Considerations Regarding the Different Behaviour to Vibratory Cavitation Erosion-Corrosion of Brass and Bronze Used in the Cooling and Power Systems of Railway Engines

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Abstract: *Very many components operating in liquid environments are manufactured from copper-based alloys, i.e. brass and bronze. Most often, these alloys are selected based on their resistance to chemical corrosion and their high level of heat transfer capability. Some of these components are subject to cavitation stress. In consideration of the above, this paper presents the different resistances to vibratory cavitation erosion-corrosion of brass (CuZn39Pb3) and bronze (CuSn12-C) in semi-finished state, used to manufacture the components of valves installed in the cooling systems and hydrodynamic power transmission of railway vehicles. To show these differences in the behavior and resistance of the material when it is subject to cavitation microjets from the vibratory cavitation process, we are using SEM and photographic images of the eroded surface structure. The assessment of the difference in resistance is made based on the MDE(t) curves and the specific parameters: average erosion depth, cavitation resistance and the average roughness, as appearing in the profile diagram for the eroded surface. The experiments were performed using the standard piezoelectric crystal assembly, available in the Cavitation Research Laboratory at the Polytechnic University from Timisoara.*

Keywords: *Cavitation erosion-corrosion, microstructure, erosion depth, cavitation resistance, roughness, brass, bronze.*

1. Introduction

Copper-based alloys (brass and bronze) are largely used in the industry, especially in the construction of the vehicle water-cooling systems, due to their technological properties (allowing the production of semi-finished components by casting, rolling, forging, due to their adaptability to mechanical processing and heat treatments, etc.), and due to their physical and mechanical characteristics, which make them withstand the chemical corrosion during operation, as well as the thermal and hydrodynamic stress, such as cavitation. Thus, components manufactured out of brass and bronze alloys, in semi-finished state, can be found in all the equipment and installations processing liquids (hydraulic turbines and pumps, hydrodynamic transmissions, command and control equipment from the hydraulic drive systems, pipelines, valves, fittings and pumps on the water-supply and irrigating systems), where the hydrodynamic effect occurs as a result of pressure variations (i.e. decrease below vaporization threshold and sudden increase) [1]. In time, operation under cavitation determines the decommissioning for repairs or replacement, because of the damages caused by the erosion of cavitation microjets. According to the type of brass or bronze allow, the degree of damage is different. In consideration of the above, this paper presents the research results of the exposure to vibratory cavitation of brass (CuZn39Pb3) and bronze (CuSn12-C) in initial state (as delivered), in order to understand the damage mechanism and choose the best practical solution for components operating in cavitation conditions.

2. Materials under analysis

The materials used in our research are two alloys: a copper-zinc alloy (brass) and a copper-tin alloy (bronze). We have chosen these two alloys because they are used in the production of a wide range of components operating in low-intensity cavitation conditions (discharge tap and valve bodies), as well as in the production of pump rotors and hydrodynamic drive turbines, and ship propellers, where the cavitation forces exceed moderate values. For these reasons, it was necessary to know the behavior and resistance to cavitation erosion, as created in the piezoelectric crystal assembly, available in the Cavitation Research Laboratory at the Polytechnic University from Timisoara, which creates quite a high destruction intensity, much higher than the one in the real operating conditions for the above-mentioned components.

