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METHODOLOGY OF CAVITATION EROSION ASSESSMENT OF LASER PROCESSED MATERIALS

ABSTRACT

In this paper some results of cavitation erosion studies of various constructional steels (15GA, 15HN, 45, 2H13) processed superficially by laser beam are presented. The erosion tests were carried out by using the rotation disk facility. Constant values of the erosion rate were found for each stage of the material damage. Proposition of the evaluation of the relative cavitation erosion resistance of laser processed materials in the incubation period of damage consisted in direct comparing of the constant rates of the erosion.

INTRODUCTION

Cavitation erosion of the materials occurs the most frequently in the fluid-flow machines operating in cavitation conditions. It is especially met in turbines, ship propellers, pumps or motor engines.

Gas-steam bubbles generated in the vortexes in the zone of increased fluid velocity – a decreased pressure – are imploded in the higher pressure zone. Resulting shock waves or microjets generated at the vicinity of solid surfaces struck the material and the pressure of interaction could achieve the value of tens of MPa [1].

In cases when the elimination of cavitation by appropriate design of the construction is not possible, a reduction of cavitation erosion rates may be achieved by application of the materials of higher erosion resistance.

Relative resistance of the materials to cavitation erosion is usually evaluate by comparisons of their erosion curves: $\Delta m = f(t)$ or $\Delta V = f(t)$, that means mass or volume loss as a function of time, as well as curves of the mass or volume loss rates: $\Delta m/dt = f(t)$ or $\Delta V/dt = f(t)$. The adduced curves are the basis for evaluation of the single-value parameters, defined in [2]: average duralibity of the material, time of the incubation, maximum rate of the erosion or mass or volume loss in defined time of the exposition.

However, the above parameters can not be used at the beginning of the erosion, for there are not observed any measurable loss of the material in this period of damage (up to the end of the incubation period, when the massive loss of the material is unmeasurable or confined to very small value defined a priori). On the other hand, the response of the material to cavitation loading in the incubation period is very important and decisive for further development of the erosion. During the incubation time the dislocation structure is formed and such processes occur as strain hardening, aging of the material or structural transformations linked to the appearance of the stress fields. Moreover, the net of microcracks is also formed at that time. Therefore, the methodology of evaluation of the materials erosion under the cavitation loading in the incubation period of damage should be defined.

Materials processing by laser beam is convenient method of forming a large variety of structures. The results of numerous works prove that laser remelting, transformation hardening, alloying or cladding lead to the substantial increase in the cavitation erosion resistance of solids (e.g. [3-7]).

In this paper some results of cavitation erosion studies of various constructional steels (15GA, 15HN, 45, 2H13) are presented. Materials were selected because of (1) their feasibility of laser treatment and (2) diversity of their mechanical properties resulted in expected different performance under the cavitation attack. In order to change of cavitation erosion resistance of the steel surface layers the laser technique was employed. The erosion tests were carried out by using the rotation disk facility. The way of evaluation of cavitation erosion resistance of laser processed materials in the incubation period of damage was proposed.

PERFORMANCE OF THE EXPERIMENTS

The tested samples were manufactured of 2H13 chromium steel (Polish Standards PN-71/H86020), 15HN steel for carburisation (PN-89/H84030), 15GA low alloy steel of elevated strength (PN-72/H84018) and carbon steel 45 (PN-75/H84019). Their chemical composition and thermal processing are presented in Table 1.

