

Modification of the average durability for CuSn12 bronze at cavitation erosion using volumetric treatments

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Abstract. The bronze CuSn is used sometimes for equipment components working in cavitation conditions, as for example ship propellers, bodies and other parts of valves. To increase the working time, in cavitation conditions, those elements can be subjected to volumetric thermal treatments. The present research is concerned with the increase of the mean durability $\bar{\delta}_{cav}$ of the bronze CuSn12 by applying two volume treatments: quenching both at 700°C and 800°C, with tempering at 500°C. The cavitation erosion behavior was experimentally tested using the standard vibratory device of the Cavitation Laboratory of Timisoara Polytechnic University. Comparing the results we found that the durability, in both cases, is substantial increased, the better solution being the quenching with the lower temperature.

1. Introduction

Erosion is among the worst effect of cavitation which appear during operation of the technical equipment, working with or in water, such as hydraulic turbines, pumps, hydraulic drive control devices, vanes, details of the water supplies and irrigations networks [1-8]. Specific damages appear in most components when rapid pressure variations take place. When the pressure falls below the value of the saturation one in the liquid flow appear small bubbles. At the increase of pressure those bubbles imploded and on small areas appear very high pressures. With all the researches done in the laboratories or upon the industrial devices, till now there was not found materials enough perfectly resistant to the implosion of cavitation bubbles. That is way cavitation erosion resistance remain a permanent preoccupations of the specialists. Many details working in such conditions are made in bronze, both through casting or by processing through rolled bars, with or without heat treatments.

Most of such details have a biphasic structure with α and $\alpha + \delta$, containing max. 25-30%Sn and good casting properties a result of excellent fluidity and large solidification intervals but also as a result of the improvement obtained by the increase of their physical-mechanical properties by heat treatments, or by alloying with Zn, P and Ni [3], [8]. The present research is concerned with the increase of mean durability defined by K.J. Steller [9], by applying some volume heat treatments for the bronze CuSn12 used for a lot of details running in cavitation conditions. We found that the bronze quenched at small temperature has the maximum cavitation erosion behavior.



2. Material used. The testing device and the research procedure

The researched bronze is of the type Cu-Sn, with content of Pb, Fe, Ni, and Zn, obtained from the Rolling SRL Timisoara, in the form of laminated bars having a diameter of $D = 20$ mm, symbolized as CuSn12-C in conformity with DIN EN 1982. His chose for research is bounded with [1-3], [6-8]:

- the use for ship propellers demand: resistance at high mechanical stresses, good behavior at cavitation and corrosion in salted water,
- technological properties such as: high antifriction, good fatigue resistance, good machining by cutting, great hardening, satisfactory weldability, and good wear resistance. A lot of this properties are given by the solid solution „ α „ (the soft constituent which wears out in the running time) and the phase „ δ „ (the hard constituent which takes all the mechanical stresses).

Analyzes realized in the laboratories of Timisoara Polytechnic University, found the following values:

- for 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;
- for mechanical properties: fracture strength $R_m = 300$ MPa, yield point $R_{p0.2} = 150$ MPa, Brinell hardness = 92 daN/mm², fracture elongation $A_5 = 9$ %, longitudinal elastic modulus $E = 97$ GPa, density $\rho = 8.77$ g/cm³;
- the structure is a biphasic one, formed from grains of solid solution α and grains of the eutectoid ($\alpha + \delta$) [8], see Figure 1.

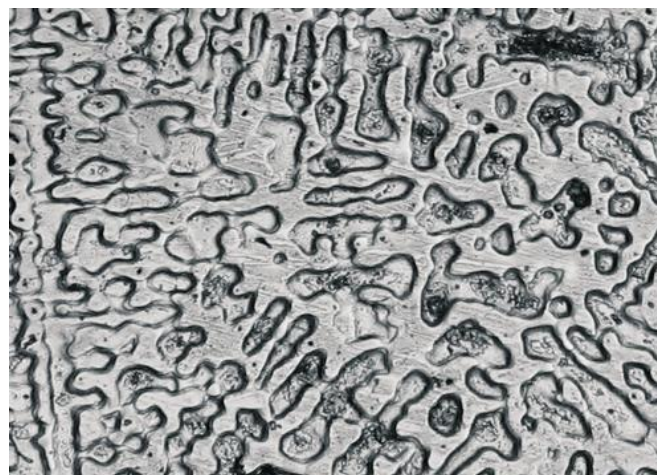


Figure 1. CuSn12 structure (image taken from [8])

The testing program was effected on five states: the delivery state and 4 volume heat treatments (quenching at 700 °C with cooling in water, quenching at 700 °C + tempering at 250 °C, as well as tempering at 500 °C and quenching at 800 °C + tempering at 500 °C).

In Figure 2 is presented the diagram of the volume heat treatments.

