The behavior to cavitation erosion-corrosion of the 
CuZn39Pb3 brass structures, obtained by in-depth heat 
treatments

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Abstract. The paper highlights the behavior at the vibratory cavitation erosion of CuZn39Pb3 
brass microstructures, as obtained by in-depth heat treatments. Two heat treatment cycles are 
analysed (hardening at 800ºC, followed by cooling in water, and hardening at 800ºC, with 
cooling in water, followed by tempering at 400ºC with cooling in air). The micro-hardness 
measurements show that the change in the microstructure, relative to the initial status of the 
material (semi-finished), determines higher values of the micro-hardness. The studies of the 
cavitation erosion, using the vibrating standard piezoelectric crystal assembly, available in the 
Cavitation Research Laboratory at the Polytechnic University from Timisoara, presented in the 
paper, shows significant increases in the surface resistance to the stress determined by the 
cavitation micro-jets, as compared to the initial state of the material (semi-finished).

1. Introduction
Brass is a copper alloy, widely used for water supply systems, but also in the construction of hydraulic 
equipment. This is because brass transfers heat very easily and withstands the corrosive exposure to 
liquid environments, but also because, after being subject to specific heat treatments, its structural 
changes improve its mechanical properties, thus having a positive impact on its service life when 
exposed to dynamic stress, such as the stress created by the cavitation micro-jets [1], [2].

In order to attain elevated mechanical properties, especially hardness and to obtain a structure able 
to reduce the speed of cavitation erosion, the literature [3-5] recommends the use of tempering heat 
treatments, as well as hardening and tempering treatments. Based on the aspects mentioned above, this 
chapter presents the results of the research conducted on the behavior and resistance to the vibratory 
cavitation erosion, using two types of in-depth heat treatments, applied to the CuZn39Pb brass.

The comparison with the control materials, known for their good resistance to cavitation erosion 
and used in industrial environments, with hydrodynamic currents causing cavitation erosion (hydraulic 
machinery and ship propellers), has shown that, by increasing the resistance to cavitation, this material 
can be used for producing parts which are subject to higher cavitation stress.
2. Material used and heat treatments applied

The brass (CuZn39Pb3) used in our research study (chemical formula, according to the standard EN 10204:2004) was made available by SC Color-Metal SRL, a company from Timisoara, as a 20-mm rod which, besides zinc, also contains lead as main chemical element.

The assays performed in the specialized laboratories within the Polytechnic University from Timisoara have resulted in the following values:
- chemical composition: 57.7% Cu, 38.49% Zn, 3.3% Pb, 0.2% Fe, 0.1% Ni, 0.2 %Sn, 0.01% Al;
- mechanical properties: tensile strength R_m = 502 MPa, fluid flow R_p0.2 = 365 MPa, breaking elongation A5 = 18%, Vickers hardness = 121.75 HV0.5, coefficient of longitudinal elasticity E = 97 GPa, density ρ = 8.47 g/cm3;
- the two-phase structure, made up of the solid solution α (approx. 60%) and the electronic compound β (approx. 40%), Figure 1, [6-8].

![Figure 1](image_url).

Figure 1. The structure of brass (CuZn39Pb3) (image taken from [6], [7])

The samples under research have been subjected to two types of in-depth heat treatments, as follows:
- hardening at 800°C (maintained for 40 minutes, followed by cooling in water) – marked as C 800;
- hardening at 800°C (maintained for 40 minutes, followed by cooling in water), then tempering at 400°C (maintained for 60 minutes, followed by cooling at ambient temperature) – marked as C 800/R 400.

The heat treatments have determined changes in the sample microstructure, as seen in the images obtained with the Olympus optical microscope, in Figure 2.
The C800/R400 heat treatment

Figure 2. The microstructure resulted after the application of heat treatments

The analysis under the microscope, as shown in Figure 2, indicates as follows:
- the hardening at 800°C, maintained for an adequate interval, determines the dissolution of most of the α-phase and the formation of a chemically homogeneous β-phase. The sudden cooling in water slows down the diffusion phenomena so that, at ambient temperature, we obtain a hardened microstructure, made up mainly of super-saturated β-phase solid solution and, in small quantities, of α-phase solution, which does not undergo any transformations (Figure 2 a).
- by tempering at 400ºC and slowly cooling in air, we obtain an acceleration of the precipitation process of phase α from phase β, as well as an acceleration of the coalescence process of these particles, especially within the grain-boundaries (Figure 2.b).

The test bars were 100 mm long. After the heat treatment was applied, we took 4 samples for the vibratory cavitation erosion tests (3 compulsory samples, and one spare sample). It is well-known that the surface hardness, as indicated in the research studies of Garcia & Hammitt [9], as well as in the researches performed as part of the PhD studies at the Cavitation Research Laboratory at the Polytechnic University from Timisoara [10], [11], is one of the mechanical properties which influences the resistance to cavitation. Therefore, 8 HV0.5 hardness measurements were performed on each of the samples subject to heat treatments. The resulting arithmetic averages are as follows: 167 HV0.5 for the C800 heat treatment, and 128 HV0.5 for the C800/R400 heat treatment.