Table 1. *Chemical compositions [% wg] and thermal processing of the substrate samples*

	C	Mn	Cr	Ni	Si	S max	P max	Other max	Heat treatment
2H13	0.16–0.25	max 0.8	12–14	max 0.6	max 0.8	0.03	0.04		Softening (delivered state)
15HN	0.12-0.18	0.4–0.7	1.4–1.7	1.4–1.7	0.17–0.37	0.035	0.035		normalisation, 870°/16 min/air
15GA	max 0.18	0.7–1.3	_	_	0.3–0.55			0.1Mo 0.3Cu	normalisation, 870°/16 min/air
45	0.42– 0.5	0.5–0.8	_	_	0.17–0.37				normalisation, 850°/16 min/air

Prepared samples were superficially remelted using CO_2 laser beam radiation. The laser installed in Institute of Fluid-Flow Machinery in Gdańsk was used. The areas of the steels were covered by attached or separated parallel traces (Fig. 1). As a result of the heating, the surface layers were remelted up to 0.3 mm in depth. The laser beam parameters and the conditions of the processing are presented in Table 2.

The surface layers of some samples made of steel 45 were additionally alloyed with the niobium or iron-chromium and silicon carbide powders. More details on applied processing of the materials are included in the previous paper [8]. Because of the high roughness of the sample surfaces appeared due to laser treatment, the surfaces of the samples required to be polished.

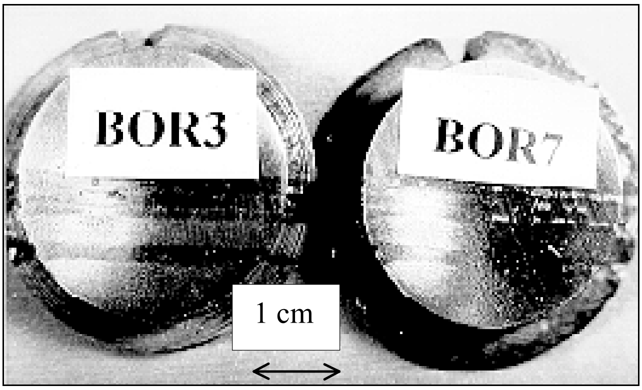


Fig. 1. View of the samples after 38 minutes exposition to cavitation attack

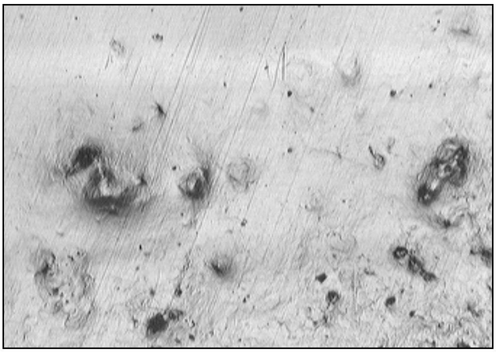
Table 2. *Laser beam parameters and the processing conditions*

Laser beam power [W]	1000
Laser beam mode	TEM 1.0
Diameter of the laser beam [mm]	8
Focussing element	ZnSe lens
Laser beam spot on the sample [mm]	1,6
Sample velocity [cm/s]	0,6
Shielding gas	Argon
Velocity of the gas [m/s]	47

Workpieces tested were subsequently subjected to cavitation loading at the rotating disk facility [9]. The cavitation was generated there by bolts situated on the disk surface along circumference of 300 mm in diameter. Cavitation bubbles collapsed in core of vortexes appeared behind the bolts. The specimens were inlaid in the disk, downstream of the bolts. Their rotation speed stand for 3000 r.p.m. Resulting mean gauge pressure was 1550 hPa. Total duration of the samples exposition to the cavitation attack was 38 minutes and the tests were performed in 2.5 or 5.5 minutes long runs. After each run the microscopic observations of the sample surfaces were done and the level of darkness caused by an increase of cavitation pits and indentations was registered.

