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BOLESŁAW GIREŃ[*]

A single-parameter predictor of the effectiveness of the cavitation erosion process

Key words

Cavitation, erosion, scaling, fatigue.

Słowa kluczowe

Kawitacja, erozja, skalowanie, zmęczenie materiału.

Summary

A parameter pertaining to material susceptibility to cavitation damage under identified loadings is proposed. A probability mass function of cavitation loadings is suggested to represent environmental conditions and fatigue performance of a material at a specified standard regime, as the material properties are considered to control the performance of the erosion process and are suggested to be taken into account for its quantification. Therefore, the value of the parameter is assumed to follow from calculations employing the probability mass function of the loadings and fatigue characteristics of the material, as well as energy absorption in stress-strain cycle of the loading, corrected for the presence of inhibiting processes. The appropriate threshold conditions for erosion are assumed to follow from the relationship between the inverse fatigue function and the loading distribution. In this paper, a preliminary experimental verification of the correlation between the postulated parameter and the cavitation erosion parameter is carried out. The reliability and applicability of the parameter as well as the sources of inaccuracy and uncertainties are also discussed.

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[*] The Szewalski Institute of Fluid Flow Machinery of the Polish Academy of Sciences, 80-231 Gdańsk, ul. Fiszera 14, Poland, e-mail: giren@imp.gda.pl.

Introduction

Approaches to the prediction of cavitation erosion performance

According to the description in [1], surface damage of materials placed within the collapse zone of a cavitation cloud occurs under the action of forces arising from bubble implosions, occurring as collective or uncorrelated events. Cavitation erosion may be a vital problem in many liquid-flow systems, such as ship propellers, hydraulic turbines or valves, being a reason of major concern for hydraulic equipment designers and users. Quantification of material damage under cavitation loading consists in assessing surface changes in the initial period of the process or measuring the mass loss in the advanced stage of the erosion.

A quantitative description of the process by model equations, usually founded on conservation laws, refers to either energy or dynamics criteria. Both the loading conditions and temporary physical properties of the impinged solid surface should be taken into account in the quantitative description of the process that may be considered stationary only in a probabilistic sense.

Specifically, cavitation erosion depends on the type of the loading cloud, its spatial distribution, average pressure, the dynamics of local forces, the amplitude and probability mass function of pulses, the surface morphology of the solid, its chemical composition, microstructure, physical state (e.g. residual stress), and resulting strength parameters. Moreover, when thin coatings are under consideration, the dependence of the process on solid geometry should not be neglected. The influence of various determinants on eroded material performance was investigated by numerous researchers, e.g. [2–7]. The precise prediction of the cavitation erosion progress is a challenging task due to the high sensitivity of the process, which is proven by the enormous scatter of the mass loss recorded in different experimental tests conducted at conditions differing only by quality characteristics of the loadings [8].

The noticeable diversity in relationships between the performance of the erosion and (1) time/space characteristic of the loadings of given magnitude or (2) the variation of microstructure with given physical parameters is due to the stochastic nature of the process, including the stochasticity of the initial conditions (e.g. [9]). The appropriate stochastic description may be derived using the analogy of the fatigue process, where material degradation is modelled by a chosen stochastic process in the continuous time domain [10].

However, the problem of predicting cavitation erosion effectiveness is still unresolved satisfactorily, since the known phenomenological and others models, e.g. [11–19], are of limited applicability, due to (1) radical simplifications, (2) the necessity to use experimental data of an actually investigated process or (3) troublesome and extended experimental work for setting model parameters. Another deficiency is that formulations of the models do not account for incubation, acceleration, and long-term exposure wear periods with equal precision.

On the other hand, a promising way of setting the method for cavitation aggressiveness prediction consists in finding the convenient scaling or similarity laws. There were some attempts to do so (e.g. [20–23]), especially to find a dependence of the erosion intensity on fluid velocity, geometric length scale, and acoustic impedance of the liquid. The revealed dependencies are mostly valid in the incubation period of the erosion. Semi-empirical formulas applicable in scaling can be found in other works, e.g. [14, 24–26]. The power-law relationship between the average erosion rate and cumulative erosion was defined in [24], the aggressiveness of the loading during the incubation period was analysed quantitatively in [26] using obtained similarity laws. Analytical formulation of the cavitation erosion rate was derived in [14], having taken into account both the properties of the material being eroded and the cavitation flow conditions. However, mechanical and material parameters are defined under specific cavitation load conditions, which makes the cavitation erosion test experiment necessary for each considered case.