For cavitation generation it was used a vibratory device with piezo ceramic crystals realized in the Cavitation Laboratory of Timisoara Polytechnic University [10-13]. For each state there were tested three specimens. The results are presented as specific curves and the value of a point is the result of the mean for three tested specimens. The curves for approximation/mediation of the experimental values are realized with the analytical relations established [15], [16]. The manner in which was prepared the specimens, the total duration of cavitation exposure, respectively the number and the extension of the 12 intermediate steps (one after 5 and 10 minutes and all others after 15 minutes) the registration and processing of the experimental data are specific for the laboratory customs described in [17], [18], [20] and in concordance with the recommendation of the international standard ASTM G32-2010 [19]. During the testing interval, the running parameters of the device (frequency and amplitude of vibrations, power of the electronic exciter generator for the piezo ceramic transducer) were controlled and maintained at the prescribed values [11], [12], [18], [20]. As liquid medium was

used drinking water at the temperature of $22 \pm 1^\circ\text{C}$. Before the tests the area exposed to cavitation was polished at $R_a = 0.8 \mu\text{m}$, as shown in Figure 3.

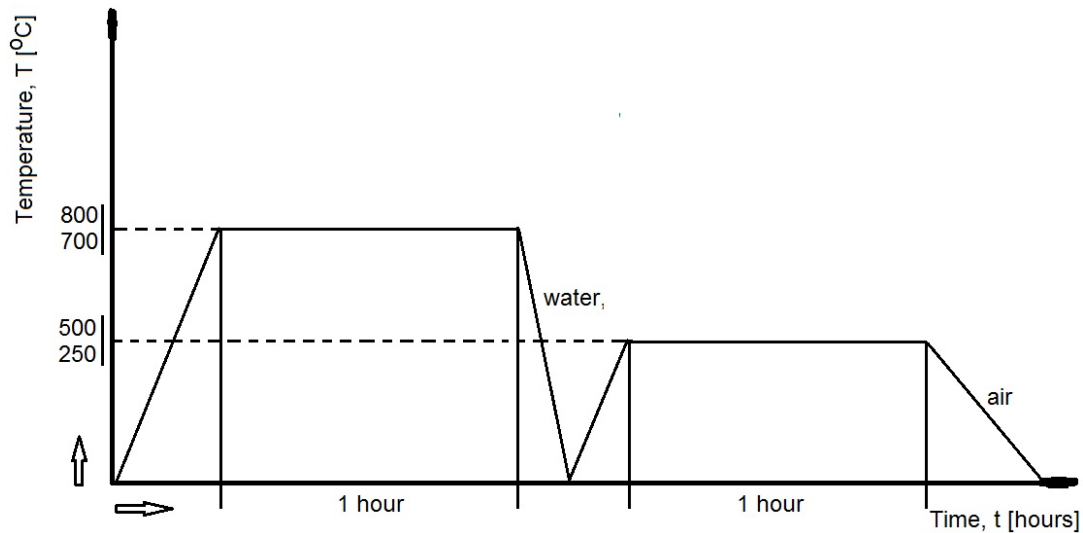


Figure 2. Diagram of volume heat treatments



Figure 3. Image of the exposed surface before the exposure to cavitation (0 min.)

In order to obtain the behavior of the surface at the impacts of the cavitation bubbles there were realized photos after each intermediate interval, with a high resolution Canon apparatus, as shown in Table 1.

3. Experimental results

After each testing interval the lost mass was measured. On this base were computed the values of lost volumes [2].

The computation relation for the cumulative lost volume is:

$$V_i = \sum_{i=1}^{i=12} \frac{M_i}{\rho} \quad (1)$$

where:

M_i – is the lost mass (mg) after each test interval (“i”),

ρ - bronze density ($\rho = 8.77 \text{ g/cm}^3$)

In Figure 4 it can be seen the distribution of experimental values (a point represent the mean of the three tested specimens) and the specific curves, realized analytically with relations of the type [14], [15]:

$$V(t) = A \cdot t \cdot (1 - e^{-Bt}) \quad (2)$$

The procedure for statistically determining the coefficients A and B is given in [14], [15]. These curves put into evidence the different behavior of the same material subjected to different volume heat treatments.

