International Journal of Fluid Power 2 (2001) No. 1 pp. 25-30

COMPARISON OF CAVITATION EROSION TEST RESULTS BETWEEN VIBRATORY AND CAVITATING JET METHODS

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Abstract

The relationship between the vibratory and cavitating jet test methods was determined experimentally. Six metallic specimens were made of aluminum alloy, superduralumin, high-strength brass, stainless steel, carbon steel and chromium-molybdenum steel. The specimen surface was eroded as fine and uniform pattern with the vibratory method, but was rough and ring-shaped with the jet method. Striation and plastic deformation were clearly observed in the specimens eroded by jet cavitation. The volume loss was the largest for aluminum alloy, followed by superduralumin, high-strength brass and steel. Both test methods yielded the same descending order for the volume loss. The ratio of volume loss by the vibratory method compared to the cavitating jet method became constant as the time proceeded.

Keywords: cavitation, erosion, jet, vibratory, water, metals

1 Introduction

Cavitation erosion is a serious problem for hydraulic equipment. It is caused by collapse of bubbles at or near the solid boundaries. In a couple of decades a large number of studies have been made on cavitation erosion (Knapp, et al 1970). Many test methods have been proposed, and then vibratory (ASTM, 1989) and cavitating jet (ASTM, 1995) methods were standardized by the ASTM.

The advantages of the vibratory method consist in the compactness of the apparatus and easily exchangeability of test liquids. Accordingly, the method is used widely for evaluating materials against cavitation erosion (Endo, et al 1966; Hobbs, 1967; ASTM, 1970, 1989), but is unsuccessful in testing brittle and coated specimens. The rise in temperature of liquids and thermal distortion of the oscillating horn also result in experimental errors.

The advantage of the cavitating jet method is that the data obtained in laboratories shows a relatively good agreement with the results of field experience. It is noted that cavitation due to a liquid jet is almost the same as that in valves and restrictors in hydraulic equipment (Lichtarowicz and Kay, 1983; Yamaguchi and Shimizu, 1987; Shimizu and Yamaguchi, 1988; Shimizu, et al 1991). However, high-pressure pumps and reservoirs are required, so that the size of the experimental facility becomes large.

In the past both these tests had been carried out separately, and the relationship between them has not yet been reported. The aim of this study is to prove the relationship between the vibratory and cavitating jet methods using six types of metallic specimens made of aluminum alloy, superduralumin, high-strength brass, stainless steel, carbon steel and chromium-molybdenum steel. The difference in mass lost and metallographic structures of the specimens eroded was determined. Subsequently, the cavitation erosion indices for both methods were evaluated.

In this experiment, the characteristic of erosion resistance of metals in water was examined. The reason for testing with water instead of oil was that water-hydraulic systems have been gradually replacing oil-hydraulic systems in a few applications in recent years, because of waters' environmental and human-friendliness. In addition to that, the cavitation erosion by water is more severe than that by oil.

This manuscript was received on 29 March 2000 and was accepted after revision for publication on 2 November 2000

2 Experiment

2.1 Vibratory Cavitation Erosion Apparatus

Conforming to the ASTM standards (1989), the experimental apparatus of the cavitation erosion for the vibratory method was built with some enhanced modifications. This apparatus consisted of an oscillating horn, its amplifier and controller, an oscillating dummy sample, a stationary test specimen, a specimen-mount, a beaker, and a circuit system to circulate the test liquid.

The diameter d_l of the stationary test specimens was 18 mm and the diameter of the hole bored at the center for the flow passage was 3 mm. The specimens were made of six types of metals; aluminum alloy (A5056BE), superduralumin (A2024), high-strength brass (C6782), stainless steel (SUS304), carbon steel (S45C) and chromium-molybdenum steel (SCM435). The designations in the parentheses are taken from those of the *Japanese Industrial Standards*, JIS (see Appendix). These mechanical and chemical properties are listed in Tables 1 and 2 respectively. The accuracy of measurement for Vickers microhardness H_{mv} and Vickers hardness H_v was ±2~5 % and ±1~2 % respectively.

The stationary specimens were fitted on the specimen-mount. The mount was installed on another mount which could be adjusted slightly and vertically by a micrometer screw with a reading precision of 0.5 µm. The specimen and the specimen-mount were immersed in the test liquid in the beaker.

