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QUANTITATIVE PREDICTION OF EROSIVE DAMAGE TO METALLIC MATERIALS EXPOSED TO CAVITATION ATTACK

Akihiro Sakamoto, Hiroshi Funaki and Masanobu Matsumura

Department of Chemical Engineering, Hiroshima University
Higashi-Hiroshima, JAPAN

Abstract: *Cavitation erosion tests on metallic materials were conducted by using a water tunnel facility and vibratory units. On the basis of the results, a method to predict the material damage caused by Cavitation attack was established as follows: The depth of the pit was chosen as the index of the damage. This increased linearly against testing time after an incubation period during which no pit appeared. With an increase m the intensity of Cavitation attack, the incubation period became shorter and the slope of the linear line (damage rate) larger. The extrapolation of these pit depth vs. testing time lines back to the beginning of the test resulted in a crossing of the lines on the time-0 axis. The point depended not on the intensity of Cavitation attack but on the material in that each material had its own characteristic point on time-0 axis. The slope of the line (damage rate) was related to the sum o f the occurrence frequency of Cavitation impulsive pressure of which the intensity was larger than the tensile strength of the material. The characteristic point was related to the amount of plastic deformation which occurred beneath the damage surface of the material. By obtaining the characteristic point in a vibratory test and measuring the Cavitation impulsive pressure in a hydraulic machine, the depth of the pit originated on the machine component material can be predicted at any running time.*

l. INTRODUCTION

An International Cavitation Erosion Test program started out in 1988 under the coordination of Dr. J. Steller, Institute of Fluid-Flow Machinery, The Polish Academy of Science, Gdańsk, Poland. The objectives of this program were to compare the assessment of selected materials with respect to their resistance to cavitation attack based on test results under different laboratory conditions throughout the world, to determine the dependence of the assessments on the test conditions and to work out the basis for further standardization of material testing. In our laboratory, which was a participator in this program, cavitation erosion tests were conducted on the selected materials, and the test results were sent to Gdańsk, where they are now in the course of analysis together with the data from the other laboratories worldwide. The matter described below is based on the same experimental results that were sent to Gdańsk, but the analysis here is independent.

The amount of cavitation damage caused to a material depends on both the cavitation intensity and the resistance of the material to it. The assessment of these factors is, therefore prerequisite for the quantitative prediction of erosion damage to the material. Though the resistance of a material cannot be represented by any single mechanical property of the material, which is a matter of common agreement, the relative value of the resistance will be assessed through the amount of damage caused to it in any accelerated test. The intensity of cavitation attack may be assessed precisely by impulsive pressure measurements with a piezometer. Relative intensity will be conveniently determined by the amount of damage to a standard material. In the case where the damage rate changes with the duration of exposure to cavitation, however, it is very difficult to present the cavitation intensity and the material resistance in terms of a single number, even if they may be relative values, which makes the quantitative assessment of cavitation damage almost impossible.

2. TESTING APPARATUS AND MATERIALS

The following three kinds of apparatuses were used.

(I) A vibratory unit [l] in which a disc-shaped specimen of 16 mm diameter was vibrated vertically in a test liquid at a high frequency of 20 kHz and with a double amplitude of 25 urn.

(II) A vibratory unit with a stationary specimen [2] which was located 0.4 mm from a vibrator nozzle which was set in place of the specimen in the above mentioned unit (I).

(III) A water tunnel developed by Louis [3,5]. The test section was a rectangular channel (40 X 30 mm) with two semi-circular columns by which the fluid flow was accelerated to generate cavitation.

The test specimen shape was common for the there apparatuses. The test liquid was tap water for the water tunnel and de-ionized water (conductivity of 0.2 μS/cm) for the vibratory units. The temperature of the test liquids was maintained uniform at 40°C. As testing materials, five metals were chosen out of the six standard materials of the Gdańsk program. A rough chemical analysis and the mechanical properties are listed in Table l.