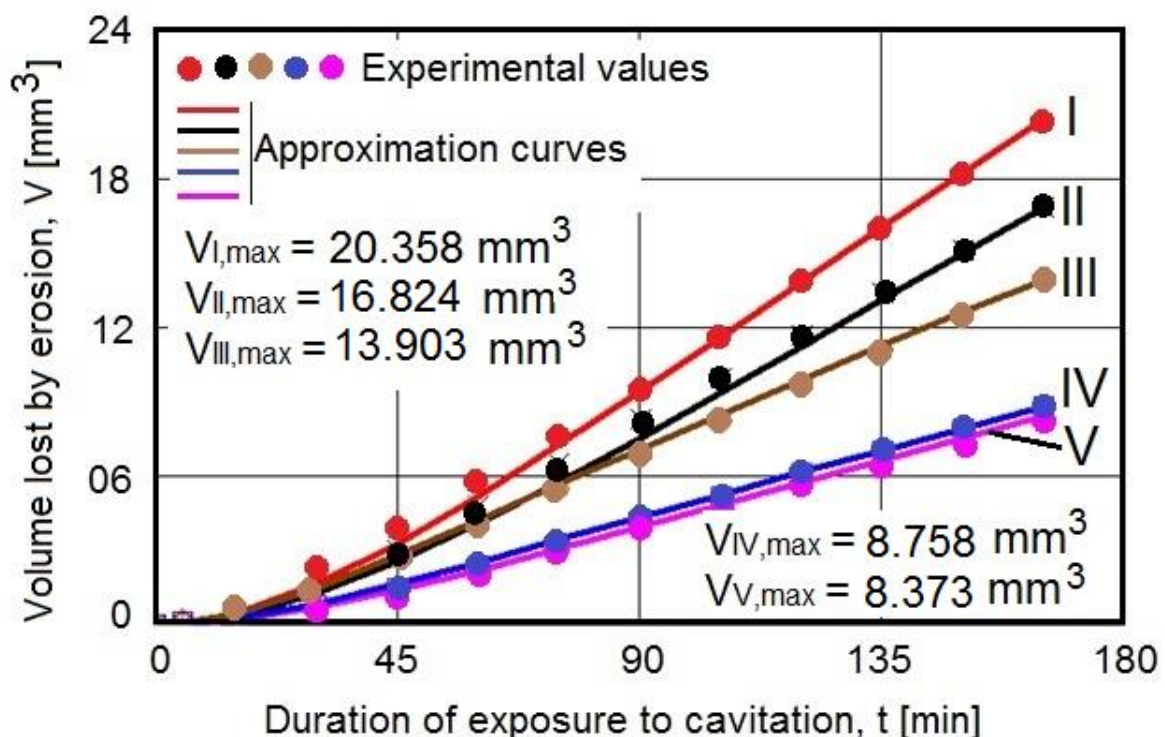


Figure 4. The variation of the lost volume against the cavitation exposure time.
I-the delivered state; II- specimen quenched at 800 °C + tempered at 500 °C; III-quenched at 700 °C + tempered at 500 °C; IV- quenched at 700 °C + tempered at 250 °C; V quenched at 700 °C

The approximation mod of experimental values by the curves $V(t)$, especially the tangent made with the abscissa, show the beneficial of the volume heat treatment for the increase of the resistance to cavitation. For a better understanding of the parameter “mean cavitation durability $\bar{\delta}_{\text{cav}}$ ” in Figure 5 there are presented the experimental values obtained for the mean depth erosion. To obtain the curves MDER (t) there were used the analytical method using the relations established by Bordeasu and collaborators [11], [14], which has the form:

$$\text{MDER}(t) = A1 \cdot (1 - e^{-B1t}) + A1 \cdot B1 \cdot t \cdot e^{-B1t} \quad (3)$$

The determination of the statistical coefficients $A1$ and $B1$ is similar with those used for A and B and is also given in [14], [15]. The values for the rates MDER are determined from the mean depth of erosions, using the relation:

$$MDER_i = \Delta MDE_i / \Delta t_i = \frac{4 \cdot \Delta V_i}{\pi \cdot d_p^2 \cdot \Delta t_i} \quad (4)$$

Where:

Δt_i – is the duration of the intermediate period (“i”), in minutes;

ΔV_i – is the volume of the material expelled in mm³ during the interval Δt_i , (it was used the arithmetic mean of the three tested specimens);

d_p – is the diameter of the surface exposed to cavitation, ($d_p = 15.8$ mm)