Apart from blackening of the controlled area (1.73x2.2 mm), the number of indentations was measured. The definite level of blackening (z = level of darkness caused by an increase of cavitation pits and indentations) was automatically calculated by the programme MultiScan on basis of the registered histogram the investigated picture (Fig. 2).

$$z = \frac{\sum_{n=0}^{t} h(n)}{\sum_{n=0}^{255} h(n)} \; x\,100\%$$



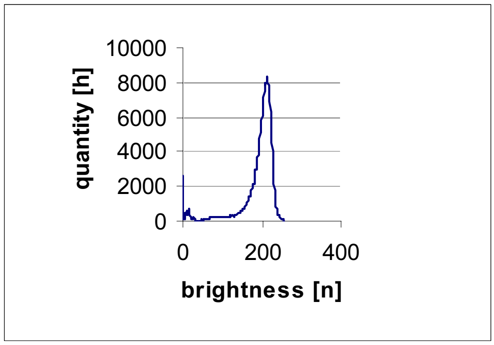
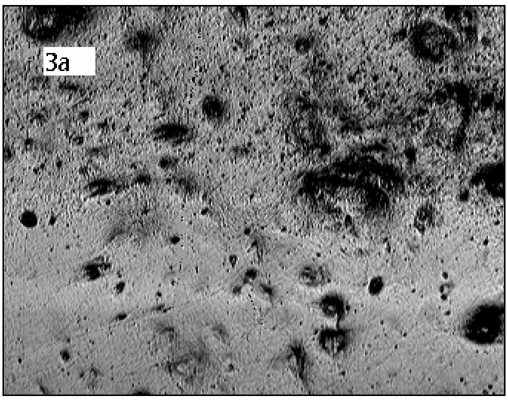


Fig. 2. Eroded surface and its histogram used to define level of blackening (z)

The binarisations of the pictures were done at downward thresholds (t) of 100, 70 or 40 from the range of 0 to 255. The examples of the monochromatic and binary (at the threshold of 40) pictures are presented in Fig. 3. After the cavitation tests had been accomplished, the microhardness assays were carried out.



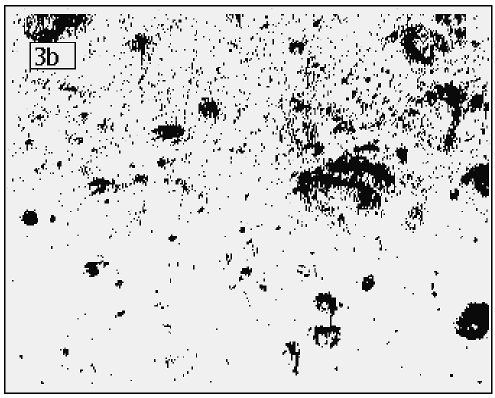
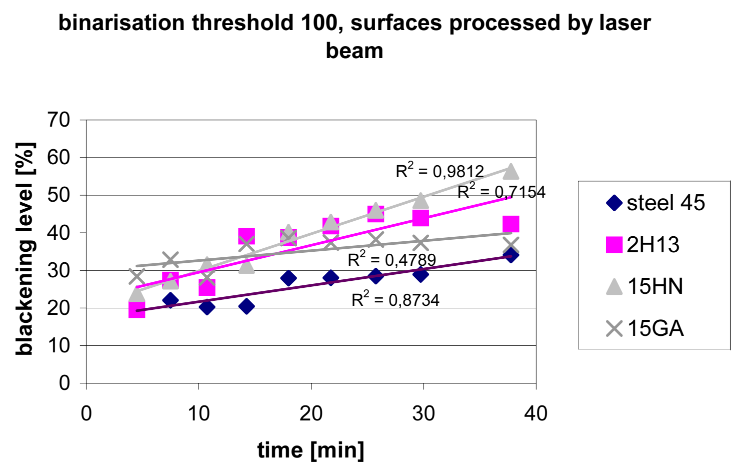


