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CAVITATION EROSION - PROCESS AND DEVELOPMENT OF TESTING METHODS

KAVITACIONA EROZIJA - PROCES I RAZVOJ METODA ZA ISPITIVANJE

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Keywords
- cavitation resistance
- metallic and non-metallic materials
- mass loss
- choice of materials

Abstract

The paper presents an ultrasonic vibration method for laboratory testing of the resistance of materials to the effect of cavitation. The description of the test method and device, the test procedure, and the interpretation of test results are given in accordance with ASTM G32 standard. A comparative overview of the test results of different types of materials is presented: metal (steel, aluminium alloys); ceramics (based on pure and mixed refractory fillers); composite materials with a polymer base; refractory castings and protective coatings. Based on the test results, the correlation of structural characteristics, mechanical properties of materials are determined as a basis for quick selection of materials in hydrodynamic conditions of application.

Ključne reči
- kavitaciona otpornost
- metalni i nemetalni materijali
- gubitak mase
- izbor materijala

Izvod

U radu je prikazana ultrazvučna vibraciona metoda za laboratorijsko ispitivanje otpornosti materijala na dejstvo kavitacije. Opis metode i uređaj za ispitivanje, procedura ispitivanja, kao i interpretacija rezultata ispitivanja dati su u skladu sa standardom ASTM G32. Prezentiran je uporedni pregled rezultata ispitivanja različitih vrsta materijala: metalni (čelik, legure aluminijuma); keramika (na bazi čistih i mešavine vatrostalnih punioca); kompozitni materijali sa polimernom osnovom; vatrostalni livački i zaštitni premazi. Na osnovu rezultata ispitivanja određena je korelacija strukturnih karakteristika, mehaničkih svojstava materijala i svojstava kavitacione otpornosti materijala kao osnova za brz izbor materijala u hidrodinamičkim uslovima primene.

INTRODUCTION

Cavitation is a type of wear and represents the emergence, growth and implosion (collapse) of vapour or vapour-gas bubbles in hydrodynamic conditions. These phenomena take place in very short time intervals, less than 1 μs, during which high temperature and pressures occur, followed by the emission of micro-jets, cavitation vortices and shock waves of high intensity /1-3/. The energy of shock waves and micro-jets is dissipated within the liquid, and part of the energy is absorbed by the solid surface which is in contact with the flowing liquid. In the case of metallic materials, the accumulation of energy induces deformation strengthening and damage to the surface layers of the material, whereby micro-pits or pits of larger dimensions (holes) are formed. With the development of surface damage, the material gradually becomes more brittle, the capacity for further deformation decreases, cracks appear and they deepen over time by removing particles from the edges of the crack and the fracture surface. The degree of damage to the material is influenced by a number of factors, primarily the increase in the velocity of the liquid in relation to the solid surface, the wall of the current pipe, chemical reactions of the material and the environment, the structure and properties of the material, the initial roughness of the surface. Development of damage to the surface of the material can cause the destruction of the material which represents damage due to cavitation (cavitation erosion) /4, 5/. Unlike metallic materials, according to data from the available literature /6-7/ and our works /8-10/, non-metallic materials (ceramics, composites, refractory and protective coatings) show that under the effect of cavitation, surface damage appears, and mass loss with the material surface, without plastic deformation /11-18/.

In engineering practice, cavitation is considered and undesirable phenomenon, because it damages and destroys the material of important parts of machines and devices. However, the effects of hydrodynamic cavitation have been used in recent decades in new specific areas of application: wastewater treatment, especially mine wastewater, diesel fuel production, liquid/solid, liquid/gas, liquid/liquid filtration, mixing and mixing processes /19-21/. The use of ultrasound is widely applied for the synthesis of various chemicals, medicines, foodstuffs, nanomaterials, degradation of polluting materials in water treatment, in the food industry, metal processing, textiles, and the like, /22, 23/.

