

ULTRASONIC CAVITATION EROSION OF ELECTROCHEMICAL SELECTIVE PLATED COPPER AND NICKEL COATINGS

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Received on July 22, 2024

Presented by Ch. Roumenin, Member of BAS, on September 17, 2024

Abstract

This study investigates the extent of cavitation erosion and the changes in surface topography of two types of bronzes commonly used in cavitation environments, as well as two types of electrochemical selective plated copper and nickel coatings. The degree of cavitation erosion is determined through the ASTM G32-16 standard test method for cavitation erosion using a vibratory apparatus. The losses in mass, volume, and the average depth of erosion were measured after five cycles of 50 min in distilled water. Changes in macrostructure and surface roughness during the cavitation erosion test were also investigated. Results showed that the selective electroplated copper and nickel coatings exhibit superior resistance to cavitation erosion compared to conventional phosphor bronze and nickel aluminium bronze materials. The improved performance is attributed to the formation of a damping layer during the deposition process, which absorbs and disperses some of the impact energy from the cavitation effect.

Key words: copper coatings, nickel coatings, selective plating, cavitation erosion, ASTM, G32

Introduction. The process of cavitation erosion is highly destructive and can cause serious operation losses. Cavitation occurs in a liquid with an uneven velocity distribution and is the formation of vapour-gas bubbles caused by a local change in the pressure of the liquid below the critical one. They form in areas of

<https://doi.org/10.7546/CRABS.2024.11.09>

lowest pressure, move with the fluid, and implode in areas of increased pressure [1]. The released energy manifests as vibrations, noise, and deformations (hollows, depressions, caverns) on the surfaces of solid bodies subjected to impact pressure. Cavitation effects are commonly observed in hydro turbines, ship propellers, and machine parts that operate in heterogeneous environments, such as the impellers of centrifugal pumps [2, 3]. Prolonged cavitation can cause erosion, wear, deformation, tearing, and other forms of damage. To minimize these effects, modern design techniques and technologies are employed. When selecting materials, it is crucial to consider factors such as mechanical and physical properties, production and maintenance costs, and repairability [3].

Protective coatings offer unique capabilities for effective control of both cavitation and corrosion [3]. These coatings are widely used to provide long-lasting protection against various conditions, from atmospheric exposure to highly aggressive environments. Their main function is to create a protective barrier that prevents reactive materials from interacting with aggressive liquids, solids, or gases [4]. To effectively fulfill their purpose, protective coatings must form a defect-free, uniform, and continuous layer. Even minor defects can become focal points for increased cavitation, corrosion, and structural failure. Therefore, ensuring the quality and integrity of the coating is critical for maintaining long-lasting performance and protecting the underlying structures [5]. In a cavitation environment, it is essential for materials to absorb the impact energy of cavitation without causing surface deformations [6].

In the present study, a comparative analysis was performed to assess the degree of cavitation erosion of two conventional bronze alloys and of two types of selective electroplated coatings based on copper and nickel.

Conventional materials subjected to cavitation erosion include nickel-aluminum bronze CW307G and phosphor bronze CuSn5, commonly used in cavitation environments [7,8]. The tested electroplated coatings were obtained by the method of selective electrochemical deposition from two electrolyte solutions of copper and nickel [9,10]. A characteristic of the application method is that in the process of deposition, the columnar structure is formed, which implies the damping properties of the coatings [10].

To determine the degree of cavitation erosion, a standardized method according to ASTM G32-16 Standard Test Method for Cavitation Erosion Using Vibratory Apparatus was used [11].

Experimental. Samples from two of the most commonly used copper alloys, Phosphor bronze CuSn5 and Nickel-aluminium bronze CW307G, were cut to dimensions of $20 \times 20 \times 3$ mm using a low-speed cutting machine, model DTQ-5. The samples were then cleaned using isopropanol in ultrasonic bath, washed with deionized water and air-dried.

The following solutions of metal salts were used to form the selective electrochemical coatings based on copper and nickel:

- copper-based electrolyte solution with a temperature of 20 °C, pH 8.5, metal content of 80 g/l, and a deposition voltage range of 3 to 6 V.
- nickel base electrolyte solution with temperature 20 °C, pH 2.3, metal content 110 g/l and deposition voltage range 6 to 10 V.

