The behavior to cavitation erosion of CuSn12-C bronze structures, as obtained by in-depth heat treatments

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Abstract. CuSn bronze alloys are some of the most used in the casting of freshwater ship propellers. Through in-depth heat treatments, the microstructure and hardness are substantially altered when compared with the initial state of the material after casting. The work highlights the change in the behavior and resistance to the vibrating cavitation erosion of the CuSn12-C bronze microstructures, after being subject to two in-depth heat treatments (hardening at 700°C, followed by cooling in water, and two hardening treatments at 700°C, with cooling in water, followed by tempering at 500°C and 250°C, with cooling in air). The experimental tests are performed using the vibrating standard piezoelectric crystal assembly, available in the Cavitation Research Laboratory at the Polytechnic University from Timisoara.

1. Introduction

In-depth heat treatments are required in industrial applications, in order to obtain certain physical and mechanical properties and to modify the structure of the material, by varying the temperatures, the tempering duration and the cooling environment/speed [1], [2]. The choice of in-depth heat treatments is determined by the fact that the changes produced in the properties and structure of the part material does not determine significant changes in the geometric shape and in the part dimensions, which are usually brought to their final shape and dimensions after cutting/machining, which are applied after the heat treatments.

In the case of bronze and brass alloys, in order to attain elevated mechanical properties, especially hardness and a structure able to reduce the speed of cavitation erosion, the literature [3], [4] recommends the use of tempering heat treatments, as well as hardening and tempering treatments. Therefore, this paper presents the results of the research regarding the behaviour and resistance to vibratory cavitation erosion, recorded for two types of in-depth heat treatments, applied to the CuSn12-C bronze alloy. The results show that, by changing the structure and hardness of the material, important changes in the behaviour and resistance of bronze are obtained, when compared to the control, semi-finished state.
2. Material under research. Heat treatments

The Cu-Sn bronze alloy, received from the "Dunarea de Jos" University from Galati, contains Pb, Fe, Ni and Zn, it has a two-phase structure, made up of a solid grain solution $\alpha$ and eutectoid grains ($\alpha + \delta$) [5], [6], as seen in Figure 1, and it was chosen because it is recommended for use where the stress is higher and where wear and tear endurance in corrosion and cavitation conditions is needed the most [6]. The assays performed in the specialized laboratories within the Polytechnic University from Timisoara have resulted in the following values [6]:

- chemical composition: 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;
- mechanical properties: yield strength $R_m = 312$ MPa, fluid flow $R_{p0.2} = 157$ MPa, Vickers hardness (average from 8 measurements) = 105.75 HV0.5, breaking elongation $\Delta 5 = 9\%$, modulus of longitudinal elasticity $E = 97$ GPa, $\rho = 8.77$ g/cm$^3$.

The material samples under research have been subjected to two types of heat treatments, as follows:

a) hardening at 700°C (held for 60 minutes, followed by cooling in water) – marked as C 700;

b) hardening at 700°C (held for 60 minutes, followed by cooling in water), followed by tempering at 500°C (held for 60 minutes, followed by cooling in ambient temperature) - marked as C 700/R 500.

The procedure used was as follows:

- each of the heat treatments was performed on a cylindrical bar, 20 mm in diameter and 100 mm in length;
- four samples were taken from the heat-treated bars, 3 for the cavitation-erosion tests, and 1 for metallographic examinations and hardness measurements.

Figure 2 shows the microscopic image, recorded with the Olympus optical microscope, of the structure resulted from the C700 heat treatment.
Figure 2. The microstructure resulted from the C700 heat treatment

By studying Figure 2, we notice that, during the heating-holding steps, the initial microstructure, made up of the solid grain solution α and eutectoid grains α + δ, (see Figure 1), turns into a mixture of β-phase solid solution and a part of undissolved α-phase solution. By cooling the sample in water at room temperature, the diffusion processes become slighter, β-phase becomes super-saturated, with an aspect similar to the martensitic phase in steels, while α-phase does not undergo any other transformations. Therefore, the hardness of the material increases up to 153.375 HV0.5 (arithmetic average of the values obtained from eight measurements), when compared to the hardness of the control material (without heat treatment), resulting in a 45% increase.