For the application of different materials under conditions of cavitation loads, the goal is to classify materials according to their resistance to the effect of cavitation and, if possible, to correlate their resistance with the structure and classical mechanical properties such as hardness, elasticity, tensile strength, toughness /1, 3, 24-25/. Testing the resistance of materials to the effect of cavitation can be performed in the field, on hydraulic machines, turbines and pumps, but the tests are expensive and not often carried out. In contrast, laboratory test methods (vibration device, the Venturi tube method, rotating disk, liquid jet impact test method) are simple, fast and economical, and extensively used in practice to rank the resistance of materials to the effect of cavitation by over 200 industrial alloys /26-28/. These methods make it possible to determine the resistance properties of materials under the effect of cavitation in a short test time (4-10 h). In recent decades, modern equipment for experimental research, hydrodynamic water tunnels of high liquid flow rates, with modern measurement technique based on lasers, is developed for detailed research of the cavitation phenomenon, but for now, this method is not standardised /1/. Experimental techniques have also been developed where, with high-speed cameras, simultaneous observation of cavitation, changes in the liquid structure, and measurements of acoustic emissions are performed. This led to a series of new findings about the nature of complex processes and cavitation phenomena, the correlation of relevant process parameters, microstructural and material properties with resistance to damage caused by cavitation, /28/.

We present an overview of the results of cavitation resistance tests of various types of metallic and non-metallic materials using the ultrasonic vibration method with a stationary sample according to ASTM G32 standard /30/. Based on the data presented in this work, proposals are made for the conditions of material testing on the same experimental device with minor modifications when it comes to non-metallic materials. This is the advantage of this method because it provides the possibility of viewing and evaluating the properties of materials, determining their service life in extreme application conditions in which excessive pressure drop, or high fluid flow rates are expected.

MATERIALS AND METHODS

In order to study damage in conditions of cavitation, tests are conducted on metal materials (steel and aluminium alloy), ceramic materials based on basalt, cordierite, mullite, zirconium-silicate, pyrophyllite, as well as materials with a mixture of refractory fillers in order to improve the properties of cavitation resistance. Composite materials based on a polymer base and protective coatings based on basalt, cordierite, mullite, zirconium-silicate, talc, and pyrophyllite are also used.

The paper /8/ investigates the process of formation and development of cavitation damage in chrome-nickel martensitic stainless steel, composition: 0.05% C; 0.60% Si; 0.65% Mn; 0.02% P; 0.01% S; 13% Cr; 4.1% Ni; 0.48% Mo. The choice of the chemical composition of steel samples and the heat treatment regime are chosen in order to achieve a compact martensitic structure resistant to wear and corrosion with good mechanical properties, such as high values of tensile strength, yield stress and dynamic strength, high resistance to corrosion, as well as good impact toughness. Thanks to their good properties, these steels are widely used in practice for the production of hydropower equipment elements, both in the gas and oil industries, for the manufacture of surgical instruments, knives, and some cutting tools, /9/.

Chemical composition of aluminium alloy AlMg4.5Mn used for experimental research: 0.13 % Si; 0.21 % Fe; 0.04 % Cu; 0.66 % Mn; 3.95 % Mg; 0.03 % Zn; 0.06 % Cr; 0.025% Ti. Due to the high requirements in terms of mechanical properties (especially increased resistance at elevated temperatures, corrosion resistance), aluminium alloys are characterised by a complex chemical composition. In addition to silicon, aluminium alloys are alloyed with copper, manganese, chromium, etc. This three-component alloy of aluminium with magnesium and manganese is characterised by relatively low weight, good strength, and is corrosion resistant, easy to process and weld. The alloy of these characteristics is primarily used in shipbuilding, /27/.

The paper examines the cavitation properties of ceramic materials based on basalt, cordierite, mullite, zirconium-silicate, talc pyrophyllite, Table 1 /14-17/. Synthesis and characterisation of tested samples take place under the same conditions. Refractory fillers are micronised to a grain size of 20 μm, pressed under 10 MPa and sintered in a laboratory furnace at 1200 °C with the sintering mode: raising the temperature to 1000 °C at a rate of 5 °C/min for 250 min; 1000-1200 °C with a heating rate of 2 °C/min for 150 min; at 1200 °C, the sintering of samples lasted 60 min. These ceramic materials are widely used for the manufacture of various parts of devices and equipment in the ceramic industry, construction, mechanical engineering, mining and metallurgy.

Table 1. Chemical composition of refractory fillers (%), /14-17/.