Coatings were applied to Phosphor bronze test samples following the established technology [9]. Preliminary preparation of the substrate was carried out, including electro-cleaning, electrochemical etching, and surface activation operations, using solutions suitable for the substrate material. A 1 μm -thick Ni sublayer is provided to support diffusion processes during deposition. Two types of coatings were obtained: copper-based (Copper coating) and nickel based (Nickel coating) with a thickness of 40 μm and an area of 3 mm^2 . The thickness of the coatings was calculated using the operating mode parameters (ampere-hours) according to the application area. A current source (impulse power supply unit) with the ability to control current and voltage, as well as change the polarity, is used in the operations of preparation and application of coatings.

According to ASTM G32-16 Standard Test Method for Cavitation Erosion Using Vibratory Apparatus, cavitation conditions are simulated using an ultrasonic apparatus consisting of a 20 kHz ultrasonic transducer with a touch screen capable of changing power, time, amplitude, and temperature tracking of the liquid during operation (Fig. 1). The test specimen is mounted stationary in a container of distilled water while the titanium sonotrode vibrates with a certain amplitude and causes a cavitation erosion effect on the surface. Titanium sonotrodes with

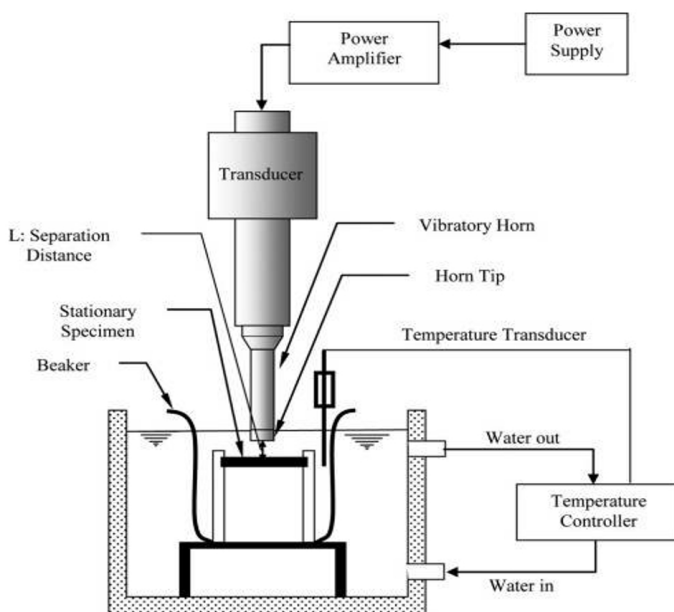


Fig. 1. Scheme of ultrasonic vibration apparatus

an area of 1.766 cm² and 0.785 cm² were used in the conducted research. The distance between the vibrating tip of the sonotrode and the test specimen is fixed at 2 mm.

To maintain a certain temperature interval, a cooling system with water cooling is provided, which consists of a thermostat and a cooling bath. Five test cycles of 50 min duration were carried out, with distilled water as the working fluid. After each test cycle, the cumulative mass loss Δm of each test specimen was recorded using an electronic balance, having previously been cleaned with acetone and dried with hot air.

The values of the cumulative losses of volume ΔV and the cumulative average depth of erosion MDE were calculated, relative to the area of the sonotrode used (Fig. 2).

Cavitation erosion time, min	50	100	150	200	250
Copper coating					
Cumulative mass loss Δm , g	0.0003	0.0005	0.0007	0.0011	0.0018
Cumulative volume loss $\Delta V = \Delta m / \rho$, sm ³	0.000034	0.000057	0.00008	0.000125	0.000205
Indenter area S , sm ²	1.766	1.766	1.766	1.766	1.766
Cumulative mean depth of erosion, MDE = $\Delta V / S$, μm	0.193	0.322	0.45	0.708	1.158
Nickel coating					
Cumulative mass loss Δm , g	0.0005	0.001	0.0012	0.0013	0.0013
Cumulative volume loss $\Delta V = \Delta m / \rho$, sm ³	0.000056	0.000112	0.000135	0.000146	0.000146
Indenter area S , sm ²	1.766	1.766	1.766	1.766	1.766
Cumulative mean depth of erosion, MDE = $\Delta V / S$, μm	0.318	0.636	0.763	0.827	0.827
Nickel Aluminium Bronzes CW307G					
Cumulative mass loss Δm , g	0.0009	0.0011	0.0014	0.0017	0.002
Cumulative volume loss $\Delta V = \Delta m / \rho$, sm ³	0.000113	0.000138	0.000176	0.000214	0.000252
Indenter area S , sm ²	0.785	0.785	0.785	0.785	0.785
Cumulative mean depth of erosion, MDE = $\Delta V / S$, μm	1.442	1.763	2.243	2.724	3.205
Phosphor bronze CuSn5					
Cumulative mass loss Δm , g	0.0004	0.0014	0.0026	0.0037	0.0062
Cumulative volume loss $\Delta V = \Delta m / \rho$, sm ³	0.000045	0.000157	0.000292	0.416	0.697
Indenter area S , sm ²	1.766	1.766	1.766	1.766	1.766
Cumulative mean depth of erosion, MDE = $\Delta V / S$, μm	0.2545	0.89073	1.65422	2.35408	3.94467

