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Cavitation erosion, influence of electrochemical corrosion on cavitation – a review

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Variations in local pressure of liquids lead to growth and successive collapse of bubbles filled with vapour or gases. This phenomenon is called cavitation. Cavitation can occur in almost all hydrodynamic systems e.g. pumps, valves, marine propellers, hydraulic turbines, and hydrofoils and in most cases is undesirable because of forces, formed during implosion of cavitation bubbles, which results in erosion failure of neighbouring solid surfaces and in production of noise. Erosion of materials is achieved by emission into the solid of stress pulses, arisen either by generation of pressure waves or by the formation of high-velocity jets of liquid. Cavitation erosion resistance highly depends on mechanical properties of material, but also on metallurgical state, hydrodynamic and chemical properties. The effect of cavitation on the corrosion behaviour depends on corrosion product or protective layer detachment and increase of mass transport. Additionally, synergistic effect of cavitation erosion accompanied by electrochemical corrosion of metals and alloys may also have large influence on material failure. Because of chaotic nature of this process, former equipment limitation, and lacks in knowledge, influence of electrochemical factors on cavitation failure is not well described and needs further investigations.

Keywords: cavitation, corrosion-erosion

Introduction

If the pressure of liquid suddenly falls below the vapour pressure, the tensile stress imposed on the liquid generates cavities, which grows on the numerous small solid and gaseous cavitation nuclei generally present in the real liquid. Later, when they are submitted to a higher pressure these cavities collapse violently generating stress pulses which can cause plastic deformation and erosion of neighbouring solid surfaces. In order to characterize relationship between the flow velocity and the overall pressure and therefore to estimate susceptibility of cavitation appearance of liquid flow, the value of cavitation number was defined below (1):

$$\sigma = \frac{p_R - p_v(T_R)}{\frac{1}{2}\rho_L U_R^2} \quad (1)$$

where p_R and U_R are reference pressure and velocity of the flow, $p_v(T_R)$ stands for vapour pressure at referred temperature and ρ_L is liquid density. In hypothetical flow, when σ is large enough, no cavitation bubbles occur and the flow will be single-phased, but below some value of the cavitation number σ_i , a liquid cannot withstand any tension and vapour bubbles appear instantaneously on nucleations. There is a relationship between the incipient value of cavitation number and the pressure coefficient $C_p(x_i)$:

$$C_p(x_i) = \frac{p_i - p_R}{\frac{1}{2}\rho_L U_R^2} \quad (2)$$

$$\sigma_i = -C_{p\min} \quad (3)$$

where $p(x_i)$ is local pressure at a point i . The cavitation number have major influence on the size of nucleation which is needed for generation of cavitation bubble and the quantity of generated bubbles.

Bubble dynamics

Cavitation bubbles may grow on two types of nucleation: homogenous, which is due to thermal motion in solution and heterogenous; at interfaces between liquid and solid phase, on micron-sized bubbles of contaminant gas or on small particles suspended in the solution. Cosmic radiation also may be source for nucleation, during the collision between a particle of sufficiently high energy and a molecule of the liquid. During the nucleation of bubble the pressure may fall even 10^6 times. The collapse of bubble take place as a result of pressure gradient between the bubble and ambient liquid. This happens when the bubble grow too large, resulting on very small pressure inside the bubble, or when the local ambient pressure increases. Maximum

pressure generated during the collapse may be even up to 10^{10} times the ambient pressure, with maximum temperature 10^4 times the ambient temperature [1,2]. The greatest stresses are generated when the bubble implosion is spherical, although bubbles that occur in a cavitating flow are often far from spherical. The magnitude of the impact stress may be as high as 1000 MPa, which is considerably greater than the yield stress of the usual industrial alloys. Fig. 1 presents a schematic image of collapsing cavitation bubble. Denotation 0 is marked to be initial sphere, of maximum radius, just before the collapse. It can be seen that in the beginning, 1-4, shape of the bubble is close to spherical, but after some time one of sides starts to collapse faster, 5-8, resulting in the microjet penetration and eventually in implosion of cavitation bubble. This phase is much faster than the spherical collapse: duration of implosion is of value of about 2-3 μ s, while speed of cavitation collapse may reach even 500 m/s.

