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Time dependant measurements of cavitation damage

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ABSTRACT

Due to the extremely long length of experiments, in most studies of cavitation erosion only damage in the incubation period is measured and the final damage (mass loss rate) is then predicted by extrapolation. The methods of extrapolation are usually very basic since there were almost no in depth time dependant measurements of cavitation erosion performed in the past. A rotating disc test rig that generates a very aggressive cavitation and pure copper specimens, as erosion sensors, were used to investigate the correlation between the damage within the incubation period and final mass loss. The damage was measured optically three times during the incubation period and by weighing the specimen during the rest of the experiment.

The results confirmed that the same clear relationship between the damage in the incubation period and the final mass loss rate exists, what means, that the mass loss rate can indeed be qualitatively predicted on the basis of measurements performed within the incubation period. This is a good basis for developing laws of extrapolation from a short time scale (laboratory measurement within the incubation period) to the real time scale (machine operation).

1. Introduction

Cavitation denotes the appearance of vapor cavities inside an initially pure liquid medium due to local drop in static pressure. The phenomenon is usually considered to be undesired since it can cause changes in flow dynamics, drop of efficiency or head of hydraulic machines, noise and also severe erosion of submerged surfaces.

Liquid breakup can be achieved by different means although rapid local increase of fluid flow velocity and ultrasound induced vibrations are the most common and the easiest to reproduce during experiments. Local increase of velocity can be generated by narrowing of the flow tract or by inserting an obstacle into the path of the fluid flow. Increase of velocity causes a drop in pressure and consequently formation of vapor bubbles. In the other case usually piezoelectric transducers that excite with frequencies in the range between 20 and 60 kHz (Zeqiri et al. [1], Whillock and Harvey [2]) are used to generate ultrasonic cavitation. Here, due to the inertia, the liquid cannot follow the oscillations of the sound field—if the pressure oscillations are high enough (if the pressure drops below the critical pressure), cavitation bubbles repeatedly appear and collapse.

The phenomenon of cavitation erosion is a complicated process. It is probably a combination of the so-called micro-jet (Benjamin and Ellis [3]) and the spherical collapse of microbubbles (Tong et al. [4]) after the micro-jet impact that cause the formation of a pit. If a solid object is exposed to cavitation, first small plastic deformations (pits) appear on its surface. This period of pit accumulation is referred to as the incubation period. After a sufficient time of exposure enough pits are accumulated to weaken the surface of the solid object—material starts to separate. Past measurements show that, as the time progresses, the material separates from the surface, first at an exponential and later at a linear rate (Franc and Michel [5]).

Although cavitation erosion is a very ubiquitous problem its influence is usually seen only after a long time of exposure. Hence a wide variety of test rigs exist where the process is either accelerated or only a study of the damage in the incubation period is performed.

To evaluate erosion in the incubation period usually visual methods are used. Specimen is exposed to cavitation for a relatively short time (up to 1 h) and the erosion is then evaluated according to the number and the size of the pits (Dular et al. [6]) or by sum of the damaged area (Dular and Osterman [7]). When the specimen endures many pits and is subjected to significant material loss, the erosion can only be evaluated by weighing the specimen or by interferometry (Bachert et al. [8]).

One of the unanswered questions which is addressed in the paper is how to relate the results of measurements in the incubation period to the mass loss rate during severe erosion.

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Nomenclature

A (mm^2) damaged area
A_{dam} (%) damaged surface
f coefficient between damage rates
$f_{acoustic}$ coefficient between damage rates for acoustic cavitation
L (mm) length of the boundary between the damaged and the undamaged surface
R (mm) characteristic pit/hole size
$\dot{V}_{inc}$ (mm^3/h) pit volume growth rate
$\dot{V}_{mass\ loss}$ (mm^3/h) volume loss rate

A set of experiments on a rotating disc test rig was performed. The test rig is designed to generate very aggressive hydrodynamic cavitation that closely mimics erosion in hydraulic machinery and, at the same time, decreases the duration of the experiment to a, still plausible, length of about 100–300 h (depending on the material of the specimen). The present paper shows, for the first time, a combination of optical and mass loss measurements of cavitation erosion.