Figure 3 shows the microstructure resulted from the C700/R500 heat treatment. It can be noted that, after the tempering at 500ºC, a slight increase in the dimensions of the precipitated phases is obtained. This phenomenon results in a decrease of hardness, up to 146.125 HV0.5 (arithmetic average of the values obtained from eight measurements), when compared to the hardness resulted from the hardening process, i.e. a 5% decrease, yet an increase in hardness, when compared to the hardness of the control material (without heat treatment), i.e. a 38% increase.
When considering that, based on the previous research studies made by Hobbs [7], [8], Bordeasu [9] and Franc [10], hardness is the main mechanical property resulted from the in-depth heat treatments that positively influences the resistance to the cavitation erosion-corrosion, expressed by the values of the parameters MDE (average erosion depth) and MDER (mean depth of penetration rate), as seen below, the study results confirm increases in the resistance to vibratory cavitation erosion, when compared to the hardness of the control material; nevertheless, the hardness values resulted from the two types of heat treatments are different.

The values of the HV0.5 micro-hardness (arithmetic average of the values obtained from eight measurements) in the round surfaces of the samples, before the cavitation erosion tests, are as follows: 153.375 HV0.5 for the C700 heat treatment (a 45% increase, when compared to the hardness of the control material), and 146.125 HV0.5 for the C700/R500 heat treatment (a 38% increase, when compared to the hardness of the control material).

3. Experimental results
The research regarding the behaviour and resistance of the surfaces of the samples subject to heat treatments was conducted using the standard piezoelectric crystal assembly, available in the Cavitation Research Laboratory at the Polytechnic University from Timisoara [11-14]. The experimental procedure used strictly observes the provisions in the ASTM G32-2010 international norms [15] and the laboratory protocols regarding the test duration and phasing, as well as regarding the recording, processing and interpretation of the experimental results.

As the behaviour and resistance of any surface to the damage caused by the microjets and shock waves resulted from the hydrodynamic environment, specific for vibratory cavitation erosion [12], both depend on the structure of the sample material, we will present and discuss the damage to these structures after they have been subject to heat treatments.

3.1. In-depth hardening at 700°C

a) The morphology of the structure damaged by cavitation erosion
Figure 4 shows photographic images of how erosion has expanded within the area of the exposed surface. The images presenting one of the samples, show the effect of the 700°C hardening heat treatment on the behaviour and resistance of the surfaces of the samples subject to the cyclical stress
of the cavitation microjets. These images show that, after 15 minutes of cavitation stress, the damage to the surface area is represented by extended dulling, presenting multiple pittings/indentations, networks of cracks and plastic deformations [9], [10]. After this time has elapsed, the erosion increasingly manifests in the sample structure as well and, after 120 of cavitation stress, the outer ring of erosion can be noticed, with visible crevices, in the form of streaks towards the margins of the eroded area.

![Min 15](image1.png) ![Min 120](image2.png) ![Min 135](image3.png) ![Min 165](image4.png)

**Figure 4.** The evolution of the eroded area in relation to the duration of the cavitation erosion process (recorded with a Canon A480 camera)

The investigation of the cavitation-eroded surface under the electron microscope (Figure 5) reveals ductile tearing, while the α-phase grain boundaries represent the micro-areas where the cavitation pitting starts and further develops (as the α-phase has a softer composition, susceptible to plastic deformation). Also, we can notice the cracks, pitting and cavities created due to grain expulsion. This damage is determined by the mechanical properties of the material, especially the hardness resulted from the C700 heat treatment, in response to the impact pressures of the cavitation microjets.

![SEM image](image5.png)

**Figure 5.** The SEM image of the structure damaged by cavitation erosion, after 165 minutes of exposure
b) The morphology analysis of the structure damaged by cavitation erosion

Figure 6 shows an analysis performed with the Mitutoyo SJ 201 P analyzer on one of the three samples subject to the cavitation erosion process. This image shows the damage to the structure in the eroded surface, as seen in the microscopic image from Figure 5.

![Figure 6. Values of the roughness parameters](image)

3.2. In-depth hardening at 700°C, with tempering at 500°C

a) The morphology of the structure damaged by cavitation erosion

The expansion of the damage to the exposed area, caused by the cavitation erosion process, can be seen in the photographic (macro) images from Figure 7. It should be noted that, after this heat treatment is applied, the outer ring separating the eroded area from the surface area exposed to cavitation presents well-defined star-shaped crevices after 90 minutes.

![Figure 7. The evolution of the surface erosion damage in relation to the duration of the cavitation test](image)
The investigation under SEM of the sample surface subject to cavitation (Figure 8) shows the formation of irregular micro-craters as a result of the expulsion of the precipitated secondary-phase particles from the super-saturated β-phase solid solution, as well as the propagation of the cracks occurring mainly in the grain boundary areas.

