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FEATURES OF CAVITATION AND CAVITATION EROSION OF WAVEGUIDES OF POWERFUL ULTRASONIC UNITS AT HIGHER-THAN-AVERAGE PRESSURE OF THE MEDIA

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The features of the acoustic effects of cavitation created by the rod waveguides of powerful ultrasonic magnetostriction units in different liquid media at a pressure to 5 MPa have been investigated. It has been established that, under the conditions of maximum acoustical activity of cavitation realized at the medium's higher-than-average pressure, the erosion damage to the waveguides is of an unusual structurized character and develops from the central part of the end to its periphery. A result of the erosion damage may be the total loss of operating capacity by the waveguides manufactured from the most erosion-resistant materials (stainless steel and titanium alloys) even after a few hours of tests.

Ultrasonic cavitation, known for many decades, has attracted continuous attention in connection with the great scope for its practical application [1]. The unique features of cavitation zones characterized by local pulses of high pressures and temperatures make it possible to use them for efficient cleaning of surfaces, decontamination of media, acceleration of physicochemical processes, dispersion of materials, and destruction of substances.

Industrial realization of such ultrasonic technologies makes it necessary to create powerful (kilowatts or tens of kilowatts) ultrasonic units with a high acoustic-radiation intensity (10–100 W/cm^2). To improve the activity of cavitation processes one can ultrasonically treat liquid media at a higher-than-average static pressure. However, such a treatment is frequently accompanied by the heating of the medium and by the formation of chemically active radicals (compounds) in it. Also, it is well known that the occurrence and collapse of cavitation bubbles may give rise to microspark discharges in the cavitation zone and cumulative (high-velocity) liquid microjets. As the experimental investigations of recent years [2, 3] have shown, aggregates of cavitation bubbles may occur in the immediate vicinity of the radiating surfaces of ultrasonic waveguides. These surfaces may be acted upon by a combination of several factors: mechanical vibrations in a chemically active heated medium with a higher-than-average static pressure, local pulses of high pressures and temperatures, microspark discharges, and hydraulic impacts of high-velocity microjets. Pronounced erosion damage to the waveguide material can be a consequence of such an action.

Most of the existing numerous investigations on cavitation erosion of materials [4–7] have been carried out on samples installed in water at normal pressure with a relatively low specific acoustic power (1–10 W/cm^2). Under these conditions, the character of erosion of the samples from different materials was nearly the same: the sample's surface became covered with microcraters (caverns) after a certain incubation period; the velocity of linear removal of material reached a maximum but thereafter decreased and reached nearly a constant level; the removal of material was uniform over the surface. It has been noted, e.g., that an increase of 0.1 to 0.5 MPa in the water pressure leads to a pronounced growth (by nearly an order of magnitude) in the velocity of removal of materials. Also, it has been established that such materials as titanium or stainless steels, in particular, those with a high content of nickel, possess a high erosion resistance.

We have investigated the cavitation resistance of rod waveguides manufactured from similar materials on an ultrasonic unit with a magnetostriction transducer of power W to 5 kW and specific acoustic power I_a to 40 W/cm^2 under the conditions of different media (water, hexane, mixture of liquid hydrocarbons) at pressures P to 5 MPa. The

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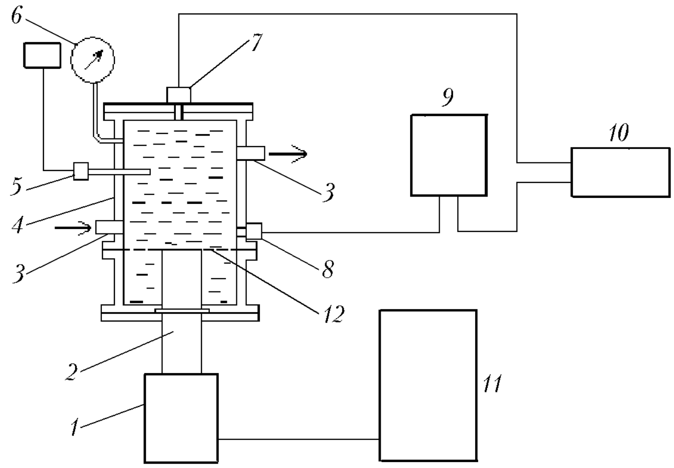


Fig. 1. Diagram of the setup: 1) magnetostriction transducer; 2) waveguide; 3) inlet and outlet pipes; 4) lower part of the high-pressure chamber; 5) thermocouple sensor; 6) manometer; 7) piezoelectric sensor; 8) wide-band acoustic detector (hydrophone); 9) electron unit; 10) digital oscilloscope; 11) generator of electric pulses; 12) diaphragm.

experiments have shown that erosion is of an unusual nonuniform character under these conditions and the destruction of waveguides may have disastrous consequences with the loss of their operating capacity even within a few hours from the beginning of the tests.

