Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 18
ISSUE 1-2
September–October
2006

On the importance of initial volume of eroded material for cavitation erosion curve

M. Szkodo *
Faculty of Mechanical Engineering, Gdańsk University of Technology,
80-952 Gdansk, ul. Narutowicza 11/12, Poland
* Corresponding author: E-mail address: mszkodo@pg.gda.pl

Received 15.03.2006; accepted in revised form 30.04.2006

Analysis and modelling

ABSTRACT

Purpose: Cavitation erosion is a surface degradation mechanism which occurs most frequently in fluid-flow machines operating in cavitation conditions. To find way to prediction the cavitation erosion progress, simple mathematical model was proposed.

Design/methodology/approach: The model assumes that curve of cumulative volume loss as a function of time approaches initial volume of eroded material. This principle causes dependence of cavitation erosion curve not only from mechanical properties of eroded material and cavitation loading but also from dimensions of initial volume i.e. eroded area of material and even height of cross-section of eroded initial volume of material.

Findings: Assessment of cavitation erosion resistant of material upon the base of cavitation erosion curve has to take into account this influence. In the paper the influence of these parameters on the cavitation erosion curve was discussed.

Research limitations/implications: Future research concerning cavitation erosion resistance of materials ought to takes into account influence of initial volume of eroded material for cavitation erosion curve. Reported research ought to be completed and full cavitation curves (volume loss in time) for different initial volume of eroded material must be done.

Practical implications: Existing standards have recommended assessment of cavitation erosion resistance of materials by comparison of their erosion curves (volume loss in time and volume loss rate of erosion). For this reason one should strive to explanation all factors influencing on the cavitation erosion curve.

Originality/value: The work proposes a mathematical model which permits to define the influence of initial volume of eroded material on the cavitation erosion curve.

Keywords: Computational material science; Cavitation erosion curve; Evaluation of cavitation erosion resistance

1. Introduction

Cavitation is defined as the phenomenon of formation and collapse, within liquid, of cavities or bubbles that contain vapour or gas or both of them. The bubbles appear in a liquid at locations of low pressure in a flow field. Next bubbles expand until they enter regions of higher pressure and implode violently. During these implosions pressure peaks are emitted from the bubbles, which may have an amplitude of some 10 000 bars and higher [1-4]. A great amount of noise is emitted during implosions but the most important effect is cavitation erosion of material. Cavitation erosion is a progressive loss of material from a solid due to the impact action of the collapsing bubbles or cavities in the liquid near the material surface. Cavitation erosion is a common problem in engineering parts in contact with a liquid in which the local pressure fluctuates, and cavitation damage will lead to shortening of service life or maintenance cycle. The failure of mechanical heart valve, pipelines, pumps, water turbine blades and other hydraulic sets can often be attributed to cavitation erosion. This work proposes a mathematical model which permits to define the influence of initial volume of eroded material on the cavitation erosion curve.

2. Cavitation erosion of materials

It is well known that typical cavitation erosion curves determined in the lab have four period of destruction of eroded material. The first, incubation stage, is an initial period of damage in which the volume loss of material is non-measurable. The intensification of damage is observed in the second period of cavitation erosion. In this time fast increase of the volume loss rate of erosion follows. Volume loss rate reaches maximum value at the end of this period. Next a weakening of damage is observed, and the volume loss rate decreases (Fig. 1). Finally, the fourth period, is characterized by an almost constant volume loss rate of erosion.