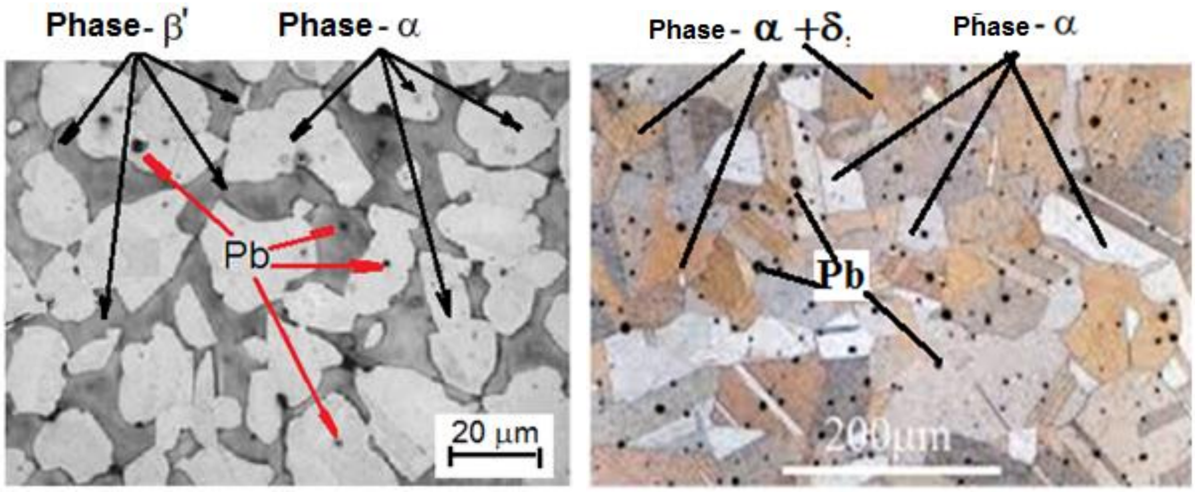
The brass (CuZn39Pb3) was made available by SC Color-Metal SRL, as a 20-mm rod which is mainly used for pipe fittings and valve stoppers.

The chemical composition, as determined by laboratory tests, is as follows: [2] 57.7 % Cu, 38.49 % Zn, 3.3 % Pb, 0.2 % Fe, 0.1 % Ni, 0.2 % Sn, 0.01 % Al.

The mechanical properties, as determined by laboratory tests, are as follows: tensile strength R_m = 502 MPa, fluid flow $R_{p0.2}$ = 365 MPa, Vickers hardness (average of 8 measurements) = 121.75 HV0.5, breaking elongation A5 = 18 %, coefficient of longitudinal elasticity E = 97 GPa, density ρ = 8.47 g/cm^3.

The two-phased structure made up of the solid solution α (approx. 60%) and the electronic compound β (approx. 40 %), figure 1, [2].

The bronze alloy (of the type CuSn12-C) was received from the "Dunărea de Jos" University from Galati, as a 20-mm diameter rod, turned from a cast semi-finished product. This alloy, in comparison with brass (CuZn39Pb3) is more widely used for components which need to withstand wear and tear by chemical corrosion and cavitation [2], such as: discharge valve bodies, fittings, hub for removable blade impellers, pump and turbine rotors for hydraulic machines, ship propellers.



a) b)

Fig. 1. Structure of brass CuZn39Pb3 (a) and bronze CuSn12-C (b)

(image taken with [2])

The chemical composition, as determined by laboratory tests, is as follows [2]: 85.16 % Cu, 11.18 % Sn, 0.4856 % Zn, 0.7983 % Pb, 0.5226 % Fe, 0.6933 % Ni, 0.2 % Sn, 0.0304 % Mn, 0.0382 %S, 0.0714 %Sb, < 0.003 %P.

The mechanical properties, as determined by laboratory tests, are as follows [2]: tensile strength R_m = 312 MPa, fluid flow $R_{p0.2}$ = 157 MPa, Vickers hardness (average of 8 measurements) = 146.125 HV0.5, breaking elongation A5 = 9 %, coefficient of longitudinal elasticity E = 97 GPa, density ρ = 8.77 g/cm^3.

The two-phased structure made up of α-phase solid solution and eutectoid grains (α + δ) [2], figure 1b.