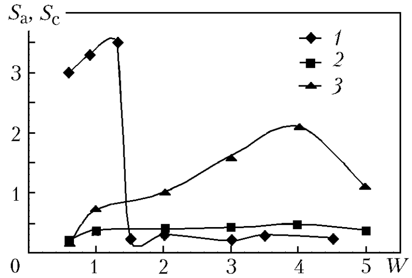
1. Description of the Experimental Setup. A diagram of the experimental setup on which investigations on cavitation resistance of ultrasonic waveguides were carried out is presented in Fig. 1. Waveguide 2 of the ultrasonic unit incorporating a PMS15-18A magnetostriction transducer 1 and a UZGV5-22 generator 11 of electric pulses with an output (transducer-consumed) power to 5 kW was hermetically fixed in the lower part of a high-pressure chamber 4. The diameter of the waveguide's radiating part was 50 mm and the operating frequency was 17.3–17.7 kHz. The intensity of acoustic radiation in water, measured by the calorimetric method, varied from 6 to 37 W/cm^2, as the power consumption increased from 0.7 to 5 kW. The chamber's structure made it possible to install thin diaphragms 12 manufactured from different materials and playing the role of protective coatings against erosion action directly against the waveguide's radiating surface.

The liquid medium used entered the chamber under a prescribed pressure controlled by manometer 6 via the lower branch pipe 3 and was removed via the upper pipe. The maximum static pressure could attain P = 10 MPa in the chamber. Heating and cooling devices for maintaining a prescribed level of the medium's temperature measured with the thermocouple sensor 5 were built into the water-supply main.

An LKh-610 piezoelectric sensor 7 for measuring pressure pulsations of the acoustic field at the operating frequency of the ultrasonic unit (S_a) was installed in line with the waveguide in the chamber's upper cover. The sensor made it possible to measure pressure pulsations to 5 MPa at a static pressure of to 20 MPa. The signals of the sensor were recorded and processed using the digital oscilloscope 10.

The (acoustical) cavitation activity was determined from an analysis of cavitation noise with an IC-3 cavitometer developed by N. V. Dezhkunov [8]. The cavitometer (indicator of cavitation activity) consisted of the wide-band acoustic detector (hydrophone) 8 (see [8]) and the electronic unit 9. The detector sensed acoustic pulses in a frequency range of 5 kHz to 10 MHz. The axis of the detector was at a distance, from the waveguide's end, of about 1/4 of the wavelength in the liquid medium at the operating frequency of the ultrasonic unit. The signals of the detector were amplified in the electron unit-analyzer of cavitation noise. The analyzer made it possible to determine the relative integral intensity of cavitation noise in different frequency ranges (A_0–A_5).

It is assumed at present that acoustic noise with frequencies higher than 600 kHz is related predominantly to pressure pulses (hydraulic impacts) developed on collapse of cavitation bubbles less that 10 μm in size [9]. Aggregates of bubbles in the cavitation zone may produce acoustic noise in a wider range: 100 kHz–10 MHz [10]. In the present



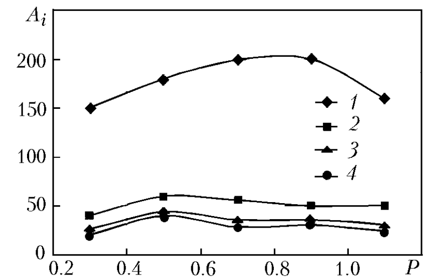


Fig. 2. Acoustic-pressure amplitude S_a (1) and relative acoustical cavitation activity S_c (2) medium's pressure 0.1 MPa; 3) 0.6 MPa) vs. power consumption of the ultrasonic setup W. S_a, 1/10 MPa; W, kW.

Fig. 3. Spectral signals of the acoustical cavitation activity A_i for different frequency ranges vs. static pressure of water P: 1) A_2; 2) A_3; 3) A_4; 4) A_5. A, mV; P, MPa.

experiments, we predominantly used frequency regimes of the cavitometer of 200 kHz to 10 MHz, which enabled us to minimize the influence of the reference ultrasonic frequency and its nearest harmonics to the recording of cavitation noise.