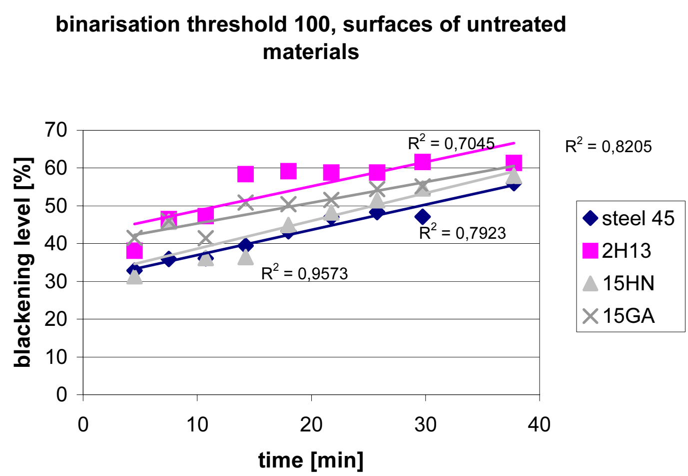
Fig. 3. Surface of steel 45 deformed by cavitation impingement after 14 min of cavitation attack. 1a – monochromatic picture, 1b – the same picture registered at the binarisation threshold 40. Upper part of the photo refers to the unremelted zone of the material and the lower part comprises the zone treated with laser beam

RESULTS AND DISCUSSION

Time variations of the blackening (depicted as z) caused by the surface deformations of the investigated steels are presented in Fig. 4, whereas the time variations of a number of pits with the areas exceeding 200 μm^2 are presented in Fig. 5. The less number of indentations detected after 38 minutes of cavitation than the number of indentations detected after 15 minutes of exposure ensued from their overlapping. The feature worth to be noticed is that experimental points shown in Fig. 4 could be for any single material approximated by the regression line with high correlation coefficient. At the beginning of the cavitation ($t = 0$) the blackening due to indentations presence equals zero ($z = 0$). Under such assumption the dependence of blackening on time (function $z = f(t)$) could be described by two straight lines: $z_1 = a_1 t$ until the time t_1 and $z_2 = a_2 t + b$ after the time t_1. In present investigations the time t_1 was defined as the time of the first measurement of surface blackening. Significantly greater values of the erosion rates at the initial stage is probably linked to the lack of the material strengthening. It is the time of multiplication of the dislocations due to cavitation impingements. The course of the curve $z = f(t)$ enables to find the time of entire covering of the surface by the pits ($t_{100\%} = (100-b)/a_2$). The actual time $t_{100\%}$ is longer due to increase of the probability of indentations overlapping. After that time the surface is deformed again, which usually leads to mass loss of the material. Unevenness of the surface causes the state of multi-axes stresses facilitating the extractions of the material pieces. However, the time $t_{100\%}$ cannot play role of the criterion of cavitation resistance of the material, despite its importance for the erosion assessment. The effects of the material deformations after the time $t_{100\%}$ in case of ductile or brittle materials are expected to be different.