3. Method and equipment used for the experimental tests

The equipment used to generate cavitation conditions is a standard piezoelectric crystal plates equipment, shown in figure 2, from the Cavitation Laboratory [3-10] within the Polytechnic

University from Timisoara, whose operational parameters are constantly monitored and kept within the limits provided for in the ASTM G32-2010 standard [11], as follows:

- Vibration amplitude (double) = 50 µm;
- Vibration frequency = 20 ± 0.02 kHz;
- Power of the electronic ultrasound generator = 500 W;
- Liquid environment = double-distilled water;
- Liquid temperature = 22 ±1° C.

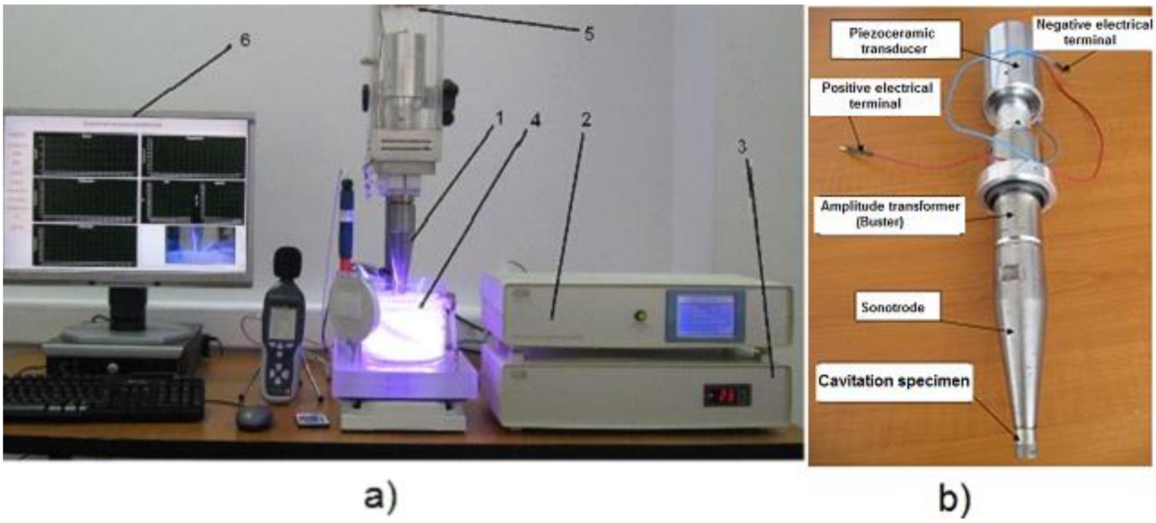


Fig. 2. Vibrating piezoelectric crystal plates

a) Image of the equipment used (1 - sonotrode; 2 - electronic system used to generate the vibration frequency and the power necessary for the 20 KHz/500 W piezoceramic transducer; 3 - water temperature regulator; 4 - container for the liquid, with a serpentine cooler; 5 - piezoceramic transducer ventilation/cooling system; 6 - computer, used to command and control the vibratory equipment parameters).
b) The vibratory mechanical system

Before the cavitation tests were performed, the samples were brought to the shape and dimensions in figure 3, while the surfaces subjected to cavitation attack were polished to a roughness Ra ≅ 0.02 µm. In keeping with the laboratory protocols, at least three samples were tested for each of the states of the materials under research [5, 6], [10], [12].