During experiments first a pit-count method (Dular et al. [6]) was applied to evaluate damage during the incubation period, while specimen weighing was used to determine the mass loss later on.

2. Experimental set-up

The rotating disc test rig (Fig. 1) was developed to generate an aggressive type of cavitation. The test rig consists of a closed water loop and the rotating disc with four holes where cavitation appears (Fig. 1, right). Positions where the material specimens can be mounted are noted by p1 to p6. For the present experiments specimens were mounted in positions 1–4 and the damage evaluation was only carried out on specimens in positions p1 and p2. Specimen holders in positions p5 and p6 were empty to enable visual observation of cavitation. Asymmetrical distribution of specimens lead to different cavitation aggressiveness on evaluated specimens—this is described in more detail later on.

Pure copper specimens (surface hardness: HV40, yield strength: 200 MPa) with a size of 10 mm × 18 mm × 65 mm were mounted in the casing on the same radius as the holes on the rotating disc—so that as the disc rotates, the cavitation causes erosion on the specimens.

The disc has a diameter of 500 mm and is driven by a 35 kW motor, which is controlled by a frequency converter, what enables the variation of the rotational frequency. The other parameter that defines the operating point is the cavitation number, which can be adjusted by variation of the static pressure. Due to several hours of operation, maintaining a constant temperature is an issue that was solved by mounting an integrated and temperature controlled cooler into the system.

Experiments at two different rotating frequencies (1500 min^{-1} and 1800 min^{-1}) were performed. For easier comparison the cavitation number was held constant at $\sigma = 0.16$ what meant that the pressure had to be adjusted to 0.8 bar (1500 min^{-1}) or to 0.96 bar (1800 min^{-1}). The water temperature was held below 40 °C during the whole experiment. Unprepared tap water was used. The Van Slyke method (Brandt [9]) was used to measure the content of dissolved and undissolved gases during the test—a value of 27 ± 0.5 mg$_g$/l$_w$ (milligrams of gas per liter of water) was determined for all experiments.

3. Damage evaluation

Two different methods were used to evaluate the damage—the pit counting and specimen weighing.

3.1. Pit-count method

Pits on a solid surface have a diameter in order of magnitude 10^{-5} m, and can be distinguished only by sufficient magnification. Magnified images (50:1) of the pitted surface were acquired using an Olympus BX-40 microscope and a CCD camera.

The pit-count method (Dular et al. [6]) is based on the assumption that the area of the pitted surface and the number of pits in a certain time of exposure to cavitating flow give a quantitative measure of the intensity of cavitation erosion.

3.2. Specimen weighing

For the case of copper specimen, significant (measurable) mass loss occurs only a few hours after the start of the experiment. The test rig was operating during night in intervals between 6 and 15 h. The specimens were removed and prepared for weighing by blowing all the water off by compressed air between each interval.

The specimens with mass of approximately 95 g were weighed with the Sartorius BP301S precision balance scale. It has a maximal capacity of 303 g, readability of 0.1 mg and linearity of 0.3 mg.

4. Results

Fig. 2 shows images of the copper specimens after different periods of exposure to the cavitating flow for the case of low rotating frequency (1500 min^{-1}).

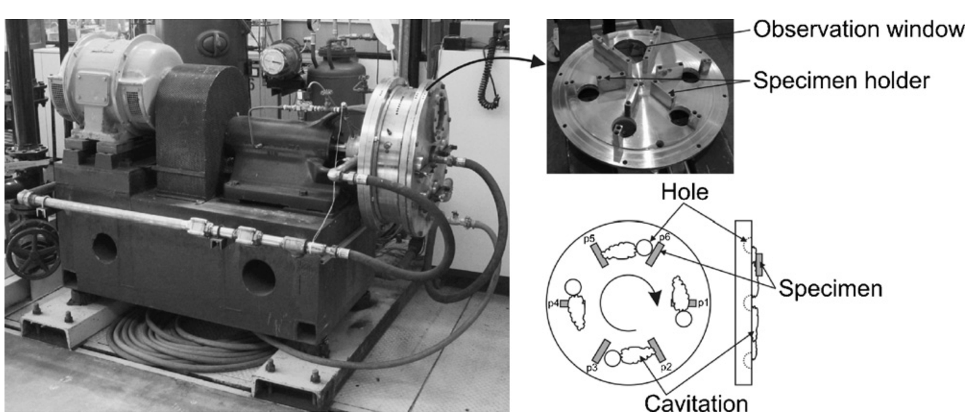

Fig. 1. Rotating disc test rig (left) and cover with specimen holders and cavitation (right).

