SEM Studies of Particles Produced by Cavitation Erosion*

Shemy Mohamed AHMED**, Kazuo HOKKIRIGAWA***,
Kinya KIKUCHI****, Jiro HIGUCHI*****
and Risaburo OBA*****

Scanning electron microscopic investigations of particles produced by cavitation erosion and fracture surfaces for 304 stainless steel, revealed that the dominant mode of cavitation erosion is fatigue failure. In addition, the surface roughness facilitates the separation of particles, especially the longitudinal ones. The gathered particles can be classified into three types according to their shapes, namely the longitudinal, the triangular and the mixed quadrangle hexagon. The spherical particles, which were reported in a previous study on cavitation erosion, are not observed in this work.

Key Words : Cavitation, Erosion, Multiphase Flow, Turbomachinery, Eroded Particles, Roughness

1. Introduction

With increasing operation speed of hydraulic machinery or instruments, severe damage due to cavitation erosion often occurs. Growing interest has therefore been shown in establishing a practical method for predicting the probable rate of erosion, or in minimizing erosion using a high-cavitation-resistance material.

Concentrated research efforts have been initiated to aid in the development of improved materials based upon effective failure investigation. Examination of the eroded surface and the erosion particles produced by cavitation erosion would lead to better understanding of the failure mode, and clarification of tested surface effects on erosion. Furthermore, the observa-

tion of particles can be used as a means of detecting cavitation erosion in closed systems so that remedial action can be taken before the breakdown point is reached. Kenkermath and Thiruvengadam⁽¹⁾ analyzed the particles, and reported that many particles were layered, which perhaps is indicative of fatigue fracture. Also, they observed spherical particles, which were similar to those produced by rolling contact wear⁽²⁾⁻⁽⁴⁾, sliding contact wear⁽⁵⁾ and fretting wear⁽⁶⁾. Recently, Tomlinson and Chapman⁽⁷⁾ examined particles in vibratory tests on a copper specimen, and reported that the particles eroded by amplitudes of 13.5 and 67.5 μm had a similar size and shape.

According to the literature, several types of cavitation with their own aspects, behavior and erosion ability have been found^{(8),(9)}, which are very sensitive to test conditions, especially to the cavitation nuclei of the dominant factor⁽⁹⁾. None of the existing vibratory-erosion tests⁽¹⁰⁾⁻⁽¹⁴⁾, however, show the cavitation nuclei and/or the cavitation aspects; hence, to the authors' knowledge, no rigorous erosion results can be found. In a previous paper⁽¹⁵⁾, therefore, the authors reported test conditions necessary for maintaining the uniformity of nuclei according to

* Received 22th April, 1992. Paper No. 90-1562 A

** Assuite University, Egypt

*** Yamagata University, 4-3-16 Jounan, Yonezawa 992, Japan

**** Tohoku Gakuin University, 1-13-1 Chuuo, Tagajo 985, Japan

***** Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980, Japan

ASTM standards in such vibratory erosion tests.

The objective of the present work is to conduct careful erosion tests on a typical machinery material, 304 stainless steel, under specified conditions of uniform nuclei-size distribution. Both the eroded surface and the particles are examined using a scanning electron microscope (SEM) and an X-ray microanalyzer is used to identify the particles. Based on the gathered information, further clarification of the cavitation erosion mode is presented.

2. Apparatus and Test Procedure

The apparatus, the test procedures and the uniformity of the cavitation nuclei with respect to time have been described elsewhere^{(15)–(17)}. The vibratory frequency is 19.5 kHz and the peak-to-peak displacement amplitude is 50 μm . The water temperature T_w is $22 \pm 1^\circ\text{C}$ and is controlled by cooling water circulated around the beaker. The test pieces are made of 304 stainless steel and its mechanical properties and chem-

ical composition are shown in Table 1 conforming to JIS standards. All test surfaces are very smooth having been polished using #3000 emery paper. The resulting maximum height roughness R_{max} is 0.025 μm .

The particles to be examined are removed from the test water through a perforated membrane filter with a pore diameter of about 0.45 μm , and then are deposited on a polished copper surface.

The fracture of the eroded surface and the particle characteristics are examined using the SEM, while the chemical composition of particles is determined by the X-ray emission microanalysis. The rapidly changing cavitation aspects with time are photographed using a Xenon flash lamp with 1 μs exposure time, and the cavitation nuclei distributions are measured using a specially made Coulter counter⁽¹⁸⁾. The air content rate α/α_s is measured using a van Slyke apparatus⁽¹⁹⁾, where α is the total air content and α_s is the saturated air content rate at the water temperature T_w .