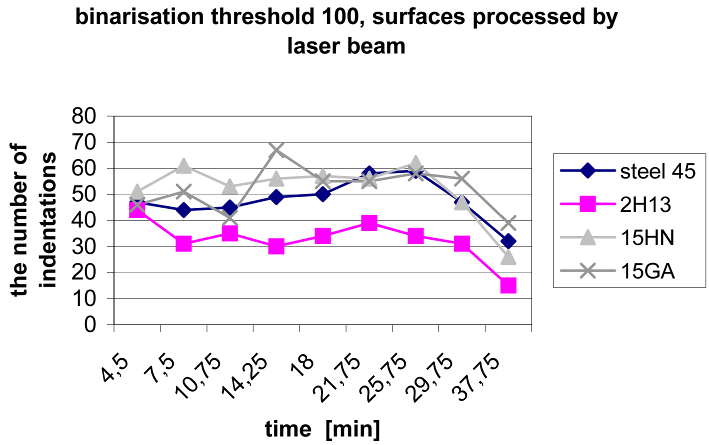


4a

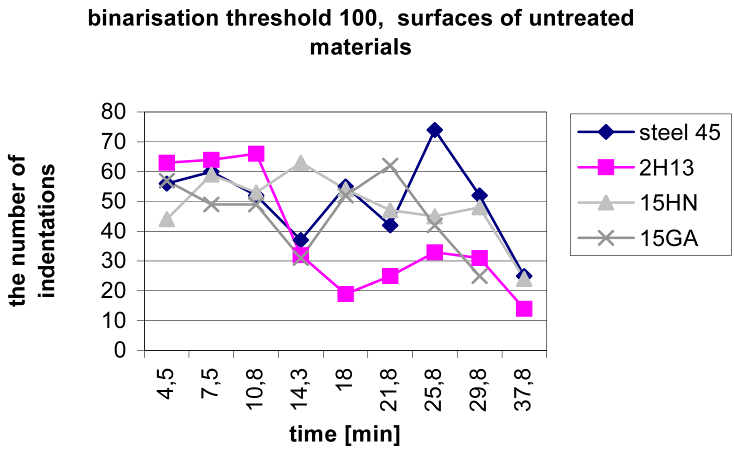


4b

Fig. 4. Variations of the blackening level of the samples with respect to the time of the exposition to cavitation loading: Fig. 4a comprises the results refering to the surfaces processed by laser beam and Fig. 4b comprises the results refering to the surfaces of untreated materials



5a



5b

Fig. 5. The number of indentations of the areas greater than 200 μm^2 detected on the surfaces hardened by laser beam (fig. 5a) and not processed (fig. 5b)

Relaxation of the stresses in ductile solids goes through deformations and subsequent microcracks appearance, whereas in brittle solids relaxation goes mainly through cracking (Fig. 6).

The dependence of the erosion rates a_1 a_2 on the hardness of the material is presented in Fig. 7a. It could be inferred that there exists the correlation between the rate a_1 and the hardness according the approximation function: $a_1 = 85.4(HV)^{-0.443}$. There was not found any correlation between a_2 and the hardness of the material surface.

Various curves of the function z = f(t) for specified single material at various intensities of the cavitation (depicted as I) are plotted in Fig. 7b. It is seen that rates of the material blackening were decreased at less intensity of the cavitation. The relationship between z and I enables the direct determination of cavitation intensity when the value of a_2 is known.

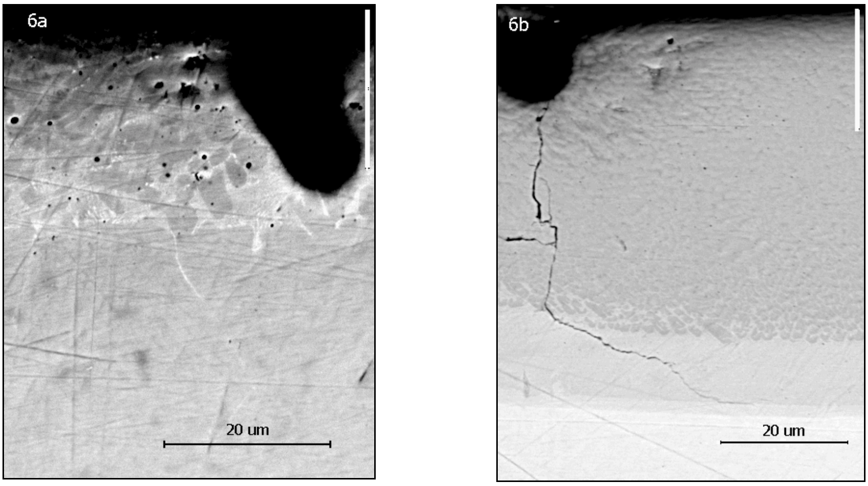
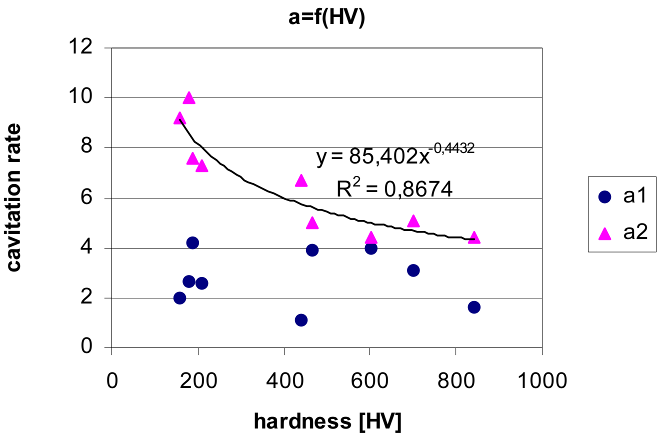
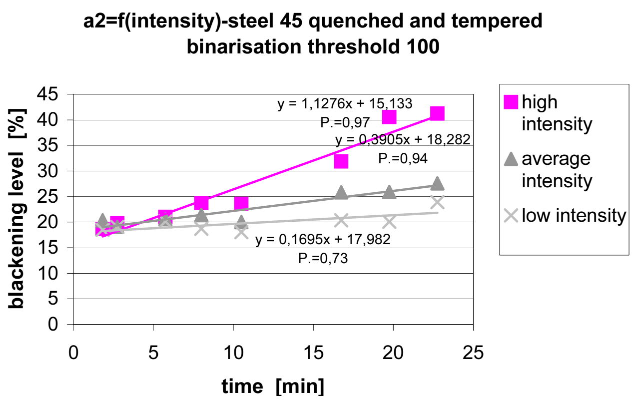