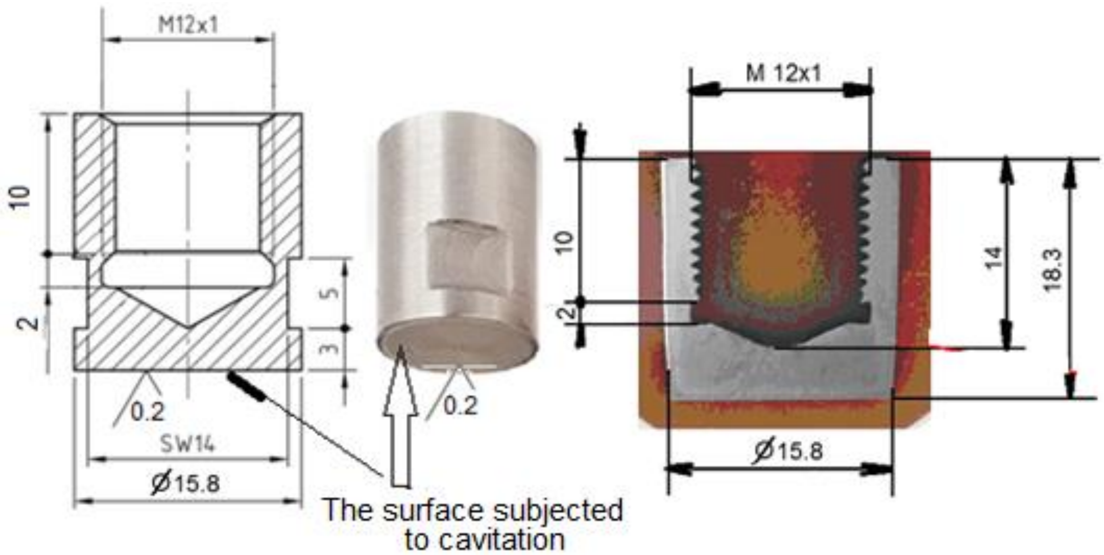


Fig. 3. The sample used for the cavitation test

According to the methodology observed in the Cavitation Research Laboratory, and in compliance with the requirements established by the ASTM G32-2010 standards [9], [11], the total duration of a vibratory cavitation erosion-corrosion test was 165 minutes. This duration was divided in intermediate durations: 5 minutes (one), 10 minutes (one), and 15 minutes (the remaining 10 durations), in order to observe the behavior of the surface subjected to cavitation.

4. Experimental results. Analysis and discussions

4.1. The evolution of the morphological damage in the semi-finished slabs

Figures 4 and 5 show SEM and macro images of the surfaces eroded by vibratory cavitation, after 165 minutes of exposure to the vibratory cavitation erosion-corrosion process. These images show that, at the end of the 165 minutes of exposure to erosion by vibratory cavitation, the crevice sizes increase, while the crack propagation expands both at the surface and in depth, with cracks forming along the grain boundaries.
In the case of brass (figure 4), it can be seen how the β′-grain is removed and how the cracks propagate. The distinct characteristics of the cavitation-eroded sample surface are determined by a number of irregular crevices, resulted from the removal of the Cu-Zn compound (β′ - phase), i.e. increased toughness and brittleness. Also, other crevices are caused by the Pb-inclusions inside solid-state solution α grains, resulted from the substitution of Zn with Cu.