3. Results

3.1 Characteristics of particles

The particles were collected in a time interval of 5 min after the test pieces were vibrated for $t=40$ min. The number of particles was small, because the test pieces were still in the incubation stage⁽¹⁶⁾. However, the analysis of these particles, collected at the end of the incubation stage, i.e., before the superposition of damage occurs, will clearly show the mechanism that produces these particles. This will be accomplished by comparing the particle characteristics of the individual crack features formed on the

Table 1 Mechanical properties and composition of SUS 304

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 2max Si 1 max, P 0.045max S 0.03 max, Cr 18 - 20 Ni 8 - 12

Fig. 1 Micrograph of longitudinal particles (i) and X-ray emission spectra from the particles (ii)

eroded surface before the cracks overlap, as will be explained in the next section.

Generally, the observed particles have three different shapes: longitudinal, triangular and mixed quadrangle hexagon as shown in Figs. 1–3. In these figures, (i) refers to the scanning electron micrograph and (ii) refers to the X-ray emission spectrum from the particles showing the chemical composition of these particles. The first type appears to be similar to lamellae, as shown in Fig. 1, because all particles are viewed at an angle of 35° . Some longitudinal particles contain what appear to be parts of the original face of the specimen as shown in Fig. 1 (a). Some of these longitudinal particles are curved and this waviness is due to plastic deformations which occurred on the

surface. The ratio of maximum to minimum length of these longitudinal particles is about five. Figure 2 shows the second type. As observed, this kind of particle is larger in size than the longitudinal one, and it has a thickness of about $0.5\text{ }\mu\text{m}$. It is worth noting that the edges of these particles show the steps of crack tip opening displacement. Also, the surfaces of particles show traces of the virgin surface and a secondary crack at the top of the particle. The third type is different from the aforementioned types, since the thickness is greater than $1\text{ }\mu\text{m}$. Some of these particles have a rough surface as shown in Figs. 3 (a) and (b), and are quite distinctive in appearance from the smoother-surfaced particles previously reported. Also, the rough surfaces are indicative of fatigue

Fig. 2 Micrograph of triangular particles (i) and X-ray emission spectra from the particles (ii)

Fig. 3 Micrograph of mixed quadrangle hexagon particles (i) and the X-ray emission spectra from the particles (ii)

fracture.

It is important to note from the preceding classification and characterization of particles that the authors did not observe the spherical particles which were observed by Kenkermath and Thiruvengadam⁽¹⁾, for 52 100 steel, 1 020 steel and aluminum in both distilled water and lubricated oil. Proctor⁽²⁰⁾ reported that he had not observed any spherical particles in his investigation on the debris resulting from the cavitation erosion of pure copper in distilled water.

Fig. 4 Micrograph of the eroded surface showing the formation of the longitudinal particles ($t=40$ min)

3.2 Examination of the eroded surface

When ductile materials such as SUS 304 are subjected to cavitation erosion, their exposed surfaces will be deformed plastically resulting in undulation of the surface. In addition, pits will be formed. With time, plastic deformation lines grow in height and width but the shape remains constant. In contrast, the diameter and the shape of the pits do not change with time. The rate of formation of pits with time is high, initially, but decreases with work hardening of the surface⁽¹⁷⁾. Once the work hardening capacity of the surface reaches a critical level, cracks are initiated where stress concentration conditions are favorable such as at the discontinuities of slip bands, polishing lines, pits and microvoids⁽²¹⁾. It is also observed⁽²²⁾ that the roughness, even if it is very small ($R_{\max}=0.025$ μm), facilitates the propagation of cracks longitudinally and laterally, which tear the surface into strips and result in the formation of longitudinal particles. Further investigation of the roughness effects as well as the mode of fracture is reported in this section.

