Laser beam treatment effect on AMPCO M4 bronze cavitation erosion resistance

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Abstract. Ship propellers must resist simultaneously to ocean water corrosion and cavitation erosion. Until now, the best material used is the bronze with great copper content. These materials are expensive and there is the tendency to reduce the copper content while maintaining good properties. Such a material is AMPCO M4 used for manufacturing details for aircraft retractive landing assemblies. As a consequence we undertake cavitation erosion tests upon this bronze. In natural state (cast or even extruded) the cavitation resistance is not acceptable so, we improved the specimens by treating them with laser beams at three different impulse powers (160, 180 and 220 W). The cavitation erosion resistance was tested in the Cavitation Laboratory of Timisoara “Politehnica” University using a vibratory device respecting the conditions imposed by ASTM G32-2010 Standard. The comparisons with the genuine material (without any treatments) show that the applied procedure increased the hardness of the melted layer as well as the cavitation erosion behavior.

1. Introduction
Finding cheep materials with excellent cavitation erosion is till now an unsolved problem neither for hydraulic machineries nor for ship propellers. Researches upon new materials and new manufacturing procedures are undertaken in present, to find good and economic solution.

Statistic data show that for ship propellers the best materials are bronzes with high copper content [1], [2]. Even for such materials there occurs cavitation erosion on the propeller blades, especially for high velocity ships. In the present paper it is analyzed the increase of cavitation resistance by melting the superficial blade layer using laser beams with controlled parameters.

For laboratory test there have been chosen samples from extruded AMPCO M4 alloys. This material with good mechanical and corrosion properties is recommended for heavy-duty, high-loaded mechanical and corrosive applications involving abrasive wear, friction and chemical corrosion [3].

The cavitation researches were undertaken in the Cavitation Laboratory of the Timisoara “Politehnica” University using a vibratory device respecting the recommendations of the ASTM G32-2010 Standard [4].

The results are encouraging because the cavitation erosion resistance was improved.
2. Researched Material and Applied Treatments

The researched material is a bronze with approximate 75% Cu, 5% Ni, and 10% Al was initially developed to manufacture pieces for aircraft retractable landing assemblies [3]. Taking into account the cost and the corrosion properties of this material we proposed it for repair works or even manufacturing ship propellers.

The detailed chemical composition of this bronze is: 10.5 % Al, 5% Ni, 4.8 % Fe, 1.5 % Mn, others max. 0.5, the rest is copper. The mechanical properties with significance for the cavitation erosion resistance are: Tensile strength $R_m$ = 1000 MPa, Yield strength $R_{p0.5}$ = 793 MPa, Brinell hardness = 286 HB30, Fatigue (100x$10^6$ cycles) =352 MPa, density $\rho$ = 7.45 g/cm$^3$ [3].

The specimen surface exposed to cavitation was treated with laser beams with the following parameters:
- pulse duration: 5 ms;
- repetition frequency of pulses: 10 Hz;
- working velocity: 4.07 mm/s;
- impulse power: 160 W, 180 W, 220 W.

Figure 1 presents the aspect of the surfaces after laser treatments. It can be observed that regardless of power value the surfaces have identical aspects, with typical undulations, uniformly distributed.

![Figure 1. Surface aspects (before cavitation attack – minute 0)](image)

The melting with laser beams determined a great increase of the micro hardness HV0.5 of the surface (see tables 1, 2, 3).

| Measured zone            | Depth of the measured point µm | HV0.5 | Mean value of HV0.5 |
|-------------------------|---------------------------------|-------|---------------------|
| Treated with laser beam |                                 |       |                     |
|                         | 53                              | 330   |                     |
|                         | 53                              | 330   |                     |
|                         | 54                              | 318   |                     |
|                         | 54                              | 318   |                     |
|                         | 54                              | 318   |                     |
|                         | 54,5                            | 312   |                     |
|                         | 57,5                            | 280   |                     |
|                         | 58                              | 276   |                     |
|                         | 58                              | 276   |                     |
|                         | 59                              | 266   |                     |
|                         | 59                              | 266   |                     |
|                         | 61                              | 249   |                     |
| Basic material          |                                 |       |                     |

Table 1. Micro hardness HV0.5 - Impulse power 160 W
The procedure for measuring micro hardness was: after 165 minutes of cavitation exposure when all the investigations upon the eroded surface were finished, the specimens were cut in two equal parts along a longitudinal axe. At the beginning, the hardness was measured in the basic layer. For all depth chosen in the basic part, it was taken a beginning line outside of both the melted zone and the thermal influenced one. The obtained data (tables 1, 2, 3) show important micro hardness increases of the layers treated with laser beams, in comparison with untreated layers (16 % for 160 W, 29.5 % for 180 W and 33.3 % for 220 W of power impulse).

