ABOUT SOME ASPECTS REAGARDING THE CAVITATION EROSION

ILARE BORDEAŞU, IOAN PĂDUREAN, MIRCEA POPOVICIU

Present a great number of researches results concerning cavitation erosions mechanism in materials with different structures. Simultaneously, it is analyzed the manner in which the energy resulted from the implosion of cavitation bubbles produced cracks and expulsion of small pieces of material. There are presented data both from literature and from the researches undertaken in Timisoara Cavitation Laboratory.

1. INTRODUCTION

Cavitation erosion is a very complex phenomenon. For this reason, the recent researches are directed towards the studies of the intimate mechanisms by which the material is eroded [17, 22, 3, 9]. Simultaneously there are undertaken researches regarding the way in which the energy developed by the imploding bubbles is consumed for producing cracks and micro fractures of the material [1], [17]. An important question is the way in which the described mechanisms are reflected in the cavitation characteristic parameters such as mass losses $m(t)$, volume losses $V(t)$, the erosion rates $\mathrm{d}m(t)/\mathrm{d}t$, $\mathrm{d}G(t)/\mathrm{d}t$, $\mathrm{d}V(t)/\mathrm{d}t$, the mean depth penetration (MDP) or the mean depth penetration rate (MDPR), etc. [1, 2, 8, 25].

In the present paper is made an analysis of the cavitation erosion mechanisms, in association with the developed energy, on the basis of the researches undertaken in the Timisoara Cavitation Laboratory, taking into account also the results published in the literature.

2. THE FRACTURE MECHANISM AS A RESULT OF BUBBLES IMPLOSIONS

The produced mechanisms of cavitation erosion are the same regardless of test facility used [2], [8], or the type of the hydraulic machine (turbines, pumps etc), but the velocity of the erosion can be very different. This differences are caused by: the magnitude of the stress during the implosion (from hundreds to thousands of MPa [11, 15]), the characteristic time in which the phenomenon take place (from 2 to 5 microseconds [10]), the velocity of the phenomenon (from 100 to 200 m/s for the implosion of hydrogen bubbles in water [11] till 500 m/s in the case of the implosion of a bubble filled with vapors and also the frequency of the implosions.

"Politehnica" University of Timişoara

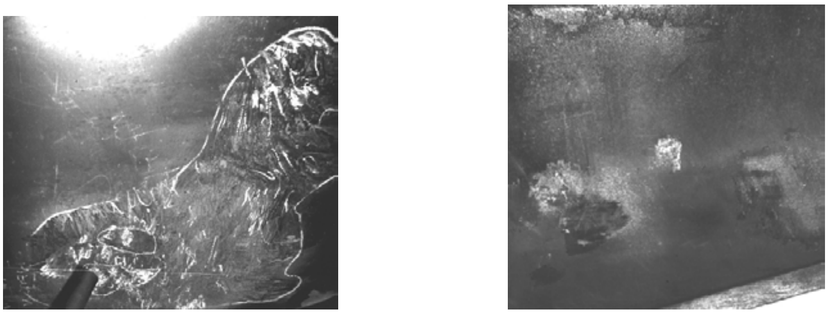
Rev. Roum. Sci. Techn. – Méc. Appl., Tome 52, N^o 2, P. 133–142, Bucarest, 2007

Depending on the manner in which the structural bonds are destroyed there are three main mechanisms for the material deterioration: ductile, brittle and by fatigue. The erosion results from any of these mechanisms or by any combination of them, depending on the material characteristics such as: crystalline structure, microstructure and physical mechanical properties. The erosions presented in Fig. 1 are eloquent in respect to the damages produced by cavitation to the runner blade of a high power Kaplan turbine manufactured out of martensitic-alloy steel. The Fig. 2 is a cross section of a laboratory sample, manufactured out of stainless steel 20Cr130.

3. INFLUENCE OF INCUBATION PERIOD AND DEFORMATION VELOCITY

To understand the erosion mechanisms there have been undertaken researches both for pure metals and alloys. The most interesting results will be analyzed in the following paragraphs.

Heathcock a. o. [14] studied the cavitation erosion on various materials: iron, ferritic stainless steels, cobalt, nickel alloys and some polymers. These materials were subjected to cavitation in rotating disc facilities, hydrodynamic tunnels and in industrial equipments, where can be observed also the incubation period. In this period there are only plastic deformations and formation of multiple cracks (the phenomena was observed by all the researchers). This cracks are associated with the fatigue, resulting from repeated stresses induced by the implosions of a great number of bubbles, at approximate the same place. As a result, occur material losses by ductile or brittle failures and by crack propagation.