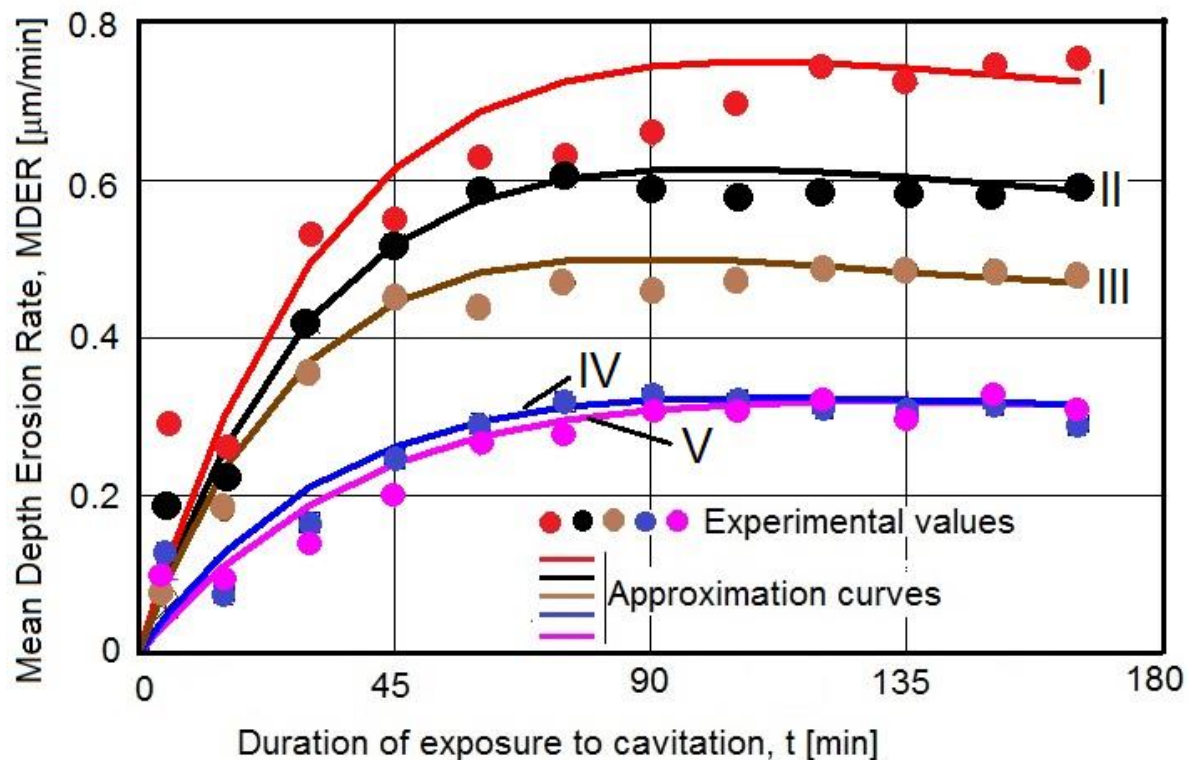




















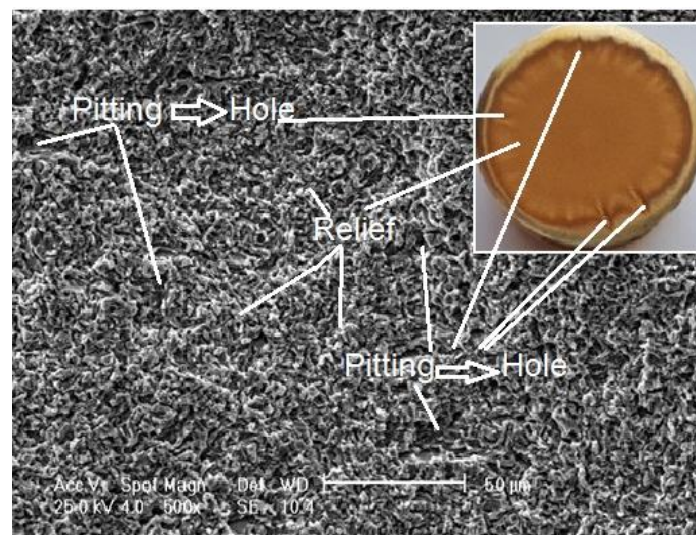


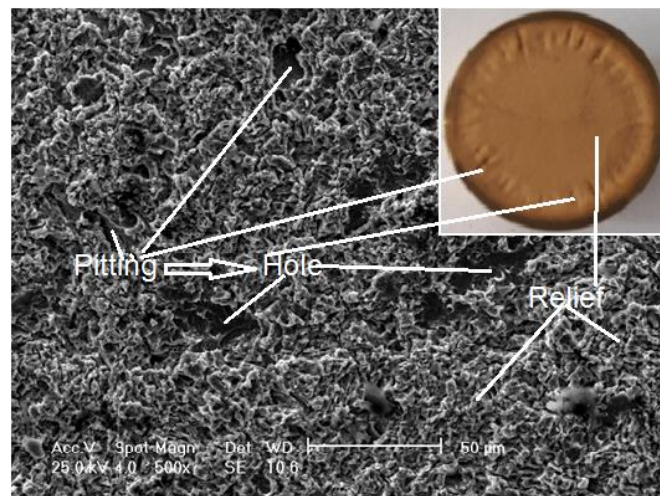
Figure 5. Evolution of the MDER with the exposure time
 I-the delivered state; II- quenched at 800 °C + tempered at 500 °C; III-quenched at 700 °C + tempered at 500 °C; IV- quenched at 700 °C + tempered at 250 °C; V-quenched at 700 °C

The scatter of the experimental points with regard of the analytical curves $MDER(t)$ show that the material resistance at cavitation erosion is strongly dependent on the type of volumetric heat treatment, but in all cases there are increases with regard of the material in delivery state. Those differences appear in the first 5 minutes of cavitation exposure, as can be seen with the photos presented in Table 1, selected for some characteristic times (5, 45, 105 and 165 minutes), as well as in the images of Figure 6 recorded with an electronic microscope at the end of the cavitation exposure (165 minutes).