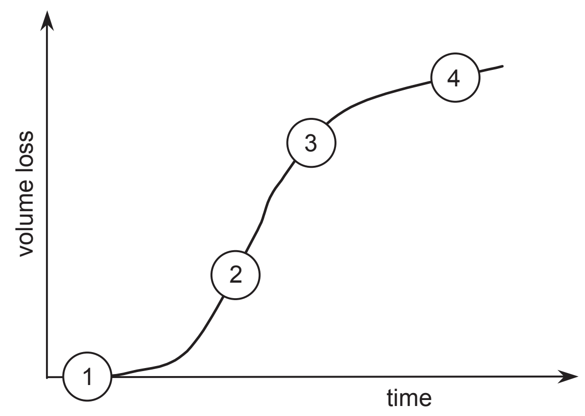

Fig. 1. Cavitation erosion curve

3. Mathematical model describing of cavitation erosion curve

In order to mathematical description of cavitation erosion curve it was made an assumption that the volume loss curve approach initial volume of eroded material i.e.

$$\lim_{t \to \infty} V(t) = V_0 \tag{1}$$

It is worthwhile to notice that this principle causes that cavitation erosion curves depend not only on the mechanical properties (cavitation erosion resistance of eroded material) and intensity of cavitation loading but also depend on the dimensions of initial volume of eroded material (see Fig. 2).

By examining Fig. 2 can notice that incubation time, maximal volume loss rate, total volume loss after defined time and other factors characterising the cavitation erosion resistance of materials defined upon the base of cavitation erosion curves are different and depend on the initial volume of material. In the presence of that quantitative estimation of cavitation resistance based on traditional single-number parameters, like MDPR or incubation period can lead to ambiguous conclusions.

For example during International Cavitation Erosion Test (ICET) which was coordinated by Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdańsk, results of cavitation erosion resistance measurements for six investigated materials obtained in different scientific centers in all over the world were incomparable.

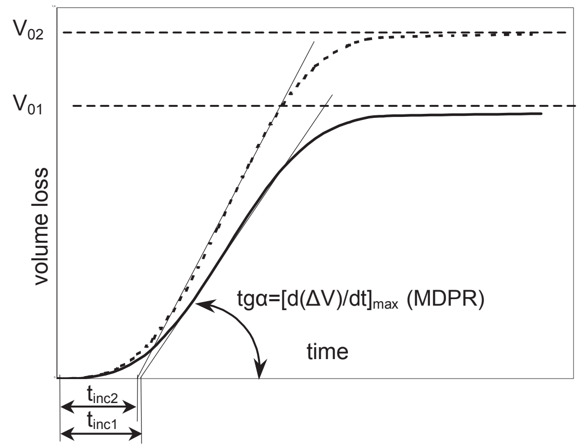

Fig. 2. Cavitation erosion curves for the same materials and the same intensity of cavitation loadings but different initial volume (V_{01} and V_{02})

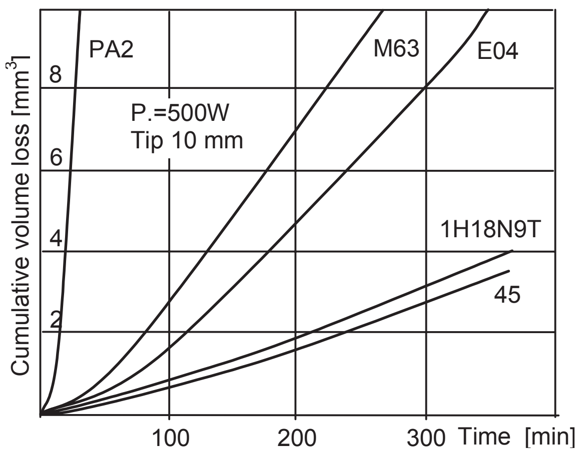

Fig. 3. Cumulative volume loss curves of the ICET test. Materials tested at the vibratory rig in University of Cape Town, Rondebosch, South Africa

The experimental programme consisted in testing 6 selected materials (single phase aluminium alloy – PA2, single phase brass – M63, Armco iron – E04, mild carbon normalised steel – 45, chromium-nickel austenitic stainless steel – 1H18N9T and polyamide 6 plastics). Chemical composition, mechanical properties and further data, including main design and operating parameters of the test rigs as well as heat treatment conditions of metallic materials are to be found in Refs [5-8]. Some results of ICET test are presented on the Fig. 3 and 4. As can be seen from these figures proper interpretation of results obtained is not possible without taking account of not only the mechanical properties of tested materials and intensity of cavitation loading but also initial volume of eroded materials. Comparison curves for example for brass M63 revealed that volume loss after 200 min is higher for curve obtained in University of Hull (12 mm^3) than in the same time in University of Cape Town (7 mm^3) in spite of input power was lower (200W in University of Hull and 500W in University of Cape Town). It was the case because in lab in University of Hull cavitation loading comprise greater area (tip diameter 13 mm in University of Hull and 10 mm in University of Cape Town). The initial volume is a product of surface area and height of sample. Thus both the parameters influence on the cavitation erosion curves.

