Актуальність вивчення процесу кавітації до сьогоднішнього дня не втратила своєї сили. Причиною тому многофакторность причин виникнення кавітації і, як наслідок, складність боротьби з нею. Одним з ефективних способів боротьби з кавітаційним руйнуванням є застосування спеціальних матеріалів, стійких до кавітаційної ерозії в перекачуючому обладнанні, в якості основи, наприклад, виготовлення нового робочого колеса.

Для цілей захисту поверхонь від кавітації був розроблений спеціальний матеріал на поліуретановій основі (ДК-2), який дозволяє чинити опір кавітаційному впливу без руйнування самого захисного шару. Для визначення ефективності застосування розробленого матеріалу був обраний метод ударного способу вивчення ерозійної стійкості матеріалів. Суть такого дослідження полягає в тому, щоб піддати дослідний зразок циклічному ударному навантаженню. Для оцінки здатності досліджуваного матеріалу чинити опір ударному навантаженню були розроблені зразки у вигляді циліндрів, а товщина досліджуваних зразків була обрана з практичних умов відновлення обладнання, а саме виходячи з оптимальної товщини матеріалу, що наноситься при відновленні. Досвідченим шляхом було встановлено значення товщини шару в межах 2–5 мм. Експериментальне навантаження досліджуваних зразків показало високу ефективність застосування розробленого матеріалу в якості захисного при кавітаційному руйнуванні деталі для різних режимів навантаження. У зв'язку з тим, що полімерний матеріал ДК-2 має високий рівень плинності, було запропоновано додати загущувач у вигляді скломісного наповнювача типу «Оросіл». Крім того, з огляду на складний вид зносу перекачуючого обладнання, було запропоновано зміцнити полімерний матеріал мелкодісперсним абразивним матеріалом. У даній роботі виконувалось експериментальне опробування впливу додаткових включень на міцність полімерного шару

Ключові слова: захист поверхонь від кавітації, матеріал на поліуретановій основі, кавітаційна стійкість матеріалів

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EXPERIMENTAL STUDY OF CAVITATION DESTRUCTION OF A PROTECTIVE COMPOSITE POLYURETHANE-BASED MATERIAL

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1. Introduction

Despite the large number of scientific papers and reported studies, investigating the process of cavitation has remained relevant up to now. The reason for this is the multifactorial causes of cavitation. In pumping mechanisms, the emergence of cavitation depends on the following factors: the physical properties of a liquid (temperature, flow rate, pressure), geometric parameters of the impeller, its material. In some cases, in order to prevent conditions for the emergence of cavitation conditions for a finished article, engineers aim to influence operating conditions. However, changing characteristics such as the temperature, flow rate, pressure of a pumping fluid entails technological changes and, therefore, is impractical. In addition, repairs to worn-out pumping equipment are carried out through surfacing work. This recovery technology requires additional equipment as well as mechanical processing. The use of a polymeric material makes it possible to restore equipment on site without the use of additional equipment.

2. Literature review and problem statement

The results of studies into surface hardening with plasma melting are reported in papers [1, 2]. It was shown that forming a wear-resistant, carbide-containing layer could significantly improve the surface resistance to abrasive wear. However, the issues related to the complexity of applying a plasma surfacing method remained unresolved. In addition, the use of this method is expedient in the manufacture of a new part and is not effective for repair work. The reason for this may be objective difficulties associated with the technology of applying the hardening layer, as well as the fundamental inability to strengthen parts with end-to-end wear of the surface. The use of composite and polymeric materials [3, 4] allows the restoration of worn surfaces of any level of complexity, both on the curvature of the surface and the thickness of recovery. However, the cited studies did not consider a technique for using composite materials under conditions of cavitation destruction. Advancements on the cavitation-corrosion wear [5, 6] consider the use of metallic coatings at the level of nanomaterials, as well as the application as the base for stainless steel materials. It should be noted, however, that the cost of such strengthening makes the cited studies impractical for use under conditions of pumping equipment. Utilization of specialized materials that are resistant to cavitation erosion as the base (making a new impeller) is an effective but impractical method from an economic point of view under conditions of large machines. A variant to overcome corresponding difficulties might be the local hardening of a part. This approach is used in work [7], but the issue of reliability of adhesion between heterogeneous materials, as well as the conditions for achieving its maximum value, has not yet been studied. All this suggests that it is a relevant task to undertake a study into development of a polymeric material that would ensure a comprehensive cavitation-corrosion protection.