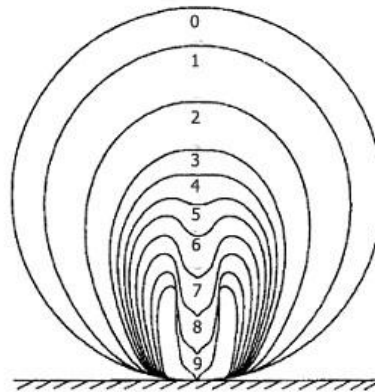


Fig.1 – Implosion of cavities

A source for the stress pulses, which are directed always towards the solid walls is connected to either generation of a pressure wave, or the formation of a high-velocity jet of liquid. When this collapse occurs close to a solid surface, these intense disturbances generate highly localized and transient surface stresses, which may be sufficient to induce plastic deformation and detachment of material from the surface. Even if stresses are below yield point of material, repetitive loadings due to repeated collapses cause local surface fatigue failure which eventually lead to subsequent flaking off of pieces of material eventually leading to its erosion. This fatigue-like damage will be a result of an increase in the dislocation density.

The violent and catastrophic collapse of cavitation bubbles results in the production of noise as well as the possibility of material damage to nearby solid surfaces. The noise is consequence of the momentary large pressures which are generated when the contents of the bubble are highly compressed.

Cavitation erosion

In most cases the major method to prevent or to reduce cavitation damage is application of materials with greater cavitation erosion resistance, therefore it is of great interest to design materials for its better use. Knowledge of metallurgical state of metals and its relation to erosion resistance is of great value. The martensitic steels seem to possess the highest erosion resistance followed by the austenitic stainless steels, while the ferritic steels have very poor cavitation erosion resistance. Investigations, which were made for many metals and alloys allowed to draw a conclusion that a higher erosion resistance is generally related to low stacking fault energies which results in higher work hardenability. In low stacking fault energy materials planar slip mode of deformation delays the development of localized stresses required to initiate fracture.

A lot of works have been made to correlate erosion resistance of materials, R_e , with other mechanical properties like hardness, strain energy and ultimate resilience or fatigue resistance of materials but investigations made on this subject shown that cavitation erosion resistance is an unique property of material and cannot be unequivocally compared to other mechanical properties [1-3, 5]. The value of R_e is a function of weight loss of material during the erosion process, and is defined as the converse of mean depth of penetration range MDPR of erosion.

$$R_e = \left(\frac{1}{MDPR} \right) \quad (4)$$

the value of MDPR in equation above (4) is established from:

$$MDPR = \frac{\Delta W}{10A\rho\Delta t} \quad (5)$$

where A and ρ are surface area and density of sample, ΔW is weight loss of sample in time Δt . Other attempts were also made to forecast erosion rate of materials using volume loss of material, coverage of sample surface with craters or correlation between the erosion rate and acoustic power of cavitation noise.

The erosion course, evaluated from size of erosion rate of samples during the measurement always has the same shape, divided to four or five stages. The difference between materials is apparent in length of particular stages, in angles and shapes of curves. This relationship fit for most of materials although for some of them final stages may not be evident or may fluctuate.