The micro hardness remains approximate unchanged for the same depth (either of the untreated material or for the treated one). As the depth of the measured point increases, the micro hardness decreases (untreated: from 290 HV0.5/56,5 μm to 271 HV0.5/58,5 μm, treated: at 220 W, from 420 HV0.5/47 μm to 301 HV0.5/55.5 μm).
3. Experimental results

Respecting ASTM G32 Standard, three specimens were tested for each material. The regression curve was obtained for the arithmetic mean. To put into evidence both the material homogeneity and the constancy of the produced cavitation there were computed the tolerances intervals for 99% probability see Figures 2-4, and was determined the Standard Error of Estimation $s_{yx}$ see table 4.

![Figure 2. Measured points, regression curves and tolerance interval – Laser beam impulse power 160 W](image)

![Figure 3. Measured points, regression curves and tolerance interval - Laser beam impulse power 180 W](image)
Even for this great probability we obtained a narrow interval of tolerance attesting both good homogeneity of the tested material after the laser beam treatment and reliable results of the test [5], [6], [7], [8], [9].

Table 4. Values of important parameter values <μm>

| Laser beam power       | 160 W | 180 W | 220 W |
|------------------------|-------|-------|-------|
| Measured final mean depth erosion (165 minutes) | 6,511 | 6,346 | 4,984 |
| Final mean depth erosion from the tolerance interval (maximum value) | 7,843 | 7,477 | 5,875 |
| Final mean depth erosion from the tolerance interval (minimum value) | 5,179 | 5,215 | 4,093 |
| Standard error of estimation (s_{y/x}) for 99% probability | 0,444 | 0,377 | 0,297 |

With the increase of the impulse power, the experimental measured point’s scatter decreases, see Figures 2-4. For 160 W impulse powers, in the first period appear the greatest deviation from the regression curve (till approximate 0.444 μm). With the increase of the power impulse the scatter became smaller (remaining under 0.297 μm for 220 W). Because the parameters of cavitation remain constant, the causes of differences must be explained by the material behavior. The surface subjected to cavitation has in all situations an undulated shape. When, on the crests of these undulations there
are weak points they are easy removed and the mass loss is great. It result the conclusion that great power impulse reduce those weak points, probably by melting and hardening the exposed area. When these initially weak points are removed, the material shows its real behavior towards the resistance to cavitation erosion and the scatter around the regression curves is reduced.

Figures 5-7 present the obtained experimental data for the cumulative mean depth of erosion and the evolution of mean depth erosion rate. In the figures “a” are presented photographs showing the aspect of the attacked surface at three different exposure times. It is to be remarked that, from the beginning, almost the entire surface is subjected to erosions (corresponding to the requirements of ASTM G32-2010).

The experimental data are approximated with a regression curves taking into account only the arithmetical mean [10], [12], [13].

![Figure 5](image1.png)  
**Figure 5.** Cavitation erosion characteristic curves (160 W):  
a) Mean depth erosion against time  
b) Mean depth erosion rate against time

![Figure 6](image2.png)  
**Figure 6.** Cavitation erosion characteristic curves (180 W):  
a) Mean depth erosion against time  
b) Mean depth erosion rate against time
Figure 7. Cavitation erosion characteristic curves (220 W):
   a) Mean depth erosion against time
   b) Mean depth erosion rate against time

For the specimens treated with 160 W laser beam, the approximation of the measured data on the curve MDE(t) is very good in the intervals of 90-165 minutes; for the MDER(t) the same approximation is very good in the interval 120-165 minutes. The stabilization value for MDER(t) is 0.043 μm/min.

For 180 W impulse power, the MDE(t) curve approximate very good the experimental data in the interval of 75-165 minutes and the MDER(t) curve in the interval 15-165 minutes; the stable velocity value is 0.042 μm/min.

For an impulse power of 220 W the whole regression curve MDE(t) approximate very good the experimental data and the stable value of the velocity is 0.031 μm/min.

In the range of 60-75 minutes, all specimens treated with laser beams show a maximum value in the velocity curves. This maximum differ with the impulse power (160 W / 0.045 μm/min; 180 W/0.044 μm/min; 220 W/ 0.035 μm/min).

The small differences between the maximum values of the parameter MDER(t) and the stabilization value show that the tested materials have good cavitation erosion behavior [5], [10], [11] and testify about the increase of cavitation erosion resistance through laser beam treatments.

