20	30	40	50	60	90	120
S_k	0.2	1.7	0.8	1.5	0.3	0	-0.2	-1.6	-1.7	-1.7
K_u	2.8	3.4	3.1	3.6	2.0	2.7	2.5	2.7	2.5	3.0

profile must be moderate in sharpness.

5. Conclusions

Vibratory-erosion tests were carried out on a typical erosion-resistant material made of 304 stainless steel. The erosion patterns and the surface roughness aspects were carefully observed with respect to test time t , under a specified condition of uniform cavitation nuclei, by a scanning electron microscope (SEM) and a profilometer. The obtained results are summarized as follows:

(1) Clearly, from Figs. 4 and 5, observations of the eroded surfaces are quite different for the three stages I, II and III. In stage I, for the case of $t < 20$ min, a number of circular erosion pits are randomly distributed on the surface and wavy tracks are also observed, which probably result from the accumulation of a huge number of local plastic deformations. In stage II, for the case of about $30 \text{ min} < t < 50$ min, a number of crack lines were initiated and developed along the wavy tracks as shown in Fig. 5(b); there was also very local material removal from the weaker portions along the tracks. In stage III, when $t = 60$ min or more, several parts of the surface, thin layer of several ten of grains, had begun to be rapidly removed from the original surface.

(2) R_a , R_{rms} and R_{max} can be classified into three stages I, II and III which correspond to the observable stages of erosion patterns.

(3) R_a , R_{rms} , R_{max} increase monotonically with t in stage I. They rapidly increase and double in the transient region I-II, and remain almost constant within stage II as the end of the incubation stage is approached. With further increase in t , R_a , R_{rms} , R_{max} and MDP increase again in the transient region II-III, which corresponds to the acceleration stage, and very slowly increase in stage III.

(4) During stages I and II, i.e., the incubation stage, the profile has a positive skewness value, so that the profile is said to be dominated by peaky protuberances. During stage III, the profile has a negative skewness value which is consistent with the mass removal.

(5) The kurtosis is always positive and within a

range from 2.8 to 3, so that the profile is moderate in sharpness.

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