Experimental study of cavitation erosion of quartz in the presence of surfactant molecules

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Abstract. The interaction of bubbles with a solid flat surface of amorphous quartz, in the presence of surfactants in water, in the presence of ultrasonic action, was experimentally investigated. The study of surface properties with the use of an atomic force microscope made it possible to study the mechanism of ultrasonic degradation of the surface of solid plates, including those with surfactants adsorbed on their surface. The experiments have shown that the changes, under the action of ultrasound, of the surface properties, in these experiments, consist in the formation of chips on the surface of quartz crystals, which leads to an increase in the average surface roughness by three times in comparison with the plates that were not subjected to ultrasonic action. It was found that the distribution of the surfactant layer on the surface of the plates depends on the concentration of the surfactant in the solution, and its presence at the solid-liquid interface leads to a decrease in the ultrasonic erosion of the plate surface. The mechanism of heterogeneous cavitation in the presence of surfactants is to reduce the probability of interaction between an inertial cavitation bubble and a solid surface, because of which the probability of local destruction of the surface decreases.

1. Introduction

In the last decade, the use of ultrasound (US) actively studies in the field of ore dressing by flotation [1]. US has also found application in the processes of creating nanostructured surfaces [2-5], and the use of US in improved methods of shot blasting of metal surfaces (USSP) made it possible to increase the strength properties of metals and their resistance to wear [6].

The studies of the activity of cavitation processes are of particular interest. Ultrasonic action on a liquid contributes to the emergence of two types of cavitation: inertial and non-inertial. Non-inertial cavitation is a process of formation of large gas bubbles drifting mainly at the nodes of the ultrasonic wave and growing in diameter due to coalescence processes the lifetime of such bubbles can reach tens of seconds. However, inertial cavitation bubbles exist at times of the order of the period of ultrasonic oscillations and collapse creating microflows of liquid, local heating of the liquid and shock waves. In the presence of a solid body, the wave is predominantly direct towards the solid body [7]. When inertial cavitation bubbles interact with a solid surface, its structure changes.

Heterogeneous nucleation occurs in the presence of microscopic gas cavities at the solid-liquid interface on the surface of a solid. Heterogeneous nucleation on a wetted surface occurs when the surface
tension of the solid-vapor interface is less than the surface tension of the vapor-liquid interface. In this case, cavitation occurs at the solid-liquid interface [8]. Bubbles located close to the interface cause higher pressure than bubbles located further away, thus the process of surface destruction depends on the distance from the surface the bubble collapses [9]. It is known that the collapse of bubbles occurs at a short distance of several tens of nanometers above a solid surface, and the collapse rate is several hundred meters per second. Thus, several factors affect the degradation process of a solid surface: the main factors are the power of ultrasound exposure and the chemical composition of a solid. In addition, the processes of surface destruction by cavitation bubbles are influenced by the physicochemical properties of the liquid and the surface properties of solids [10, 11]. Thus, the hydrophobicity of surfaces strongly affects the nucleation of bubbles on the surface, more precisely, the more hydrophilic the surface, the less likely the occurrence of gas nuclei near the surfaces [12].

The effects of heterogeneous cavitation activity studied in [13]. The authors found that the development of surface cavitation depends on time and can accelerated if the surface initially contains a large volume of gas domains. Gas adsorption strongly depends on the surface energy of the substrates, while hydrophobic regions are more favorable for the growth of the gas layer. Surface cavitation on pre-prepared samples, due to the large amount of adsorbed gas, begins much earlier than in the case of ultrasonic treatment under standard conditions.

Thus, the purpose of this work is to qualitatively and quantitatively estimate the change in the surface structure of quartz immersed in distilled water subjected to ultrasonic action in the presence of surfactants in the liquid. Studies on the study of the effect of surfactants on the cavitation activity of quartz not found in scientific works; therefore, the question of heterogeneous cavitation in the presence of surfactants remains open and requires additional research.

2. Experimental Procedure
The experimental setup (Fig. 1) was a rectangular plexiglass cavity with dimensions $110 \times 116 \times 160$ mm$^3$. The electrodynamics source of ultrasound was flush with the bottom of the cuvette, the power of the ultrasonic generator was $P = 100$ W, and the frequency was $f = 40$ kHz.