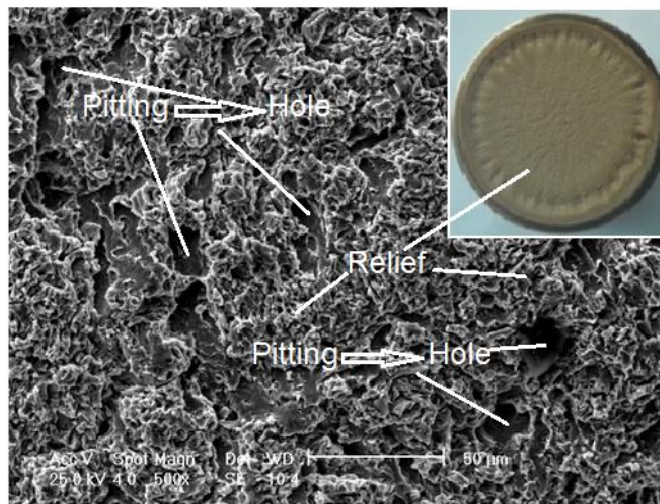
Table 1. The erosion evolution on the exposed area

Material (symbol)	Time of cavitation exposure [min]			
	5	45	105	165
I				
II				
III				
IV				
V				

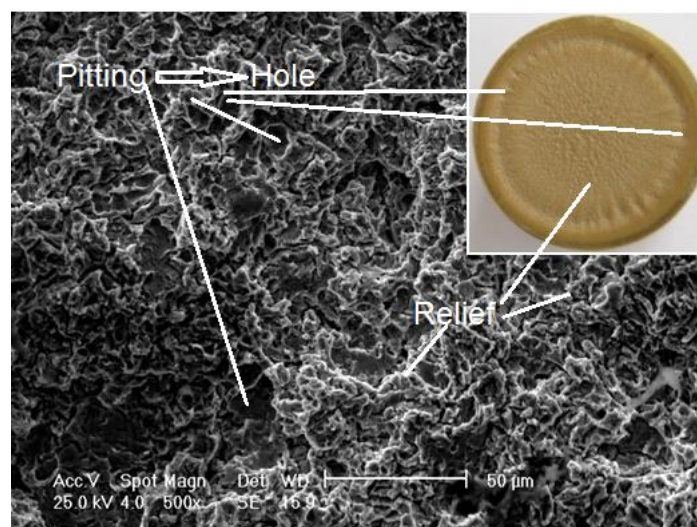
**a.** Bronze in delivery state (x 500) (symbolization I)



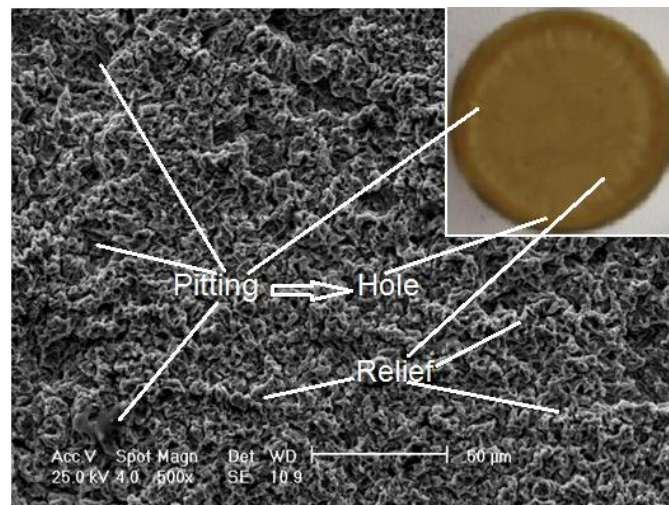
b. Bronze Quenched 800+tempering 500 (x 500) (symbolization II)



c. Bronze Quenched 700+Tempering 500 (x 500) (symbolization III)



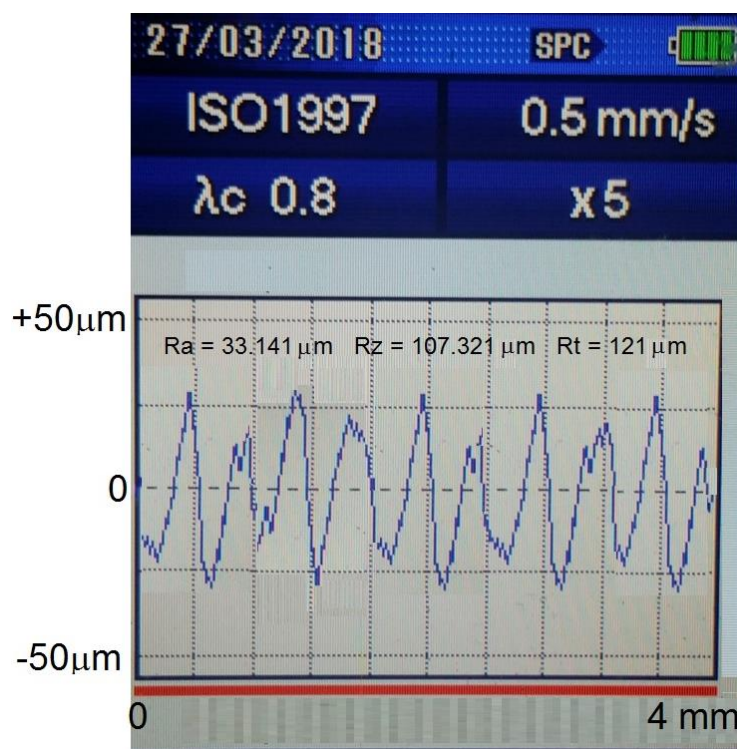
d. Bronze Quenched 700+Tempering 250 (x 500) (symbolization IV)



