Wear 344-345 (2015) 120–129

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Determination of cavitation load spectra—Part 2: Dynamic finite element approach

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ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form
4 September 2015
Accepted 7 September 2015
Available online 25 September 2015

Keywords:
Cavitation pitting
Finite element simulation
Strain rate sensitivity
Natural frequency
Cavitation pitting mechanism

ABSTRACT

Cavitation erosion is a well-known problem in fluid machineries which occurs due to repeated hydrodynamic impacts caused by cavitation bubble collapse. Cavitation pitting test is often used for the quantification of flow aggressiveness required for lifetime prediction of hydraulic equipment. Understanding the response of the target material under such hydrodynamic impact is essential for correctly interpreting the results obtained by cavitation pitting test. Moreover the proper knowledge of cavitation pitting mechanism would enable us to design new materials more resistant to cavitation erosion. In this paper, the dynamic behavior of three materials 7075 Aluminum alloy, 2205 duplex stainless steel and Nickel–Aluminum Bronze under cavitation hydrodynamic impact has been studied in details by using finite element simulations. The applied load due to hydrodynamic impact is represented by a Gaussian pressure field which has a peak stress and, space and time evolution of Gaussian type. Mechanism of cavitation pit formation and the effect of inertia and strain rate sensitivity of the materials have been discussed. It is found that if the impact duration is very short compared to a characteristic time of the material based on its natural frequency, no pit would form into the material even if the impact stress is very high. It is also found that strain rate sensitivity reduces the size of the deformed region and thereby could enhance the cavitation erosion resistance of the material.

1. Introduction

In hydraulic equipment such as fluid machineries, pipes, ship propellers and valves, cavitation erosion may occur due to repeated hydrodynamic impacts caused by the individual or collective collapse of cavitation bubbles. Initially the material undergoes plastic deformation in the form of cavitation pits and repeated impacts cause strain accumulation leading to damage and material-loss [1,2].

The basic mechanism [1–4] of cavitation erosion is the following. In a high velocity flow, vapor cavities generate usually from trapped micron gas particles in the region where the local pressure drops below the vapor pressure of the fluid. Subsequently, these vapor bubbles collapse in higher pressure regions with the formation of high intensity micro-jets and shock waves. The intensity of such micro-jet and shock wave depends on various parameters including the pressure gradient, bubble size and distance of bubble collapse from the solid wall.

When the magnitude of such impact load due to the combined or solo effect of micro-jet and shock wave exceeds certain value for which equivalent stress into the target material exceeds the yield strength, a cavitation pit is formed. Repetition of such impacts, which occur randomly in space and time, causes hardening of the surface layer of the target material through plastic deformation [5] and subsequently strain accumulates. When the strain exceeds the ultimate strain, the material starts to degrade locally i.e. damage initiates and continues to propagate until complete failure in terms of material removal occurs.

From an experimental viewpoint, two types of erosion tests are generally done, cavitation pitting test and cavitation erosion test. The main difference between the two is the test duration. Pitting test (introduced by Knapp [6,7]) is done for a short period of time to avoid any mass loss and the pits are considered as the signature of individual bubble collapse. Cavitation pitting test is focused on the assessment of cavitation flow aggressiveness. Erosion test is done for a long period of time to track the mass loss over time, which occurs due to repeated impacts.

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http://dx.doi.org/10.1016/j.wear.2015.09.005
0043-1648/

Cavitation erosion tests are done to classify materials according to their resistance to cavitation erosion and, as far as possible, to correlate their resistance with material properties like hardness, yield strength, ultimate strength etc. [4]. Various laboratory devices have been developed to carry out accelerated cavitation erosion test such as ultrasonic horns [8,9], cavitating liquid jets [8–12], rotating disks [13] and cavitation tunnels [14,15]. Generally, the rate of mass loss or the erosion depth is used as a measure of cavitation erosion damage. Though these tests are practically used, they are far from being universal and transposition from model to prototype still remains an issue [4]. Recently focuses are being made to an alternative numerical approach to predict mass loss and Fivel et al. [16] have laid down the foundation for such numerical approach.

Regarding the assessment of cavitation flow aggressiveness, conventional or special transducers can be used to measure the impact forces [4,17], which are then converted to impact stresses based on the transducer's exposed surface area. The flow aggressiveness is defined by the frequencies of peak impact stresses as a function of amplitude. Generally the estimated values of peak stresses are not very reliable, because of the transducer's bigger size and higher rise time compared to that of hydrodynamic impact.