![Fig. 1. Schematic of the experimental setup. 1 - Ultrasonic generator, 2 - organic glass cavity, 3 - quartz plate](image)

Distilled water and sodium dodecyl sulfate (SDS) solution at various concentrations used as the working fluid. As a solid, flat quartz, plates with dimensions of $10 \times 10$ mm$^2$ used. The plate placed in the cuvette in a strictly horizontal position at a height of 5 mm from the bottom of the cuvette, after which the ultrasound source turned on. The ultrasonic exposure time varied from 1 min to 20 min, the
liquid temperature in the experiments was $t^o = 20 \pm 2 \, ^\circ C$, PH = 7 throughout the experiment. The preparation of the plate for the experiment carried out as follows: the sample was immersed in distilled water, then treated with an aqueous-alkaline solution of NaOH with a 25% mass concentration, after which it was immersed in a solution of ethyl alcohol, then again in distilled water. Then the sample scanned by atomic force microscopy using an Integra-Prima microscope. For each new series of experiments, a new plate was used. First, the plate was scanned with an atomic force microscope, after which ultrasound experiments were carried out, then the plates were analyzed again. To obtain a representative sample of data, various sections of the plates were analyzed at least ten times, after which the data were averaged over all analyzed sections.

3. Results

Thus, in this series of experiments, it was found that coating the surface with sodium dodecyl sulfate (SDS) molecules apparently leads to a decrease in the intensity of cavitation activity near the surface and, therefore, the surface becomes more resistant to cavitation erosion than pure amorphous quartz not coated with surfactant. Figure 1 shows the results of force atomic microscopy, which show the distribution of molecules on the surface of quartz. In fig. 1 (a), the light areas are areas likely to be covered with a surfactant, and the dark areas are a clean quartz surface. In fig. 2 (b), it can be observed that with an increase in the surfactant concentration in water, the surface area covered by the surfactant increases.

![Fig.2. Results of atomic force microscopy, 2 (a) - surfactant concentration of 1 mM, and 2 (b) surfactant concentration - 10 mM.](image)

Surfactant molecules can promote the displacement of gas nuclei at the solid-liquid interface, thereby reducing the likelihood of heterogeneous cavitation near the surface. It was found that in the absence of surfactant molecules, the average surface roughness of amorphous quartz changed by 6.2-7.8 nm in 5 minutes of ultrasound exposure and by 11.8-14.7 nm after 10 minutes of ultrasound exposure in water. After 20 minutes of exposure, the average roughness ranged from 18.1 to 24.5 nm. Figure 3 (a), (b) shows the results of atomic force microscopy, 2 (a) - 3D scan of the surface of amorphous quartz with a size of $1 \times 1 \, \mu$m² and 2 (b) 2D scan of the surface, before ultrasonic processing.
According to the results of surface profile analysis, the peaks formed by quartz crystals have single sharp-angled ends before US treatment. After 1 minute of processing, you can detect chips on the profiles when one of the crystals has several sharp-angled peaks. When the SDS surfactant concentration was 1 mM/l in water, the average surface roughness after 5 minutes of US exposure varied from 3.1 to 4.1 nm. This is two times less than in pure water; at a concentration of 5 mM/l, the average roughness was from 3.8 to 4.5 nm, and at a concentration of 10 mM/l SDS, the average roughness of the sample was from 2.4 to 4.8 nm. The roughness of the samples changed slightly at such surfactant concentrations and a 5-minute exposure time. It is possible that 5 minutes is not enough for the first chips to form and the destruction process to start. It is known that after the formation of the first chips, gas nuclei are fixed on them, which accelerate the process of ultrasonic erosion [14]. Figure 4 (a), (b) shows the results of atomic force microscopy after ultrasound exposure.

Figure 4 (a) shows the chips formed because of ultrasonic exposure, the depth of the chips reaches 6 nm. This result is consistent with the work of researchers of such phenomena, when ultrasound begins to destroy first individual areas, and then cavitation begins to destroy nearby areas, since at the boundary of the cleavages there is an opportunity for fixing gas bubbles [14].
4. Conclusion
According to the results of the experiments, it was found that the average roughness of the samples coated with surfactants, at a fixed concentration, increases with time according to a law close to linear. It was not possible to find a definite relationship between the roughness and the SDS concentration at the same exposure time; it is possible that in the studied range from 0.5 mM/l to 20 mM/l, the surfactant concentration turned out to be excessive. To clarify these effects, it is necessary to conduct additional experiments in the range of low SDS concentrations from 0.05 mM/l to 0.5 mM/l, that is, for values significantly lower than the critical micelle concentration for SDS of 8 mM/l.

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