To compare the data of the present work and the results of other investigations we also used the relative (reduced) value of the signal recorded by the detector 8 in a frequency range of 0.2 to 10 MHz; this valve was taken as the relative value of the acoustical cavitation activity (S_c). Normalization was carried out on the basis of the signal recorded by the cavitometer in the case of ultrasonic action on tap water with a specific acoustic power of 10 W/cm^2 at atmospheric pressure and a temperature of 20^{o}C. Under the conditions of the present tests, the value of such a signal was 160 mV in the frequency range A_1 and 120 mV in the range A_2.

2. Experimental Results. *Cavitation Activity.* With increase in the power consumption of the ultrasonic unit and at a constant static pressure of the medium, we observed the characteristic changes in the amplitude of sound pressure S_a and the level of acoustical cavitation activity S_c. Figure 2 plots as an example the changes in these parameters under the ultrasonic action on a mixture of liquid hydrocarbons with a density of 905 kg/m^3.

The sound-pressure amplitude first increases with ultrasonic-source power; the S_a signal has a pronounced sinusoidal shape corresponding to the fundamental harmonic of oscillations of the waveguide. For a certain threshold power of the ultrasonic flux, the S_a value attains a maximum following which it sharply drops by about an order of magnitude. The signal shape is perturbed; pressure pulsations become random.

The cavitation activity S_c (in the frequency range A_1) at atmospheric pressure of the medium first grows with sound-pressure amplitude up to the pressure threshold. In the range of power consumptions corresponding to a sharp decrease in the sound-pressure amplitude, the rate of growth in the cavitation activity S_c decreases. The S_c maximum is attained for a certain source power exceeding the value of the threshold (for the parameter S_a) power. The value of the latter is dependent on the composition, pressure, and temperature of the medium.

Increase in the static pressure of the medium causes the threshold values of the ultrasonic-source power to change. As the medium's pressure increases to several atmospheres, the sound-pressure amplitude drops for higher values of power consumption.

In the range of low ultrasonic-source powers $W < 0.7$ kW, cavitation activity of the medium was lower at a higher-than-average pressure than that at atmospheric pressure. However, with increase of more than 0.7 kW the cavitation activity rapidly grew in proportion to the medium's pressure (Fig. 2). For example, at P = 0.6 MPa, the cavitation activity S_c attained its maximum at the level of power composition W = (3.5–4.0) kW; the S_c value exceeded the signal at atmospheric pressure more than 4 times.

With further increase in the medium's pressure, the maximum attainable S_c level continued to grow to the limiting value and thereafter began to decrease. Figure 3 shows spectral curves of the cavitometer signals (A_i) for frequency ranges (A_2–A_5) as functions of the pressure in the case of ultrasonic action on water with a constant power consumption W = 3 kW. As is seen, in this frequency interval, the largest contribution to the acoustical cavitation activity is made by acoustic noise in the range 0.6–1.5 MHz and 5–10 MHz. The maximum value of the signals is attained at a pressure of about P = 0.8 MPa in the A_2 range and about P = 0.45 MPa in the A_3–A_5 range.

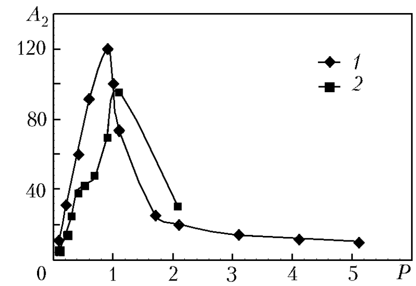


Fig. 4. Acoustical cavitation activity A_2 vs. pressure P: 1) hexane; 2) mixture of hydrocarbons.

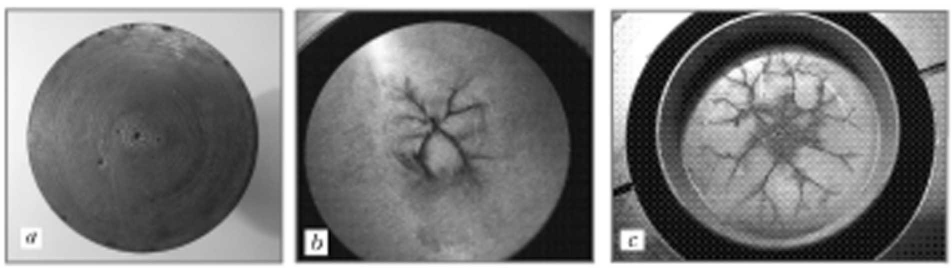


Fig. 5. Order of erosion destruction of waveguides (40Kh steel): a) first sings of erosion within 2 h of operation; b) subsequent destruction of the waveguide within 4–5 h of operation; c) surface of the waveguide's end within 10 h of operation.