The dummy sample was screwed on to the end of the oscillating horn. The sample was made of martensite type stainless steel (SUS440C in JIS), whose diameter d_u was 14 mm. The sample and the end of the horn were immersed in the liquid. The depth of the surface of the sample from the surface of the liquid was set at 10 mm. The oscillating dummy sample and the stationary specimen were situated parallel to each other with a mean gap of 0.6 mm.

The preliminary test revealed that the eroded volume of the oscillating dummy sample was considerably less than that of the stationary specimen. To avoid the effect of its erosion on the test results, however, the dummy sample was replaced every forty hours.

The horn made of titanium alloy was oscillated at 19.7 kHz of frequency and 50 µm of amplitude by an ultrasonic generator whose maximum output power was 600 W. In the preliminary experimentation, the frequency and amplitude were measured and confirmed by using an eddy-current and non-contact type clearance sensor located at the stationary specimen and a fast Fourier transform (FFT) analyzer.

Deionized tap water was used as the test liquid. The temperature of the liquid was measured at the inlet and outlet of the beaker during testing. It was kept within 313±1 K by a circulating circuit system with an electric heat exchanger. The liquid was supplied through the hole of the stationary specimen and re-circulated in the system so as to keep the temperature of the liquid constant and to remove the remaining bubbles in the gap between the oscillating dummy sample and the stationary test specimen. The flow rate Q through the hole was held at $6.7 \cdot 10^{-6}$ m³/s for all tests, which did not play an important role in specimen's erosion in this experiment.

At the beginning of each test, the apparatus was operated for thirty minutes so as to stabilize the temperature of the apparatus and the test liquid as well as the quantity of air contained in the liquid. During the test, the specimen was removed every thirty minutes; dried sufficiently, and weighted by the precision balance with a reading precision of 0.1 mg. At the same time, the surface was photographed and its profile was recorded.

Table 1: Mechanical properties of specimens

Designation in JIS	ρ kg/m³	E GPa	σ_Y MPa	$\sigma_{0.2}$ MPa	σ_B MPa	σ_T MPa	ϕ %	ψ %	H_v	H_{mv}
A5056BE	2730	69.6	124	-	272	223	30.2	49.3	77	98
A2024	2868	72.3	-	423	563	549	17.0	85.1	152	171
C6782	8226	98.1	-	301	596	579	26.8	72.3	179	206
SUS304	7988	179	-	301	660	470	76.1	34.5	194	221
S45C	7895	206	398	-	714	612	22.6	57.7	241	263
SCM435	7918	204	-	792	908	553	18.3	39.3	307	303

Table 2: Chemical composition of specimens

Designation in JIS / Chemical composition %									
	Cr	**Cu**	**Fe**	**Mg**	**Mn**	**Si**	**Ti**	**Zn**	**Zr**
A5056BE	0.07	0.01	0.09	4.53	0.08	0.08	0.01	0.01	-
A2024	0.04	4.22	0.26	1.45	0.63	0.24	0.03	0.03	-
	Al	**Cu**	**Fe**	**Mn**	**Ni**	**Pb**	**Si**	**Sn**	**Zn**
C6782	0.79	57.37	0.51	0.69	0.43	0.33	0.03	0.26	37.31
	C	**Cr**	**Cu**	**Mn**	**Mo**	**Ni**	**P**	**S**	**Si**
SUS304	0.05	18.69	0.40	1.35	0.18	8.10	0.034	0.026	0.27
S45C	0.49	0.14	0.13	0.69	-	0.10	0.016	0.010	0.23
SCM435	0.34	1.14	0.01	0.79	0.15	0.03	0.015	0.018	0.22

2.2 Cavitating Jet Test Apparatus

The experimental apparatus of the cavitating jet method and the experimental procedure were described in the previous paper (Yamaguchi and Shimizu, 1987). The experimental conditions in this paper were as follows: the supply pressure p_u was 9.9 MPa; the cavitation number σ which was defined by the ratio of the pressure p_d in the chamber to the supply pressure p_u was 0.02; the diameter d of the specimen was 15 mm; the stand-off distance L between the outlet of the nozzle and the surface of the specimen was 25 mm; the diameter and length of the nozzle were 1 mm and 4 mm respectively; the test liquid was tap water and its temperature was kept at 313±1 K. This value of L chosen was the distance which produced the maximum mass loss eroded in the preliminary test. The test specimens were made of the same materials as those used in the vibratory method.