Fig. 2. Cumulative mass loss, cumulative volume loss, and cumulative average depth of erosion of CW307G nickel-aluminium bronze, CuSn5 phosphor bronze, and selectively applied copper- and nickel-based electrochemical coatings after cavitation erosion testing in distilled water

The change in the surface topography of the test specimens was investigated, and the average value of the surface roughness Rz after each test cycle was calculated (Fig. 4). The change in the macrostructure of the studied materials after an exposure time of 250 min is presented in Fig. 3.

Results and discussion. Macrostructure after cavitation tests. The process of cavitation erosion is the result of mechanical and electrochemical actions

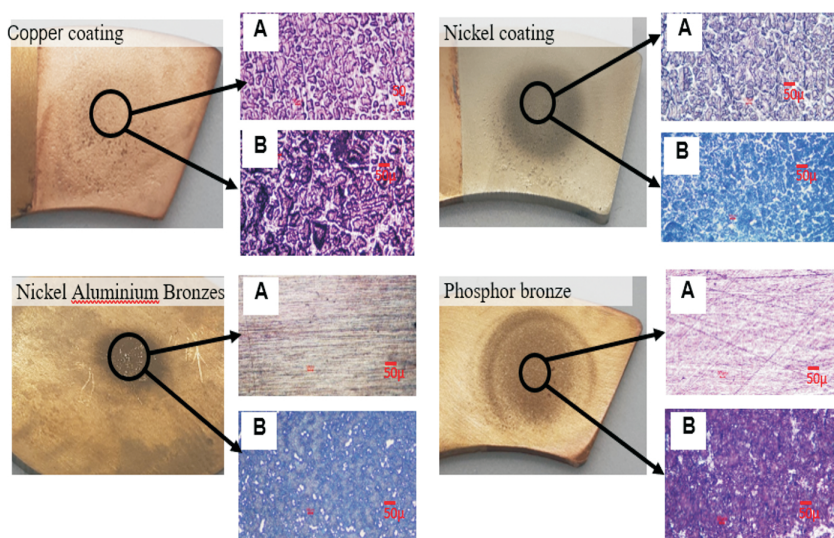


Fig. 3. Surfaces of CW307G nickel-aluminium bronze (Ni-Al bronze), CuSn5 phosphor bronze (P bronze) and selective plated copper (Cu coating) and nickel (Ni coating) coatings, (B) before and (A) after cavitation erosion test for 250 min in distilled water

and is determined by the response of the material to the cavitation energy. Initially, the generated shock wave produces compressive stress on the surface, then it is reflected and produces tensile stress. Cavitation wear is similar to surface fatigue wear. The imploding steam bubbles impose an impulse load, which leads to the appearance of microcracks on the surface of the material. Microcracks initiate around grain boundaries and inclusions [13,14]. The surface of the material first undergoes elastic deformation and then plastic deformation, causing depressions and caverns to appear over time. A critical aspect of the cavitation wear process is the destruction of the surface and breaking off of particles. The amount of damage that cavitation causes depends on the amount of liquid, pressure, and velocity that creates the vapour bubbles. The change in the macrostructure of the test specimens after each test cycle was investigated. The resulting surface defects and the type of structure after an exposure time of 250 min are presented in Fig. 3. In the test samples of Nickel Aluminium bronze and Phosphor bronze, a distinct oxide layer formed on the base metal can be observed on the surface, which significantly changes the topography on the surface. This oxide layer has a protective function and can lead to an increase in corrosion resistance in corrosive conditions [13]. In the working fluid distilled water, in both materials, after an exposure time of 250 min, uniformly distributed micro caverns were observed over the entire surface covered by the sonotrode. Phosphor bronze is the material with the most defects on the surface and has the highest degree of cavitation erosion (Fig. 4).