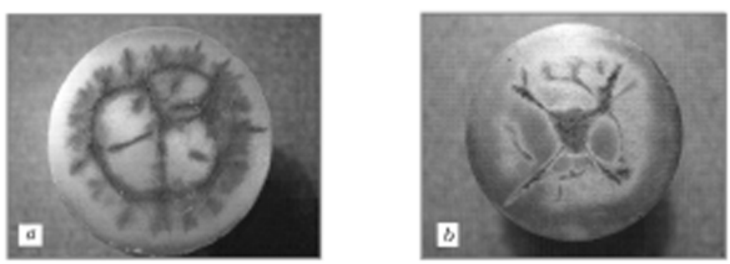


Fig. 6. End parts of the waveguides with radial and annular erosion striations: a) formation of annular and radial intersecting striations on the waveguide's end; b) waveguide's end with nonintersecting striations.

The trend of the change in the cavitometer signal as a function of pressure is preserved in the case of ultrasonic action on other liquid media, too. Figure 4 gives such curves obtained when chemically pure hexane and a mixture of hydrocarbons were used. As the pressure increases from P = 0.1 MPa to P = (0.8–1.1) MPa, the value of the A_2 signals (mV) grows by nearly an order of magnitude. Despite the significant difference in the density of the liquid media (660 kg/m^3 for hexane and 905 kg/m^3 for the mixture of hydrocarbons), their viscosities (0.0003 and 0.17 Pa·sec) and boiling points (69 and 90^oC at the beginning of boiling of the mixture), the given curves of the cavitation activity as a function of the pressure are located in close proximity. Also, characteristically the value of the signal A_2 of water is nearly twice as high as that of the mixture of hydrocarbons and even hexane at the same pressure of the media.

Cavitation Destruction of Waveguides. Numerous experiments with waveguides manufactured from different materials (alloys of titanium, aluminum, and steel) have revealed the specific pattern of their destruction in different liquid media under the conditions of maximum S_c values. The first signs of erosion usually appear on the waveguide's end within 1–2 h after the beginning of the experiment in the form of one or more small caverns that universally occur in the zone of the waveguide's central part (Fig. 5a).

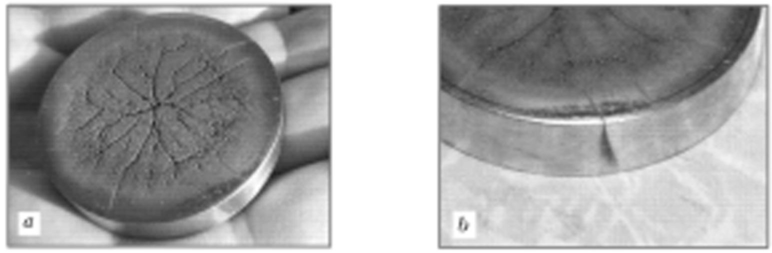


Fig. 7. End of the VT1-0-titanium waveguide with a crack on the lateral surface: a) growth of the radial striations to the boundary of the waveguide's end surface; b) crack reaching the waveguide's lateral surface.

The caverns increase to 1–2 mm with time and erosion situations grow from them in the radial direction, become deeper, and branch out (Fig. 5b and c). Annular striations intersecting the radial ones (Fig. 6a) or not contacting them may occur at a distance from the center (Fig. 6b). The signs of fusion of the material can be seen inside the striations at a large magnification. No clear signs of erosion are observed, as a rule, outside the striations and caverns on the surface of the waveguide's end.

Growth of the radial striations to the boundary of the end surface (Fig. 7a) may give rise to internal cracks in the waveguide material (Fig. 7b) which produce irreversible changes in the amplitude-frequency characteristics while putting the waveguide out of order. On certain waveguides, e.g., on those manufactured from VT1-0 titanium alloys, such disastrous damage occurred even within 8 h after the beginning of the tests.