3 Results and Discussion

3.1 Cumulative Cavitation Erosion Mass Loss

Figure 1 shows the volume loss V with respect to the test duration t for the vibratory method. The horizontal short-bars in this figure refer to the scatter of the data. The mass loss of the specimens due to cavitation erosion was converted into the volume loss V using the density ρ of each material listed in Table 1. Volume loss, instead of mass loss, was evaluated because volume lost directly influences the profiles of the flow passage as well as the bearing and seal parts in hydraulic equipment. Except for the region of the small t, V was almost increasing proportionally with increasing t. In this experiment the volume loss V in descending order was: A5056BE, A2024, C6782, SUS304, S45C and SCM435. It is shown that V for aluminum alloy was the highest. The order of V of S45C and SCM435 was not clear because of small difference in V between these two materials.

For the case of the cavitating jet method, the volume loss V was also proportionally increased with increasing t, except for superduralumin (A2024). The order (A5056BE, A2024 and C6782) of V coincided exactly with that for the vibratory method.

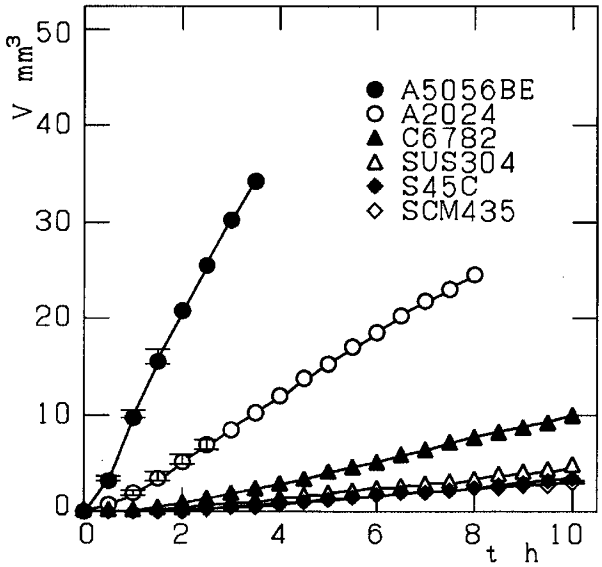

Fig. 1: *Volume loss eroded V vs. time t by vibratory method*

3.2 Comparison of Surface Damage Between Vibratory and Cavitating Jet Methods

Figures 2 and 3 show the photographs of the surfaces eroded and their cross-sectional profiles. The former and the latter are the specimens tested by the

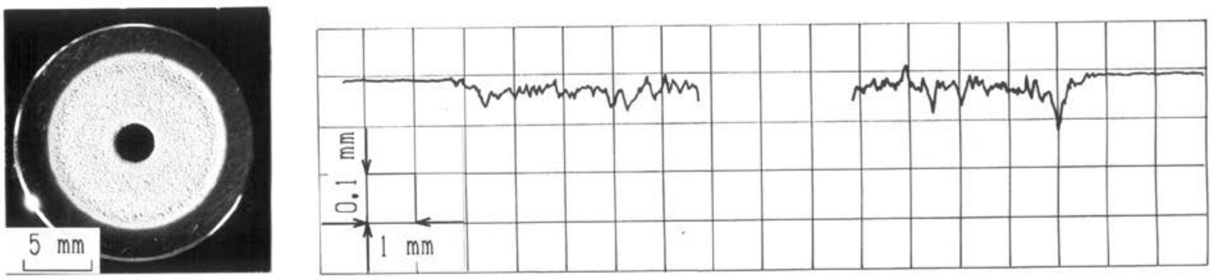

Fig. 2: *Eroded surface and cross-sectional profile for vibratory method (A5056BE, t = 30 min)*

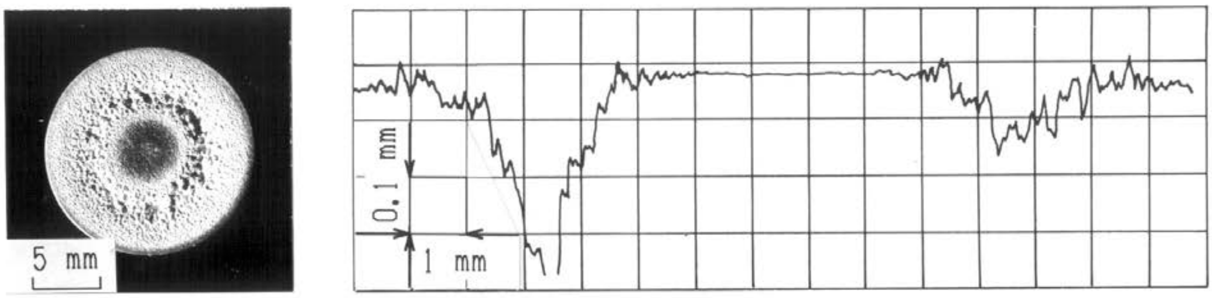

Fig. 3: *Eroded surface and cross-sectional profile for cavitating jet method (A5056BE, t = 20 min)*

vibratory and cavitating jet methods respectively. Both specimens were made of aluminum alloy (A5056BE).