Filler	Oxide content, %							
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O+K_2O	ZrO_2	TiO_2
Pyrophyllite	62.56	14.92	1.22	1.45	7.32	0.9	-	-
Cordierite	43.52	30.10	1.23	20.80	3.76	0.02	-	-
Mullite	27.89	71.80	0.06	0.10	0.05	0.02	-	-
Zirconium-silicate	32.70	-	-	-	-	-	67.20	-
Talc	60.86	4.11	4.11	32.50	1.07	-	-	-
Basalt	56.21	18.61	1.15	3.40	7.78	8.30	-	-

Given that cavitation erosion is a surface degradation mechanism that is the cause of serious damage to hydraulic machines, the paper investigates various refractory coatings for the protection of metal surfaces, as well as parts of equipment in mining and metallurgy exposed to cavitation loads. Compositions and procedures for making protective coatings based on different fillers are investigated, the chemical composition of which is shown in Table 1. The following are used in the composition of protective coatings (%): refractory filler (80-85); binder based on epoxy resin (14-15); additives (1-1.2); organic solvent up to a coating density of 2.5 g/cm^3. During the synthesis, all the components of the coating composition are gradually added with constant mixing. For testing, the obtained coatings are applied in two layers on a metal substrate, air drying time 60 min, /17/.

Prepared samples of metallic and non-metallic materials are examined by ultrasonic vibration method with a stationary sample, Fig. 1. The method is based on the creation and implosion of cavitation bubbles on the surface of the sample. Test conditions and procedures, preparation of samples as well as interpretation of results are defined by these studies in accordance with the ASTM G32 standard /9, 27, 29/.

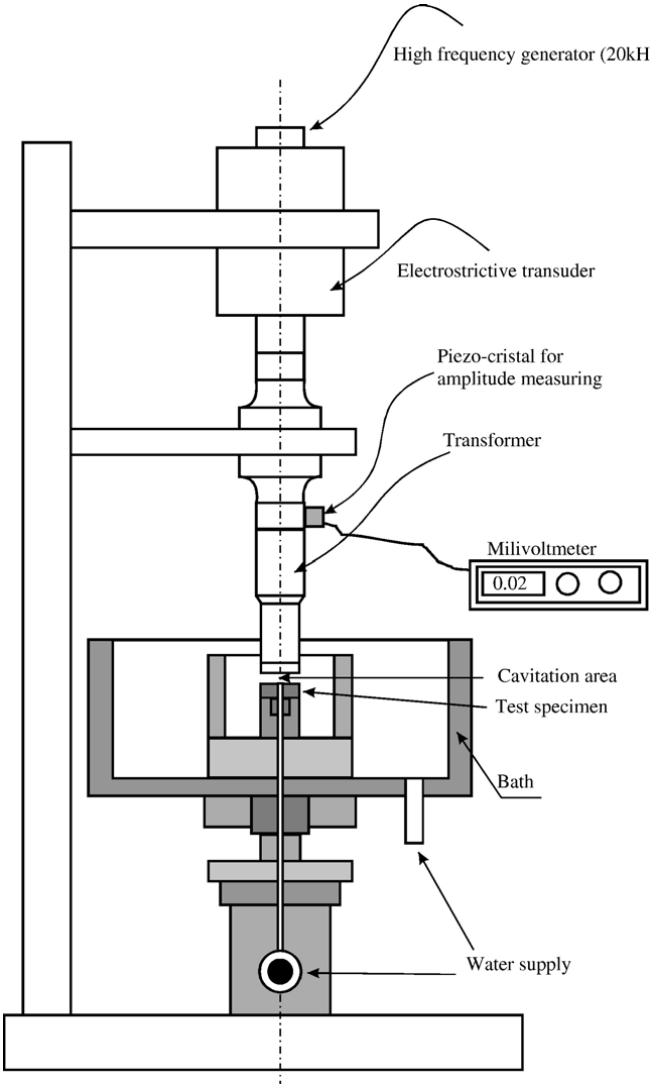

Figure 1. Scheme of the apparatus for the ultrasonic vibration method with a stationary sample.

Using the ultrasonic vibration method during the test, the loss of mass of the sample is measured at certain time intervals, and cavitation resistance is defined through the incubation period and cavitation rate. Depending on the position of the sample during the test, the ASTM G 32 standard gives two options, namely: ultrasonic method with vibrating sample-direct cavitation method and ultrasonic method with stationary sample-indirect cavitation method. In the vibrating sample method, the sample is threaded onto the top of the mechanical vibration concentrator. In the case of the stationary sample method, the sample is placed in a water bath under the concentrator of mechanical vibrations at a certain distance /27, 29/. The advantage of the method with a stationary sample is that the sample is not exposed to mechanical stress during the test, as well as in the possibility of testing samples from brittle materials that can not be treated (as in the case with the testing of ceramic samples).