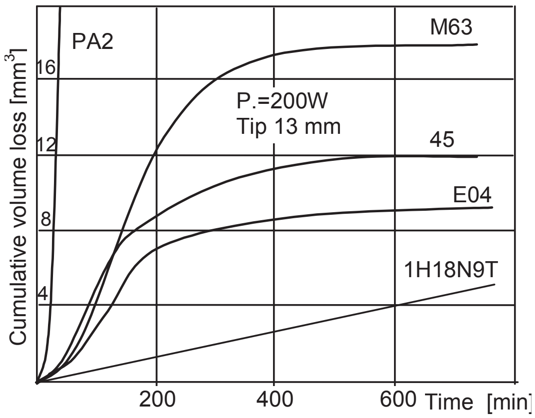

Fig. 4. Cumulative volume loss curves of the ICET test materials tested at the vibratory rig in University of Hull, Great Britain

Description of cavitation erosion curve can be written by following equation [9]:

$$V(t) = V_0 \cdot P(V_0) \tag{2}$$

with $V_0 = A \cdot H$ denoting the initial volume of eroded material and $P(V_0)$ is a cumulative volume loss probability for eroded volume V_0.

The function describing probability of cumulative volume loss has to depend on the mechanical properties of eroded material and intensity of cavitation loading. A frequently used model assumes the volume loss in the initial damage period to be proportional to the Weibull distribution function. For description of cavitation erosion curves this kind of function was proposed in [10]. Probability of cumulative volume loss can be written down as [9]:

$$P(V_0) = \left[1 - \frac{1}{e^{f(t)}}\right]^a \tag{3}$$

where a is a H/h proportion (see Fig. 5), and $f(t)$ is the erosion progress function.

Erosion progress function can be defined as [9]:

$$f(t) = E \cdot \left(\frac{t}{K_{cd}}\right)^{R_p} \tag{4}$$

where: E – energy delivered to the volume unit (eroded surface layer) by a collapsing cavities and cavitating vortices,
K_{cd} – relative stress intensity factor of hardened surface layer under cavitation loading,
R_p – relative resistance to plastic deformation under cavitation loading,
t – time.

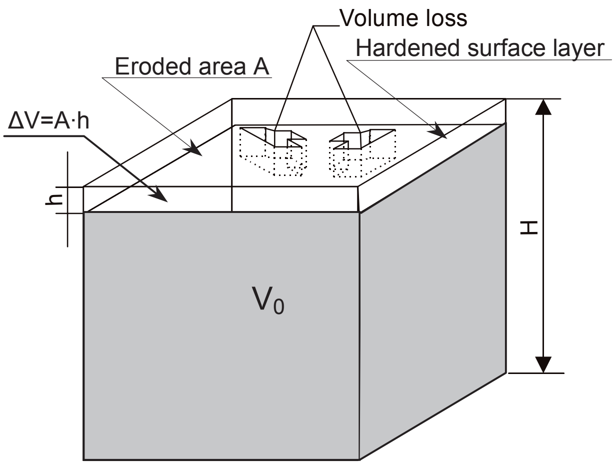

Fig. 5. Scheme of initial volume of eroded material

The concept of linking the volume loss ΔV with the energy E absorbed by eroded material is due to Thiruvenawgadam [8] who used the formula:

$$E_a = \Delta V \cdot S_c \tag{5}$$

with ΔV denoting volume of eroded surface layer and S_c erosion strength parameter.