Thus, given the above considerations, it can be concluded that the elimination or reduction of the impact of cavitation without significant financial costs is possible only when using hardening coatings applied onto working surfaces. Investigating the cavitation mechanism, one can conclude that the greatest damage to the working surface of a pump's impeller is caused by the joint action of corrosive and cavitation processes, which was confirmed by publications [8, 9]. Erosion destroys the surface of a material and contributes to the destruction of the protective oxide film, promoting the corrosive destruction of the material. Given this, it is necessary to use a corrosion-resistant and, if possible, soft material as a protective material. Rubber and plastics are successfully used as coatings. For example, resistance to cavitation erosion of nylon and polyethylene is comparable to stainless steel resistance. One of the most stable materials is titanium, but, due to its high cost, it is not widely used.

The use of polymeric materials as a protection of parts from wear is well known [10, 11]. At present, Ukrainian market offers composite materials made by many known foreign companies. The most common are Durmetall (Switzerland), Diamant (Germany), Locktite (USA), Belzona (USA), Unirep (Germany), Devcon (USA), Chester Molecular (Poland), etc. In particular, as a means to protect from cavitation, there are polymeric materials made by Belzona (USA) with the following specifications (Table 1).

Table 1

Specifications for the polymeric materials made by Belzona (USA)

Key technical information:	
Viability at 25 °C	13 minutes
Curing time for full mechanical load at 25 °C	2 days
Taber wear resistance ASTM D4060 under a load of 1 kg at 21 °C	H18 abrasive circles (wet) – 39 mm^3 loss per 1,000 cycles H18 abrasive circles (dry) – 50 mm^3 loss per 1,000 cycles
Shore hardness A – ASTM D2240	87
Cavitation resistance with the modified version ASTM G32, 20 kHz frequency and 50 μ amplitude	0.07 mm^3/h loss of volume
Mixed product volume (750 g)	682 cm³
High adhesion to materials such as	Rubber, polyvinyl chloride (PVC), aluminum, copper, steel, stainless steel, cast iron, lead, glass, wood, most types of plastic, etc.
Typical application	Internal and external coating, equipment restoration

To protect surfaces from cavitation, it is proposed [8] to use the material made by Chester Molecular (Poland) with the following characteristics (Table 2).

Table 2

Specifications of polymeric materials by Chester Molecular (Poland)

Consistency	rare
Viability of the prepared composition after mixing (at 20 °C)	35 minutes
Time to mechanical processing (at 20 °C)	4.0 hours
Full chemical resistance (at 20 °C)	in 7 days
Maximal working temperature	150 °C
Bending temperature (DIN53462)	75 °C
Compressive strength (ISO 604)	120 MPa
Bending strength (ISO 178)	110 MPa
Shear strength for steel surface (ISO 4587)	21.1 MPa
Impact strength (ISO 179)	6.3 kJ/m^2
Specific weight	1.62 g/cm^3

The well-known firm Diamant (Germany) offers a range of materials for the protection of surfaces, in particular, prokeramite, procoat, multimetal keram, with the following characteristics (Table 3).

Table 3

Mechanical characteristics of the material multimetal-keram by Diamant (Germany)

Compressive strength, MPa	160
Elongation strength, MPa	76
Shear strength, MPa	89
Bending strength, MPa	22
Modulus of elasticity, MPa	$14 \cdot 10^3$
Thermal resistance, °C (duration)	–40 to +90
Application time, min.	45
Hardening time at +5 °C, hours	72
Hardening time at +20 °C, hours	24
Density, g/cm^3	2.4

All the specified materials are inferior to conventional and special steels in their strength characteristics, but they remain rigid enough, which certainly does not contribute to their ability to effectively hinder the development of cavitation.