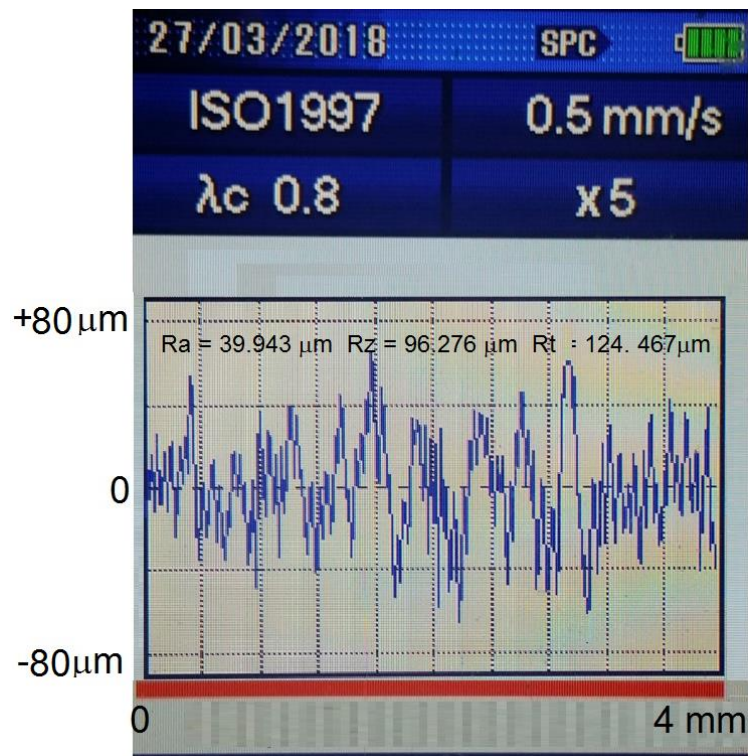
e. Quenched bronze 700 (x500) (symbolization V)

Figure 6. SEM and macro images of erosions on the exposed surface, after 165 minute of cavitation

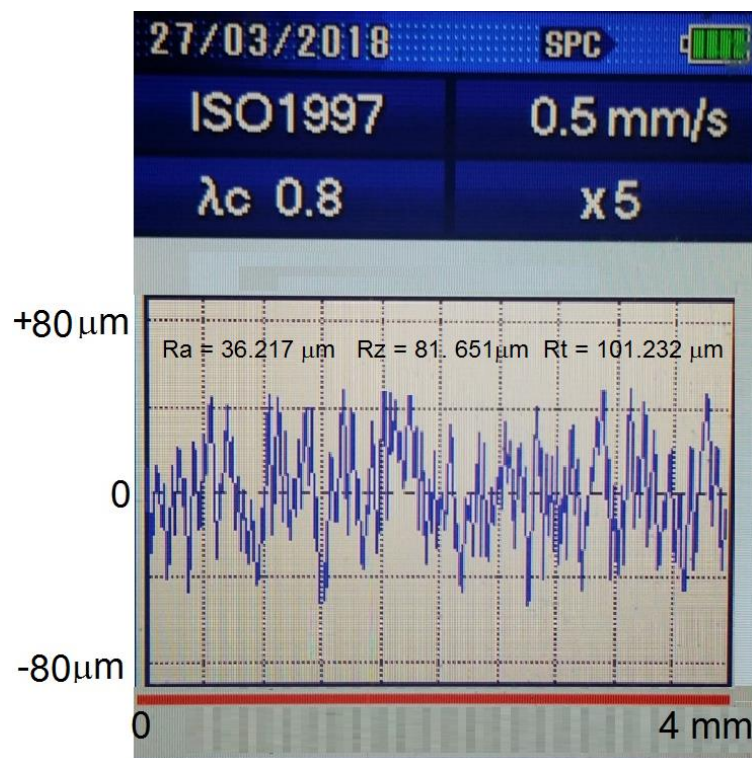
Another important indicator of the material durability is the profile of the surfaces and the values of the roughness tips given in Figure 7. We think that the mean roughness is the most appropriate value. So, this roughness was recorded with a Mitutoyo SJ 201 P device. In Figure 7 are given such records for each state of the specimen surface. They have been effected three measurements for each type of material, on a single specimen, randomly selected. For these samples there were made profile measurements on three different directions disposed at an angle of 120° in conformity with Figure 8. In the same figure there are given also the values of the parameter R_z measured on those three directions.