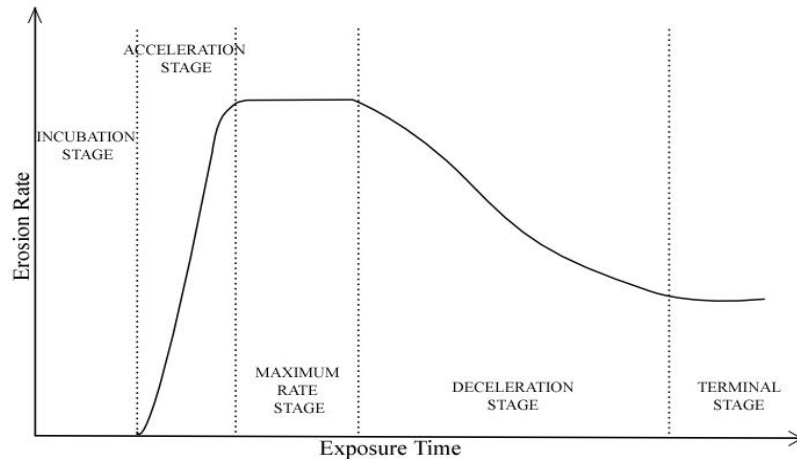


Fig. 2 – Erosion rate curve

For the first stage, called an incubation stage, only deformation of surface sample occur and material loss is negligible. After some time, when about 95% of area is submitted to plastic deformation, the acceleration stage take place, consequencing in rapid erosion rate growth up to achievement of its maximum level. The erosion rate increase due to crack development. Subsequently to acceleration stage maximum rate stage occur, where erosion rate stabilize at its highest value. The final stage is often called attenuation period, and its characterized by deceleration of erosion rate due to the increase in surface roughness and subsequent reduction of cavitation collapse pressure, or to the appearance of cushioning effect of liquid trapped in the pockets and crevices of the eroded surface. In some cases one more stage can occur after the attenuation stage, the terminal stage, during which the corrosion rate once more is getting stable but at lower values than during the maximum erosion rate stage. Erosion rate highly depends on hydrodynamic properties of liquid such as: velocity of flow, temperature, pressure, pH or gas and contaminant content therefore maintaining stable test conditions is crucial for success of the experiment. In 1987, during the ELSI VII Conference project of International Cavitation Erosion Test, ICET, was announced [4]. Its goal was to compare the test results made for different materials (carbon steels, Cr-Ni steel, brass, and polyamide) on apparatus with different types of cavitation excitation (cavitation tunnel, rotating disc, liquid jet and vibratory rig). ICET shown, that for same materials, results achieved cannot be compared among different types of apparatus. Even if two results were comparable between two methods for one material, erosion rate measurement made for another material were completely not comparable. This introduced necessity to standardize all test parameters in order to predict material performance under variable cavitation loading conditions.

Erosion-corrosion as a result of cavitation

When cavitating liquid is corrosive, the material loss of various metals and alloys is not purely mechanical, and can be subject of cavitation erosion-corrosion. Mutual interactions between cavitation erosion and electrochemical corrosion have been attributed generally to a detachment of protective oxide layer, followed by microcell formation. The best protection properties will be achieved by dense, adherent and fastly repassivating films, such as oxides on Cr-Ni steels [4,5] or on titanium [8]. A good definition of this relationship was presented by H.C. Man et al. [5]: “If cavitation attack causes accelerated removal of an existing passive film or or corrosion product layer, and if overall rate determining mechanism is the rate of replacement growth of the film or layer, then the resulting type of loss of material is referred to cavitation erosion-corrosion”. The overall damage arising from erosion and corrosion often includes interactions between them. Those may be synergistic or inhibitive, depending on material/environment system. The total cavitation erosion-corrosion rate, T , is defined as [5,6]:

$$T = E + C + \alpha \quad (6)$$

where E is the purely mechanical erosion rate, C is corrosion rate and S is synergistic effect between them. This synergistic effect may be due to increased mass transport by high turbulence levels, lowering the fatigue strength of metal by corrosion, removal of work hardened surfaces by corrosion processes which expose the underlying base metal to erosion mechanism, increase in the number of stress concentration defects resulting from micropitting etc. In laboratory measurements, overall rate of damage is said to be the erosion rate of material in corrosive medium, while mechanical erosion rate occur if no corrosion reaction take place. Such non-corrosive system is obtained either by measurement in distilled water or using cathodic protection. C is obtained from polarization curves in quiescence state. In this way synergistic influence of mechanical erosion and electrochemical corrosion can be obtained from equation (6). It has been examined, that for cast iron and carbon steels the main fraction of material loss is combined with erosion or synergic factors. Corrosion participation may be up to 15%. Material loss of copper and its alloys is solely due to erosion process, while corrosion rate fraction is negligible. Finally, austenitic steels (304 and 316L) show high erosion-corrosion resistance which is followed by very low material loss [5]. Additionally, change in corrosion potential of metal appear with occurrence of cavitation. This change may be shifted to more active regions as well as to more noble depending on environment parameters and examined metal. H.C. Man et al. measured the influence of presence of chloride ions in solution on oxide passive layer degradation. They have measured cavitation erosion-corrosion of stainless steels for 3,5% NaCl and 0.1M NaOH and found out, that change of corrosion potential under cavitation conditions is similar for both studied solutions. Obtained results, allow to suppose that in a cavitating liquid chloride ions do not play an active role in the erosion or corrosion process in the case of stainless steels.

Conclusions

Simplified mechanism of cavitation generation and bubble dynamics was presented. The main effect of occurrence of cavitation in vicinity to solid surfaces, which is erosion was examined in many laboratories from couple of decades, however present understanding of the processes involved in material erosion is far from complete. The lack of knowledge results mainly from chaotic and rapid nature of cavitation implosion, and former equipment limitations. Some investigators have tried to characterize corrosion influence on cavitation erosion. Their conclusions are drawn only on the basis of corrosion potential and mass lost changes during cavitation measurements, leaving the subject of dynamics of erosion process as well as subsequent corrosion of material not examined. Further investigations, especially on dynamics of oxide layer removal and regrowth is necessary.

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