3. TESTING METHOD AND RESULTS

3.1 Index of erosion damage

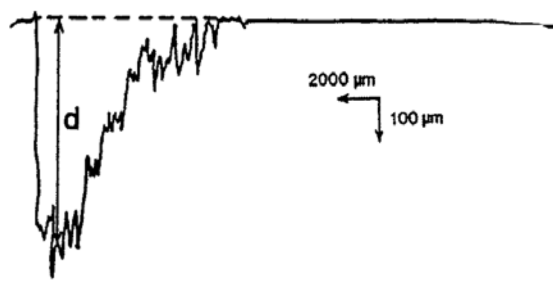

Fig.1 A profile of damaged surface and the definition of damage depth *d*.

Damage depth *d* (μm) was employed as the index of cavitation damage. It was determined at a fixed point as the distance between the profiles of the original surface and that of the damaged surface, measured with a surface roughness meter (Fig. l). Experimental results obtained on five test materials from the three testing apparatuses are shown in Fig. 2. It should be noted that the scale of ordinates (damage depth) of figures (I) ~ (III) is common but those of abscissas (exposure duration) are not. In other words, in the stationary specimen unit (II), it took nearly twice as long as in the vibratory unit (I) to attain the same depth of damage to a specimen, and in the water tunnel (III) five times as long as in unit (I). This is, of course, to be attributed to the fact that each apparatus had its own intensity of cavitation.

Table 1 Test materials

		composition	Mechanical parameters			-Dc	Δε	-Dc/Δε
		(%)	σ_s(MPa)	σ_y(MPa)	H_V	(μm)	(%).	(μm)
Aluminium	(A)	2.7 Mg	208	169	66	10	4.9	2.0
Brass	(C)	63.7Cu-36.3Zn	335	110	115	10	5.5	1.8
Armco iron	(F)	0.035C-0.10Mn	380	335	120	20	10.0	2.0
Carbon Steel	(S)	0.43C-0.63Hn-0.26Si	419	221	210	5	3.0	1.7
Stainless steel	(SUS)	0.40C-17.6Cr-9.40Ni	605	225	420	5	2.8	1.8