Figure 4 shows a typical SEM photograph of a fatigue crack, which results from void growth and coalescence along the slip bands. As seen in this figure, many secondary cracks are formed on the edges of the fatigue crack. These secondary cracks, which are formed along the polishing lines⁽²¹⁾, facilitate the sepa-

(a) $t = 35$ min

(b) $t = 40$ min

Fig. 5 Micrograph of the eroded surface showing the formation of the longitudinal particles

ration of such particles shown in Fig. 1 (a). Figures 5 (a) and (b) also show clearly the roughness effect in the formation of this kind of particle as indicated by arrows. These results are in agreement with previously reported data^{(21),(22)}, in which the roughness, even if it was small ($R_{\max} < 0.025 \mu\text{m}$), was found to have a large effect on the accumulation of pits along the polishing lines, which propagate and develop into a

(a)

(b)

(c)

Fig. 6 Micrograph of the eroded surface showing how the triangular particles are formed and also the fatigue like striations ($t = 45 \text{ min}$)

microcrack. With time, these microcracks join to form a short crack, which facilitates separation of the linear particles shown in Fig. 1. This is similar to results reported by Reda et al.⁽²³⁾ for sliding wear in which “few large longitudinal particles are occasionally found, and presumably such particles break off from the grinding marks left from surface finishing.”

Figure 6 shows clearly the traces of triangular detached particles which are similar to the second type of particles (triangular) in this paper. Fig. 6 (b) and (c) show the areas labeled I and II in Fig. 6 (a), highly magnified, in which “striations,” the most typical indication of fatigue fracture, can be observed. It can also be seen from Fig. 6 (a) that the origin of the fracture was at “O” and that the fracture propagated towards the upper right of the micrograph. Vaidya and Preece⁽²⁴⁾ observed a similar picture, in their aluminum erosion tests, and described the behavior as follows: the localization of plastic strain leads to high stress concentrations which result in the initiation of cracks at the surface. These are immediately filled with water between stress pulses preventing due to closure, and since the surface is already fully work hardened, blunting due to plastic flow is also prohibited. Therefore, once a crack is initiated, the repetitive stress mode of cavitation causes it to propagate laterally in a fatiguelike manner giving rise to the striation.

The last kind of particle, which is larger in size, especially in terms of the thickness, is shown in the eroded surface micrograph in Figs. 7 and 8. In Fig. 7, the surface has been removed, the particle surface labeled A has become rough, and the particle is at the point of detaching from the parent surface. This particle is very similar to that which appeared in Fig. 3 (a). Figures 7 and 8 show clearly that the failure mode is fatigue failure. On the fracture surfaces of

Fig. 7 Micrograph of the eroded surface illustrating the formation of the third kind of particle ($t = 40 \text{ min}$)

Fig. 8 Micrograph of the eroded surface showing the formation of the third kind of particle and the fatigue-fracture development ($t=40$ min)

these figures, the steps which reflect the crack tip opening displacement are indicated by arrows. These results not only confirm the previous finding⁽²²⁾, but also support hypothesis that the dominant mode of cavitation failure for ductile material is fatigue failure.

4. Conclusions

Vibratory cavitation erosion tests on a typical machinery material, 304 stainless steel, are carried out under a specified condition of uniform nuclei-size distribution, conforming to ASTM standards. Both the particles and the fracture surfaces were examined using an SEM and an X-ray microanalyzer was used to identify the particles. The results can be summarized as follows:

(1) According to the SEM observation of particles and the fracture surface for SUS 304, the dominant failure mode of cavitation erosion is the fatigue mode.

(2) The surface roughness facilitates the separation of particles, especially the longitudinal ones.

(3) The observed particles can be classified into three types: longitudinal, triangular and mixed quadrangle hexagon. The last type is the largest and its thickness exceeds $1\ \mu\text{m}$.

(4) The spherical particles previously observed by some investigators, which are similar to those observed in rolling contact wear, sliding contact wear and fretting wear, are not observed here.

References

(1) Kenkermath, D. and Thiruvengadam, A., Analysis and Characterization of Particles Produced by Cavitation Erosion, Proc. Conf. Cavi., I Mech E, Edinburgh, (1974), p. 285.