In Fig. 2 the curve of the profile discontinued at the center because of the hole bored beforehand in the center of the stationary specimen. It is shown that the area of the specimen (d_l = 18 mm) with respect to that of the dummy sample (d_u = 14 mm) was eroded uniformly and had a fine grain look. In contrast shown by the photograph and the profile in Fig. 2, the surface due to the cavitating jet method was eroded with deeper grooves in the form of a ring as shown in Fig. 3 (Yamaguchi and Shimizu, 1987).

The experiment was performed for all specimens. The volume loss for each specimen depended on its material, but the aspect of the surfaces was similar with the results in Fig. 2 and 3. All surfaces for the vibratory method were eroded uniformly and those for the cavitating jet method were eroded as ring-like. As a result, it was shown that the eroded surface profiles were independent of the material type for both the methods.

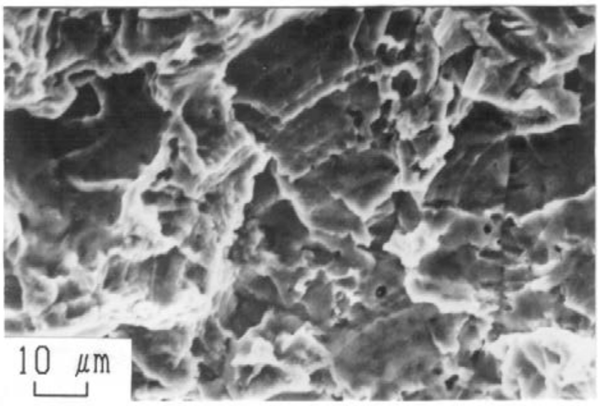

Plate 1: *SEM photograph of eroded specimen for vibratory method (A5056BE, t = 1 h)*

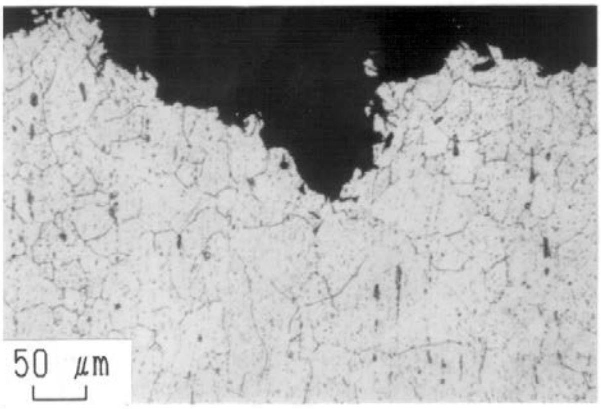

Plate 2: *Metallurgical microscope photograph of eroded specimen for vibratory method (A5056BE, t = 1 h)*

The fractographs by a scanning electron microscope (SEM) and a cross-sectional area of the specimens by metallurgical microscope for the vibratory method are shown in Plates 1 and 2 respectively. The material was aluminum alloy (A5056BE). The exposure time was one hour. Similarly, the fractographs for the cavitating jet method are shown in Plates 3 and 4. One can see that the surfaces were damaged due to fatigue fracture, plastic deformation and striation in these plates. Striation and plastic deformation were observed for the cavitating jet method.

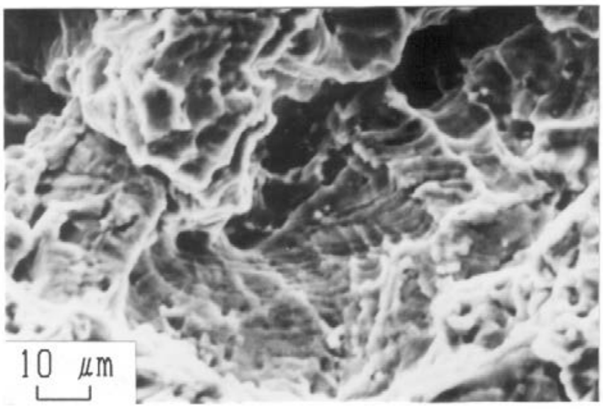

Plate 3: *SEM photograph of eroded specimen for cavitating jet method (A5056BE, t = 1 h)*