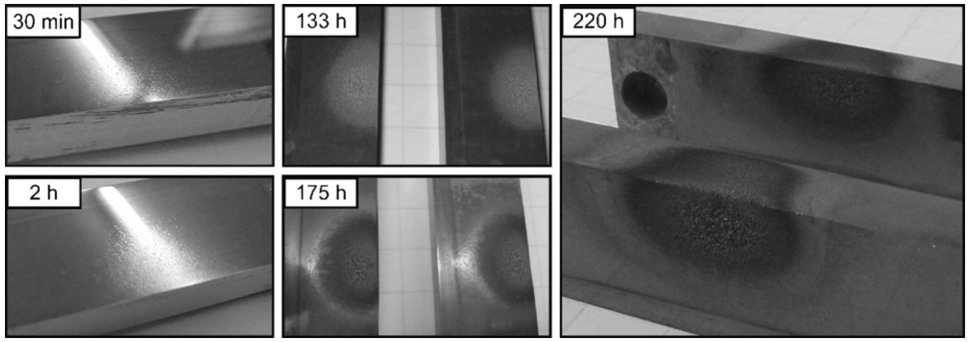

Fig. 2. Specimens after different times of exposure to cavitation.

Pitting of the surface can be seen with a naked eye almost immediately after the start of the experiment. After 30 min, pitting is already so extensive that pit-count method is not valid due to overlapping of pits, but mass loss is still not present (or at least it is not measurable). As the time progresses more and more pits appear and eventually parts of the specimen get separated. At the end of this experiment, after 220 h of exposure to cavitation, mass loss of 0.1 g was measured, what corresponds to approximately 11.5 mm^3 of lost material.

4.1. Incubation period

At the beginning of the experiment the specimens were removed from the test rig after 2, 5 and 9 min and images of the damaged surface were taken under a microscope. In all 299 images for the top surface and 138 images for the side surface were taken. Individual images were then pasted together to form a high resolution image of the damaged surface. Fig. 3 shows the surface of the specimen after 2, 5 and 9 min of exposure for the case of high rotating frequency (1800 min^{-1}). Different shading of the surface is a result of the light, which was adjusted manually and should not be related to erosion.

Even after only 2 min of exposure, pits on the surface can be evidently seen. The magnitude of damage grows significantly when the specimen is exposed to the cavitation for a longer period of time. As a result of very local aggressive cavitation that is generated by the rotating disc, the region where pits are appearing remains constant—in the middle of the specimen near the edge between the top and the front surface. In general, the top surface sustained more damage since it was oriented toward the collapsing cavitation clouds. Although damage after 9 min seems to be extensive, still no mass loss could be determined. Pursuing optical evaluation after longer exposure was meaningless since too many pits were overlapping and pit-count evaluation (quantification of results) could not be performed.

To quantify the results like those in Fig. 3 the pit-count method was applied. Figs. 4 and 5 show results of evaluation for rotating frequencies 1500 min^{-1} and 1800 min^{-1} (two specimens per each case). Only the areas within the dashed lines were directly exposed to cavitation and were later evaluated. The results are given in a form of contour diagrams where white color presents undamaged surface while the black relates to the 6.8% (1500 min^{-1}) or 10.03% (1800 min^{-1}) of the area in the individual image that was damaged–covered by pits.