The Department of Mechanical Equipment for Steel Works (The State Higher Educational Establishment "The Priazov State Technical University") designed the polymeric material DC-2. It is a two-component polyurethane-based material. This material combines protective anti-corrosion properties and, at the same time, has more elasticity and malleability than the materials considered above. The material DC-2 has the following characteristics (Table 4).

Table 4

Mechanical characteristics of the material DC-2

Composition application time (at 20±2 °C), min	40
Mixture density, g/cm^3 liquid state	1.30–1.55
paste-like state	1.8–2,0
Hardening time at 20±2 °C	24 hours
Coating thermal stability, °C	From –0 to +90

However, there is an area of the further research into the composition of the developed polymeric material. Given that parts of pumping equipment (for example, an impeller) have a large number of curved surfaces, and are of complex geometry, there is a certain difficulty in applying a polymeric material. The developed material DC-2 has a high level of liquid fluidity in a non-hardened state. An "Orosil"-type thickener is used to restore such surfaces. However, the effect of the percentage of the thickener on cavitation resistance of the received material has not been studied.

3. The aim and objectives of the study

The aim of this study is to model the cavitation load on samples composed of the base material DC-2 with the addition of a thickener with a different percentage content and to determine the optimal ratio base/thickener. This would make it possible to form a polymeric composition of the required density, without significantly reducing the strength characteristics of the material.

To accomplish the aim, the following tasks have been set:

– to design an impact installation that could control geometric parameters of the examined sample, as well as the degree of its wear;

– to determine the percentage of the composition base/thickener for a polymeric iced material, which would make it possible to perceive impact loads without destroying the protective layer itself; in this case, a given composition in the liquid state should have the minimum possible fluidity;

– to test effectiveness of the resulting mixture at existing equipment.

4. Methods for studying the cavitation resistance of a composite polymeric material

An impact method for studying erosion resistance of materials was chosen to determine the effectiveness of the designed material [1]. Its essence implies exposing a prototype to cyclical impact loading. There is a method at which the sample is fixed on the edge of the wheel, rotating at high speed, while it periodically crosses the jet of water (Fig. 1).

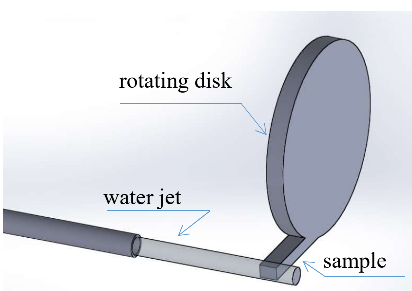

Fig. 1. Schematic of an impact installation for studying the rate of erosion destruction

A given technique is not due to cavitation factors; however, the results obtained are comparable to other studies into the cavitation process. In particular, we compared results from erosion tests obtained using three techniques: 1 – impact, applying the energy of a water jet periodically crossing the test sample; 2 – vibrational method, using a magnetostrictive vibrator; 3 – employing a hydrodynamic tube [1]. As a result of comparison, it was established that different testing methods provide indicators of the intensity of cavitation erosion, which differed insignificantly from each other. The disadvantages of the impact technique are the difficulty to study the behavior of a material after removing the load, as the duration of exposure to the force of a water flow is extremely insignificant for the detection of relaxation characteristics of the developed material. However, these methods do not make it possible to simulate the process of the effect of a single collapse of a vapor gas bubble on the tested surface. The need for such modeling is also caused by the fact that, in contrast to the metallic surface of equipment, exposed to cavitation, the composite material DC-2, which has close properties, would be deformed rather than destroyed under an impact load. From the point of view of predicting the behavior of the material, it is of undoubted interest to know patterns in the magnitude of deforming this material due to its composition under such a single impact load. To this end, an impact installation (Fig. 2) was developed, which enables, with strain gauge sensors, the recording of the force of impact and the duration of such an impact by connecting the latter to an analog-digital converter and then to a computer.