During the test, the power supply is provided via a high-frequency current generator with an output power of 360 W which generates a current whose frequency is 20-50 kHz, and which is kept constant during the test. The high-frequency current is used to power the electrostrictive converter-converter, in which the high-frequency current is converted into mechanical vibrations via a piezoelectric element (zirconium-titanate). The amplitude of these vibrations is increased by means of a concentrator rigidly connected to the converter of mechanical vibrations with a diameter of ∅ 16 mm, its lower end is immersed in a water bath, /27/.

The sample to be tested is placed under the front surface of the vibration concentrator with a gap. A strong cavitation zone is formed under the front surface of the concentrator and stationary tested sample. The water in the water bath cools the sample and keeps its temperature constant. The constant flow of water creates a pressure field that encourages the implosion of cavitation bubbles on the surface of the tested sample, /26, 27/.

Bearing in mind that the degree of material destruction depends on the type and characteristics of the device for testing the cavitation process, special attention is paid to the selection of characteristic parameters of this method, namely:

- frequency of mechanical vibrations 20 ± 0.2 kHz;
- amplitude of mechanical vibrations at the top of the concentrator 50 ± 2 μm;
- gap between test sample and concentrator 0.5 mm;
- water flow 5-10 ml/s;
- water temperature in the bathroom 25 ± 1 °C.

These parameters are controlled and maintained at the given level during the testing process. The sample exposure interval and total testing time are adapted to the behaviour of the samples during the experiments. Testing time for metallic materials (min): 60; 120; 180; 240; for ceramic materials (min): 15; 30; 60; 120; for protective coatings (min): 15; 30; 45; 60; for composite samples (min): 15; 30; 45; 60. After each test interval, the samples are dried at 110 °C for one hour to a constant mass, and then the mass of the samples is measured using an analytical balance with an accuracy of ± 0.1 mg. The measurement is performed individually for each sample after all test intervals of the cavitation effect, for the total test time.

Given that in laboratory tests of material resistance to cavitation, the loss of mass is measured during the test, as a measure of material assessment to the effect of cavitation, the cavitation rate is defined:

$$V\ (\mathrm{mg/h}) = \Delta m / \Delta t\,, \tag{1}$$

where: Δm is total mass loss in milligrams; Δt is total test time interval in hours or minutes.

To define the cavitation rate, it is necessary to draw a test time-mass loss diagram. The loss of mass caused by the effect of cavitation is applied on the ordinate axis, and the time intervals are shown on the abscissa. Using the method of least squares, the points of the diagram are approximated by a straight line. The slope of the straight line represents the cavitation rate /27, 29/. Three samples are used for each

series of tested samples, and the results represent the mean value of these measurements for each test interval.

The morphology of surface damage on the samples is analysed with a scanning electron microscope. Based on the value of cavitation rate and the analysis of the morphology of the samples, the behaviour of the tested materials during the time of exposure to the effect of cavitation is interpreted, and the stability and resistance of tested samples to given test conditions is evaluated. The assessment of the behaviour of the tested refractory samples on the effect of cavitation is analysed based on the correlation of these test results with the structure and properties of the material, primarily hardness.

RESULTS AND DISCUSSION

Mass loss

The total mass loss during exposure and the calculated values of cavitation rates of all tested samples are shown in Table 2 and Fig. 2. The tested samples are: CrNi steel, AlMg4.5Mn, CT ceramic (cordierite-based ceramic + 20 % talc), PC 20 coating (coating with pyrophyllite filler mixture + 20 % cordierite), PM 20 coating (coating with pyrophyllite filler mixture + 20 % mullite), B coating (basalt-based coating), PS/B composite (composite with polymer base and basalt-based reinforcement).

Table 2. Total mass loss during exposure and cavitation rate.