Another scaling approach to cavitation damage was presented in [27], where mass loss was linked to impact energy and presented as a function of the threshold level of loading intensity for material damage and cumulative impact energy exceeding the threshold value. The existence of the threshold level was revealed experimentally. “Threshold level” in that concept is a material property being a parameter facilitating the prediction of cavitation erosion.

The aim and the scope of the work

The aim of the present paper is to consider the usefulness of setting up a predictor (κ), pertaining to material susceptibility to cavitation damage under identified loading conditions. Such a parameter is to be unambiguously linked to cavitation erosion efficiency by conditions of the experiment.

Having assumed that cavitation damage is strongly correlated with the fatigue strength of the material, κ is being proposed to follow from calculations employing both environmental conditions and material properties including the following:

- The probability mass function of cavitation loadings and
- The fatigue performance of the material at a specified standard regime,

including energy absorption in stress-strain cycle of the loading and the presence of an inhibiting processes.

The appropriate threshold conditions for erosion are assumed to arise from the relationship between inverse fatigue (Wöhler) function and loading distribution.

In this paper, preliminary experimental verification of the correlation between the postulated parameter and cavitation erosion parameter MDPR (mean depth penetration rate) is carried out. Moreover, the reliability and applicability of the parameter as well as sources of inaccuracy and uncertainties are discussed.

Physical premises

Cavitation erosion as individual process

Cavitation erosion should be dealt with as an autonomous type of material damage, governed by its own rules. The need for this approach is due to the peculiarities of cavitation loading: short impact time, comparable to relaxation period of viscous volume forces of fluid [28], infinitesimal area of impact action, and the randomness of the impingements, allowing for a large number of different destruction mechanisms occurring at the same time. Observations of stress fields and material degradation modes have revealed a lack of any similarities of cavitation erosion to other damage processes in solids [29]. This conviction may be also derived from simple mathematical inference: let ξ be the rate of changes in solid surface morphology quantified by variable ζ, that is $\frac{\partial \varsigma}{\partial t} = \xi(F, x_1, \ldots.., x_n)$, where ξ is a function of temporary loading level (force) F and (x_1 , ..., x_n) a set of temporary physical parameters of the material. The simplest relationship between ξ and F may, by assumption, take the form $\frac{D\xi}{Dt} = \alpha F$, where α is a coefficient of proportionality. Assuming the function $\xi(F, x_1, \ldots, x_n)$ is implicit yields the function $\alpha F = \vartheta(F, x_1, \ldots.., x_n)$ which is also implicit. Furthermore, an ambiguity of dependence of ξ on physical parameters of the material increase if stochasticity of the considered variables are taken into account.

Fatigue nature of cavitation erosion process

On the other hand, it has been established that cavitation damage is strongly correlated with fatigue strength of the material [30–33], e.g., a linear relationship, in the dual logarithmic system, between cavitation erosion resistance of three structural steels and their fatigue strength under random tension-compression with zero mean value was found [33], and production of fatigue-like deformations and damage accumulation was confirmed by finite element modelling [32]. One can also find some results that support this opinion in an indirect way [34, 35].

Accounting only for cavitation loading makes the assumption on the process progress according to the cumulative damage law well founded. Fatigue-like erosion within an incubation period follows Miner's law of impact loads, regardless of the cavitation conditions and the materials [36].

Threshold value of impacts for contribution to cavitation erosion

Due to the nature of the process, only pulses with height exceeding a certain threshold value contribute to fatigue damage of the material surface layer [37]. In [38], the threshold loading pressure corresponding to the inception of damage pits was evaluated. Other relevant experimental observations were presented in [26, 36].

Inferences from Griffith theory

An accumulation of the plastic deformations during the fatigue process makes a state of the material that fatigue cracking is of the brittle nature [39–41].