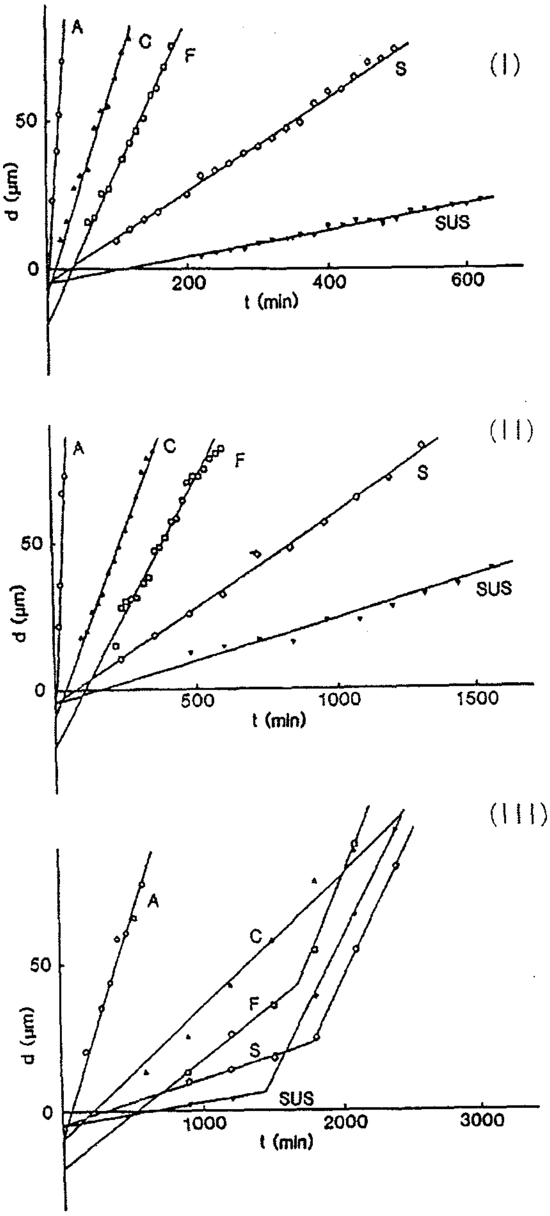

Fig.2 Damage depth vs. exposure duration plot in vibratory unit (I), stationary specimen vibratory unit (II) and water tunnel(III).

The most important and favorable feature of the figures was the linear relationship between the depth and time even though the straight lines did not go through the origin because of the incubation periods. In the water tunnel test (III), the *d* vs. *t* lines of Armco iron (F), stainless steel (SUS) and carbon steel (S) were bent upwards. This was attributed to a sudden occurrence of corrosion at that time point. Detailed discussion on this corrosion effect will be given elsewhere and the discussion here shall be limited to within the first half of the bent lines. The second of the features was that in each figure test materials were rated in a common order, A>C>F>S>SUS, based on the slope of the *d* vs. *t* line, namely the damage rate. The third was that the extrapolation of *d* vs. *t* line back to the beginning of the test crossed the ordinate at a certain negative depth, Dc, and that this depth depended totally on the material but was independent of the testing apparatus as shown in Table l.

This is called the characteristic point hereafter.

3.2 Characteristic point

The experimental result that the value of Dc was specified by the material tested irrespective of the testing apparatus, seemed to indicate that it might be related to some mechanical properties of the material, or more positively speaking, to its resistance to cavitation attack. Another possibility was the incubation period, because the more negative the value of Dc, the longer the incubation period was, even if the damage rate (the slope of *d* vs. *t* line) was the same. During this period, plastic deformation of the specimen surface proceeded without any separation of the material from the surface. As deformation proceeded with exposure time, plastic strain must accumulate gradually in the specimen until saturation was reached. Then, the separation of material from the surface, or mass loss must begin to take place and the incubation period must be terminated. Thus, the value of Dc might be specified by the plastic strain at saturation. We determined this strain through the "one to one correspondence" between hardness and strain [4] for each material as follows. Firstly, hardness distribution was measured on the cross section of a test specimen which had been exposed to cavitation for a longer time than the incubation period (Fig.3). The distribution curve was extrapolated to the damage surface in order to determine the hardness there. The hardness thus determined indicated one and the same value irrespective of exposure duration, which convinced us that this was the hardness corresponding to the plastic strain at saturation. Secondly, the extent of the strain at saturation was derived from the hardness in a way very similar to that through which plastic strain was brought about on a test specimen by cavitation impulsive pressure: a stress (load/contact area) vs. strain (diameter of indentation/diameter of ball) curve was determined in a universal testing machine by pressing a small steel ball (3.17 mm in diameter) down on the surface of the test material. On the curve, the yield point was specified at the point where the beginning of the set-off from the linear stress-strain relation was located (point (D in Fig.4). It had been already established by Tabor [4] that the hardness of a metallic material is proportional to its yield stress, and that the hardness/yield stress ratio is one and the same, even after the metal is plastically deformed to give rise to some increase in yield stress as well as in hardness. By use of the ratio, we could determine the yield point of the same material but after the strain corresponding to the hardness of the damaged surface was brought about (point (2) in Fig. 4). A straight line starting at this yield point and running parallel to the linear portion of the stress-strain curve crossed with the abscissas to indicate a cut of strain, the plastic strain at saturation. It was closely related with Dc as shown in Table l: the Dc/ $\Delta\varepsilon$ ratio was nearly constant irrespective of the material tested. Figure 5 shows how wide the range of damage rate is saturation. Secondly, the extent of the strain at saturation was derived from the hardness in a way very similar to that through which plastic strain was brought about on a test specimen by cavitation impulsive pressure: a stress (load/contact area) vs. strain (diameter of indentation/diameter of ball) curve was determined in a universal testing machine by pressing a small steel ball (3.17 mm in diameter) down on the surface of the test material. n the curve, the yield point was specified at the point where the beginning of the set-off from the linear stress-strain relation was located (point (D in Fig. 4). It had been already established by Tabor [4] that the hardness of a metallic material is proportional to its yield stress, and that