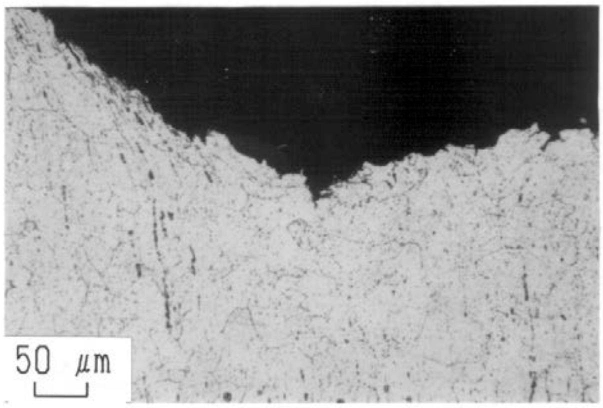

Plate 4: *Metallurgical microscope photograph of eroded specimen for cavitating jet method (A5056BE, t = 1 h)*

3.3 Relationship between Vibratory and Cavitating Jet Methods

Figures 4 and 5 plot the relationship between the representative erosion indices versus the erosion resilience rate $\dot{V}^{-1}$ which is the inverse number of the rate $\dot{V}$ of the volume loss to test duration t. The correlation of the erosion indices was evaluated at t = 3 h in these figures.

Mechanism of cavitation erosion has not yet been understood completely, and thus the relationship between erosion and material properties is unclear at the present. Many parameters; for instance, the size and structure of crystal grains as well as hardness, strength and elastic modulus, would influence erosion. The erosion indices chosen in this paper are the following: H_{mv}^2/E, H_v^2/E, proof resilience PR, ultimate resilience UR and σ_B^2E because these indices consist of the mechanical properties which can be obtained relatively easily. For the list of these indices, the corresponding correlation factors were obtained as: 0.294, 0.460, 0.160, 0.071 and 0.885 for the vibratory method ($\dot{V}_v^{-1}$), and 0.186, 0.360, 0.111, 0.033 and 0.861 for the cavitating jet method ($\dot{V}_j^{-1}$) respectively. Accordingly, the correlation factors of $\sigma_B{}^2E$ for both methods was the largest in this experiment. This means that the higher elastic modulus contributed to erosion resistance. The physical interpretation of this result should be discussed in detail in the further study.

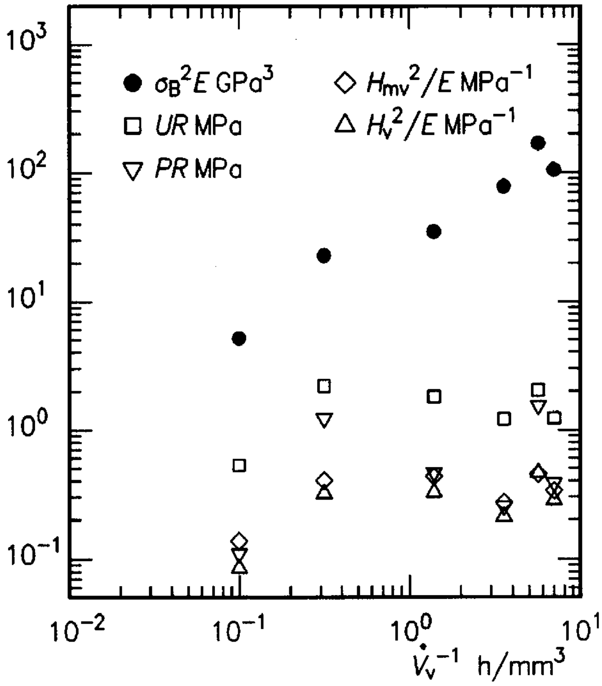

Fig. 4: *Relationship between erosion indices and erosion resilience rate for vibratory method (t = 3 h , Vertical axis refers to: $H_{mv}{}^2/E$ [MPa^{-1}], $H_v{}^2/E$ [MPa^{-1}], PR [MPa], UR [MPa] and $\sigma_B{}^2E$ [GPa^3])*