Griffith's theory assumes that derivatives of crack surface energy and elastic (volume) energy with respect to crack growth are equal for brittle cracking. Therefore, the sum of volume energy (E_v) and surface energy (Γ) at critical (unstable – brittle cracking) conditions are constant: $(E_v + \Gamma) = const = \lambda$. Energy absorbed during interaction is considered to depend solely on the type of the cracking process and material state, as well as its temporary properties. The critical state of the material is reached under cyclic loading both at standard fatigue or cavitation erosion tests. Assuming the proportionality of λ to the number of cavitation impacts of various amplitudes, yields: $\lambda = \alpha f_{cav}(n_1, n_2, ...n_i)$, where n_i means the number of operative (over-threshold) loadings with heights from the *i*-th subinterval. A similar relationship may be valid for the fatigue process: $\lambda = \beta f_{fat}(n_1, n_2, ...n_i)$. Hence $\frac{f_{cav}(n_1, n_2, ...n_i)}{f_{fat}(n_1, n_2, ...n_i)} = \eta$, η is constant over the whole range of impacts levels for the probability mass function of cavitation loadings preserved invariable.

Proposal for a new index

Methodological concept

Plots of the cavitation pulses distribution (Curve 1) and the inverse Wöhler fatigue function (Curve 2) are presented in an ideological diagram in Fig. 1. The curves pertain to specific erosion conditions (Curve 1) and the fatigue function of a chosen standardised type for the material under consideration (Curve 2). The number of pulses in the cavitation-loading curve refers to the fixed time of material exposition to the loading, e.g. 5-min. Each point in the curves drawn as continuous lines represents the average number of pulses/cycles in the loading interval of specified width surrounding the point under consideration. Usually, those types of curves are presented in logarithmic scales.

The probability of material damage in a fixed time of exposition (accompanied with material piece extraction) due to the action of impacts greater than pressure assigned by "*b*" is 1. If the impact pressure lies between points "*a*" and "*b*," the probability of the material damage depends on the ratio of the number of impacts to the number of cycles revealed in diagram. Impacts of pressure less than pressure assigned by "*a*" do not contribute to the process of material erosion.

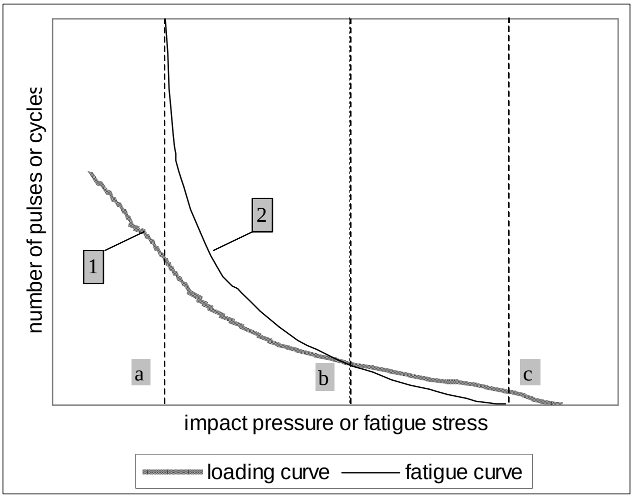

Fig. 1. Ideological presentation of the following functions: distribution of cavitation loading pulses (Curve 1) and inverse Wöhler fatigue function (Curve 2): "a" – lower limit of fatigue loading, "b" – pressure at which the number of fatigue cycles equals the number of detected impulses of the same pressure level, "c" – the highest detected pressure of the impacts

Rys. 1. Zestawienie schematycznego przedstawienia funkcji rozkładu impulsów kawitacyjnych (krzywa 1) oraz funkcji odwrotnej do funkcji zmęczeniowej Wöhlera (krzywa 2): „a" – minimalne naprężenie w procesie zmęczeniowym, „b" – naprężenie, przy którym liczba cykli zmęczeniowych jest taka sama jak liczba rejestrowanych impulsów o tym samym ciśnieniu, „c" – najwyższe rejestrowane ciśnienie impulsów

An approach presented enables to assess the probability of (any) piece extraction in the unit time and to find out the probability distribution function. The latter should be a three-parameter logarithmic-natural distribution function [42, 43].