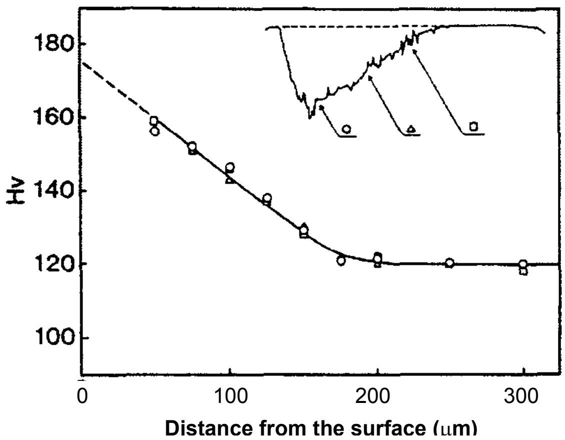

Fig.3 Hardness distribution on a cross section of water tunnel test specimen

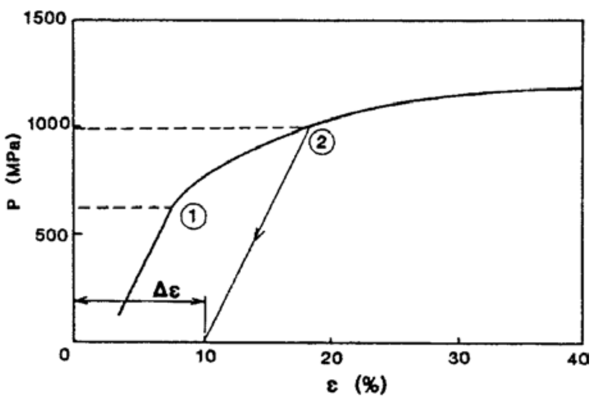

Fig.4 Stress-strain diagram obtained by pressing a small steel ball down on the surface of