3. Results of the cavitation analysis
The research on the behavior and resistance to cavitation erosion has been performed using the standard piezoelectric crystal assembly, available in the Cavitation Research Laboratory at the Polytechnic University from Timisoara [10], [11 ]. The cavitation tests were performed on three samples taken from the test bars subject to each of the heat treatments, having the shape and sizes indicated in [7], in compliance with the provisions in the ASTM G32-2010 norms and the laboratory protocols [12]. The liquid environment was tap water, with a temperature kept at 22 ±1 ºC.

3.1 The evolution of the morphological damage in relation to the duration of exposure to cavitation
The analysis of the surface and structure damage, occurred after the samples were subject to vibratory cavitation erosion, was performed based on the photographic images and the images taken with the scanning electron microscope (SEM).

a) In-depth hardening heat treatment, at 800°C
Figure 3 shows images taken with the high-resolution Canon A480 camera, where we can see the evolution of the erosion in the area subject to cavitation, in terms of development and depth. These images show that the sample surface starts to be damaged, with deformations, the formation of cavities, pittings and networks of cracks, starting from the first minutes of cavitation exposure and,
after 15 minutes of exposure, a great part of the sample area is eroded. If the cavitation exposure is continued, the impact of micro-jets cause the crevices to deepen so that, after 90 minutes, the damaged area is very well defined in the exposed surface. After this interval has elapsed and until the test is ended (total test length: 165 minutes), cracks and expulsions of material occur in the area of the surface under cavitation exposure, yet the speed of damage slows down, due to the buffering effect of the air that has penetrated in the crevices and the hardening of the surface layer, determined by the mechanical settling under the impact with the cavitation micro-jets.

Figure 3. The evolution of the eroded area in relation to the duration of the cavitation erosion process (recorded with a Canon A480 camera)

The SEM and macro images from Figure 4 show that the new structure and the increased hardness have contributed to an increased surface resistance to cavitation erosion. As a result, we notice an even degradation of the sample surface, with slight indentations caused by ductile tearing; the area subject to cavitation exposure for 165 minutes has a porous appearance, with cracks, reliefs and crevices.

Figure 4. SEM and macroscopic images of the eroded microstructure, after 165 minutes of exposure to cavitation erosion (images taken from the inferior area of the surface subject to cavitation)

Figure 5 shows the profile diagram with the values of the three reference parameters ($R_a$, $R_z$ and $R_t$), as recorded with the Mitutoyo SJ 201 analyzer; this is a new means [11] to assess the behaviour and resistance of the brass sample surface, after a 800°C hardening treatment. The shape of the profile diagram follows the type of the erosion-damaged structure, as shown in the image from Figure 3, but also the macroscopic appearance of the samples, at the end of the cavitation tests (Figure 2).

Figure 5 shows the recording of the roughness parameters, measured on three 120° axes. The values of the three parameters, shown in the footnote, are calculated as an average of the measurements on the three axes.
Figure 5. Values of the roughness parameters (after 165 minutes of exposure to cavitation erosion)

**b) In-depth hardening at 800ºC, with tempering at 400ºC**

Figure 6 shows images with the evolution of erosion, as the sample is exposed to cavitation erosion - we can notice here that the eroded area becomes visible relatively fast in the exposed sample area (after 75 minutes of exposure), and this leads us to conclude that, by using this heat treatment (hardening at 800ºC, with tempering at 400ºC), we obtain a lower hardness and resistance to cavitation than in the case of the 800ºC hardening heat treatment. The longer the cavitation exposure, the more numerous and deeper the crevices are.

Figure 6. The evolution of the surface erosion damage in relation to the duration of the cavitation test

The SEM and macroscopic images from Figure 7 show that the change in microstructure, obtained by tempering at 400ºC (see figure 2b), has lead to an increased number of crevices and indentations occurring in the surface of the material subject to cavitation erosion. This is because the elastic tension and the material hardness are lower than those obtained by hardening the material at 800ºC.
Figure 7. SEM and macroscopic images of the eroded microstructure, after 165 minutes of exposure to cavitation erosion (images taken from the inferior area of the surface subject to cavitation)

The profile diagram from Figure 8, with significant differences in the values for the roughness parameter, recorded with the Mitutoyo analyzer, shows the evolution and the structural deterioration of the material subject to in-depth C800/R400 heat treatment, in the exposed area. This shape is a 2D image of the eroded structure from Figure 6, having the microscopic appearance shown in Figure 7a.