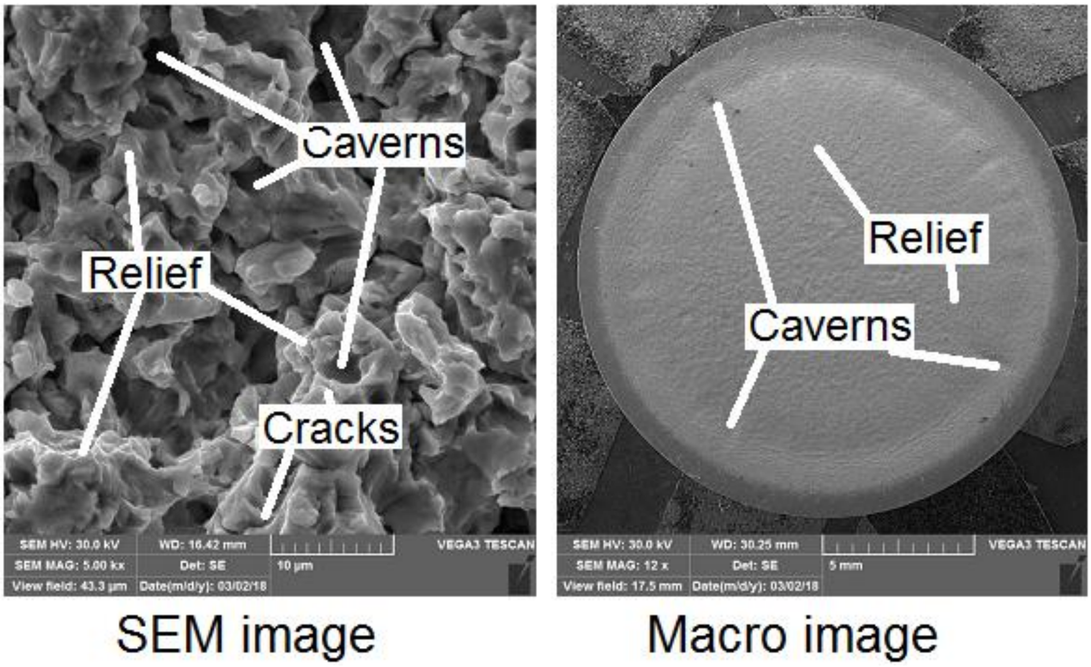


Fig. 4. SEM and macro images of the brass (CuZn39Pb3) sample microstructures, in the semi-finished state, after 165 minutes of exposure to cavitation erosion-corrosion

The SEM and macro images of the bronze (CuSn-12C) sample from figure 7 show the propagation of cracks and the formation of indentations and crevices by grain removal and coalescence of such cracks, as a result of the cyclical stress on the sample surface, caused by cavitation microjets and shock waves, specific to the fatigue process, thus resulting in a porous and very rough surface. Also, the SEM investigation reveals the formation of evenly distributed pitting in the matrix of solid solution α, which substitutes SN in Cu, and the occurrence of polyhedral indentations in the former δ-electronic compound areas, characterized by increased brittleness.

