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Considerations regarding the erosion mechanism of vibratory cavitation

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Abstract. The cavitation erosion researches conducted on vibratory devices presents a way of degradation very similar with those encountered in industrial equipment. Photos of the cavitation cloud as well as the eroded surfaces, at various exposure periods, are the basis of the present work in the description of this destruction mechanism. For the experiments, there were used two materials: gray cast iron with lamellar graphite and a high resistance bronze. The used device is that of the Timisoara Polytechnic University Cavitation Laboratory which respects integrally the prescriptions of ASTM G32-2010 Standards. For the description of the results there are used both the roughness profiles and the structure images of the eroded areas, after four different exposure times (5, 60, 120 and 165 minutes). The cavitation erosion behavior is expressed both by the mean depth erosion (MDE) and the parameters of roughness values of the affected areas. The conclusion show that the specific degradation is determined by the cavitation hydrodynamics, as well as by the repeated implosion of individual bubbles which forms the cavitation cloud attached to the exposed surface.

1. Introduction

All researches regarding cavitation erosion realized in laboratories or in industrial installations (hydraulic turbines, pumps, vanes etc.) show that the aspect and dimensions of the eroded zones depend in principal on the type of cavitation (gaseous, vaporous, swirl, fixed, attached, on profile or interstitial) and on the type of material [1,2]. The researches realized in laboratories on various devices vibratory, with rotating disk or hydrodynamic tunnels show that the shape of the affected area depends on the type of the used installation [1-3]. The researches carried out on vibratory devices with cylindrical test specimen show that regardless of type of the used device (magnetostrictive tube, piezoelectric or ferritic transducer) or the tested material, the cavitation erosion present a specific mode of degradation evolution [2], [5-8]. The photographic images for different exposure periods show that the zone with expelled material begins with a ring, placed at the periphery of the specimen, which in time migrates towards the inner zone, simultaneously receiving at the periphery large caverns. Especially for weak materials, the eroded area receives an accentuated star appearance. For comparisons there have been chosen two materials with great differences of the resistance: grey iron (with weak resistance) and bronze (with good resistance). The cavitation device is one with piezoelectric crystals realized in Timisoara Polytechnic University Laboratory for Cavitation respecting all the requirements of ASTM G32-2010 [5, 6], [9-11].

2. Researched materials

The material selection was made in such a way to put into evidence even small differences in the evolution of the eroded area.

The selected materials are:

- grey iron with lamellar graphite EN-GJL-150 (SR EN 1561-2012), casted in industrial details, used for manufacturing the bodies for the hydraulic units for control, distribution and adjustment, valve bodies, turbine and pump volutes, etc. [1, 2]. The used specimens were manufactured from the body of a pressure valve (DN 32). The laboratory analyzes indicate the chemical composition as being: 3.22 % C, 1.87 % Si, 2.12 % Mn, 0.16% P, 0.12 % S, and having the following mechanical properties: breaking strength R_m = 225 MPa, Brinell hardness (HB) = 180 daN/mm^2, density ≅7.2 kg/dm^3, and
- bronze CuAl10.5Ni5Fe4.8Mn1.5, in annealed state used for manufacturing ship propellers [11], having the following chemical composition: 10.46 % Al, 4.85% Ni, 4.72 %Fe, 1.41 % Mn, rest Cu; fracture strength R_m = 980 MPa, yield point $R_{p0.5}$ = 789 MPa, Brinell hardness (HB) = 283 daN/mm^2, elongation A_5= 8 %, impact test KCU= 7 J, density ≅7.45 kg/dm^3.

In Figure 1 and 2 are presented microstructural images, obtained with an optic microscope.

3. Laboratory test device

For each material, four cavitation specimens were tested in the Standard Vibratory Cavitation Device of the Timisoara Polytechnic University Cavitation Laboratory [5, 6], [10-12]. Before testing, the active surface of each specimen was carefully polished till a roughness of Ra = 0.012÷0.025 μm, see Figure 3. For both materials, the test procedure fully complied with the ASTM G32-2010 recommendations [9]. The total time exposure, the intermediate measuring periods, the washing, drying and the way to keep the specimens between the measurements respected the laboratory procedure [2], [4-8], [10], [12].