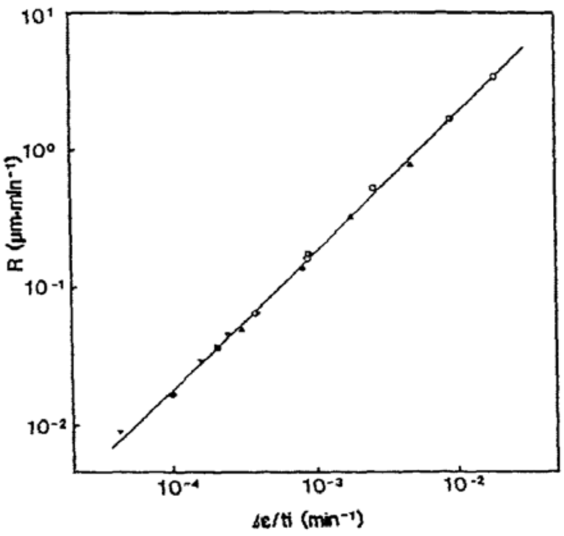

Fig.5 Verification of Δε

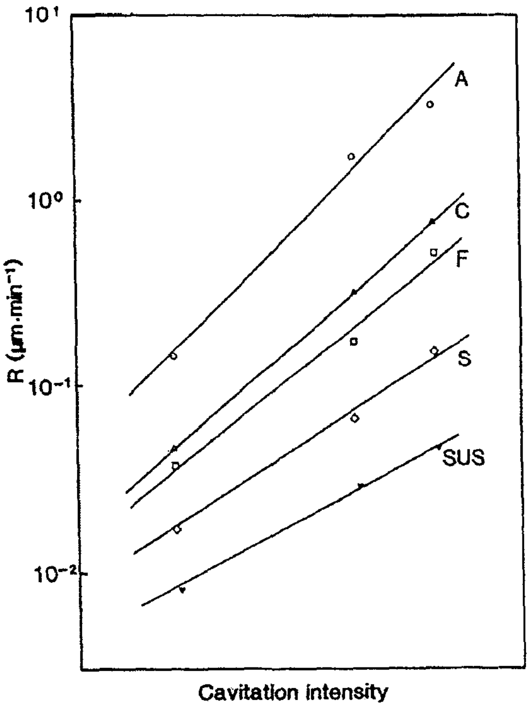

Fig.6 Damage rate vs. cavitation intensity plot.

the hardness/yield stress ratio is one and the same, even after the metal is plastically deformed to give rise to some increase in yield stress as well as in hardness. By use of the ratio, we could determine the yield point of the same material but after the strain corresponding to the hardness of the damaged surface was brought about (point (2) in Fig. 4). A straight line starting at this yield point and running parallel to the linear portion of the stress-strain curve crossed with the abscissas to indicate a cut of strain, the plastic strain at saturation. It was closely related with Dc as shown in Table l: the Dc/ Δ ε ratio was nearly constant irrespective of the material tested. Figure 5 shows how wide the range of damage rate is in which this correlation is valid, where ti is the duration of the incubation period. A good correlation is recognized for the range over10^3.

3.3 Damage rate

As shown in Fig. 2, the damage rate of a material (the slope of line) varied with the testing apparatus, indicating that it depends on the intensity of cavitation attack, as well as on the resistance of the material. Though the exact numerical values of the cavitation intensity of these apparatus were not known, relative intensity was determined in the following way: two points were arbitrarily chosen on the abscissa of the damage rate vs. cavitation intensity diagram (Fig. 6). The maximum and the minimum damage rates of Armco iron (F), as an example, were plotted on the diagram at each appointed intensity. Then we let the point of middle damage rate fall on the tie-line of the points. Thus relative values of cavitation intensity for the three apparatuses were all determined on the abscissa. The rate vs. intensity plottings were made for the other materials on the diagram resulting in the beautiful arrangement of all points on each straight line for each material, as shown in Fig. 6. Accordingly it was proved that the relative intensities of cavitation attack for each apparatus were determined quite adequately.

It should also be noted that the slopes of the straight line in Fig. 6 are not identical but the larger the slope, the higher the damage rate is. In a previous study, we installed a piezometer in the surface of a water tunnel specimen and measured cavitation impulsive pressure frequency profiles at several points on the surface of different cavitation intensities (Fig. 7). We

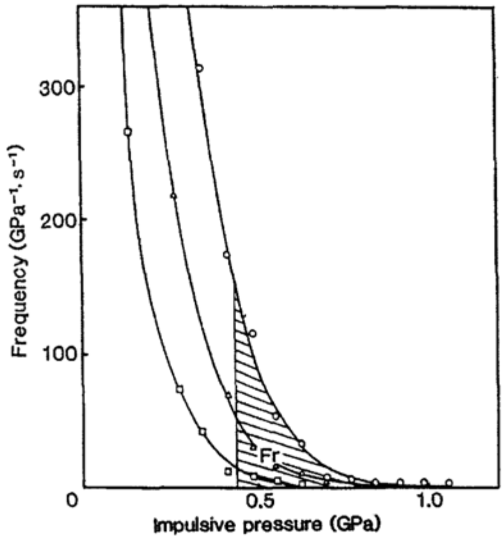

Fig.7 Occurrence frequency of cavitation impulsive pressure and the definition of Fr

