INFLUENCE OF AGEING TIME ON CAVITATION RESISTANCE OF 6082 ALUMINUM ALLOY

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The use of aluminum-based alloys in components of thermal machines, hydraulic machines, which work in cavitation currents, required the finding of solutions to reduce the erosive effect of the surface eroded by micro-jets and shock waves produced during cavitation. In this direction is also included the research of the resistance to vibration cavitation erosion of alloy 6082 subjected to heat treatment of ageing at 180℃, with three durations of the heat regime (one hour, 12 hours and 24 hours), generated by the standard vibrating device, with piezoceramic crystals, from the Cavitation Erosion Research Laboratory, of the Polytechnic University of Timișoara. The results of the research, compared to the gauge sample, taken from the rolling state, analyzed based on the curves and parameters recommended by the ASTM G32-2016 standards, show that the best resistance is obtained for the 24-hour regime of maintaining at 180℃. Macro and microscopic photographic images show differences between the erosions produced on the surfaces, as a result of changes in structure and mechanical properties, created by the maintaining times at the ageing temperature and which are consistent with the values of the reference parameters that characterize the erosion resistance by cavitation.

Keywords: aluminum alloys 6082, cavitation, ageing, micro and macrostructure

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1. Introduction

Aluminum is a material with some of the widest technical applications; it has enjoyed a widespread due to its low specific weight, excellent thermal and electrical conductivity and high corrosion resistance. Although the mechanical properties are modest, by alloying with different chemical elements they have been improved, resulting in a very wide range of alloys with different properties.

In this paper, we will analyze the behavior of cavitation erosion of one of these alloys, namely 6082 rolled aluminum alloy, a material with good corrosion resistance, good weldability, and which due to its good mechanical properties is suitable for most machining processes. This alloy has a good hardness, higher than 6060 or 6063 alloys in the same category. Due to these properties, especially corrosion resistance and very good machinability, this alloy is used in a very wide range of applications, especially those working in liquid environments, where there are complex applications consisting of mechanical stresses, chemical and electrochemical erosion, cavitation erosion.

Among these applications we mention: components of hydraulic systems and related equipment [1-5], such as: hydraulic pump housings, directional and presure valve body, hydraulic blocks, flanges, equipment drilling, subjected to high loads; component of thermal engines, boilers, radiators, pipes, hydraulic turbines [6]; boat construction, masts, starboards, various components of boat construction; various structures made up of motor vehicles, aeronautics, bicycle frames, metal scaffolding, tent frames, etc. In these applications, the material is subjected to a combination of mechanical stresses, chemical and electrochemical erosion, thermal shocks, cavitational erosion, etc.

A destructive effect often encountered in equipment working in the hydrodynamic field is the cavitation phenomenon.

Research on samples made of such material has shown that by applying thermal, thermochemical or mechanical treatments to them, some mechanical properties can be improved without significantly affecting other characteristics, such as the structural constitution [6].

2. Experimental Procedure

Researched material

The research was performed on sample sets, processed from the EN-AW 6082 ISO: AlSi1MgMn rolled alloy. In the delivery state, according to the T651 symbol in the quality certificates provided by the manufacturer, the material has been subjected to T6 hardening treatments, for putting in solution and ageing and relaxation operations during controlled stretching [2].

Table 1

Characteristics of the material in the delivery state

Mechanical characteristic: rectangular bars - EN 755-2:2013						
Alloy	Material condition	Dimension	Ultimate Strength Rm	Yield Strength $Rp_{0.2}$	Elongation at Break	Brinell Hardness
		(mm)	(N/mm^2)	(N/mm^2)	(%)	(HB)
EN AW-6082	rolled	30x30	226.05	161.71	10	67

Table 2

Chemical composition of the material in the delivery state

Chemical composition, wt%.								
Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
EN AW- 6082	0.7-1.3	≤ 0.5	≤ 0.10	0.4-1	0.6-1.2	≤ 0.255	≤ 0.20	≤ 0.10	Rest

The samples were taken from rectangular bars of 30x30 mm, from which were made 12 cylindrical samples, with a diameter of 15.8 mm and high 10 mm three samples for each treatments state, according to the requirements of ASTM G32-2010.