In Figure 8 there are given comparisons of the laser treated bronzes both with untreated bronzes and with a material (CuNiAl III RNR) which in the past was characterized with very good or excellent resistance both in laboratory and in field running. The final conclusion is that the laser beam treatment is beneficial for the cavitation erosion resistance [5], [11]. The best results were obtained for laser beam treatments with 220 W impulse powers.

Figure 8. Comparisons of Cavitation erosion characteristic curves
   a) Mean depth erosion against time
   b) Mean depth erosion rate against time
The increase of cavitation erosion resistance for an impulse power of 220 W is 38.7% in comparison with those for 160 W impulse powers and is 35.48 % greater than for 180 W. This amelioration can be explained by the hardness increase of the exposed surface (220 W gives an increase with 17%, in comparison with 160 W and 5.6 % in comparison with 180 W.

Comparing the tested bronzes, in natural states (curve 1) and after laser beam treatment (curves 3, 4, 5) with the high resistance bronze CuNiAl – III RNR (curve 2) it can be seen that the applied treatment increase the cavitation erosion behavior, regardless of the impulse power beam. Using small power values (160 W and 180 W) we have obtained only small increases (1.07 and 1.1 times). For a power impulse of 220 W the obtained resistance was 1.48 times greater than that of the non treated sample. The final conclusion of figure 8 is the possibility to increase the cavitation erosion resistance by laser beam treatments. Upon our opinion, the existent technology for laser beam treatment allows improving only small surfaces of the blades; it means that the procedure is easy to be applied for the repair works of previously eroded areas.

4. Eroded microstructure investigation
The micrographic images presented in Figures 9 and 10 confirm the favorable results obtained by the cavitation tests and show the formation of a fine martensitic structure which gives a significant increase of the cavitation erosion resistance. On the interface “treated layer/basic layer” do not appear porosities, micro cracks or other defecions and the thermal influenced zone has a small extension.

![Micro photographs of melted layer and ground layer, digital microscopy HIROX 1300](https://via.placeholder.com/150)

**Figure 9.** Micro photographs of melted layer and ground layer, digital microscopy HIROX 1300
5. Conclusions

1. The reduced extension of the tolerance interval for a probability of 0.99, for all three specimens tested and for all treatments, confirms the great homogeneity of the tested material and the uniformity of the produced cavitation phenomena.

2. The surface subjected to cavitation has in all situations an undulated shape. When on the crests of these undulations there exist weak points those are easy removed and the mass loss is great. It result the conclusion that great power impulse reduce such weak points, probably by better melting and hardening the exposed area. When these initially weak points are removed the material shows its real behavior towards the resistance to cavitation erosion and the scatter around the regression curves is reduced.

3. The laser beam treatment increases the hardness and by this way the cavitation resistance is highly improved. The micro hardness values increases with the impulse power of the beam when the other parameters (pulse duration, repetition frequency, and manufacturing speed) remain constants.

4. The shape and the position of the regression curves for laser beam treated bronzes recommend the procedure for increasing the cavitation erosion resistance.

5. The researches must be continued in order to obtain the best value for the power impulse of the laser beam.

6. Using the procedure of laser beam treatment of the bronzes M4 determines a great increase to cavitation erosion resistance in comparison with natural state of the material. The resistance

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**Figure 10.** Scanned structure after final exposure time (165 minutes)
Laser MICRO VU- Excel 664-UM

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| Property | Actual |
|----------|--------|
| Distance |        |
| X        | 0.0007 |
| Y        | 0.0046 |
| Z        | 0.0000 |
| XY       | 0.0046 |
| XYZ      | 0.0046 |

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| Property | Actual |
|----------|--------|
| Distance |        |
| X        | 0.0149 |
| Y        | 0.0048 |
| Z        | 0.0001 |
| XY       | 0.0688 |
| XYZ      | 0.0688 |

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| Property | Actual |
|----------|--------|
| Distance |        |
| X        | 0.0026 |
| Y        | 0.2566 |
| Z        | 0.0061 |
| XY       | 0.2566 |
| XYZ      | 0.2566 |
became greater than that of the excellent CuNiAl III RNR bronze; in consequence the method is recommended for repair works of ship propellers.

7. The metallographic investigations confirm the formation of a fine martensitic structure determining a substantial increase of the cavitation erosion resistance.

8. The interface between treated layer/basic layers is free of porosities or micro cracks and the depth of thermal influenced zone is relatively small.

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