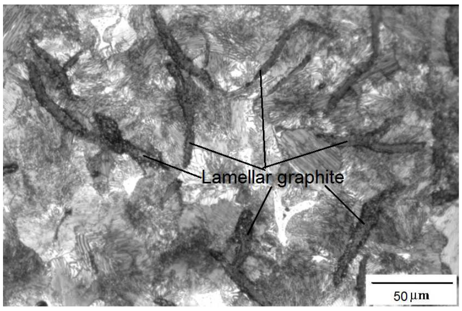


Figure 1. Gray cast iron EN-GJL-250 having perlite ferritic structure whit lamellar graphite.

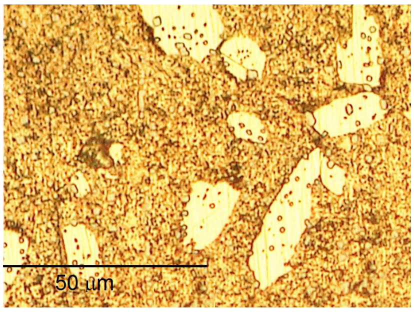


Figure 2. Bronze CuAl10.5Ni5Fe4.8Mn1.5.

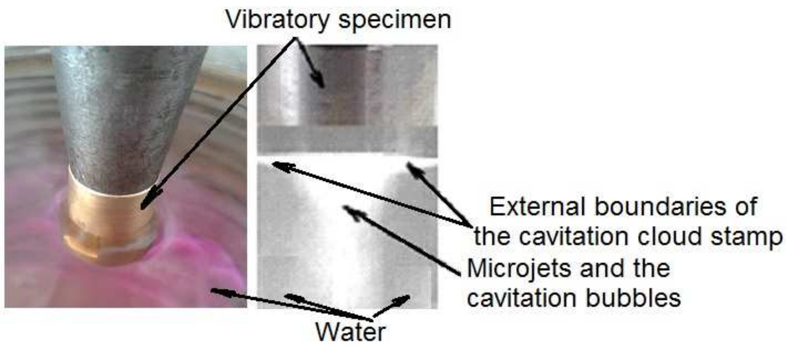
Gray cast iron

Bronze

Figure 3. Surface aspects before exposure to vibratory cavitation (Ra = 0.012÷0.025 μm).

4. Analyzes of the surface destruction specificity

In vibratory cavitation devices, as a result of the contraction and dilatation of the sonotrode, the active surface of the specimen has lifting/lowering movements. This movements give rise to a cavitation cloud. The formation and implosion of the individual bubbles depend on the technical and functional parameters of the device such as frequency and amplitude of the vibrations, specimen diameter, the nature and temperature of the working liquid [1-3]. The implosion of the cavitation cloud give rise of microjets and shock waves (see Figure 4), which produce pressure peacks acting upon the active surface. On vibratory devices this pressure remain constant as the result of maintaining the running parameters in the prescribed limits [1,2], [11].



a) b)

Figure 4. Bubble cloud below the specimen surface.

The surface erosion degree is given by two factors: the stresses determined by the implosions of the cavitation bubbles and the material response to these stresses (through the physical-mechanical properties, the crystalline and inter-crystalline structure obtained after the heat treatments applied [2, 3], [4-8], [10-12]). Practically a part of the energy created by bubbles implosion is taken over by the material and determines elastoplastic deformations, cracks and material expulsions and another part is transformed in heat. The shape in which the surface is affected in time, after the photos taken after various periods of cavitation exposure, is determined by the zones in which appear the maximum pressure picks.