Obviously the specimen 1 receives more damage than the specimen 2. The reason lies in the arrangement of the specimens on the circumference of the rotating disc. As already mentioned specimen holders in positions p5 and p6 (Fig. 1) were empty what gave cavitation enough time or space (180 degrees of the disc rotation) to grow and severely damage the material specimen in position p1. Specimen in position p2 sustained less damage because cavitation did not have enough time (space) to grow (only 60 degrees of the disc rotation) and to become more aggressive. This “discrepancy” was actually desired since it increased the ensemble of the tested cavitation conditions. Despite different aggressiveness of cavitation the affected regions are the same for both specimens. A more detailed study of this “anomaly” can be found in Bachert [10].

Results obviously show a great increase of damage as the rotating frequency was increased to 1800 min^{-1}. It is well known that a power law relation with exponent lying in the range from 5

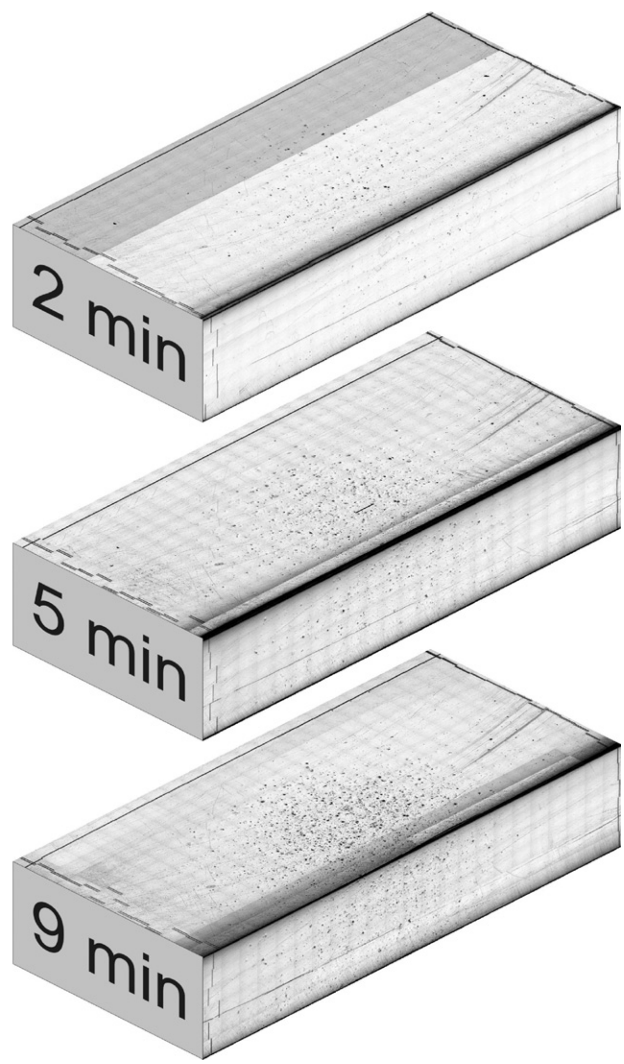

Fig. 3. Surface of the specimen after 2, 5 and 9 min of exposure to cavitation (1800 min^{-1}).