Application of a Teflon coating to the waveguide surface can increase the time of appearance of the first erosion caverns to nearly 4 h; however, this does not lead to a subsequent marked retardation of the processes of cavitation destruction of the basic material. Attempts at creating, on the waveguide's end, a protective layer in the form of thin (0.5 mm thick) diaphragms (see item 1) manufactured from different materials (steel alloys, copper, and plastic materials) and tightly pressed via a silicone lubricant have not been successful. Strip breakage of the diaphragms in the central zone occurred approximately within 0.5–1.5 h after the beginning of the tests, and thereafter the waveguide material was erosionally damaged.

3. Discussion of Experimental Results. It may be assumed that local erosion in the form of caverns and striations on the waveguide surface, which resembles Lichtenberg figures, is related to the appearance of cluster formations from vapor-gas cavitation bubbles at these sites. Photographs of such formations resembling fractal clusters in structure are given in [3]. The external plan view of cluster formations is similar to the geometric pattern of erosion damage presented in this work. The occurrence of strong waveguide-generated hydrodynamic flows is mainly responsible for the appearance of the aggregates of cavitation bubbles near the radiating surface. The results of experimental investigations of the formation of averaged flows excited by a cylindrically shaped vibrating body in the liquid are presented in [11]. As follows from the results of this work, under the conditions of longitudinal high-frequency vibrations of the cylindrical body, we might expect the appearance of two torroidal vortices rotating in opposite directions near the end edge to form a conic liquid flow directed from the end of the body along its axis. Just at the end surface, the liquid moves in the radial direction from the edge to the center. Decrease in the medium's static pressure in the zone of the waveguide's end part is a consequence of such flows, which can stimulate the formation of cavitation bubbles in this region with their subsequent clusterization in the form of stable (stably preserved) structures.

Vibrational displacement of the end surface is a perturbing factor leading to an asymmetric collapse of the adjacent bubbles to form a cumulative jet directed toward the waveguide. Multiple collision of high-velocity jets with the surface gives rise to caverns which sharply increase the pressure pulse of microjets retarded in them. Further destruction of the waveguide material is more rapid now and develops in the form of striations appearing predominantly in the primary surface caverns.

It is likely that annular striations occur in the zones of action of toroidal vortices which can create local annular portions with a low static pressure of the medium. In investigating the acoustical effects of cavitation, it has been noted that the acoustical cavitation activity in different media (water, hexane, and a mixture of hydrocarbons) has its maximum at a static pressure of the medium of 0.8–1.1 MPa and a power of the ultrasonic unit of 3.5–4.5 kW. The process of destruction of the waveguide material is substantially accelerated under these conditions. It is significant that the character and rate of development of erosion damage were weakly dependent on the material of the waveguides, among which the largest erosion resistance was displayed by the waveguide manufactured from 40Kh steel.

Erosion striations are, apparently, concentrators of mechanical stresses that ultimately lead to cracking of the waveguide material with irreversible changes in the amplitude-frequency characteristics. Such a disastrous destruction of the waveguides may present serious problems in the commercial use of powerful ultrasonic units.

CONCLUSIONS

1. It has been established that the acoustical cavitation activity (frequency range 200 kHz–10 MHz) in different liquid media, such as water, hexane, and a mixture of hydrocarbons, has a maximum at a static pressure of 0.8–1.1 MPa and a power of the ultrasonic unit of 3.5–4.5 kW. The acoustical-activity maximum exceeds values recorded at atmospheric pressure by nearly an order of magnitude.

2. Under the conditions of the maximum acoustical cavitation activity, rod waveguides manufactured from different materials (titanium, steel, and aluminum alloys) undergo nonuniform erosion in the form of characteristic deep striations on the rod ends; these striations may give rise to cracks inside the material and may lead to a disastrous destruction of the waveguides within 8–10 h of operation. The character and rate of development of the erosion damage were weakly dependent on the material of the waveguides, among which the largest erosion resistance was displayed by 40Kh-steel waveguides.

3. To reveal the mechanisms of unusual erosion damage to waveguides one must study the features of formation and evolution of cavitation zones under the conditions of their maximum activity.

NOTATION

A_0, signal of the acoustical cavitation activity in the range 5 kHz–10 MHz, mV; A_1, the same, 200 kHz–10 MHz, mV; A_2, the same, 600 kHz–10 MHz, mV; A_3, the same, 1.5 kHz–10 MHz, mV; A_4, the same, 3–10 MHz, mV; A_5, the same, 5–10 MHz, mV; I_a, specific acoustic power, W/cm^2; P, pressure, MPa; S_a, amplitude of the sound acoustic pressure of cavitation, MPa; S_c, relative value of the acoustical cavitation activity; W, power, kW. Subscripts: a, acoustical; c, cavitation.

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