Sample	Total mass loss during exposure (mg/min)	Cavitation rate (mg/min)
Cr-Ni steel	12/240	0.05
AlMg4.5Mn	55/180	0.285
CT ceramic	19.6/120	0.163
PC20 coating	8/60	0.133
PM20 coating	13/60	0.217
B coating	2.8/60	0.071
PS/B composite	20/60	0.33

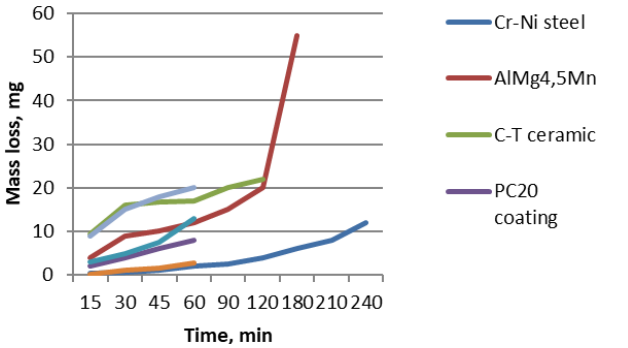

Figure 2. Diagram of mass loss of the tested samples.

Given that the samples are tested under the same test conditions, the properties of resistance to cavitation can be compared. Of the metallic materials, samples based on chrome-nickel steel show the lowest cavitation rate, $V = 0.05$ mg/min, while Al alloys show lower resistance with a cavitation rate $V = 0.285$ mg/min. Ceramic materials based on cordierite with 20 % talc (CT20 ceramic) show good resistance properties with cavitation rate $V = 0.163$ mg/min. This means that they can be used under cavitation conditions. Protective coatings with ceramic filler exhibit different resistance properties.

The highest resistance is provided by B coating $V = 0.071$ mg/min, followed by PC 20 % coating with $V = 0.133$ mg/min and PM 20 % coating with $V = 0.217$ mg/min. Basalt-based coatings have high resistance to cavitation and can be used to protect parts of equipment exposed to fluid flow in metallurgy and mining. Composite PS/B based on recycled polyester resin and 5 % basalt powder, grain size 15 μm show resistance with cavitation rate $V = 0.33$ mg/min.

Analysis of wear surface

The test results show that in the case of metal materials, the formation and development of damage under the effect of cavitation takes place gradually with the removal of material particles from the surface, with the appearance of smaller pits that deepen into larger pits (holes) during exposure and then cracks and greater destruction of the material appear. Metal materials under cavitation load begin to deform at the moment when the loads are greater than the value of the tensile strength of the material. Figure 3 shows SEM microphotographs of the surface of metal samples: Ni-Cr steel and AlMg4.5Mn alloy before cavitation, after 60 and 120 min of exposure.

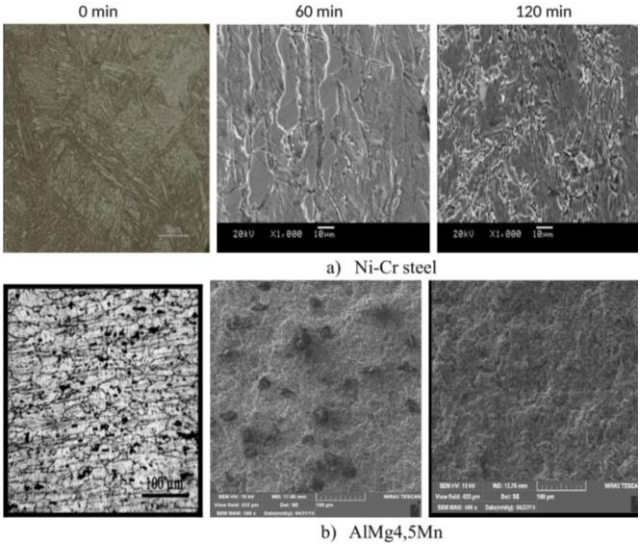

Figure 3. SEM microphotographs of sample surfaces: a) Ni-Cr steel; b) AlMg4.5Mn before cavitation, after 60 and 120 min of exposure.

Ceramic samples during the formation and development of damage in cavitation conditions have a loss of mass from the surface with the formation of pits, and the loss of mass is gradual with a lower speed of damage (CT ceramic sample), Fig. 4.

Figure 5 shows SEM microphotographs of the PS/B composite sample surface before cavitation and after 60 min of exposure.

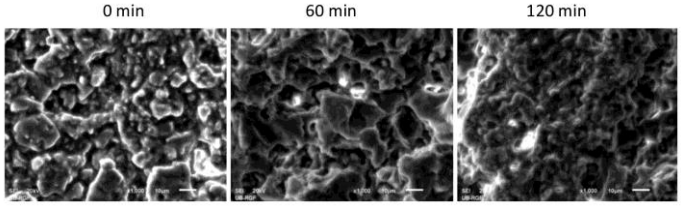

Figure 4. SEM microphotographs of CT ceramic sample surface before cavitation, after 60 and 120 min of exposure.