Fig. 6. Cavitation pits on the steel 45 surface alloyed with niobium (fig. 6a) and with FeCr+SiC powders (fig. 6b)



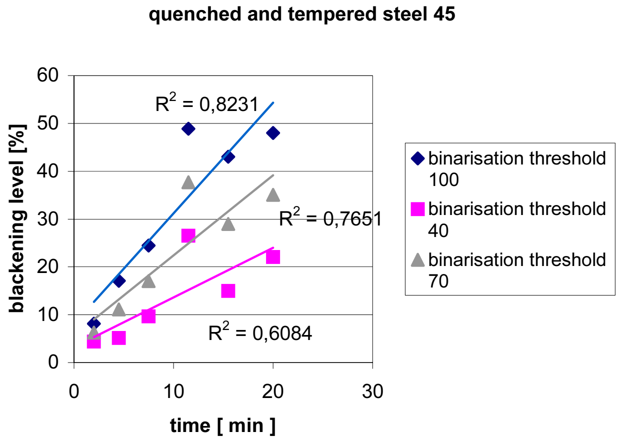
7a



7b

Fig. 7. Dependence of cavitation rate on the material hardness (fig. 7a) and function z(t) for various cavitation intensities (fig. 7b)

The graphs of the function z = f(t) for various thresholds of binarisation are presented in Fig. 8a. It is worth to be underlined, that inclination (a_2) of the lines plotted increases for higher threshold of binarisation. Simultaneously, the correlation coefficient increases.



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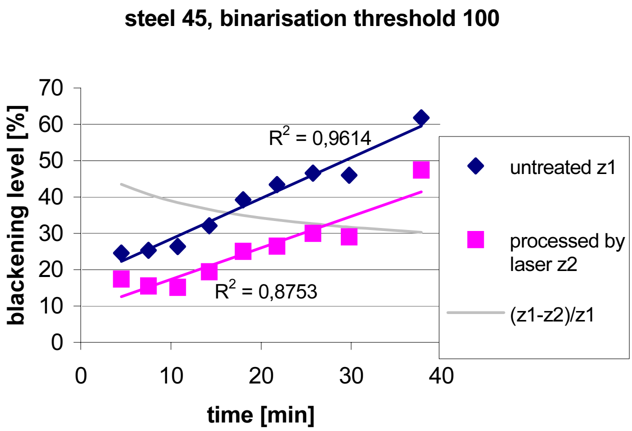