Erosion on the suction side of the blade
(Stainless steel OH12NDL)

Erosion on the turbine chamber
(Carbon steel OL37-3k)

Fig. 1 – Cavitation erosions on various components of a Kaplan turbine.

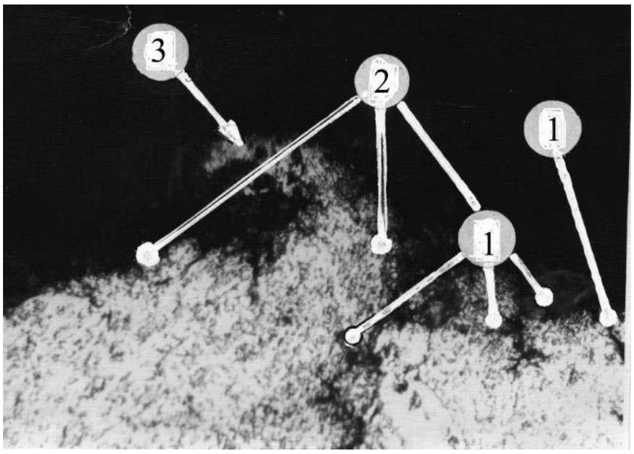


Fig. 2 – Cavitation erosions on a laboratory sample manufactured out of stainless steel 20Cr130; the tests have been carried out on the magnetostrictive facility in Timisoara Cavitation Laboratory (1000×) [2]: 1 – cracks with different orientations; 2 – hardened zone; 3 – plastic deformed grains.

The researches of Heathcock a. o. [13] upon the austenitic stainless steels AISI 409, AISI 430 and the alloy symbolized 3CR12 showed that the reduction of cavitation erosion resistance is determined by the material sensibility at velocity strains. They observed that high strain velocity, a feature typical for cavitation, is determinant for the brittle failure. They concluded also that materials with reduced brittle failure are those with reduced content of chromium (see the chemical composition of materials in discussion). At same conclusions reaches also Binder and Spendelow [4] who supplementary show, that the synergic effect of the presence of chromium (for concentrations of 15–18 %), combined with critical concentrations of carbon and nitrogen improves the sensibility to high velocity strains, especially for materials having body cubic centered structure.

Studies carried out on the alloy 3Cr12, having a chemical composition close to that of AISI 409, which after annealing at a temperature over 750°C present a fine-grain microstructure, composed out of ferrite and martensite. The authors observed that for the steel 3Cr12 with ferrite structure the fracture manner is almost completely brittle, while for the alloys with fine-grains the fracture is ductile and the resistance to cavitation attack increases also with the volumetric percentage of the fraction of martensite [13].

Our opinion is that cavitation resistance increases for fine-grain microstructure because the expelling process is slow, while the cracks formed in ferrite cannot close their evolution being continuously deviated by martensite, so the cracks evolutes by forming numerous branches.

Erdmann-Jesnitzer and Luis [7] studied the behavior of aluminum, zinc and Armco steel. They identified, for pure aluminum and Armco steel the same mode of failure as that exposed by Heathcock [14]. Supplementary, they show that at the beginning of the cavitation process, the plastic deformations are associated with fatigue and produced the cracking in a thin material layer. This process of plastic deformations, cracking and material expelling is continued during the whole cavitation process.

4. INFLUENCE OF CRYSTALLIZATION STRUCTURES

Because, the metallic materials undergoing cavitation attacks are, generally, alloys with different crystallization structures such as: body-centered cubic (bcc), face centered cubic (fcc) and hexagonal close-packed (hc), it is seems important to correlate the cavitation erosion with these structures.

For pure aluminum (fcc), Erdmann-Jesnitzer and Luis noted that cracks propagation directs to ductile failure. For Armco iron (bcc) the cavitation erosion has the same kind of evolution (plastic deformations followed by crack propagation). For both materials the erosion is produced by ductile failure and cleavage.

Our opinion is that indifferently of the moment of cavitation evolution (incubation, accumulation etc.), as a result of the intercrystalline bounding forces (Frank a. o. [8], Bordeasu [2]), occur elastic deformations which are difficult to be observed and were neglected by Heathcock [14] and Erdmann-Jesnitzer [7].