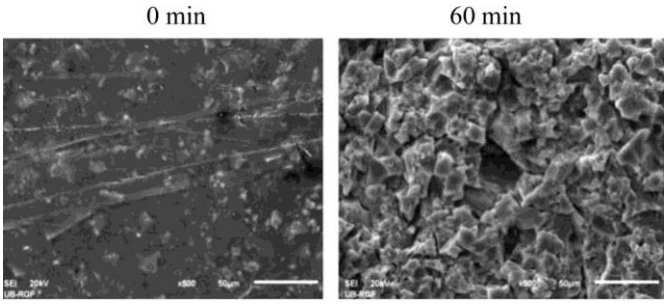

Figure 5. SEM of PS/B composite sample surface before cavitation and after 60 min of exposure.

It is shown that the examined protective coatings have a satisfactory resistance to the effect of cavitation, and the increase in cavitation resistance is primarily influenced by the higher hardness of the refractory filler, Fig. 6.

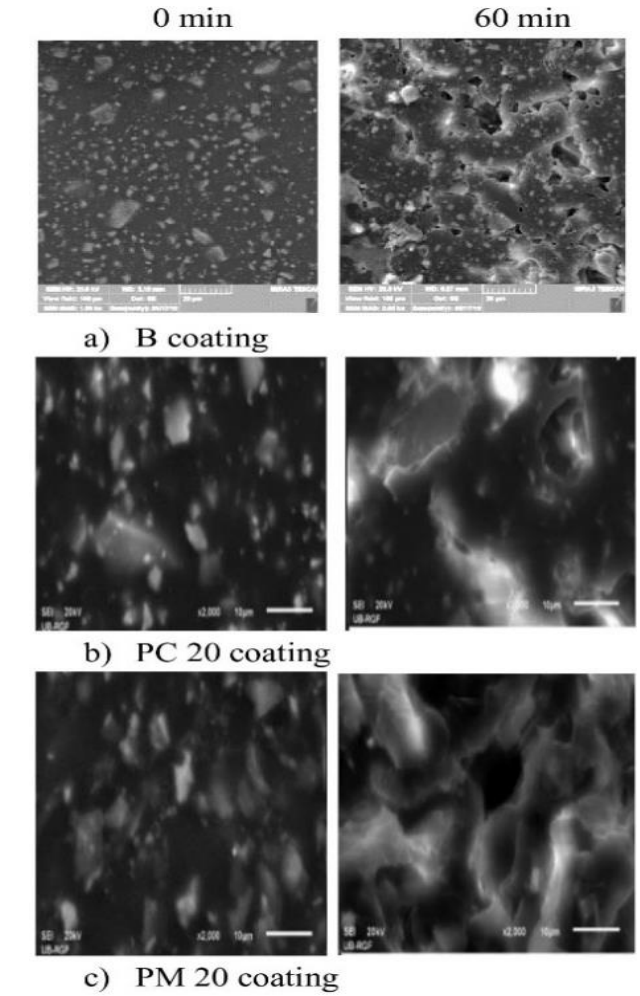

Figure 6. SEM microphotographs of coating samples surfaces: a) B coating; b) PC 20 coating; c) PM 20 coating before cavitation and after 60 min of exposure.

In future research, it is necessary to use other types of resins (epoxy resin, for example) and a reinforcer with a smaller grain size (below 10 μm) to obtain polymer-based composites with better properties.

CONCLUSIONS

It has been shown that martensitic Ni-Cr steels have high inherent cavitation resistance and can be widely used in industrial practice under conditions of high cavitation loads. Also, it has been shown that ceramics based on a mixture of refractory fillers based on cordierite and 20 % talc have good cavitation resistance and can, in some cases, replace metallic materials. In order to protect the surface of equipment parts exposed to fluid flow of different speeds during exploitation, different coatings can be applied, primarily coatings with fillers of high hardness (about 7 on the Mohs scale) based on basalt, cordierite, mullite, zirconium-silicate. Also, coatings with fillers based on a mixture of refractory materials with lower hardness (about 7 on the Mohs scale) can also be successfully applied. Investigations of the cavitation resistance of composites with a polymer base and a reinforcement based on a higher hardness filler, such as basalt, are initial. Further research should be applied with polymers with better properties and reinforcements with a smaller grain size, below 10 μm.

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