The number and its interpretation

Therefore, the usefulness of index κ (defined by Formula (1)) for the assessment of the effectiveness of the cavitation erosion of materials is submitted for consideration:

$$\kappa = \sum_{i=1}^{k} p_i \tag{1}$$

where $p_i = \frac{n_i}{N_i}$, for $i \in <1, s)$ and $p_i = 1$, for $i \in < s, k >$;

p_i – is to be interpreted as probability of material damage, as in [44].

k – is the number of subintervals in the impact loading pressure range, for impacts contributing to erosion, i.e. the number of subintervals in the interval of pressure between lines "*a*" and "*c*" in Fig.1 or the index of the uppermost subinterval of pressure subintervals employed in calculations;

s – is the number of subintervals in the interval of pressures between lines "*a*" and "*b*" in Fig.1;

n_i – stands for the number of impacts with pulse amplitude in the *i*-th subinterval of pressure levels, recorded during the test run;

N_i – stands for the ultimate number of fatigue cycles with stress level in the *i*-th subinterval.

The sense of κ is analogous to a constant (usually depicted as "*C*") in Palmgren-Miner linear damage hypothesis. However, *C* is determined for failure as a final result of the fatigue process, and κ is determined for material damage due to cavitation loading of specified conditions and duration.

For unification of calculations, the decision on both recording time of cavitation pulses and the area of loading recording should be made. For example, a 5-min period and unitary area may be chosen. Admissible space scaling of cavitation erosion (if there are such) allows setting other values, if needed.

Obviously, cavitation impacts and fatigue cycles are not identical energetically. Taking into account that the effectiveness of cavitation erosion depends linearly on the energy delivered to the material, as was found for aluminium and copper [13], and fatigue curves refer to the total strain energy density per cycle vs. the number of cycles to failure [45], a compliance with energy criteria should be attained. Then, a correction of Formula (1) should be introduced. The correction refers to the volume work performed during each impact or fatigue cycle action. The value of this work equals the surface area of the field determined by the adequate hysteresis. The correction coefficient for each subinterval *i* may take the form:

$$\varsigma(r,\upsilon,\sigma,T,\omega)=\frac{S_{cav}(\sigma_i,\upsilon,T,\omega)}{S_{fat}(\sigma_i,r,T,\omega)} \tag{2}$$

where S_{cav} and S_{fat} are hysteresis field areas following from cavitation impact and fatigue loading cycle, respectively. In general, the hysteresis are stochastic functions of loading amplitude σ_i [46] and the physical state of the material. S_{fat} depends on the type of fatigue test r. Using available results of impact fatigue investigation, e.g. [47–49], it can be assumed that S_{cav} changes in time due to a strengthening process, porosity increase, and depends on the characteristics of the impact pulse.

Symbols used in Formula (2) are as follows:

ω – random variable,
σ – loading amplitude,
T – material temperature,
r – type of fatigue test,
υ – parameter for impulse characteristics.

Since it is impossible to trace hysteresis of each individual pulse, the average values should be accepted.

The presented approach is still burdened with significant simplification for the part of the hysteresis energy that is dissipated through heating, vibration, and non-propagating defects [50]. In fact, a special procedure for estimating the specimen lifetime under random fatigue loading is to be applied [51].

In order to avoid referring to experimental results of cavitation tests and remembering that closed hysteresis loops may not be observed for random loading, the coefficient ζ could be found using the appropriate relationship between the energy of impacts and the energy delivered to the material. The dependence of dissipated energy on the number of cycles for various numbers of fatigue cycles as presented in [46] can stand for an example.

Other events to be taken into account in some circumstances are crack closure phenomena [52] and the reflected stress waves in the case of the erosion of coatings [53].

Summarising, the number κ may take one of the following alternative forms:

$$\kappa=\left(\sum_{i=1}^{s}\frac{n_i+m_i}{N_i}+k-s\right)(1-\xi_{av})\zeta_{av} \tag{3}$$

if line “c” is situated on the right side of line “b” in Fig. 1;

$$\kappa=\sum_{i=1}^{k}\frac{n_i+m_i}{N_i}(1-\xi_{av})\zeta_{av} \tag{3’}$$

if line “c” is situated on the left side of line “b” in Fig. 1.