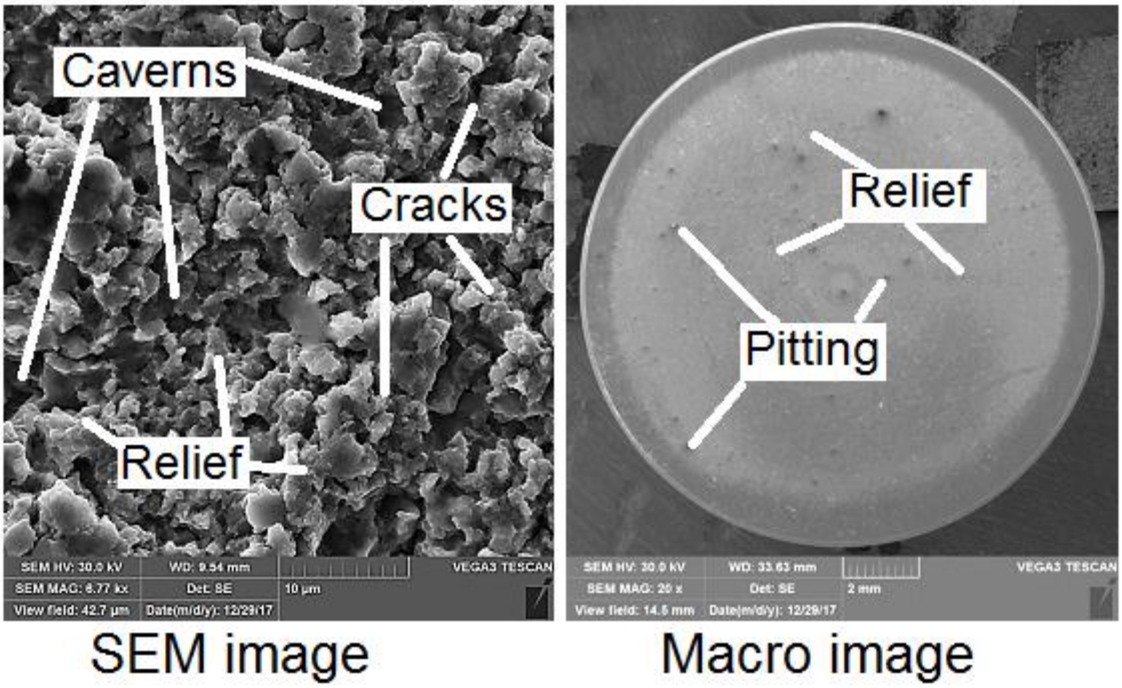


Fig. 5. SEM and macro images of the bronze sample microstructures, in the semi-finished state, after 165 minutes of exposure to cavitation erosion-corrosion

4.2. Comparison of the research results for the semi-finished slabs

The curves and parameter values illustrated in diagrams in figures 6 and 7 show the differences and similarities between the behaviors and resistances to cavitation of the two materials. The points on the diagrams are experimental values, arithmetic average values of the experimental results obtained for the three samples taken from each of the materials, while the curves show an averaging of the experimental and analytical values, with their specific relations, as calculated in the Cavitation Research Laboratory at the Polytechnic University from Timisoara [2, 3], [5],[6], [13].

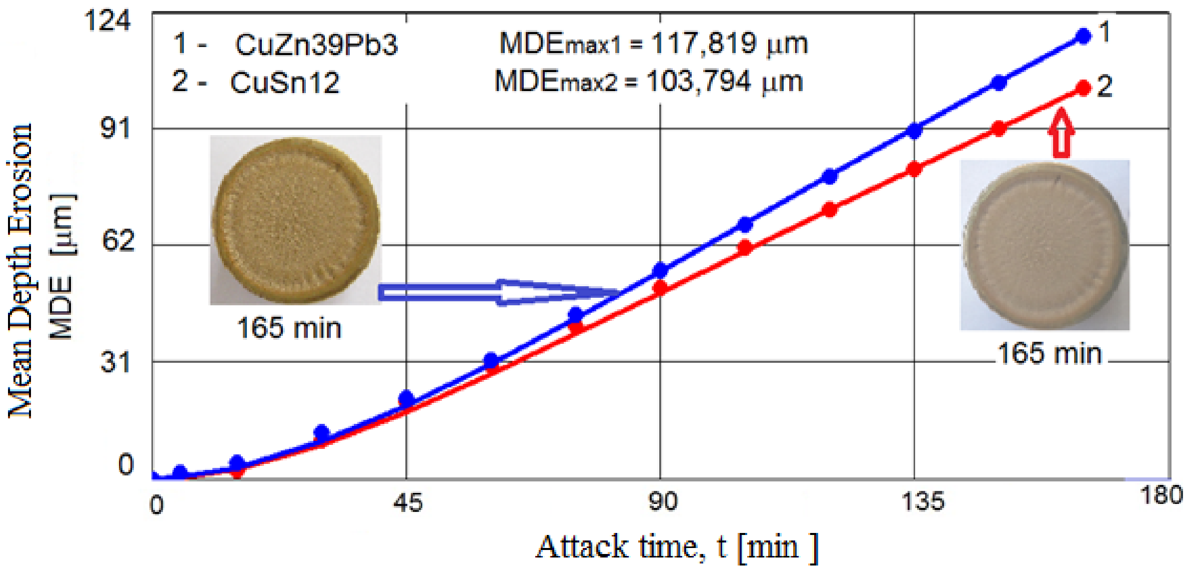


Fig. 6. The variation of the average erosion depth, in relation to the duration of the cavitation test (compared)