The examination of the cavitation eroded surfaces, with naked eye as well as with microscopes, for the characteristic times given in Table 1, put into evidence the following aspects:

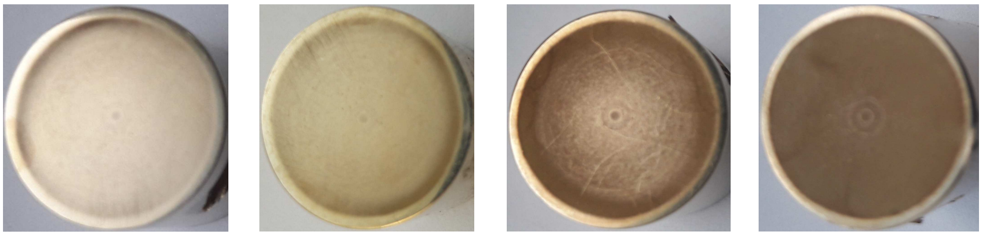
- After 5 minutes of cavitation the exposed surface receive a darker color, the luster is lost and towards the margins appear a ring with zones of expelled material. The explanation consist in the breaking of the roughness picks and the emergence of a networks of cracks on the whole surface and small dimension caverns in the marginal ring.
- After 60 minute of exposure the erosion is extended on the whole surface of the specimen, regardless of the tested material. For weak materials such as grey iron the erosions depth (caverns) in the high eroded marginal ring is increased and the erosion receive a stellar shape. For resistant materials (such a bronze) even if the stellar shape cannot be seen however the greater deeps of the caverns appear in the roughness records.
- Between 60 and 165 minutes of cavitation exposure the erosion intensity increases visibly and for weak materials such as grey iron the stellar profile becomes more expressive.

This evolution of the surface erosion can be explained by the evolution of the pressure picks generated by the bubble implosions from the cavitation cloud (having a smaller mark that the exposed area, see Figure 4b):

- in the first five minutes of attack, as a result of the very good polishing (Ra = 0.012 - 0.025 µm), the material is only deformed in the case of bronze but is visibly cracked radially towards the exterior for the grey iron, because this material has a reduced resistance and is brittle. This explain the formation of the peripheral ring

- when the duration of the exposure increases (especially after 60 minutes) the crack network also increases and caverns appear on the entire attacked area for both materials, in function of the granulation of the structural constituents; for the grey iron where even exist a weakened external ring with caverns and cracks, the erosion is accelerated and became extremely visible.

Table 1. Cavitation erosion evolution (images with CANON camera).

Vibratory cavitation exposure time [min]			
5	60	120	165
			
Bronze CuAl10.5Ni5Fe4.8Mn1.5			
			
Grey cast iron EN-GJL-250			

This explanation is justified and well put into evidence by the profile diagram presented in Figure 6 and 7. The registrations were obtained with a Mitutoyo device. There have been made measurements on the eroded area, both in the central zone and in the peripheral one. For the grey iron specimens which present very visible caverns we considered of interest to obtain photos for the sectioned specimen. For this purpose some specimens were sectioned and half of them embedded in resin.

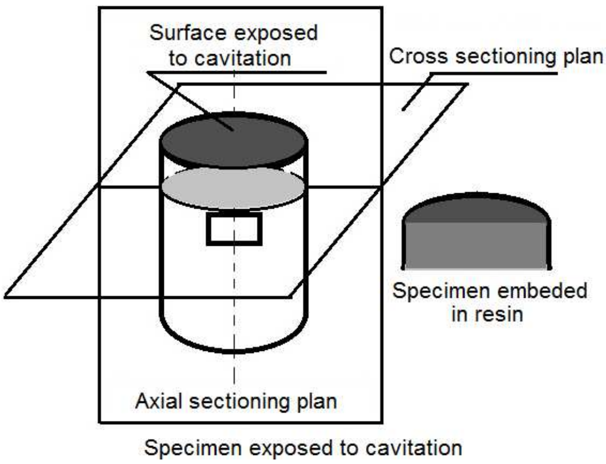


Figure 5. Specimen slicing pattern.