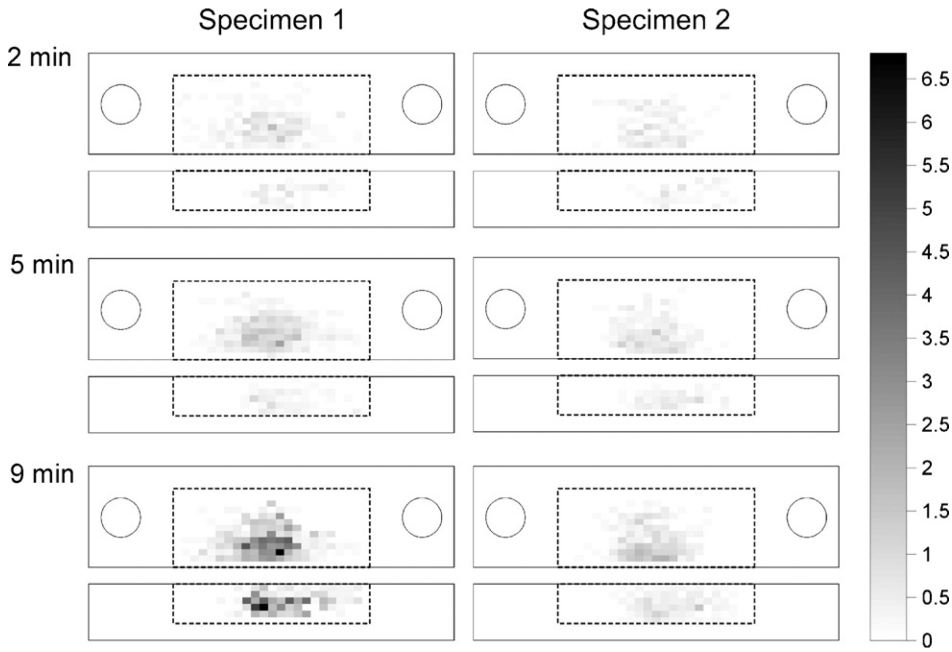

Fig. 4. Pit-count evaluation of damage at rotating frequency 1500 min^{-1}.

to 8 between cavitation aggressiveness and velocity exists (Franc and Michel [5]). To investigate whether the present measurements agree with this law the whole damaged area (the part of the whole surface that is damaged (covered by pits)) was deducted from the pit-count measurements. The exponent for the present case corresponds to the range 5–8 as it varies from 5.7 to 8 with an average value of 6.82.

Obviously the damage grows at a linear rate when erosion within the incubation period is observed. As expected the pitting rate is higher at a higher rotating frequency and on the first specimen. The fact that the damage grows at an linear rate means that pit-count method is valid even after a very short period of exposure and also that the pitting rate can possibly be related to the mass loss rate after longer period of exposure to cavitation. If this is so, the time of measurements of material resistance to cavitation could be significantly reduced.

4.2. Mass loss

The periods between weighing of specimens varied during the experiment—from every half an hour at the beginning to as long as every 15 h at the end of the exposure to cavitation. Figs. 7 and 8 show results of mass loss measurements for both cases—low and high rotating frequency (for two specimens in each case).

About 20 h of exposure were needed to detect mass loss (0.1 mg) for the case of low rotating frequency. After that the mass loss grew at an exponential rate until it settled at a constant rate. This occurred after about 170 h. As expected, due to the already men-

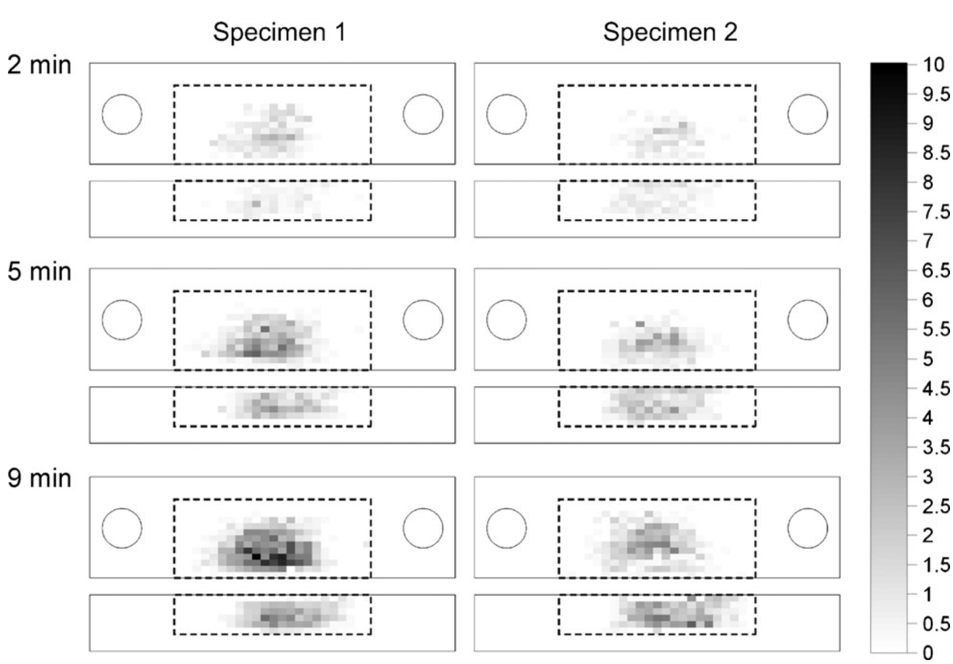

Fig. 5. Pit-count evaluation of damage at rotating frequency 1800 min^{-1}.