The notation used in Formulae (3) is as follows:

m_i is the number of reflected stress waves with amplitude in the i-th subinterval of pressure levels, recorded during the test run;

ξ_{av} is the average probability of the impact or reflected stress wave energy being used for crack closure. Its value can be derived from the general model considerations, presented in [17];

ζ_{av} is the average value of correction coefficient ζ.

Actually, due to the random nature of n, m, N and η, the value of number κ should be obtained from the realisation of the relevant stochastic process.

Assumptions on calculation methodology

Sources: measurements and assumptions

The quantities necessary to calculate κ are obtained as experimental results or following the assumptions.

As it is, the fatigue curves and pressure distribution of cavitation pulses are derived from measurements. However, the type of the fatigue test and testing parameters should be determined once and retained as obligatory for standardisation purposes.

Such quantities as loading area, time of exposition, pressure interval division constituting the number of subintervals should be appointed arbitrarily for the purposes of comparison. The assumption necessary for standardisation refers also to the area of pulse interaction with the material. The number of pulses of various amplitudes is derived from records performed using pressure transducers of a defined interaction area. Due to dependence of the recorded signal on the transducer characteristics, one type of transducers should be used. Thus, calculation of pulse height and approximate recalculation of real impact pressures for the approximate area of interaction is possible.

It seems that the correction coefficient ζ can be calculated using the experimental data and accessible scaling rules. As the last resort, the discussion on the loss of accuracy of κ due to neglecting the ζ coefficient in (2 and 2’) should be carried out if it is to be omitted. This time one may expect different κ number values.

Correlation with cavitation erosion parameters

Applicability of the number κ as a measure of erosion process effectiveness will be corroborated if any convincing correlation between κ and cavitation erosion parameters MDPR (mean depth of penetration rate), MPR (maximum penetration rate), incubation time or other as according to ASTM G40-88 [54] is found.

Comments on accuracy and uncertainties

The closer the nature of the process taking place during fatigue test to that of cavitation erosion, the better is the correlation between the performance of the material under fatigue and cavitation loading. The better the correlation between fatigue properties of the material and its response to cavitation loading, the better is the accuracy by which the number κ can be determined. However, complete affinity is unachievable due to the nature of cavitation impingement - discrete, short time pulses impacting over small area of the target, which leads among others to significant increase in temperature and alteration of the physical properties of materials. Moreover, the stages of the fatigue process depend on the loading cycle frequency, whereas cavitation impingement is a stochastic process that may show only some features of periodicity.

Randomness of the loading and the choice of fatigue tests

Performance of materials under regular and random loading may be different. Random loading may cause increased fatigue damage in comparison to the constant amplitude loading [55]. In the case of uniaxial random processes, the mean stress Goodman criterion and the Palmgren-Miner linear cumulative damage rule are mostly used [56]. A similar procedure may be applied to multiaxial random loading, which seems to be the most comparable case of fatigue test approximating the cavitation damage process.

However, regardless of the choice of the fatigue test type, additional non-linear effects derived from the high rate of applying cavitation loading force (1) and its local action area, in distinction from the volume forces suffered by a solid sample subjected to a fatigue test (2) make the cavitation erosion process and the fatigue damage process, as developed within any of standardised test procedures, permanently disjunctive. Therefore, the choice of the type of fatigue test may be a matter of stipulation.

Reliability of fatigue tests

Because of the noticeable scatter of fatigue results encountered in the literature, the limits for fatigue curves are to be measured each time in accordance with the requirements of the appropriate standard.

Accuracy of the loading measurements

The accuracy of cavitation loading measurements depends mainly on applied measurement technique. Reliable registration of cavitation pulses requires using transducers with a resonance frequency up to the GHz level (e.g. PVDF) and adequate rates of signal ascent and descent as well as other elements of the measurement trail with appropriate adjusted parameters. Moreover, accuracy depends (1) on the number of subintervals of the whole pressure extent, or equivalently, the extent of each subinterval and (2) on taking for calculations the right value of the average area of cavitation force action. The latter is crucial for obtaining an exact value of κ. The actual impact pressures may be found in the most reliable way by employing the dimensions of cavitation indents for calculations, as described in [57]. The dependence of the number κ on the average value of pit diameter is discussed in the next section of the present paper.