Ageing treatments

In the research carried out in this paper, were used the samples from the material in the delivery state, as well as samples subjected to heat treatments of ageing. The heat treatments of ageing were applied differently to three sets of three samples each and consisted of heating the samples to a temperature of 180 °C with maintenance for 1, 12 and 24 hours and cooling in air, according to the diagram in Fig. 1.

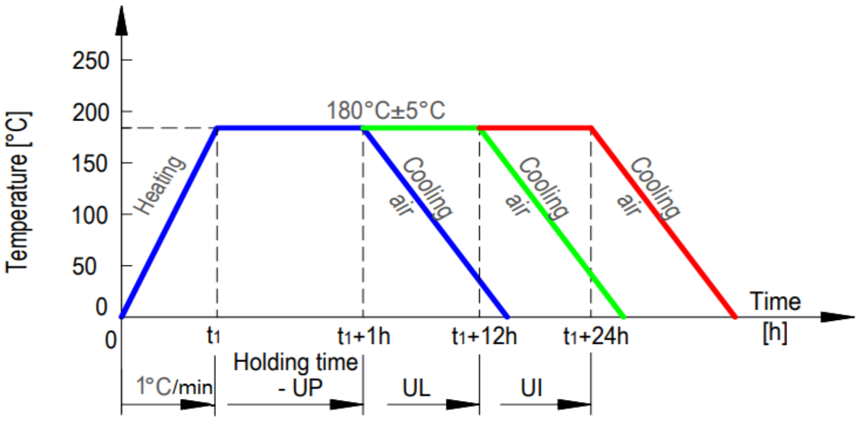


Fig. 1. Heat treatment cyclogram

To identify the samples, they were stamped with the following symbols:

U – material in delivery state;
UP – age hardening at 180°C with holding time 1h;
UL – age hardening at 180°C with holding time 12h;
UI – age hardening at 180°C with holding time 24h;

Cavitation erosion tests

The cavitation tests were performed in the Cavitation Erosion Research Laboratory within the Polytechnic University of Timişoara [7-9], on the vibrating device with piezoceramic crystals, in compliance with the requirements of international standards ASTM G32-2010 [10].

In the experiments, both the material in the delivery state and the treated samples were tested according to the procedures described above.

3. Experimental results

Analysis based on structural analysis, mass loss and mechanical properties

For each state of treatment, the mass losses and the mechanical characteristics were determined, their values being presented in Table 3.

Table 3

Macroscopic images, mass loss and mechanical characteristics

Treatment	**U**		**UP**		**UL**		**UI**	
Macro images of surfaces eroded by cavitation for 165 minutes								
Properties	Material in delivery state		180°C 1 h		180°C 12 h		180°C 24 h	
Mass loss [mg]	34.95	±1.19915	25.84	±1.92787	29.04	±0.8697	17.23	±0.7858
Mass loss [%]	2.7	±1.29539	3.7	±1.13429	3.03	±0.8696	1.8	±0.7305
HB [daN/mm^2]	67	±0.9508	67	±0.7858	67	±1.13429	81.3	±0.50992
KCU [J/cm^2]	25.9	±1.01068	24.2	±0.7305	16.3	±0.82781	8	±0.8697
Rp_{02} [MPa]	155.21	±1.03349	161.71	±0.69215	181.87	±1.86119	331.97	±0.8696
Rm [MPa]	226.05	±0.8696	249.81	±0.73799	328.98	±1.16986	406.52	±0.66545