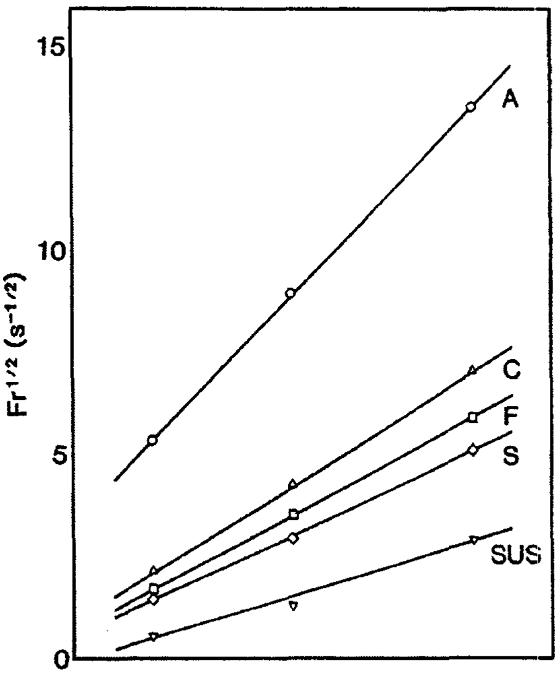

Fig.8 Fr $^{1/2}$ vs. cavitation intensity plot

found that the cavitation damage rate was proportional to the square root of the occurrence frequency of cavitation impulsive pressure having a force exceeding the specimen material strength value [5]. Referring to Fig. 7, this frequency corresponds to the area *Fr* which is surrounded by the frequency curve, the abscissa and the line which indicates the impulsive pressure corresponding to the tensile strength of the examined material.

For each material tested here, and for each frequency profile in Fig. 7, the area *Fr* was determined using the tensile strength values of the materials listed in Table l. The plot between the square root of the area *Fr* (corresponding to damage rate) and the relative intensity of cavitation (determined in a way similar to Fig. 6), are shown in Fig. 8. Figures 6 and 8 bear a close resemblance to each other, which is good evidence that the damage rates in Fig. 6 obey the square root law as well as evidence that the occurrence frequency profiles of cavitation impulsive pressure in the vibratory units are similar to that in the water tunnel, even though it is a necessary but not sufficient condition.

4. CONCLUSIONS

The depth of cavitation damage increased linearly with testing time after an incubation period. The damage rate (the slope of the line) varied depending on cavitation intensity, but the group of depth vs. time lines obtained for a single material would meet at a single point, Dc, characteristic for a given material at time zero. The above mentioned behavior of cavitation damage depth were recognized for all materials tested in the damage rate range of between 5 and 2600 mm/y, and for the extent of time duration up to at least two or three times the incubation period. Because the characteristic point bears a significant physical meaning and the damage rate is correlated reasonably to the cavitation intensity, the experimental results are possibly valid for a wider range of materials as well as for a damage rate beyond the range of this experiment.

The features observed above indicate the feasibility of predicting the service life of a material in the field. Suppose significant damage was found at a regular inspection on some fluid flow machine parts made of material *A* and that, as a substitute, material *B* were considered. The damage depth on the same parts but of material *B* can be predicted through the method described below. Using an accelerated cavitation test rig, (vibratory unit, for example), the value of Dc can be determined for both materials, *A* and *B.* Tests under different cavitation intensities or amplitudes of vibration, will give the relationship between the damage rate and the relative intensities of cavitation attack, just like Fig. 6 does for the materials we tested. The cavitation intensity on the machine parts will be indicated on the abscissa of the figure by the damage rate of material *A* parts which can be determined through the depth and the service duration on inspection. The damage rate corresponding to this relative intensity and the *Dc* of the material together give the depth vs. time relationship for the machine parts made of material *B.*

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Prof. Masanobu Matsumura
Dept of Chem. Eng.
Hiroshima University
1-4-1 Kagamiyama
Higashi-Hiroshima
739-8527 Japan