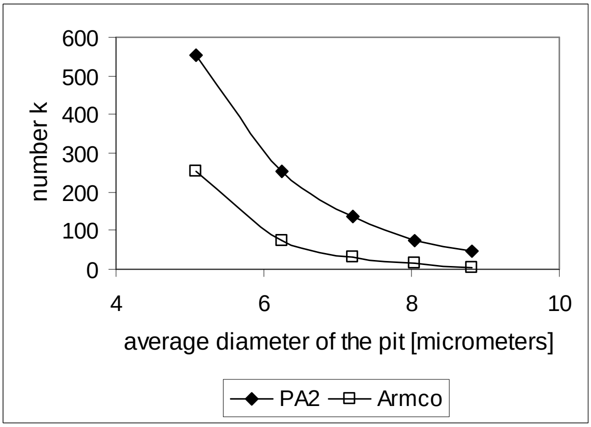

Fig. 2. Dependence of the number κ on the average value of pit diameter (for cases presented in Fig. 3)

Rys. 2. Zależność wartości liczby κ od średniej wartości średnicy pola obciążenia impulsem siły (dla przypadku przedstawionego na Rys. 3)

Preliminary experimental verification

In order to find out if there is a relationship between variations of the erosion number κ and single-number parameters quantifying material damage due to cavitation loading, an experiment has been carried out. For this purpose, both cavitation pulse distribution and cumulative erosion curves for Armco iron and PA2aluminum alloy were derived from the results of the experiment executed in a cavitation tunnel with a slot cavitator [58]. *PCB Piezotronics S113B23* transducers were used for measurements of the impact pressures. The time of impulse registration equalled 5 s. A sampling frequency of 1 MHz was sufficient for detection of single pulses as discernible loadings. The detected values of average pressure exerted on the transducer membrane enabled the researchers to determine forces (height of the loading) and, subsequently, the local pressure exerted by the single pulse. It has been assumed that the diameter of the pulse action area was 7.2 μm.

The results are presented in Figure 3, including the number of impacts at various pressure intervals /distributions of loading pressure/ for two different flow conditions as well as the dependence of limit number of fatigue cycles on loading stress /inverse functions to fatigue functions/ for Armco iron and aluminium PA2 (assignment according to Polish Norms). Chemical compositions of the materials were as follows: (1) Armco iron C0.035, Mn0.1, Si0.01, P0.026, S0.035, Fe rest and (2) aluminium PA2 Mg2.7, Mn0.3, Fe0.4, Si0.3, Zn0.2, Cr0.1, Cu0.1, Ti0.05, Al rest. The Armco iron corresponds to ASTM A424 Steel and PA2 to ASTM 5052 Aluminium.

Fatigue data were compiled from our own data and data presented in [59––62]. A low-cycle limit was unachievable and the ultimate strength was adopted instead (208 MPa for PA2 and 328 MPa for Armco).