Preece a.o. [20] analyzed the erosion of pure nickel and brass 70–30 (fcc materials) and shows that metals with such structure are isotropic and with low sensibilities at high deformation velocities.

For materials with (hc) structure Preece [20] considers that the anisotropy degree and the sensibility at high deformation velocities depend, in certain measure, on the rate c/a. He shows that zinc which has $c/a = 1.856 \neq c/a = 1.633$ (the ideal rate [36]) under the cavitation attack presents a fragile fracture. That is the reason why zinc presents a great anisotropy and a weak resistance to cavitation erosion. Preece also establish that in opposition with zinc is cobalt which has a rate $c/a = 1.623$, closer to the ideal one, for which the plastic deformation is done easy under six sliding systems, in opposite with zinc at which sliding is easy only on the system $\left(0001\right) < 11\bar{2}0$ [24]. Preece also observes [20] that cobalt does not have the transition ductile-brittle and is very resistant to cavitation erosion and his degradation take place only by a ductile fracture. Vayda a. o. [27] observed, on the eroded area of cobalt samples the existence of striations disposed at the basis of the craters, which indicates that the fracture occurs through fatigue.

Preece [20] studied also pure iron with (bcc) structure and explained that the material is deformed principally by macles. The author appreciate that the expelling of material begins simultaneous at macles and at the grains boundaries. Also they observed the crates are formed through a cleaving mechanism. This transition in the mechanism of iron erosion was observed also by Matsumura [16], which assign it to the (bcc) structure and to the rise of hardness as a result of consolidation during the cavitation process.

5. THE MECHANISM OF FATIGUE FRACTURE

Vaidya and Preece [27] studied some aluminum alloys; inclusively those structural hardened and indicate that a cause of erosion through fatigue is given by the limited consolidation of the thin layer just under the attacked surface. They considered that the erosion mechanism of low-alloyed aluminum (for example with 1% Cu) is similar with those for pure metals having (bcc) structure and is produced by ductile fracture. That manner of erosion leads to a uniform rate of material loss on the attacked area. At the same time, the mentioned authors observed that with the increased cavitation duration the rate of material losses is reduced as a result of the hardening of the exposed surface as a result of the implosions. In the opinion of the authors, this phenomenon is due because the ductile fracture is replaced by a local fatigue fracture [27].

For aluminum alloys with a great content of foreign elements (for example Al-9%Mg and AlZnMgCu) Vayda and Preece find that cavitation erosion is produced by shallow propagation of fatigue cracks on the whole attacked area. They find also that a high density of dislocations and the presence of numerous precipitates limit the propagation of dislocations in thin layer just under the attacked area and determine the rise of primers on the surface. In this way, the primers become greater and initiate the crack at surface of the material. But the cracks formed at the surface are immediately filed with water, the impact of the implosion is considerably cushioned and the cracks do not penetrate the material but is developed superficially [27].

For aluminum alloy, with medium content of foreign elements (for example Al-4%Cu), Vayda and Preece [27] notice that cavitation erosion manifests itself simultaneously through ductile fracture mechanisms and cracking through fatigue that result in microscopic cups dispersed on the whole attacked aria.

6. INFLUENCE OF HARDENING TREATMENT

Songzhou and Herman [23] studied cavitation erosion for pure titanium and the biphasic alloy after various treatments of nitriding. Before that process it was observed an initial plastic deformation followed by deep cracks assimilated with those appearing in fatigue phenomena. These two authors observed also that for pure Titanium, the cracks produced during cavitation occur at the intersection of the slipping planes, while for the alloy Ti6Al4V they are formed at the interface of phases α, β and at the slipping bands, which play the role of a cleavage surface. As consequence they consider that the erosion of alloys without nitriding is effectuated by ductile fracture while for nitrided ones the erosion occur through a fragile rupture. It is interesting to specify that Songzhou and Herman [28] consider that fatigue failure take an important role only in the first part of cavitation process. On the contrary, researches carried out by Anton [1], Bordeaşu [2], Frank [8], Hammitt [10], Garcia [12] and others, on a great variety of materials, with different test facilities show that fatigue is present during the whole cavitation attack.