In order to define parameter S_c Steller proposed in [12] a method taking account of the effective cavitation pulses distribution on the eroded surface. His conception assuming application of transducers takes account of both micro and macro pulses and make the measurement independent of the transducer membrane size. The method of distinguishing between the micro and macro pulses is based on criterion of time shift between peaks identified at two transducers. According to this conception equation describing intensity of cavitation loading has form:

$$ME = C \cdot \left(\frac{A}{A_0}\sum_i n_i p_i^2 + \sum_i N_i P_i^2\right) \tag{6}$$

where small letters have been reserved for the micro pulses acting only on a small fraction of the membrane surface while capitalics are used to describe the macro pulses due to collective phenomena acting on the whole membrane surface. A and A_0 symbols are used for the membrane surface of the current and reference transducer, respectively.

If relative intensity of cavitation erosion to write down as parameter I then according to the equation (5) energy E absorbed by eroded material will be:

$$E = \Delta V \cdot I = A \cdot h \cdot I \tag{7}$$

where: I – intensity of cavitation loading (constant on the eroded surface),
h – depth of strain hardening or maximal length of cracks on the end of incubation period,

Taking into account equations (2), (3) (4) and (7) the volume loss curve describing cavitation damage of material derived takes the form:

$$V(t) = A \cdot H \cdot \left\{ 1 - \exp\left[-I \cdot A \cdot h \cdot \left(\frac{t}{K_{cd}} \right)^{R_p} \right] \right\}^{\frac{H}{h}} \tag{8}$$

By examining equation (8) one can notice that cavitation erosion curve depends from three groups of parameters. The first group contains materials parameters i.e. relative stress intensity factor of surface layer under cavitation loading (K_{cd}), relative resistance of eroded material to plastic deformation under cavitation loading (R_p) and also depth of eroded surface layer defined as a depth of strain hardening. In the second group there is parameter describing cavitation loading intensity and parameters connected with initial volume of eroded material i.e. surface area A and height of sample H are contained in the third group respectively.

Fig. 6 presents the influence of dimension of eroded area on the cavitation erosion curve calculated upon the base of Eq. 8. How results from Fig. 6 increase of eroded area quantity causes shorten of incubation period which is one of the parameters characterising the cavitation erosion resistance of materials. Increase of eroded area causes also increase of maximum volume loss rate.

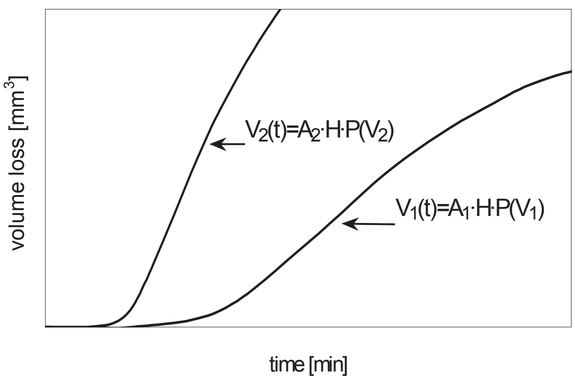

Fig. 6. Influence of eroded area quantity on the volume loss of material for the same intensity of cavitation loading

Therefore small differences in distribution of cavitation loading, can significance change of eroded area and the same change of cavitation erosion curves. In consequence prognosis of cavitation erosion resistance of eroded material is made difficult. That why for the reasons mentioned above it is very important to define of a quantity of eroded area together with cavitation erosion curve.

4. Conclusions

Existing standards [13-15] have recommended assessment of cavitation erosion resistance of materials by comparison of their erosion curves. For this reason one should strive to explanation all factors influencing on the cavitation erosion curve. Made considerations allow to draw some general conclusions concerning influence of eroded area quantity and height of eroded element on the cavitation erosion curve:

1. Increase of eroded area causes shorten of incubation time duration, shorten time after maximal volume loss rate follows and also increase maximal volume loss rate.
2. If cavitation erosion test is carry out for thin samples and depth of erosion penetration reaches value equal height of sample there is possible influence of eroded height element on the cavitation erosion curve.

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