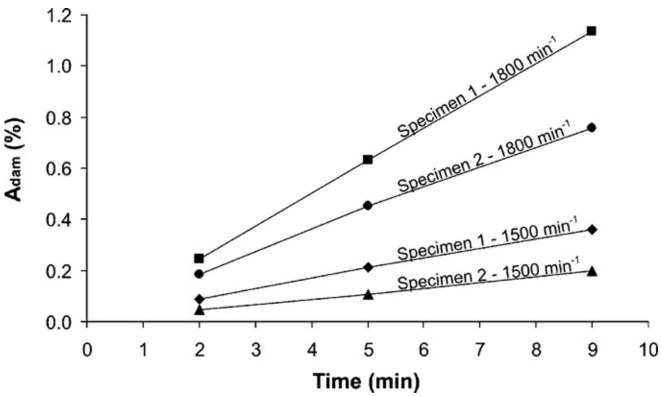

Fig. 6. Time evolution of the damaged surface area.

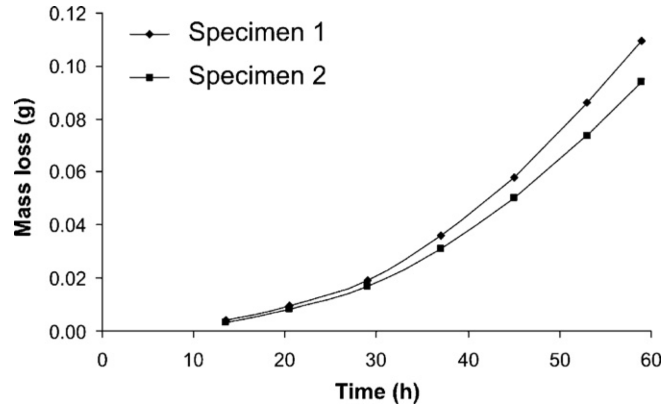

Fig. 8. Mass loss at rotating frequency 1800 min^{-1}.

tioned reasons, specimen 1 suffered more erosion. The experiment was stopped when the mass loss reached 0.1 g, what occurred after 220 h of exposure to cavitation.

For the case of higher rotating frequency the first measurement was made 13.5 h after the start of the experiment—mass loss of about 4 mg was measured at that time (the same mass loss was detected after about 70 h of exposure at a low rotating frequency). The same trend as before can be seen—an exponential growth of mass loss that begins to settle after about 45 h. The experiment was again stopped when 0.1 g of material was lost—this occurred just a little sooner than 60 h after the start of the experiment.

If one calculates the exponent in the power law (Franc and Michel [5]) and uses the time that was needed to detect 0.1 g of mass loss as the parameter of cavitation aggressiveness, a value of 7.1 is deducted, which again lies within the expected range.

5. Discussion

One of the most important questions of this study is whether it is possible to relate pit-count measurements to the mass loss rate. The easiest way to investigate the possible relation is to compare the pitting rate from the incubation period (Fig. 6) to the rate of mass loss near the end of the experiment, when it was already settled at a more or less constant value (Figs. 7 and 8).

The material volume separation rate ($\dot{V}_{\text{mass loss}}$) was compared to the rate of appearance of volume of pits ($\dot{V}_{\text{inc}}$). In order to calculate the volume of pits their depth was needed. This was deducted from the previous study where laser profilometry measurements (LEGI—Grenoble) and pit-count measurements (TFA—Darmstadt) of a pitted surface of a copper specimen were compared (Reboud et al. [11] and Lohrberg et al. [12]). The average depth of the pit was 0.7 μm. Also a conical shape of the pit was assumed (Fortes-Patella et al. [13]). This way pitting and mass loss rates in mm^3/h could be calculated and compared (dividing the mass loss rate by pitting rate)—Table 1.