7. OBSERVATIONS IN THE TIMISOARA CAVITATION LABORATORY

Bordeasu a.o. [3] studied the mechanism of the initiation of cavitation erosion for the martensitic stainless steel G-X5CrNi 13.4 used for manufacturing Bulb turbines blades. The tests have been carried out in the Timisoara Cavitation Laboratory with a magnetostrictive facility.

The most suggestive features are presented in Figs. 3 and 4. From these figures it is easy to see that after a few seconds occur indentations, which are specific for dynamic loadings, produced either by micro jets or impact waves. From Fig. 4 it is evident that plastic deformations and fatigue fractures are also present.

The researches undertaken by Bordeasu [2] on a large range of materials, inclusively on the stainless steel 40Cr130 (Fig. 2), conducted to following conclusions:

a. The first eroded components for steel alloy are the carbides formed at the grain boundaries as a result of their high brittleness. The expelling of them generates for future cavitation attacks, *primers* for cracks.
b. The crack propagation is produced preferentially either in axial or in radial direction, depending on the zone with weaker resistance.
c. At the probe surface (zone 2) occurs a local hardened zone, as a result of repetitive implosions. For materials with hexagonal close-packed structure the hardening is realized on a reduced depth.
d. The structural strongly bounded grains are at the beginning plastic deformed and only after that expelled (Fig. 2, position 3).

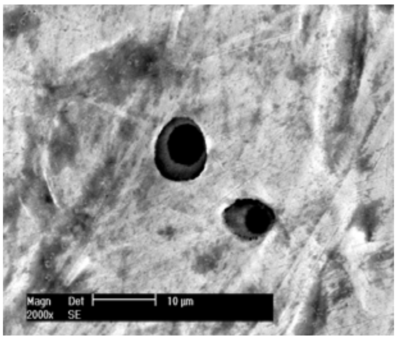


Fig. 3 – Stainless steel G-X5CrNi 13.4, after 5 seconds of attack (2000×).

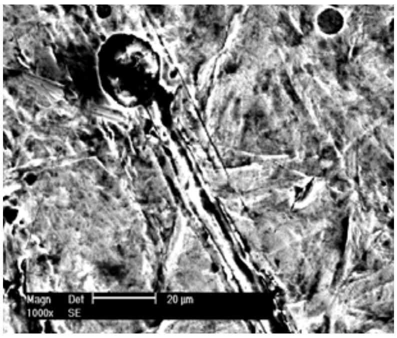


Fig. 4 – Stainless steel G-X5CrNi 13.4, after 15 seconds of attack (1000×).

8. INFLUENCE OF ENVIRONMENT AND TYPE OF LOADING

Mustapha Ait Bassidi [17] studied the mechanism of corrosion fatigue on three types of steels (KCR 171, CA 15, 304), in distilled water, drinking water and air. Although this research has not as objectives cavitation erosion, the obtained results gave explanations for numerous phenomena appearing also during this process. Thus, the author observed that during cracking in corrosive environments appear brittle striations. He also observed, that in the ferrite phase of steel KCR 171, the failures sides have a {100} orientation. In the same phase he observed that the striations perform evolutions with the amplitude of the fatigue loads ΔK. They pass from brittle striations (for reduced amplitude loads) at half-brittle (for medium and high amplitude loads), respectively at ductile striations (for very high amplitudes). Mustafa [17] studied also the correlation between the crack propagation velocity and the stress intensity ΔK, in corrosive surroundings. The results are presented as curves in logarithmic coordinates. The curves have two distinct zones, the first for $\Delta K < 20\text{MPa/m}^2$ and the second for $\Delta K > 20\text{MPa/m}^2$. When ΔK has very high values ($> 40\text{MPa/m}^2$) the cracking velocities in corrosive surrounding tend to reach the values obtained in air.

9. INFLUENCE OF DIFFERENT FACTORS UPON CRACKING INCEPTIONS

The researches carried out by Brigham a.o. [5] show that a temperature rise determines the increase of the number of cracking inceptions in the zone affected by fatigue. These researches concluded also that for the steel 304L with two phases (with 5% δ ferrite) the roughness does not influence these phenomena. For the steel 304 L with a single phase there has been recorded a monotonous decreasing of the numbers of cracking inceptions with the increase of roughness. The authors explain this phenomenon by the fact that the cracking inceptions for the single phase material are formed as a result of the inclusions dissolutions and an increased roughness produce a greater exposure of the inclusions to the external factors, inclusively to implosions.