To overcome this difficulty, a combined experimental and numerical approach has been developed by Roy et al. [18–20] to estimate the impact stresses as well as their radial extent. The method consists in using an inverse finite element (FE) computation to derive the characteristics of the impact load responsible for each pit identified on a pitted test sample. This enables the better quantification of flow aggressiveness in terms of frequencies of impacts of a given peak stress and radial extent. The approach proposed in [18–20] is however based on static computations. One of the objectives of the present work is to extend it to the dynamic case where density and strain rate sensitivity of the material would play a vital role into the deformation mechanism. The current paper explains in details the feasibility of such method to implement when the complete dynamics of the material deformation is considered. Recently, Pöhl et al. [21] have presented a similar method to estimate impact loads from cavitation pit geometries. Their method is [21] based on static finite element analysis where the material properties were characterized by nanoindentation tests and, the representative pressure field was defined by a bell-shape profile. Two different approaches are presented in references [21,18] to accomplish the same goal of estimating cavitation impact loads.

Each hydrodynamic impact has a characteristic size, peak stress and duration which are related to hydrodynamic parameters. Influence of these three parameters on the dynamics of cavitation pit formation is investigated in this paper. The paper focuses on the influence of impact duration on the mechanism of cavitation erosion that has been less studied in the literature, particularly when the material behavior is strain rate sensitive. Section 2 is devoted to the presentation of material properties with special emphasis on the integration of strain rate sensitivity via the Johnson–Cook model. The numerical model based on the use of the commercial finite element method (FEM) code ABAQUS is presented in Section 3. Section 4 is devoted to presentation of results. It includes a discussion of the effect of impact duration on pit formation, an extension of the inverse FE method presented in [18] to the dynamic case and an evaluation of strain rate during cavitation pit formation. Discussion (Section 5) is largely based on the introduction of a material characteristic time evaluated on the basis of the characteristic size of the plastically deformed volume and the associated natural frequency of the material.

2. Material properties

2.1. Constitutive model

Three materials 7075 Aluminum alloy (Al-7075), 2205 duplex stainless steel (A-2205) and Nickel–Aluminum Bronze (NAB) have been considered for the current study. Density (ρ), Young modulus (E) and Poisson ratio (ν) of these materials are presented in Table 1. Material properties were characterized by the Johnson–Cook (JC) plasticity model in the form given by Eq. (1), avoiding the thermal softening part (see [22] for more details about JC plasticity model).

$$\overline{\sigma} = \left(\sigma_y + K\varepsilon_p^n\right)\left(1 + C\ln\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right) \tag{1}$$

Here, ε_p is the equivalent plastic strain, $\dot{\varepsilon}_p$ is the equivalent plastic strain rate and $\dot{\varepsilon}_0$ is the reference strain rate at which the yield strength σ_y, strength coefficient K and strain hardening exponent n should be estimated. Parameter C is the strain rate sensitivity. At reference strain rate (taken as $0.05\ s^{-1}$) $\ln(\dot{\varepsilon}_p/\dot{\varepsilon}_0) = 0$, Eq. (1) becomes a simple Ramberg–Osgood type equation where hardening is a function of ε_p only.

2.2. Nanoindentation test

Nanoindentation tests were done on these three materials at a strain rate of $0.05\ s^{-1}$ using a spherical diamond (Young's modulus, $E_i = 1141$ GPa and Poisson's ratio, $\nu_i = 0.07$) indenter of radius, $R = 9.46\ \mu m$. Standard sample preparation procedure- initially polished by using sandpapers reducing grit size till 8.4 μm (grade P2500), then polished by using diamond paste gradually reducing the size from 6 to 1 μm and finally by using colloidal silica of 0.03 μm size.

Characterization of material properties by nanoindentation is considered to be relevant to cavitation pitting [20,23], as in both the cases deformation is compressive and confined. Material properties (σ_y, K and n) were obtained by inverse FEM simulation of nanoindentation, where σ_y, K and n were optimized in order to get a simulated load–displacement curve similar to the experimental one, as explained in details in [20]. Estimated material properties are given in Table 1 and Fig. 1 shows an example of comparison of simulated and experimental load–displacement curves for A-2205.

2.3. Integration of strain rate sensitivity

Strain rate involved in cavitation pitting is expected to be very high, up to the order of $\sim 10^6\ s^{-1}$ [4,20], and could vary depending on the bubble size and collapse driving pressure gradient. To take into account such strain rate dependencies of cavitation pit formation, compression tests complemented by Split Hopkinson Pressure Bar (SHPB) tests were done on the three materials at strain rates ranging from 0.001 to $\sim 2000\ s^{-1}$. Cylindrical specimen of equal length and diameter of 8 mm have been used.

Strain rate sensitivity parameter C was estimated by fitting the Eq. (2) to the experimental data as show in Fig. 2, as an example in

Table 1
Physical and nanoindentation mechanical properties of the materials at strain rate $0.05\ s^{-1}$.

Material	ρ (kg/m³)	E [GPa]	ν	σ_y [MPa]	K [MPa]	n
Al-7075	2810	71.9	0.33	335	396	0.30
A-2205	7805	186	0.30	508	832	0.51
NAB	7580	122	0.32	300	1150	0.58