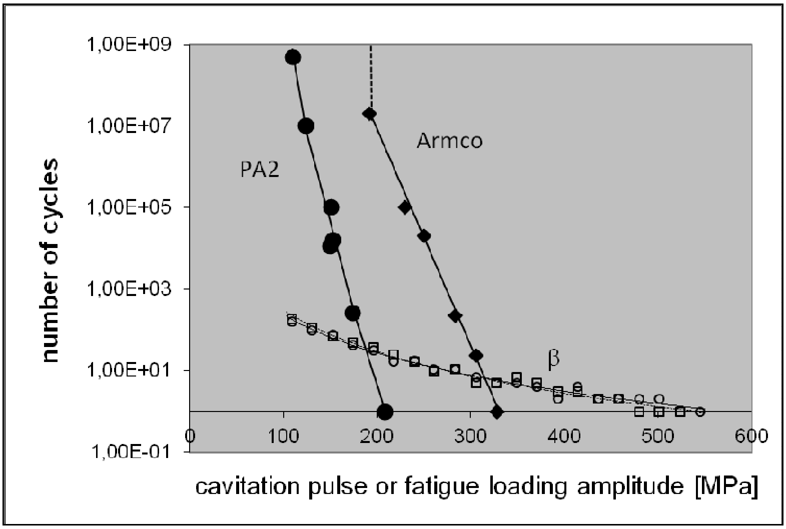

Fig. 3. Number of impacts at various pressure intervals for two different flow conditions (Curve β) and the dependence of limit number of fatigue cycles on loading stress for Armco iron and PA2 aluminium

Fig. 3. Liczba impulsów odpowiadająca różnym zakresom ciśnienia dla dwóch różnych warunków przepływowych (wykres β) oraz zależność od naprężenia liczby cykli określających wytrzymałość zmęczeniową żelaza Armco i aluminium PA2 (wykresy PA2 i Armco)

Employing the procedure described in the section *Proposal for a new index* and assuming that $\xi_{av} = 0$ and $\zeta_{av} = 1$, one can obtain the following values of the κnumber: 31.1 for Armco iron and 135.5 for aluminium PA2. Hence, the resulting ratio equals 4.3.

The cumulative erosion curves of the investigated materials have been plotted, allowing the determination of the MDPR (for maximum rate of the erosion) value. The MDPR parameters and the volume loss of Armco and aluminium samples during the erosion process as well as the ratio of their values are presented in Tab. 1. Determining precise values of other cavitation erosion measures, such as the maximum penetration rate and incubation time, from the plotted curves has been not possible.

Table 1. MDPR and the volume loss of Armco and PA2 during erosion
Tabela 1. MDPR oraz erozyjne ubytki objętości żelaza Armco i aluminium PA2

Volume loss after 350 min [mm^3]		Ratio of volume losses
Armco iron	PA2 aluminium	
0.471	2.379	5.05
MDPR [µm/min]		**Ratio of MDPR’s**
Armco iron	PA2 aluminium	
0.0026	0.0122	4.69

Both ratios of the erosion measures are consistent with the ratio of κ values found in the experiment.

Conclusions

(1) The ultimate number of fatigue cycles in the high cycle range is some orders of magnitude greater than the number of relevant cavitation pulses, which, in that case, do not significantly contribute to the erosion process and do not influence the value of parameter κ. On the contrary, its value is strongly dependent on the low cycle characteristics.

(2) As it is its nature, the parameter κ is a measure of the potential damage of the material in the defined period under defined loading conditions; therefore, it could serve for the prediction of the erosion by appropriate scaling.

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Jednoparametrowy wskaźnik efektywności procesu erozji kawitacyjnej

Streszczenie

W pracy przedstawiono wskaźnik oceny skłonności materiału do ulegania niszczeniu erozyjnemu w warunkach zidentyfikowanych obciążeń kawitacyjnych. Przyjęto założenie, że o przebiegu procesu decydują rozkład obciążeń oraz odporność zmęczeniowa materiału. Do wyznaczenia wskaźnika oceny wykorzystuje się zatem rozkład prawdopodobieństwa obciążeń jako czynnik reprezentujący warunki środowiskowe oraz standaryzowaną krzywą zmęczeniową, reprezentującą właściwości niszczonego materiału. Wartość wskaźnika jest ustalana według procedury, która obejmuje zestawienie powyższych zależności oraz wyliczenia korekcyjne, związane z absorpcją energii w cyklu zmęczeniowym i występowaniem procesów hamujących rozwój erozji. Przyjęto, że warunki progowe skutecznego niszczenia materiału określone są poprzez graniczną wartość obciążenia dla zmęczenia wysokocyklowego. Dokonano wstępnej weryfikacji istotności wskaźnika poprzez sprawdzenie występowania korelacji pomiędzy jego wartością a parametrami erozji kawitacyjnej dla określonych materiałów i warunków doświadczalnych. Przedyskutowano ponadto stosowalność wskaźnika i źródła potencjalnych błędów w określaniu jego wartości.