- (2) Seifert, W.W. and Westcott, V.C., A Method for the Study of Wear Particles in Lubricating Oil, Wear, Vol. 21(1972), p. 27.
- (3) Scott, D. and Mills, G.H., A Scanning Electron Microscope Study of Fracture Phenomena Associated with Rolling Contact Surface Fatigue Failure, Wear, Vol. 24(1973), p. 235.
- (4) Loy, B. and McCallum, R., Mode Formation of Spherical Particles in Rolling Contact Fatigue, Wear, Vol. 24(1973), p. 219.
- (5) Komonduri, R. and Shaw, M.C., A Mechanism for the Accelerated Wear of High Speed Sliding Surfaces in the Presence of Spherical Particles, Wear, Vol. 42(1977), p. 177.
- (6) Hurricks, P.L., The Occurrence of Spherical Particles in Fretting Wear, Wear, Vol. 27 (1974), p. 319.
- (7) Tomlinson, W.J. and Chapman, D., Effect of Amplitude on the Erosion and Corrosion of Copper by 20 kHz Ultrasound, Wear, Vol. 130(1989), p. 381.
- (8) Johnsson, C.A., Cavitation Inception on Head Forms. Further Tests, Proc. 12th Int. Towing Tank Conf., Rome, (1969), p. 381.
- (9) Oba, R. and Ito, Y., Cavitation Aspects in a Venturi (Johnsson Effects in a Low Turbulent Flow), Rep. Inst. High Speed Mech., Tohoku Univ., Vol. 46, (1983), p. 89.
- (10) Plesset, M.S., Temperature Effects in Cavitation Damage, J. Basic Eng., Trans. ASME, Vol. 94(1972), No. 3, p. 559.
- (11) Hammitt, F.G. and Rogers, D.O., Effects of Pressure and Temperature in Vibratory Cavitation Damage, J. Mech. Eng. Sci., Vol. 12(1970), p. 432.
- (12) Thiruvengadam, A. and Preiser, H.S., On Testing Materials for Cavitation Damage Test, J. Ship Res., Vol. 8(1964), p. 39.
- (13) Hobbs, J.M., Vibratory Cavitation Erosion Testing at NEL, Proc. Conf. Cavi., I Mech E, Edinburgh, (1974), p. 269.
- (14) Okada, T., Iwamoto, J. and Sano, K., Fundamental Studies on Cavitation Erosion (Observation of the Eroded Surface by a Scanning Electron Microscope), Bull. JSME, Vol. 20(1977), p. 1067.
- (15) Ahmed, S.M., Ito, Y., Higuchi J. and Oba, R., A Peculiar Behavior of Cavitation-Nuclei-Size-Distributions in Sample Water under Vibratory Erosion Tests, JSME Int. J., Ser. II, Vol. 33(1990) No. 4, p. 629.
- (16) Ahmed, S.M., Hokkirigawa, K., Oba, R. and Matsudaira, Y., Developing Stages of Ultrasonically Produced Cavitation Erosion and Corresponding Surface Roughness, JSME Int. J., Ser. II, Vol. 33(1990) No. 1, p. 11.
- (17) Ahmed, S.M., Hokkirigawa, K., Ito, Y., Oba, R. and Matsudaira, Y., SEM Observation on the Incubation Period of Vibratory Cavitation Erosion, Wear, Vol. 142(1991), p. 303.
- (18) Oba, R., Kim, K.T., Niitsuma, H., Ikohagi, T. and Sato, R., Cavitation-Nuclei Measurements by a

- Newly Made Coulter Counter without Adding Salt in Water, Rep. Inst. High Speed Mech., Tohoku Univ., Vol. 43(1981), p. 163.
- (19) Numachi, F., Kraftmessungen an vier Flügelprofilen bei Hohlsg, Forsch. Ing.-Wes., Vol. 11(1940), p. 303.
- (20) Proctor, R.P.M., Discussion in Conf. Cavi., I Mech E, Edinburgh, (1974), p. 413.
- (21) Ahmed, S.M., Hokkirigawa, K., Kikuchi, K., Matsudaira, Y., Oshima, R. and Oba, R., Marked Surface-Roughness Effects on the Development of Microfracture During the Incubation Period of Vibratory Cavitation Erosion, Proc. 3rd Japan-China Conf. Fluid Mach., Osaka, (1990), p. 331.
- (22) Ahmed, S.M., Hokkirigawa, K., Oba, R. and Kikuchi, K., SEM Observation of the Vibratory Cavitation-Fracture Mode During the Incubation Period and the Small Roughness Effect, JSME Int. J., Ser. II, Vol. 34(1991), No. 3, p. 298.
- (23) Reda, A.A., Bowen, R. and Westcott, V.C., Characteristics of Particles Generated at the Interface between Sliding Steel Surfaces, Wear, Vol. 34(1975), p. 261.
- (24) Vaidya, S. and Preece, C.M., Cavitation Erosion of Age-Hardenable Aluminum, Metall. Trans., Vol. 9(1978), p. 229.
-