Chastell a.o. [6]) realized cracking inceptions studies under stresses. He used a martensitic steel in a solution with 5 mol/kg sodium hydroxide and 0.5 mol/kg of sodium chloride, the stresses being applied by bending in 4 points. The results indicate that for tensile stresses the cracking inceptions are increased while for compressive stresses this susceptibility is reduced. This result is in agreement with those of Steffec a.o. [24] and Poyet a.o.[19], which studied the effect of stresses upon the cracking inceptions initiated at the micro cavities placed between the matrix and the inclusions. In such situations, the tension stresses have the trend to open the micro cavities and in this way favor the formation of cracking inceptions. By contrary, the compressive stresses closing the micro cavities increase the resistance to cracking inceptions.

Scotto a. o. [21] studied the effect of pH upon the cracking inceptions produced by fatigue and observed that the reduction of pH is favorable to the production of indentations and their diameter is increased when the pH value is below the depassivating pH.

10. CONSIDERATIONS UPON THE DISTRIBUTION OF ENERGY USED BY THE MATERIAL DURING CAVITATION EROSION

The mechanical process governing the cavitation erosion is given by the mode, in which the material takes over the energy transmitted by the implosion of bubbles. The energy absorbed by the material depends both on the mechanical properties and the crystalline and intercrystalline structure and is used for elastic
The scattering of experimental points around the curves $m(t)$ and $v(t)$, especially in the steady state zone is exemplified in Fig. 5. The periods, in which the expelling is great, alternates with others in which the energy is consumed for other purposes. From Fig. 5 it is obvious that for the curves $m(t)$ this scatters are small and difficult to be observed. On the contrary, for the curves $v(t)$ they are very pronounced. For the Fig. 5 they may be described as follows:

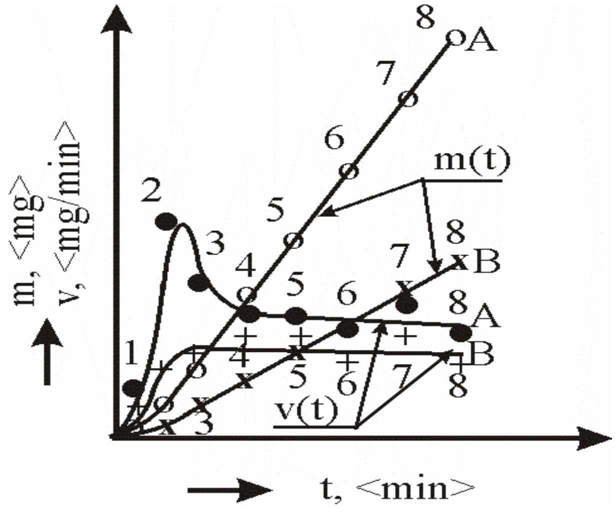


Fig. 5 – The distributions of experimental points against the curves $m(t)$ and $v(t)$and plastic deformations, cracks and expulsions of parts of grains, whole grains or even several grains [2].

– in the periods 1–2 and 6–7 the energy is consumed mostly for fracturing the crystalline and intercrystalline bonds, which determines expulsions of material; only a small part is directed for elastic and plastic deformations and the creation of cracks. Such phenomena are extremely evident for carbon steels, cast iron, brass, but there can be seen also in stainless steels;

– in the periods 5–6 and 7–8 the absorbed energy is consumed mostly for elastic and plastic deformations and the creations of cracks. Only a small part is taken for fractures of the crystalline or intercrystalline bonds, which finally conduct to the expulsions of material particles. Such phenomena are specific for high alloy steels and bronzes (for example the steels 40Cr10, Carbon I-RNR, H4142–15, OH12NDL, 20Cr130 or the bronze CuNiAl I–RNR).

– in period 4–5 the energy is approximately equal divided both for plastic and elastic deformations and for fractures. This phenomenon is characteristic for some high alloy steels (for example: G-X5CrNi13.4, T07CuMoMnNiCr165-Nb, T09CuMoMnNiCr85-Ti, stainless steel III-RNR, 33MoCr11, 41MoCr11, !8MoCrNi13, and the bronze CuNiAl III-RNR).

11. CONCLUSIONS

There have been presented the principal possibilities through which the mechanism of cavitation erosion is realized, taking into account the structure of material, on the basis of the data obtained through researches carried out in Timisoara Cavitation Laboratory but also in other laboratories.