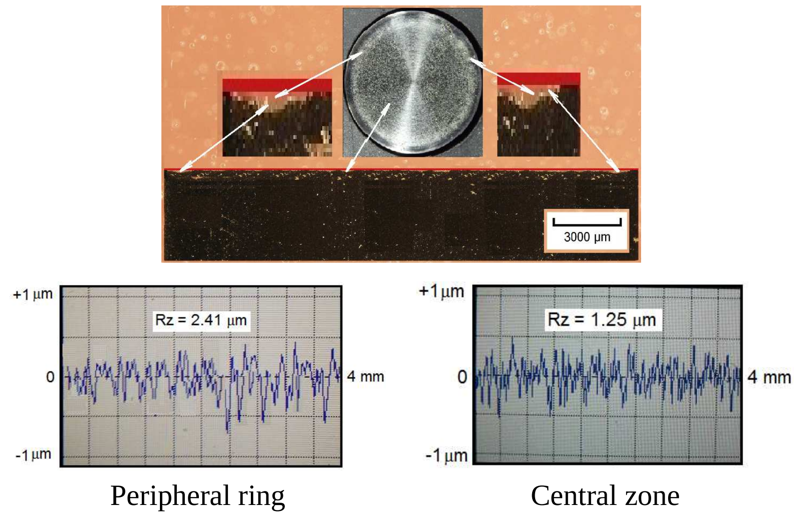


Figure 6a. Gray cast iron (after 5 minutes of cavitation exposure).

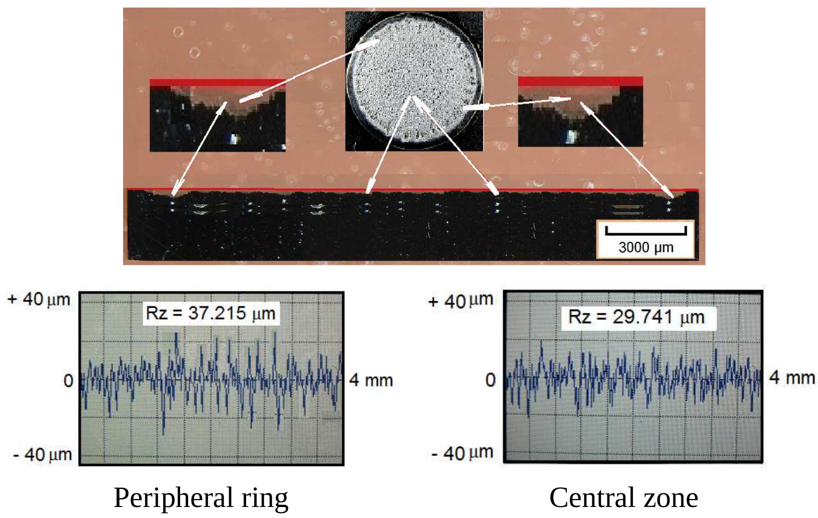


Figure 6b. Gray cast iron (after 60 minutes of cavitation exposure).

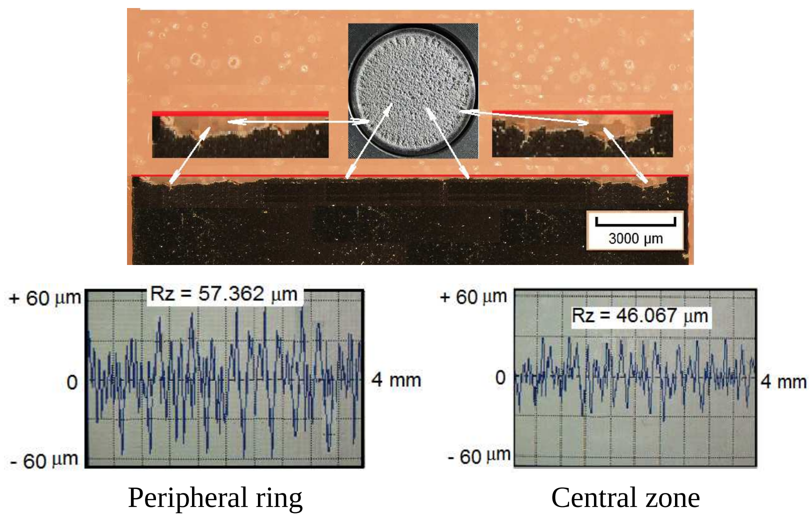
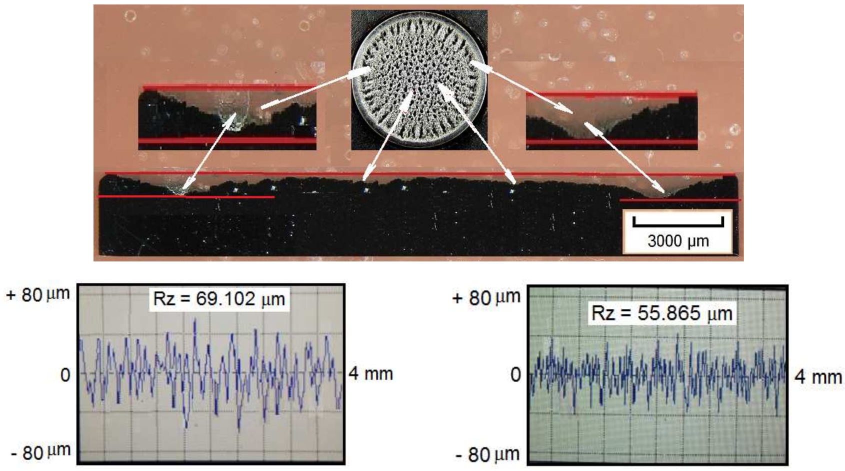