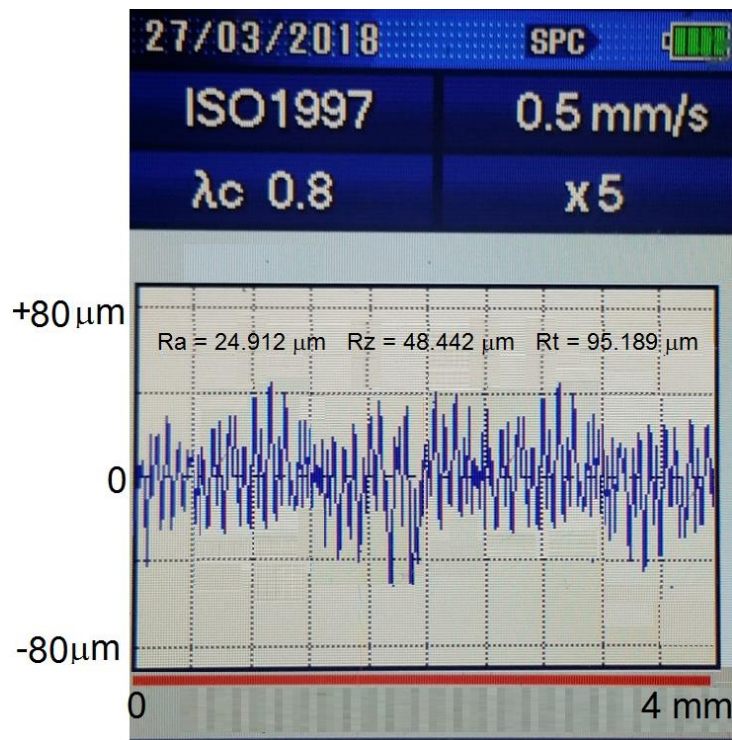
a. Delivered state (I)



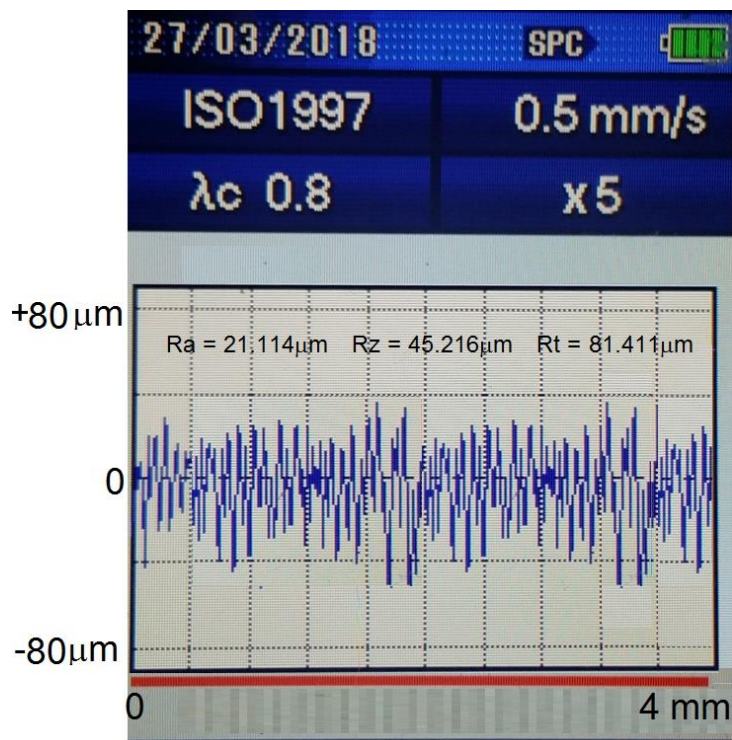
b. State: Quenched 800+tempering 500 (II)



c. State: Quenched 700+Tempering 500 (III)



d. State: Quenched 700+Tempering 250 (IV)



e. State: Quenched at 700 (V)

Figure 7. Roughness parameters and profile registered with the Mitutoyo SJ 201 P device