8b

Fig. 8. Values of z(t) function for various binarisation threshold (fig. 8a) and the relative assessment of the cavitation resistance (η(t)) of the remelted and unremelted zones of steel 45 (fig. 8b)

The values of the function z = f(t) measured for various materials could be used for making the comparisons of their cavitation erosion resistance. The relative resistance of the processed part of the material to its unremelted part could be defined by the following index: $\eta = (z_1\text{-}z_2)/z_1$, where z_1 stands for the blackening of the material 1 and z_2 refers to the blackening of the material 2. Obviously, values of η vary with time: $\eta(t) = [z_1(t) – z_2(t)]/z_1(t)$. Until the time t_1 the quantity η is constant. Since t_1 the function η(t) is homographic: $\eta(t) = [(a_2\text{-}a_2')t + (b\text{-}b')]/(a_2t + b)$, which can monotonically increase for the positive difference $(a_2\text{-}a_2')b\text{-}(b\text{-}b')a_2$, or decrease for negative value of the above difference. The comparison of the time variations of the quantity η(t) for remelted and for unprocessed zones of tested samples is accomplished in Fig. 8b. It is seen that at the beginning of the cavitation, the resistance of the processed material is over 40% higher than resistance of non-transformed structure. There could be observed that rates of deformations development in both materials tend to equalisation (after 38 minutes of cavitation the resistance of the processed structure exceeds the resistance of non-processed one of about 30%.

CONCLUSIONS

1. There exists the line correlation between the surface deformations of steels processed by laser beam and subjected to cavitation impingements and the time of cavitation loading. This correlation is better for higher intensity of the cavitation.
2. Too low threshold of the binarisation lead to omission (in registration process) of the shallow indentations and consequently to worsen of the correlation coefficient.
3. Observations of the variations of blackening of the laser remelted samples due to cavitation action let to distinguish two terms in the process of the erosion in the incubation period. Specific, constant values of the erosion rate could be ascribed to each of them. The rate refering to the beginning of the erosion is dependent on the hardness of the material.
4. It is possible to derive the relative cavitation resistance of the materials by direct comparing of the constant values of the function z = f(t) (at the beginning of the erosion) or constant rates of the erosion (in later stage of the erosion).

REFERENCES

1. J. Steller: *International Cavitation Erosion Test and quantitative assessment of material resistance to cavitation*. Wear, Vol. 233-235 (1999), pp. 51-64.
2. Z. Reymann, K. Steller: *Ocena odporności materiałów na działanie kawitacji przepływowej.* Prace IMP PAN w Gdańsku , 1978, zeszyt 76.
3. C. M. Preece, C. W. Draper: *The effect of laser quenching the surfaces of steels on their cavitation erosion resistance.* Wear Vol. 67, no. 3, 1981, p. 321-328.
4. W. J. Tomlinson, R. T. Moule, J. H. Megaw, A. S. Bransden: *Cavitation wear of untreated and laser-processed hardfaced coatings.* Wear Vol. 117, 1987, p. 103.
5. S. P. Gadag, M. N. Srinivasan: *Cavitation erosion of laser melted ductile iron.* Journal of Material Processing Technology Vol. 51, no 1-4, 1995, p. 150-163.
6. B. G. Gireń: *Cavitation erosion of steels processed with a laser beam and optical discharge plasma.* Surface Engineering Vol. 14 (1998), p. 325.
7. B. G. Gireń, M. Szkodo: *On the increase of cavitation resistance of A1 structure alloys processed by laser beam.* Journal of Technical Physics Vol. XL, 1999, p. 277.
8. B.G.Gireń: *Steel surface processing by continuous optical discharge plasma.* Plasma Chemistry & Plasma Processing, Vol. 13 (1993), p. 133.
9. K. Steller, T. Krzysztofowicz, Z. Reymann: *Effects of Cavitation on Materials in Field and Laboratory Conditions.* American Society for Testing and Materials, Special Tech. Pub. Vol. 567, 1975, p. 152.