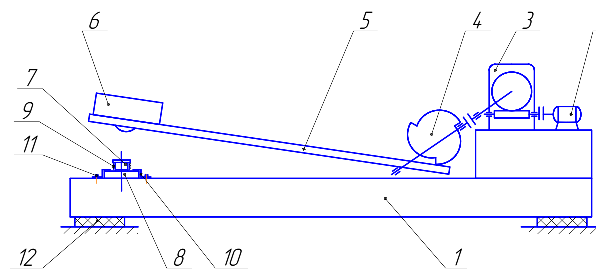

Fig. 2. Kinematic scheme of experimental installation

The installation consists of bed 1, made of a plate 250 mm thick, which hosts: electric motor 2, worm gearbox 3, and cam 4, which at rotation lowers one end of rocker 5, thus raising load 6 to the required height. After further turning the cam, its profile comes out of contact with the rocker. The rocker, under the influence of a load weighing *P*, falls on barrel 7 from height *H*, which in turn transmits the load to sample 8, mounted in a washer with a cylindrical hole. The washer is stationary fixed on the bed with clamp 10 and bolts 11. The barrel moves along guides 9, providing a coaxial location of the barrel and a sample, that is, centering the impact relative to the vertical axis of the sample. In particular, the fixing technique implied arranging the samples in metallic containers, in which we made cylindrical recesses. A sample was placed in it with an excess above the surface of the container within 2 mm. At the same time, the sample was fixed in a recess by sticking with the material that it was made of.

To assess the capability of the examined material to resist impact loading, we designed samples in the form of cylinders, of different thickness, but the same diameter. Thickness of the examined samples was chosen based on the practical conditions for restoring the equipment, namely, based on the optimal thickness of the material applied during the recovery. We chose, as a criterion for the strength of composite materials, the magnitude of the structural strength limit of a material, and, as the destruction criterion, the moment a crack appeared at the side surface of samples when reaching the limit state within a local volume.

Four groups of samples were produced to determine the ability of the material DC-2 to resist impact loads:

– "0" pure material DC-2;

– "1" material DC-2 with the addition of 15 % (by weight) of the material "Orosil";

– “3” material DC-2 with the addition of 30 % (by weight) of the material “Orosil”;

– “4” material DC-2 with the addition of 10 % (by weight) of an abrasive material.

The choice of additional fillers was dictated by the characteristics of the base of the material DC-2. When applying the material DC-2 on vertical and curved working surfaces, there is some liquid fluidity, which greatly complicates its application. Reducing its excessive fluidity can be achieved by adding a thickener in the form of the finely-dispersed powder material “Orosil”. In addition, it is known that the phenomenon of cavitation is accompanied by abrasive wear (due to the contamination of the pumping liquid), and it was suggested, therefore, using an electric corundum with a fraction of 0.2 mm as the base filler. Adding an electric corundum to the base makes it possible to create a solidified composite material with particles distributed by volume. In the process of abrasive wear of such material, the primary destruction is perceived by the particles of electric corundum, which increases the durability of the polymeric layer [3]. The examined samples were made in the form of “tablets” with a diameter of 12 mm and a thickness of 3–3.2 mm. The load used was an effort with a magnitude of 17,000 N and 25,000 N. The duration of exposure was 5 cycles (1 cycle – 1 hour). The sample was in a free state (not limited to the perimeter).

The thickness and diameter of the samples after loading were measured by the electronic vernier caliper Digital caliper A46. The reproducibility of results was achieved by measuring each sample in three cross-sections and calculating its average value. In addition, the experiment involved the use of 5 sets of samples made from the same composite mixture.