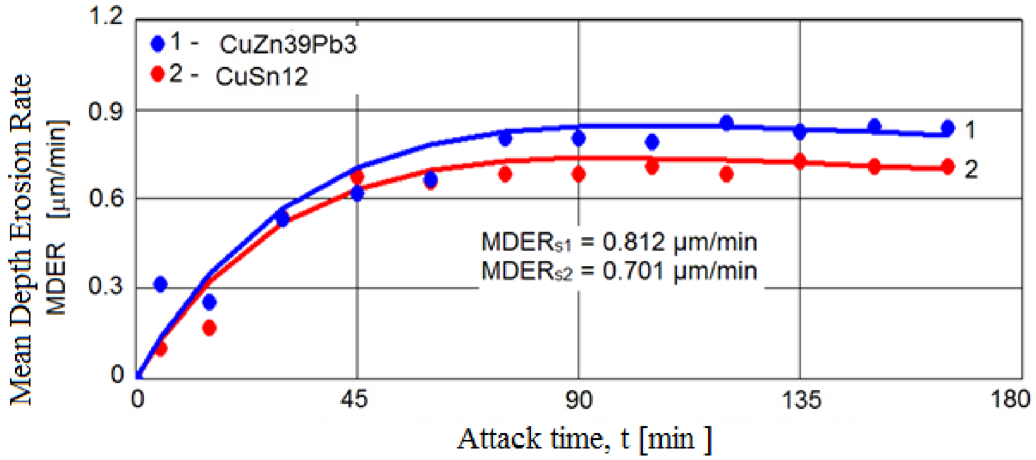


Fig. 7. The variation of the mean depth of penetration rate, in relation to the duration of the cavitation test (compared)

Findings based on the evolution of the curves and the dispersion of experimental points, from figure 6 and 7.

Similarities:

- a similar exponential evolution of the MDE(t) curves, with a plateau starting with minute 45;
- a similar evolution of the MDER(t) curves, which reach maximum values after 90 minutes of cavitation erosion-corrosion attack ($MDER_{max}$ = 0.846 µm/min – for brass, and $MDER_{max}$ = 0.737 µm/min - for bronze), and a slight decrease (4 - 5 %) towards the final, plateau value, indicating a leveling of the erosion rate ($MDER_s$ = 0.812 µm/min – for brass, and $MDER_{max}$ = 0.701 µm/min - for bronze). These similar evolutions result from the identical behavior of the sample surfaces to the cavitation attack, but showing different resistances;
- approximately identical dispersions of the experimental values and their arithmetic averages for the three samples, in comparison with the mediation curves MDER(t), starting with minute 45 of the exposure to cavitation.

Difference: a better behavior of bronze (CuSn12-C), as shown in the bar chart from figure 8, which compares the erosion parameters (cumulated average erosion depth, after 165 minutes of cavitation erosion-corrosion attack, MDE_{max} and the cavitation resistance, R_{cav} = $1/MDER_s$) and also by comparing the values of the roughness parameter R_z. It can be seen that any of the brass parameter values are lower than the bronze parameter values.