The obtained results were explained through the way in which the energy produced by bubble implosion is used by the material both for elastic and plastic deformation and for substance expelling.

The results presented in the paper open up new research directions in the field of cavitation erosion such as: the study of microstructure transformations along all the duration of cavitation attack and the analysis of the material structure till the level of crystalline structure. In this way it is possible to obtain an improved understanding of the cavitation erosion process.

Received 19 Mars 2007

REFERENCES

1. ANTON I., *Cavitația*, Vol.I, Edit. Academiei Române, Bucharest, 1985.
2. BORDEAȘU I., *Eroziunea cavitațională asupra materialelor utilizate în construcția mașinilor hidraulice și elicelor navale. Efecte de scară*, PhD Thesis, Timișoara, 1997.
3. BORDEAȘU I., a.o., *Cavitation Erosion for G-X5CrNi13.4 Martensitic Stainless Steel With Various Heat Treatments*, The 6-th International Conference on Hydraulic Machinery and Hydrodinamics, Timișoara, 2004, p. 259.

4. BINDER, W. O., SPENDELOW, H. R., Transaction American Society Metals, **43**, p. 759, 1951.
5. BRIGHAM R., J., a.o., Corrosion NACE, **29,** *33*, 1973.
6. CHASTELL D., a.o., Corrosion-Scientifique, **19**, p. 335, 1979.
7. ERDMAN-JESNITZER, F., LOUIS, H., ASTM STP **567**, p. 171, 1973.
8. FRANC J.P., a.o., *La Cavitation, mécanismes phisiques et aspects industriels*, Press Universitaires de Grenoble, 1995.
9. FRANC J.P., MICHAEL, J.M., *Fundamentals of Cavitations*, Fluid Mechanics and its Applications, **76**, Grenoble, 2004.
10. HAMMITT F.G., BHATT N.R., *Cavitation Damage Resistance of Hardened Steels*, Univ. Michigan, 1970, p.1–36.
11. FUJIAMA, S. and AKAMATSU, T., Bulletin of Japan Society of Mechanical Engineering, **21**, *152*, p. 223, 1978.
12. GARCIA R., *Comprehensive Cavitation Damage Data for Water and Various Liquid Metals Including Correlation with Material and Fluid Properties*, Technical Raport, **6**, University of Michigan, 1966.
13. HEATHCOOCK, a.o., Wear, **81**, p. 311, 1982.
14. HEATHCOCK a.o., *Proc. of the 5th int. Conf. on Erosion by Solid and Liquid Impact*, 1979, pp. 63–1
15. KARIMI, A., MARTIN J.L., International Metals Revue, **312**, *1*, p. 1, 1986.
16. MATSUMURA, M., ASTM STP 664, 1977, p. 434.
17. MUSTAPHA A., B., *Étude des mécanismes de fissuration par fatigue-corrosion de différent types d'aciers inoxydables*, Montréal, 1983.
18. OKADA, T., a.o., *Cavitation Erosion in Vibratory and Ventury Facilities*, Univ. of Michigan, Department of Mechanical Engineering, Rep.No.UMICH 014456-55J, 1980.
19. POYET P., a.o., *Mémoire Scientifique*, Revue Métalurgique, 1975, p.133.
20. PREECE, C.M. a.o., ASTM STP, **664**, p. 409, 1977.
21. SCOTTO v., a.o., Corrosion-Scientifique, **19**, p.237, 1979.
22. SIMONEAU, R., a.o., *Cavitation Erosion and Deformation Mechanisms of Ni and Co Austenitic Stainless Steels, Erosion by Liquid and Solid Impact* – Proceedings of ELSI, **VII**, Cambridge, 7–10.10.(1987), pp. 32.1–32.8.
23. SONGZHOU, K. E., HERMAN, H., Wear, **80**, p. 101, 1982.
24. STEFEC R., a.o., Corrosion–Scientifique, **18**, p.161, 1978.
25. STELLER J. K., *International Cavitation Erosion Test – Test Facilities and Experimental Results*, **2** – émés Journées Cavitation, Paris, March, (1992)
26. TRUŞCULESCU M., *Studiul metalelor*, Edit. Didactică şi Pedagogică, Bucureşti, 1977.
27. VAIDYA, S., Preece, C.M., Metall. Trans. A., **9A**, p. 299, 1978.