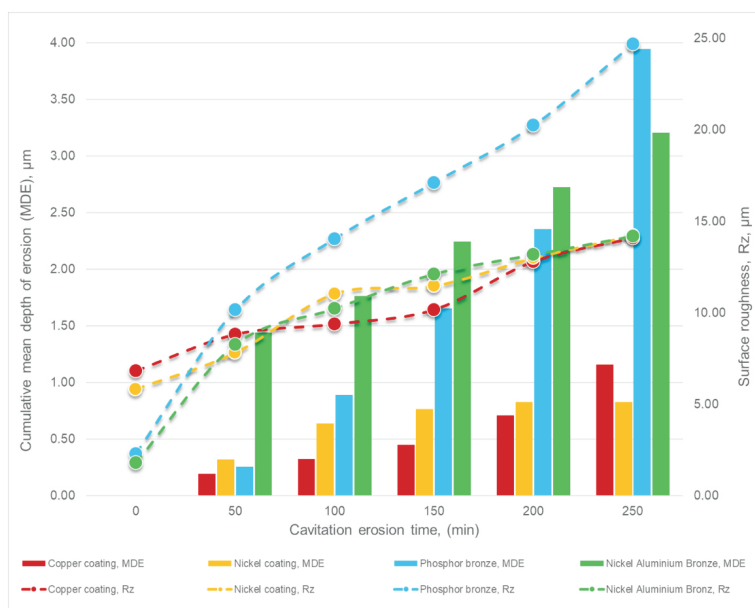


Fig. 4. Cumulative mean depth of erosion and surface roughness Rz of CW307G nickel-aluminium bronze, CuSn5 phosphor bronze, and selectively deposited copper-nickel-based electrochemical coatings during the cavitation test

In the case of selective electrochemical coatings based on copper and nickel, the characteristic layered structure obtained as a result of using high-frequency pulses during deposition is observed. After an exposure time of 250 min there are no significant macrostructural changes. The defects from the cavitation erosion have a smaller concentration, and some of them are also observed outside the area of the sonotrode. This effect supports the hypothesis of the damping properties of selective coatings that disperse the impulse load and reduce the rate of cavitation erosion.

Surface roughness. The values of initial surface roughness Rz of Nickel aluminium bronze CW307G and Phosphor bronze CuSn5 are 1.8 μm and 2.3 μm, respectively. Samples with deposited selective coatings on copper and nickel bases have higher surface roughness Rz – 6.8 μm and 5.8 μm. In the process of testing for cavitation erosion, it was established that the surface roughness of the test samples of the conventional materials varies widely, and this effect is more pronounced in the case of Phosphor bronze CuSn5 – from 2.3 μm to 24.7 μm.

In the test samples with the selectively applied copper and nickel based coatings, a smooth variation of the surface roughness is observed in narrow limits with approximately the same step. This iteration confirms the presence of a damping layer that is essential in the cavitation process. The damping layer formed in the selectively applied coating creates the possibility of absorbing part of the impact

energy in the cavitation effect. This fact is confirmed by the lower degree of cavitation erosion expressed by the calculated mean depth of erosion MDE. After an exposure time of 250 min, the surface roughness Rz of both types of coatings and Nickel aluminium bronzes is identical (Rz 14.22 Nickel coating; Rz 14.09 Copper coating; Rz 14.2 Nickel aluminium bronze). A significant difference in the surface roughness Rz is observed for Phosphor bronze, which also appears with the highest degree of cavitation erosion.

Cavitation erosion using ultrasonic vibration apparatus. In a cavitation erosion test method using an ultrasonic vibratory apparatus in a working fluid of distilled water, the lowest average depth of erosion after a test interval of 250 min was obtained for the copper selective coating. The nickel coating shows a similar behaviour in cavitation conditions, and after an exposure time of 150 min, the average depth of erosion does not change significantly. Conventional materials have lower cavitation resistance, with Phosphor bronze having the highest average depth of erosion. The change in roughness is a significant indicator of the degree of cavitation erosion. Selective coatings show better resistance to cavitation erosion in working fluid distilled water, despite the higher initial roughness Rz.

Conclusion. Selective electrochemical coatings based on copper and nickel are suitable for work in cavitation environments, and their resistance to cavitation erosion in a work environment of distilled water is better than conventional materials Phosphor bronze and Nickel aluminium bronzes. Cavitation erosion defects are of lesser degree and concentration. The damping layer of the coatings obtained as a result of the deposition method makes it possible to absorb some of the impact energy in the cavitation effect and disperse the impulse load. Significant changes in the character of the macrostructure of the coatings are not observed after an exposure time of 250 min. The surface roughness values increase smoothly in a narrow range, unlike conventional materials, where there is a sharp difference with the initial roughness.

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