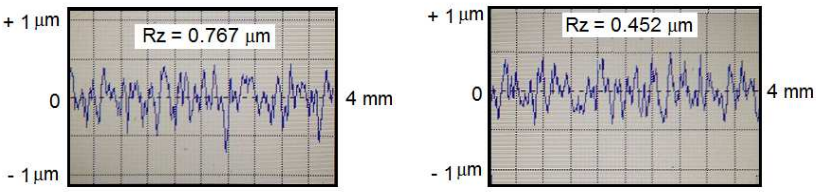
Figure 6c. Gray cast iron (after 120 minutes of cavitation exposure).



Peripheral ring Central zone

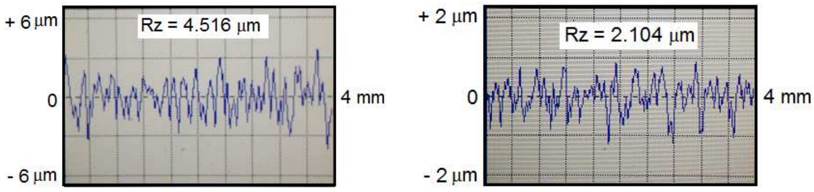
Figure 6d. Gray cast iron (after 165 minutes of cavitation exposure).

Figure 6. Profiles of the eroded zones (gray cast iron).



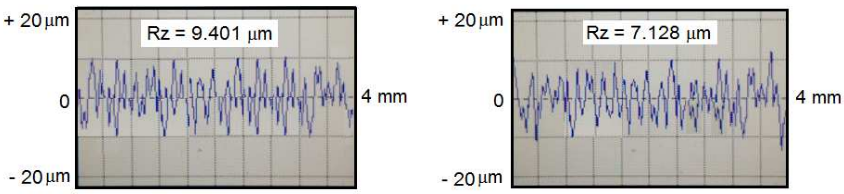
Peripheral ring Central zone

Figure7a. Bronze (after 5 minutes of cavitation exposure).



Peripheral ring Central zone

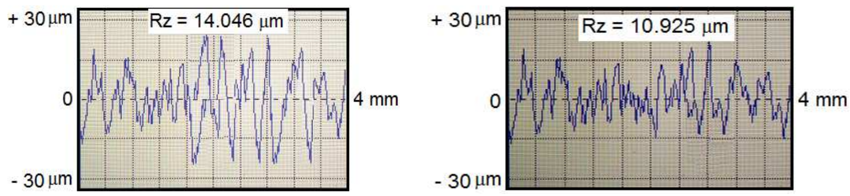
Figure 7b. Bronze (after 60 minutes of cavitation exposure).



Peripheral ring Central zone

Figure 7c. Bronze (after 120 minutes of cavitation exposure).

In the histograms presented in Figure 8 and 9, the mean depth erosion (MDE) is compared with the values Rz given by the Mitutoyo device for each exposure time. In Table 2 are made comparisons between the mean depth erosion MDE, which remain the best figure for characterising the material resistance to vibratory cavitation erosion [5], [9,10], [12] and the values of the parameters Rzi (i = 1..2) characterizing the roughness resulted by cavitation and measured with Mitutoyo device.