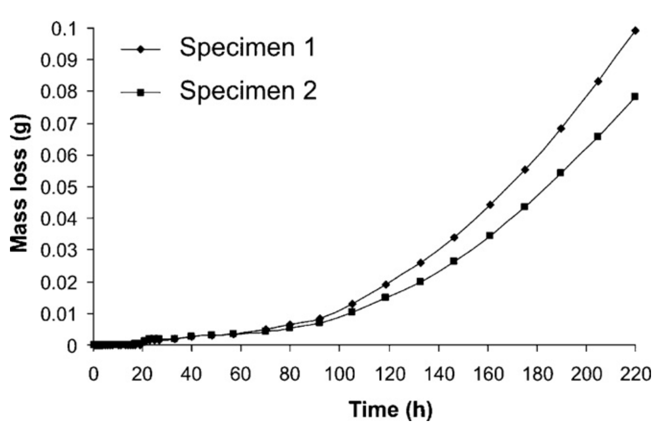

Fig. 7. Mass loss at rotating frequency 1500 min^{-1}.

If the relation exists, the factor between the pitting and the mass loss rate should be the same for all cases. We can see that it lies between 27.7 and 42.6, which is in our opinion still plausible and it proves that the pit count measurements can indeed be used for qualitative prediction of cavitation erosion rate in the period where mass loss is significant. One could argue that when the erosion rate is small the coefficient is evidently higher, but in our opinion it hard to defend such thesis at this point. If the measured trend is in fact valid (the factor between the pitting and the mass loss rate decreases in the case of more aggressive cavitation) and not just a result of a chance, we cannot, at the present time, give any plausible explanation for it.

Probably it is more important to acknowledge that the coefficient is independent of the velocity—values for both rotating frequencies are practically the same. This is more or less expected since the power law, that links cavitation aggressiveness and flow velocity, is valid for both the incubation and mass loss periods. The other conclusion that can be drawn from this is that, with additional experiments, a relatively simple scaling law could be obtained.

Also the value of the coefficients *f* should not be used as a fact—it is more important to know that they are more or less independent of the specimen position, flow velocity and cavitation aggressiveness.

Another issue regards the type of the material. Experiments where brass and stainless steel specimens are used are currently under way. The duration of these experiments is much longer than for experiments where copper specimens were used, but the first results show that qualitatively similar results will be obtained. This points to the idea that the current study is applicable to any other non-brittle metallic material.

Table 1
Results of damage rates during incubation and mass loss and coefficients between them.

	Specimen 1	Specimen 2
$\dot{V}_{\text{inc}}$—1500 min^{-1} (mm^2/s)	0.0040	0.0022
$\dot{V}_{\text{inc}}$—1800 min^{-1} (mm^2/s)	0.0130	0.0083
$\dot{V}_{\text{mass loss}}$—1500 min^{-1} (mm^2/s)	0.111	0.088
$\dot{V}_{\text{mass loss}}$—1800 min^{-1} (mm^2/s)	0.415	0.355
f, 1500 min^{-1}	27.7	40.1
f, 1800 min^{-1}	32.1	42.6

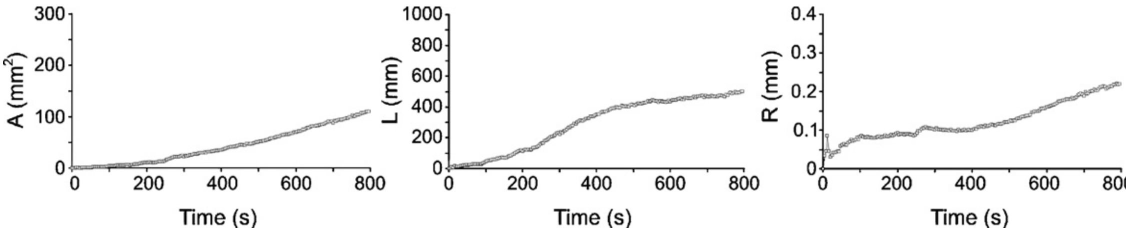

Fig. 9. Diagrams of time evolution of *A*, *L* and *R* for the experiment with acoustic cavitation.