![SEM image of structure damaged by cavitation erosion](image)

**Figure 8.** The SEM image of the structure damaged by cavitation erosion, after 165 minutes of exposure

b) **The morphology analysis of the structure damaged by cavitation erosion**

Figure 9 shows the analysis and the values for the three characteristic parameters ($R_s$, $R_z$ and $R_t$), as recorded with the Mitutoyo SJ 201P analyzer on one of the samples. Its shape confirms the microscopic aspect of the damage to the structure, as shown in Figure 8.
4. Assessment of the research results

Figures 10 to 11 show the assessment of the two types of heat treatment on the behaviour and resistance of the samples subject to the cyclical stress of the cavitation microjets produced by the vibratory cavitation erosion. These diagrams show the differences between the two types of heat treatment, but also with reference to the control state of the CuSn12-C bronze alloy [6]. Thus, it can be noted that the two types of heat treatment determine similar behaviour in the surface structure; the mediation curves MDER(t) have similar evolutions, with linear trends, after about 40 minutes of cavitation stress; however, their slopes are different, and the curves MDER(t) decrease in an inclined asymptote, towards a stabilization value, which is slightly lower than the maximum values attained by the curves; this evolution is specific to materials with a good resistance to cavitation erosion, produced in the vibration-generating equipment [9], [13].

Also, it can be noted that, after both heat treatments, the values of the MDE\textsubscript{max} and MDER\textsubscript{s} parameters show a significant increase in the resistance to cavitation erosion, as compared to the control sample. At the same time, the hardening heat treatment, conducted at 700°C, determines a significantly higher resistance than the heat treatment with hardening at 700°C and tempering at 500°C.
The comparison with the control sample clearly shows that, after the hardening heat treatment, and the hardening and tempering heat treatment respectively are performed, at the indicated parameters, both the behavior and the resistance to cavitation erosion are improved (see the shape of the MDE(t) and MDER(t) curves, and the reduced dispersions at the experimental values, in relation to the mediation curves). The dispersions of the experimental values, reduced and evenly distributed in relation to the MDER(t) curves, in comparison with the control bronze sample, are the effect of the micro-structural changes (see the photographic images with the morphological analysis of the eroded structures, Figures 5 and 8), as well as the effect of the increased hardness of surfaces.

The bar chart in Figure 12 shows a comparison between the values of the main parameters, as recommended by the ASTM G32-2010 norms, and applied in the protocols of our research laboratory.
Figure 12. Bar chart estimating the resistance to cavitation erosion, by comparing the values of the specific parameters

The comparative data from the bar chart (Figure 12) show visibly inferior values for the mean roughness, $R_z$ (as measured with the Mitutoyo analyzer and calculated according to the method described above), as well as for the maximum depths, $MDE_{\text{max}}$, while the parameter for cavitation resistance, $R_{\text{cav}}$, is visibly higher; these values were obtained after the C700 and C700/R500 heat treatments were performed.

The data in the bar chart, i.e. the three characteristic parameters ($MDE_{\text{max}}$, $R_z$ and $R_{\text{cav}}$), when compared with the characteristics of the control sample, show: a decrease in the average erosion depths $MDE_{\text{max}}$, after 165 minutes of cavitation erosion attack, from about 46%, to about 143%; a decrease in the average roughness value $R_z$, from about 74% to about 164%; and an increase to the resistance to cavitation $R_{\text{cav}} = 1/MDE_{\text{av}}$, from about 43% to about 142%.

Also, the comparison of resistances obtained after the two heat treatments indicates that, after the C700 heat treatment, the average erosion depth $MDE_{\text{max}}$ decreases after 165 minutes of cavitation erosion attack by about 66%, the roughness $R_z$ decreases by 52%, while the resistance to cavitation $R_{\text{cav}}$ increases by 64%.

5. Conclusions
- The comparison with the initial-state control samples confirms that the in-depth heat treatments remain a solution to increase the resistance to cavitation erosion;
- The degree of damage to the sample is directly related to the morphology of the structure and its roughness, as resulted from the heat treatments;
- The small differences between $MDE_{\text{max}}$ and $R_z$ are normal, as the second parameter is determined with the Mitutoyo analyzer in the eroded areas, randomly chosen, while the first parameter is calculated based on the volume loss, and this introduces errors that cannot be excluded;
- 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 evolution of the eroded area in relation to the duration of the cavitation test, with formation of the outer ring of erosion and of the star-shaped crevices, observes the same process, regardless of the
applied heat treatment, the difference being represented by the time interval needed for the ring of erosion to be well defined;
- The SEM images show that the networks of cracks are generated and propagate in the grain boundary areas;
- The investigations performed confirm that bronze CuSn-C, after it has gone through hardening or hardening + tempering heat treatments, may be used to manufacture parts subject to cavitation currents, such as pipe fittings, stoppers and valves mounted on forced-fit piping, rotors of high-volume pumps, and even ship propellers.

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