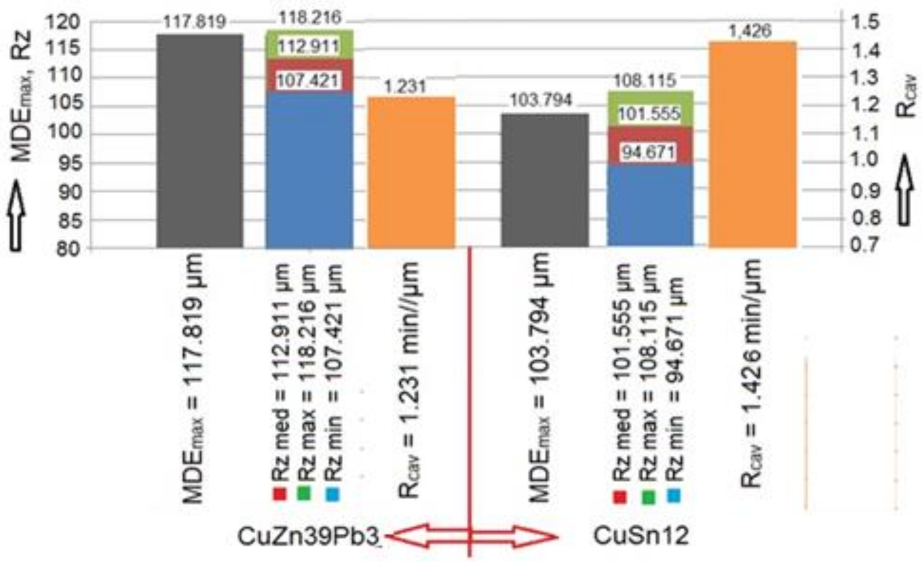


Fig. 8. Bar chart estimating the resistance to cavitation erosion-corrosion, by comparing the values of the specific parameters

Table 1 shows the percentage of decrease in brass (CuZn39Pb3) resistance to cavitation, in comparison with the bronze (CuSn12-C) resistance. It can be noted that this decrease does not differ substantially from one parameter to the other, having variations between 11% and 16%.

Table 1: Comparison of specific parameters

Reference material	Cavitation erosion parameter	Variation in comparison with bronze parameters [%]
		Brass (CuZn39Pb3) as delivered
Bronze (Cu Sn12) as delivered	MDE_{max} [µm]	↑ 13.5
	$R_{cav} = 1/MDER_s$ [min/ µm]	↓ 15.8
	$R_{z\ med}$ [µm]	↑11.2

↓ - decrease ↑ - increase

The research studies that our laboratory has been performing for more than 70 years [7], [13, 14] have shown that the differences under 15% between the erosion parameters may occur not only between different quality materials, but also between samples taken from the same material, being mainly caused by:

- different values for mechanical properties, which are not constant;
- the uneven dispersion of hardness in the structure of the surface exposed to cavitation;
- the degree of smoothness of the surface structure exposed to cavitation, as well as the existence of structural constituents that may decrease the resistance to the pressures created by the impact with the microjets and shock waves.

Therefore, we can conclude that brass (CuZn39Pb3) and bronze (CuSn12-C) have slightly different behaviors and resistances when exposed to erosion by cavitation; they are both materials displaying weak resistance to cavitation when they are not subject to heat treatments, but they can be used for components operating in low-intensity cavitation currents (elbows, manifolds, pressure and flow rate command and control equipment, machinery operating with fluids with viscosities higher than water).

5. Conclusions

1. Brass (CuZn39Pb3) and bronze (CuSn12-C) display the behavior specific to materials with evenly distributed structural components; however, they have low mechanical resistance, therefore the materials in their initial research state (as delivered) can only be used for parts operating in low-cavitation hydrodynamic conditions, i.e. hydraulic equipment (pressure valves, flow regulators, thread valves, etc.), which operate with fluids with viscosities higher than water.
2. The start and advancement of the damage under the impingement of microjets and shock waves developed in the cavitation process, occur at the boundary between the α-solid solution and the β′ electronic component, with a rapid destruction of the β′ phase - in the case of brass - and in the matrix of α-solid solution, replacing Cu with Sn and generating the occurrence of polyhedral indentations in the former δ-electronic compound areas, characterized by increased brittleness.
3. Both materials show similar behaviors to cavitation erosion-corrosion, yet they display slightly different resistances (with an approx. 11% increase for bronze CuSn12-C).
4. In order to use these two materials, i.e. brass (CuZn39Pb3) and bronze (CuSn12-C), for the production of components operating in higher cavitation hydrodynamic environments, such

as ship impellers (hub + blades) and/or hydraulic machine rotors (hydrodynamic power transmission of railway engines), the said components need to be subjected to in-depth and surface heat treatments, leading to significant increases in their mechanical characteristics (R_m, $Rp_{0.2}$ and HV).

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