5. Results of impact loading the composite polymeric samples

Analysis of results from impact loading has revealed (Fig. 3, 4) that the introduction of fillers to the material DC-2 negatively affects its strength. As shown by diagram in Fig. 3, the increase in diameter for cases when we tested samples with the introduced filler was more intense in terms of wear (thereby increasing the diameter of the sample to 12–15 % of the original value). At the same time, as shown by Fig. 4, thickness of the samples was best preserved in the absence of a filler in the form of the material “Orosil”, as well as in the sample containing corundum, which suggests that the higher characteristics of resistance to impact destruction would contribute to the higher resistance at cavitation.

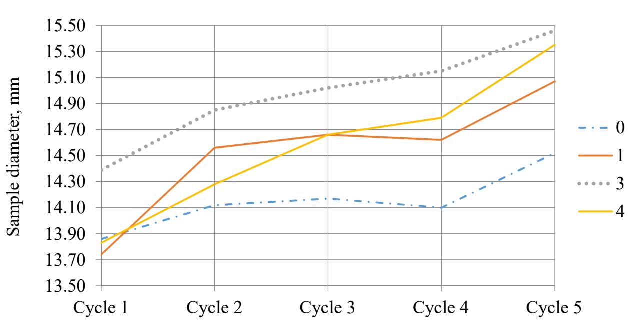

Fig. 3. Dependence diagram of change in the diameter of the examined samples on the impact load cycle at impact force 17,000 N

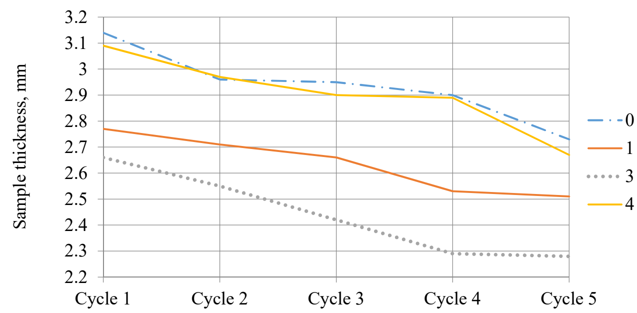

Fig. 4. Dependence diagram of change in the thickness of the examined samples on the impact load cycle at impact force 17,000 N

Similar studies under a load of force 25,000 N confirm the best resistance by samples “0” and “4” (Fig. 5, 6).

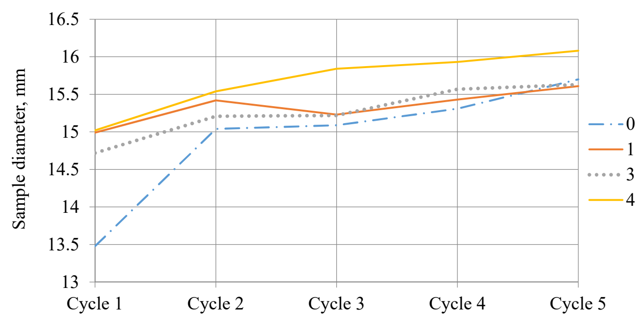

Fig. 5. Dependence diagram of change in the diameter of the examined samples on the impact load cycle at impact force 25,000 N

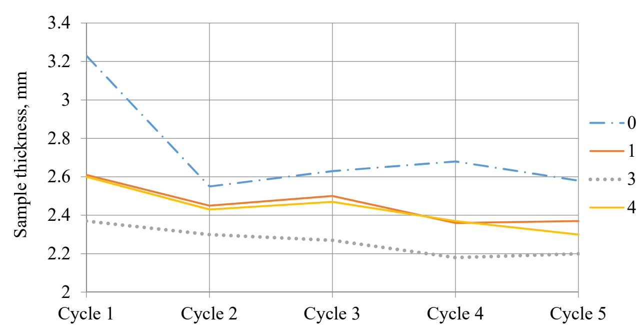

Fig. 6. Dependence diagram of change in the thickness of the examined samples on the impact load cycle at impact force 25,000 N

However, such loading could lead to plastic deformations. It should be noted that the value of 25,000 N was chosen as the boundary (maximum) one, as the static loading of the same samples at 25,000 N demonstrated the crack formation at their side ends.