Figure 8. Values of the roughness parameters (after 165 minutes of exposure to the cavitation process; example for one measurement)

3.2. Characteristic curves. Comparison of the research results
The diagrams from Figures 9 and 10 show a comparison between the MDE(t) and MDER(t) curves, characterising the behaviour and resistance of the heat-treated surfaces to the erosion caused by vibratory cavitation, in order to show differences in the behaviour and resistance of samples during their exposure to the vibratory cavitation erosion process.
The two graphs show that the MDE(t) and MDER(t) curves evolve similarly, yet we notice differences in their slopes (the MDE(t) curves) and in the speed value, where the MDER(t) curve decreases in an inclined asymptote. These similarities show that, after being subject to the two in-depth heat treatments, the resulting structures are more even, with a homogeneous distribution of the mechanical properties in the sample body and in the outer layer of the eroded surface. The differences between the values of the mechanical properties, especially hardness, are expressed by the maximum and constant values, as shown by the MDER(t) curves from Figure 10.

Regardless of the specific curve used, we notice that the resistance and behaviour to the cavitation erosion, obtained by subjecting the material to a 800°C hardening treatment (with an average hardness of 167 HV5), are higher than the ones obtained by subjecting the material to a 800°C hardening treatment, followed by tempering at 400°C (with an average hardness of 128 HV5).

The bar chart from Figure 11 shows the resistance resulted from the two heat treatment cycles, by comparing the values of the two reference parameters, i.e. $R_{cav} = 1/$MDER, and $MDE_{max}$, with the parameters of the control materials, available in the Cavitation Research Laboratory at the Polytechnic University from Timisoara:
- stainless steel OH12NDL, with a martensitic structure, used in the Kaplan rotor blades from the Iron Gate I and II Hydroelectric Power Stations [13-15], considered as having a good resistance to the vibratory cavitation erosion;
- marine-grade bronze (CuNiAl I-RNR), with a good resistance to cavitation erosion, and marine-grade brass (with an acceptable resistance), recommended by the Romanian Naval Authority for the manufacturing of maritime and river boat propellers [5-8], [16].

Figure 11. Bar chart estimating the resistance to cavitation erosion-corrosion, by comparing the values of the specific parameters

Based on the data from the bar chart, the resistance to cavitation erosion, as resulted from the two heat treatment cycles, by comparing the values of the two reference parameters ($R_{cav}$ and $MDE_{max}$) with the ones of the control samples (semi-finished state), is between 2.43 and 4.95 times higher, and the best resistance is obtained by applying the C800 hardening treatment.

When compared with the control materials, the data from the bar chart show that, by applying the C800 hardening treatment, brass becomes harder than the control materials. Thus, the maximum erosion depth decreases by 11.45% when compared with steel (OH12NDL), by 14.41% when compared with bronze (CuNiAl I-RNR), and by 174.22% when compared with the brass used in the naval industry. Based on the values acquired by the $R_{cav}$ parameter, we have noticed that the resistance to cavitation erosion increases by 5.7% when compared with stainless steel (OH12NDL), by 36.71% when compared with bronze (CuNiAl I-RNR), and by 163.29% when compared with the resistance of the brass used in the naval industry.

In the case of the C800/R400 hardening and tempering heat treatment, the data in the bar chart show that, when compared with stainless steel and bronze (CuNiAl I-RNR), the expected increase in resistance is not attained; the resistance is by 75-80% lower, when considering the average erosion depths ($MDE_{max}$), and by 43-85% lower, when considering the values of the $R_{cav}$ parameter. Therefore, these in-depth heat treatments contribute to significant increases in the resistance to cavitation erosion, when compared to the control (semi-finished) state and, for this reason, they will continue to be applied to component parts subject to cavitation stress.

4. Conclusions
- The evolution of the eroded area in the exposed surface, in relation to the duration of the cavitation test, with the formation of the outer ring of erosion and of the star-shaped crevices, observes the same process, regardless of the applied heat treatment.
The shape of the MDE(t) curves, representing the evolution in relation to the duration of the cavitation test, is specific to materials with a good resistance to cavitation erosion, and it has the tendency to become stable at the maximum value;

The SEM images show that the networks of cracks are generated and propagate in the grain boundary areas;

The damage to the surface exposed to cavitation micro-jets depends on the type, finishing and homogeneity of the structure, as well as on the surface hardness, resulted from the application of heat treatments;

When compared to the initial state of the material, any of the two in-depth heat treatments determines a significant increase in the resistance of the material to the cavitation erosion;

The comparison with the control materials shows that the resistance to cavitation erosion is visibly higher, only after the application of the C800 hardening treatment. On the other hand, after the C800/R400 hardening and tempering heat treatment, the resistance of the material to cavitation is lower than the resistance of stainless steel (OH12NDL) and marine-grade bronze (CuNiAl I-RNR), but higher than the marine-grade brass. This shows the need to continue the research studies by using other values for the heat treatments so that, by hardening and tempering, the expected resistance of the material may be attained.

The research results and the assessments made based on the specific curves or by comparison, using the values of the reference parameters, MDE_{max}, R_{cav} or R_{z}, confirms that the in-depth heat treatments are needed.

Brass (CuZn39Pb3), after being subject to the above-mentioned heat treatments, may be used to manufacture parts subject to low and medium-intensity cavitation currents, such as pipe fittings, stoppers and valves mounted on forced-fit piping, rotors of high-volume pumps, fresh-water ship propellers and some components of the water supply and pumping systems.

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