Peripheral ring Central zone

Figure 7d. Bronze (after 165 minutes of cavitation exposure).

Figure 7. Profiles of the eroded zones (bronze).

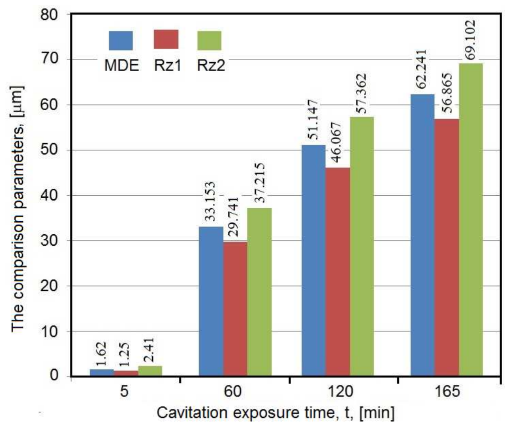


Figure 8. Comparisons between MDE (mean depth erosion) and Rz1, Rz2 roughness parameters (for gray iron): Rz1 – recorded values in central zone; Rz2 –registrated values in the preipheral ring.

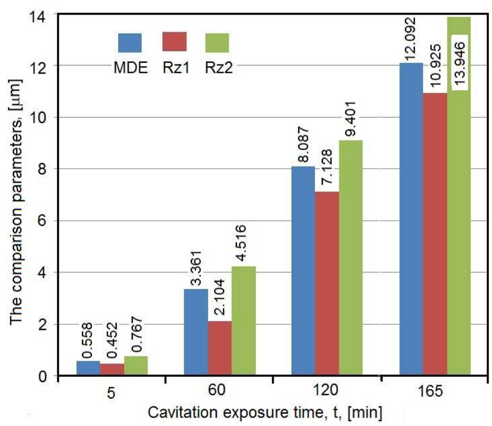


Figure 9. Comparisons between MDE (mean depth erosion) and the Rz1 and Rz2 roughness parameters (for bronze): Rz1 – recorded values in central zone; Rz2 – recorded values in the peripheral ring.

Table 2. Comparisons between MDE and roughness parameters.

Material	Ratio	Cavitation exposure time [min]			
		5	60	120	165
Gray iron	MDE-Rz1	0.37	3.412	5.08	3.376
	|MDE-Rz2|	0.79	4.102	6.215	6.861
Bronze	MDE-Rz1	0.106	1.257	0.959	1.167
	|MDE-Rz2|	0.209	1.155	1.314	1.854

From the histograms it result that mean depth erosion MDE (mean value determined from the mass loss measurements) has values comprised between Rz1 and Rz2 (mean values obtained by roughness measurements on lines having a length of 4 mm, both in the center of the specimen or in his external ring). For both tested materials the differences |MDE-Rz2| are greater than the differences MDE-Rz1|. This means that for the cavitation erosion vibratory devices the erosion depth is greater in the peripheral ring. It resulted also, that using two tested materials and the same laboratory device (this means an equal cavitation erosion intensity) the differences (MDE-RZ| and |MDE-Rz2|) are greater for the material having a weaker cavitation erosion resistance.

5. Conclusion

Both the photographic registrations and the roughness measurements show that, for laboratory testing devices with vibratory specimens, the evolution of cavitation erosion has a specific evolution. The erosion begin in a peripheral ring were the material lost is greater and afterward continues towards the center of the specimen. This process is due to the formation of the cloud of cavitation bubbles and the generations of the shock waves as result of the bubble implosions. The differences of the loss mass is easy to be observed at materials with low cavitation resistance.

For materials with great or even mean cavitation resistance (as in our case bronze) even if this phenomenon is present it is much diminished and difficult to be put into evidence.

For industrial installations (hydraulic turbines, pumps, valves etc.) such a phenomenon does not appear. On the other hand the material for such devices usually has great cavitation resistance and such phenomenon does not appear and the selection of the best material can be done with vibratory devices, regardless if the material is proposed for manufacturing or repair works.

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