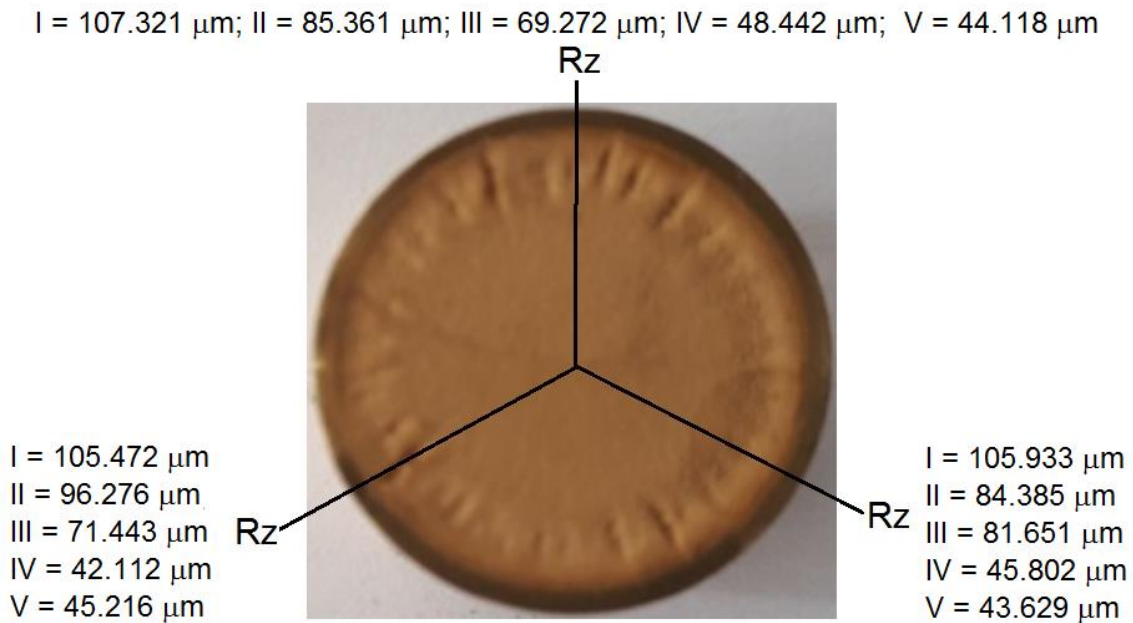


Figure 8. The registration method for roughness profile and parameters presented in Figure 7 using the Mitutoyo SJ 201 P device

4. The analyse of results

For a consistent analyze of the parameter $\bar{\delta}_{cav}$ for the evaluation of the cavitation erosion resistance in Table 2 there are given the values of other three parameters recommended by the ASTM G32-2010 Standard and frequently used in our laboratory [2], [10], [14]. Those are:

- the value $MDER_s$ at which the curve $MDER(t)$ tends asymptotically (see Figure 5), known in literature as the value at which the erosion rate tends to became stable [15];
- the mean erosion depth at the end of tests (in our case 165 minutes), MDE_{165} , computed as the mean arithmetic value of the three specimens tested for each material;
- the parameter mean roughness, Rz_{med} , computed as arithmetic mean for the three values given in Figure 8.

The value of the parameter mean durability $\bar{\delta}_{cav}$, recommended by K.J.Steller [9], was determinate with the relation:

$$\bar{\delta}_{cav} = \frac{165 \cdot (e^{3 \cdot \alpha} - 1)}{3 \cdot \alpha \cdot V_{max}} \quad (5)$$

where:

$$\alpha = \frac{3}{165} \cdot \left(\frac{165 \cdot V_{max} - \int_0^{165} A \cdot t \cdot (1 - e^{-B \cdot t}) dt}{165 \cdot V_{max}} \right) \quad (6)$$

V_{max} is the maximum eroded volume at the end of tests (165 minute in our case), see also Figure 4.

Taking as reference the delivery state the increases in durability respectively cavitation resistance, expressed through the values of the 4 reference parameters, shown in Table 2 have the following variation:

- 24 % and 151 % if for reference is taken $MDER_s$;
- 21 % and 143 % if for reference is taken MDE_{165} and $\bar{\delta}_{cav}$;
- 19 % and 139 % if for reference is taken Rz_{med} .

Table 2. Values of the parameters used for the evaluation of the cav. erosion durability

Parameter	Material state							
	I	V		IV		III		II
	E*	E*	I** %	E*	I** %	E*	I** %	E* I** %
MDER _s [μm/min]	0.724	0.288	151	0.308	135	0.468	55	0.586 24
MDE ₁₆₅ [μm]	103.832	42.704	143	44.667	132	70.91	46	85.81 21
R _{z,med} [μm]	106.242	44.321	139	45.452	133	74.122	43	88.674 19
$\bar{\delta}_{cav}$	8.232	20.013	143	19.123	132	12.044	46	9.963 21

*E**-experimental values; *I***- increase versus delivery status

It is remarkable the identical values obtained for *increase versus delivery status* both for the index cavitation durability $\bar{\delta}_{cav}$, recommended by K. Steller and the mean erosion depth MDE₁₆₅. We think that those coincidences are normal because both parameters are computed on the basis of the eroded volume (see the relations 4 and 6).

The data in Table 2 shows that there are also differences between the gains achieved by the values of the 4 parameters, relative to the reference state. This shows the effect of thermal treatment parameters on the surface resistance to shocks produced by impact with cavitation microjet. These differences are shown, percent, below:

- for state V: approximately 9 %;
- for state IV: about 2 %;
- for state III: about 28 %;
- for state II: about 26 %;

Because in absolute values those differences are between 5...12 all the parameters presented in Table 2 can be taken for the analyze of the material resistance to cavitation erosion.

5. Conclusions

As a result of the realized researches we can state that the parameter mean durability ($\bar{\delta}_{cav}$), defined by K.Steller, offer similar information upon the cavitation erosion of materials with those obtained by the ASTM G32-2010 Standard and largely used in all countries.

The volumetric heat treatments of quenching or quenching and tempering are recommended solutions for the details subjected to cavitation erosion such as ship propellers or the bodies and other details of vanes manufacture by the bronze CuSn12.

The values of all the chosen parameters show that the best results are obtained through quenching at 700°C or if when other condition must be fulfilled very good results are obtained by quenching at 700 °C + tempering at 250°C.

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