6. Ongoing research

To further simplify and accelerate the experiments a method where a thin aluminum foil is exposed to ultrasonic cavitation was developed. Here erosion was observed throughout the process and the time evolution of pitting and later on of mass loss rate could be evaluated. Visual evaluation of erosion was performed by measuring the area of the damaged surface *A* and the length of the boundary between the damaged and undamaged surface *L*. The characteristic pit/hole size *R* (*A*/*L*) was additionally calculated. Details of the experimental set-up and evaluation can be found in Dular and Osterman [7]. The first results of measurements confirmed that a relationship between the damage in the incubation period and the final mass loss rate exists.

During experiments images of the foil were taken every 4 s for a period of 800 s. The experiment was repeated at the same conditions several times. The results were comparable so any greater influences like unevenness of the foil, water quality, foil position, etc. were ruled out. The results from one of the experiments are presented in the diagrams in Fig. 9.

The first diagram represents the area of the damaged surface. It increases exponentially in time–similar to the experiments in rotating disc cavitation. The second diagram presents results of the evolution of the length of the boundary between the damaged and the undamaged surface. It grows very slowly at first, then starts to accelerate and progresses at a slightly lower rate towards the end of the experiment. This evolution can be explained by the fact, that at the beginning, single isolated pits are appearing in the foil what results in low growth rate. Isolated pits act as a quasi cavitation generator that promotes formation of new pits—this reflects in acceleration period. Finally the first holes in the foil appear—mass loss is present. Since the erosion now concentrates to the boundaries of newly formed holes, the rate of growth of the edge length decreases and remains approximately constant until the end of the experiment. Finally the characteristic pit/hole size evolution is presented in the third diagram. At first *R* is almost constant in time what can be related to the period where single pits are appearing. As the first holes appear the damaged area *A* starts to grow faster than the boundary *L*, resulting in exponential growth of characteristic pit/hole size *R*.

A question that we wanted to addressed is whether a relation between the pitting rate and the mass loss rate exists or not. Damage evolution at the beginning of the experiment shows almost a constant pitting rate, similarly the rate of “mass loss” at the end of experiment is close to a constant—this was found for all experiments. When a coefficient f_{acoustic} ($f_{\text{acoustic}} = \dot{A}_{\text{mass loss}}/\dot{A}_{\text{inc}}$) was calculated for the executed experiments, similar values were obtained—from 2.62 to 3.34. The values are not exactly the same but they still do not differ too much to reject the hypothesis of close relation between pitting rate in the incubation period and mass loss rate after longer exposure to cavitation. The values also differ significantly from the ones obtained at a rotating disc test rig but this was expected due to different type of cavitation, different material and lastly somewhat different definition of the coefficient *f*.

7. Conclusions

A long term study of cavitation erosion was performed. Damage was studied during the incubation period and also during mass loss period. The paper showed, for the first time, a combination of optical and mass loss measurements of cavitation erosion. By evaluating the pitted surface during the incubation period a linear increase of damage in time was determined. The linearity was independent of the specimen position or cavitation aggressiveness. This means that only very short tests can be conducted and the results can then easily be extrapolated until the end of the incubation period. Another important recognition is that only a short time pitting test is sufficient for evaluation of damage within the incubation period and that pit clustering and pit overlapping problems (Dular et al. [6]) can easily be avoided.

Later on specimens were removed from the test rig several times and weighed. Mass loss tests showed expected evolution of erosion (first the accelerated rate of mass loss and later a linear rate of mass loss).

By comparing the results of measurements during incubation period and mass loss period, a more or less constant relationship was revealed. Measurements actually showed a trend of a decrease of factor f for the case of more intensive cavitation, for which we cannot offer a logical explanation—we believe that it is a result of chance.

It was also found that the relationship between the damage measured within the incubation period and the mass loss rate is independent of the flow velocity (rotating frequency).

The findings of this study could lead to considerable reduction of time needed to evaluate materials resistance to cavitation erosion and could contribute to cavitation erosion prediction models that are implemented into Computational Fluid Dynamics codes (Dular and Coutier [14]).

Acknowledgments

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