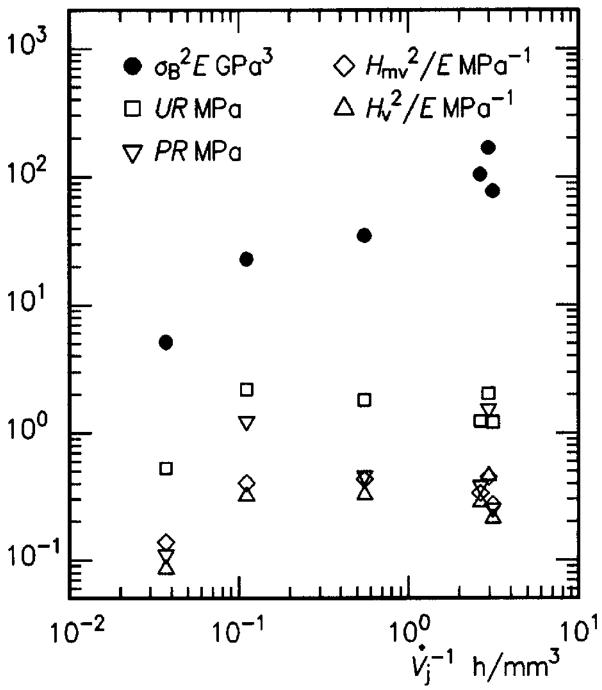

Fig. 5: *Relationship between erosion indices and erosion resilience rate for cavitating jet method (t = 3 h, Vertical axis refers to: $H_{mv}{}^2/E$ [MPa^{-1}], $H_v{}^2/E$ [MPa^{-1}], PR [MPa], UR [MPa] and $\sigma_B{}^2E$ [GPa^3])*

Figure 6 shows the relationship of the volume loss between the vibratory and cavitating jet methods. In this experiment the parameter V_v/V_j which is the ratio of the volume loss due to the vibratory method (V_v) to that due to the cavitating jet method (V_j) converged to about 0.3, as test duration *t* proceeded. Two exceptions were that V_v/V_j for stainless steel (SUS304) was about 0.5 and that for chromium-molybdenum steel (SCM435) was about 0.4 within ten hours of exposure time.

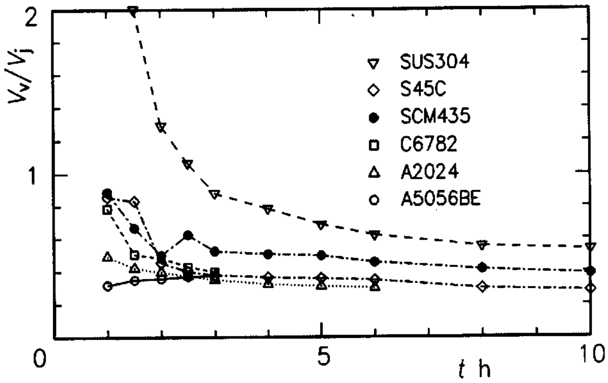

Fig. 6: *Ratio of eroded volume V_v/V_j vs. time t [hours]*

4 Conclusions

The relationship between the cavitation erosion test results obtained from the vibratory and cavitating jet methods was clarified experimentally. The conclusions are as follows:

- The ratio of the volume loss by the vibratory method to the cavitating jet method became constant as the exposure time proceeded. The ratio was almost independent regarding the material type.
- The volume loss was the largest for aluminum alloy, followed by superduralumin, high-strength brass and steel. Both test methods yielded almost the same descending order for the volume loss. The order of the specimens made of several types of steel was unclear.
- The surfaces were eroded uniformly and as ring-shaped for the vibratory and cavitating jet methods respectively. These behaviors were independent of the material type. The eroded surfaces due to the vibratory method were less rough than those due to the cavitating jet method.
- Striation and plastic deformation were distinctly observed via SEM for the vibratory and cavitating jet methods respectively.

Nomenclature

E	Modulus of longitudinal elasticity
H_{mv}	Vickers microhardness
H_v	Vickers hardness
PR	Proof resilience = $\sigma_{0.2}{}^2/(2E)$
t	Test duration
UR	Ultimate Resilience =$\sigma_B{}^2/(2E)$
V	Volume loss eroded
ρ	Density of materials
σ_B	Breaking strength
σ_T	Tensile strength
σ_Y	Yield stress
$\sigma_{0.2}$	Proof stress
ϕ	Breaking elongation
ψ	Contraction of area

Subscripts

j	Cavitating jet method
v	Vibratory method

Acknowledgements

The authors wish to express their thanks to Messrs. Jun Onodera and Nobuyuki Iwasaki for their cooperation in carrying out the experiment.

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Appendix

The designation in JIS (Japan) is compared with that in ASTM (U.S.A.), BS (U.K.) and DIN (Germany) in Table A1 (JIS, 1975; ITII, 1976; ASTM, 1987).

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