To confirm the effectiveness of using soft materials as protective under an impact influence, we have additionally considered a variant of applying a coating made of the more rigid composite “multimetal-keram”, epoxy-based, whose characteristics are given in Table 2.

Such a material, in contrast to DC-2, was more rigid; in some cases, it is used as a protective material. We studied its ability to withstand impact loads in line with the same procedure as the material DC-2; thickness of the samples was 2 mm and 4 mm. Our tests found that the magnitude of load of 25,000 N was critical on load cycle 4; the sample collapsed as a result. A similar destruction occurred at 28,000 N, but as early as on cycle 1. At the same time, reducing the load to 20,000 N made it possible for the samples to withstand all 5 load cycles. When assessing these results, in comparison with the results from studying the material DC-2, we once again confirmed the thesis on the feasibility of using a less rigid material to protect against impact loads, which could be identified as an impact caused by the collapse of a vapor gas bubble.

Based on the results obtained, we have devised a technology to protect impellers in the pump CN 3000–197 at the South Ukrainian nuclear power plant against cavitation wear. The recovery technology implies that a worn surface is pre-cleaned and degreased. Then a composite material is applied in two layers. In this case, the first layer is rubbed into the worn surface, and, after its polymerization, the second layer containing the filler "Orosil" is applied. The content of the filler "Orosil" was 10–12 % by weight. Results from a-year-long tests (about 7,500 operating hours) showed the effectiveness of the application of the devised technology. There was no washout of the applied material, the pump after inspection was recommended for further operation. The result was confirmed by inspection act No. 00.GC.Ak.41-16 as of February 20, 2019.

6. Discussion of results of studying the resistance of composite polymeric samples to impact loading

The results obtained suggest (Fig. 3, 4) that the introduction of a filler the type of "Orosil" in the amount exceeding 15 % (by weight) significantly reduces the resistance of samples to impact loading (up to 17 % compared to samples without fillers). The use of an abrasive material as a filler reduced the durability of samples by up to 5 % compared to samples without fillers. This behavior can be explained by the fact that the abrasive particles, in the polymer mixture, act as a reinforcement material. At the same time, particles of the glass-containing material "Orosil" only thicken the polymeric mixture. This is due to the fact that the finely dispersed material does not perceive the impact load, and the mixture itself becomes more porous, which additionally leads to greater deformations. It should be noted that this type of loading has made it possible to control the geometric parameters of samples at any given time, which is a significant difference from a known method of loading with a flow of liquid.

For the method used, there is a constraint due to the limited number of load cycles (predetermined by the length of the loading process). However, this limitation can be overcome by using interpolation methods, which could predict the results of loading. The advancement of the current study is seen in the application of a mathematical model of loaded objects with a complex geometric shape. The developed technology for strengthening a polymeric material with an electric corundum in the amount of up to 10 % by weight as a technique to protect against cavitation-abrasive wear has been confirmed by a-year-long industrial tests. We restored impellers in the pump CN 3000–197 at the South Ukrainian nuclear power plant. There was no washout of the polymeric material. The content of an abrasive material should be in the range of up to 10 % by weight.

7. Conclusions

1. The use of the proposed impact method for loading samples, which simulates the cavitation process, makes it possible, first, to change the force of an impact in a wide range, and, second, to control a change in the geometric parameters of the examined samples in the process of loading. For the current study, samples were loaded with an effort of up to 28,000 N and a maximum diameter of samples of up to 16 mm.

2. The results obtained suggest that the use of composite materials as a protective layer not only prevents the development of cavitation erosion, but also protects the protected surface from corrosion. The use of a thickener the type of "Orosil" is recommended in the range of up to 15 %. Further increase in the thickener content leads to a sharp decrease in the strength characteristics of the polymeric layer. Application of the material "Orosil" within the specified limits ensures the lowest possible liquid flow of the material, without significantly reducing the strength characteristics of the cured layer.

3. Adding an abrasive material makes it possible to use it to protect pumping equipment operating under conditions of cavitation-abrasive wear.

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