Macroscopic images of eroded surfaces after 165 minutes of cavitational attack show different behaviors and degrees of degradation, as illustrated in Figs. 2-5. Thus, one can be observed a good correlation between the surface appearance, mass loss and mechanical properties of the material (especially HB hardness and mechanical strength R_m and $R_{p0.2}$) for all the four treatment states. Macroscopic appearance of the eroded surfaces in frontal section is quite similar in all states, with the difference of the proportions of the most eroded surfaces. So, in delivery state (Fig. 2) the proportion of the most eroded surfaces is about 74 %, in ageing at 180°C/1h (Fig. 3) proportion is about 71%, in ageing at 180°C/12h (Fig. 4) proportion is about 69% and in ageing at 180°C/24h proportion is about 66% (Fig. 5).

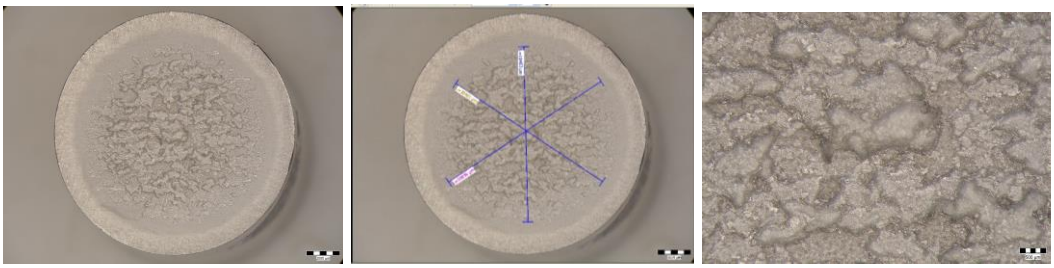


Fig. 2- Macroscopic aspects of cavitational surfaces for sample in delivery state (U)

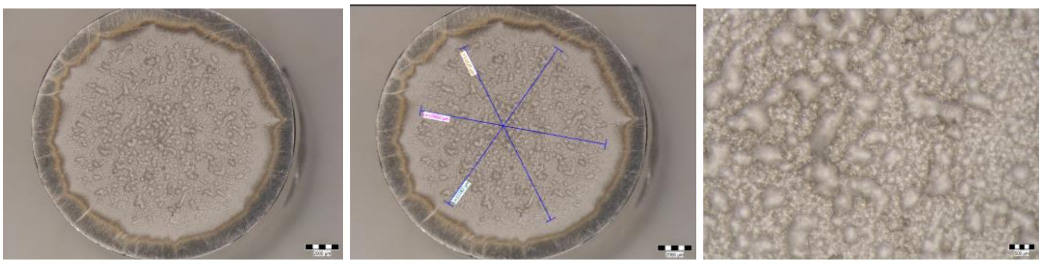


Fig. 3- Macroscopic aspects of cavitational surfaces for sample after ageing at 180°C/1h (UP)

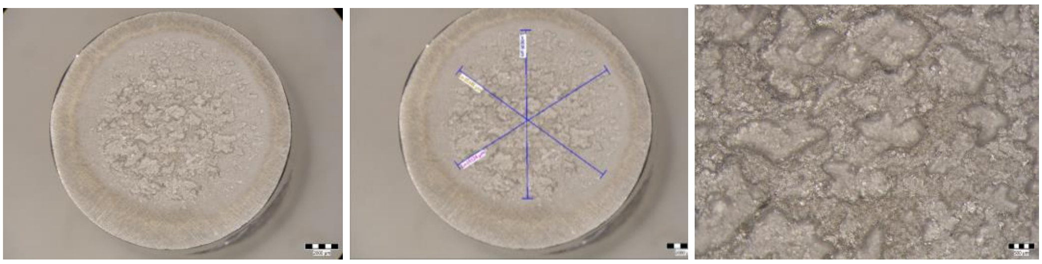


Fig. 4- Macroscopic aspects of cavitational surfaces for sample after ageing at 180°C/12h (UL)

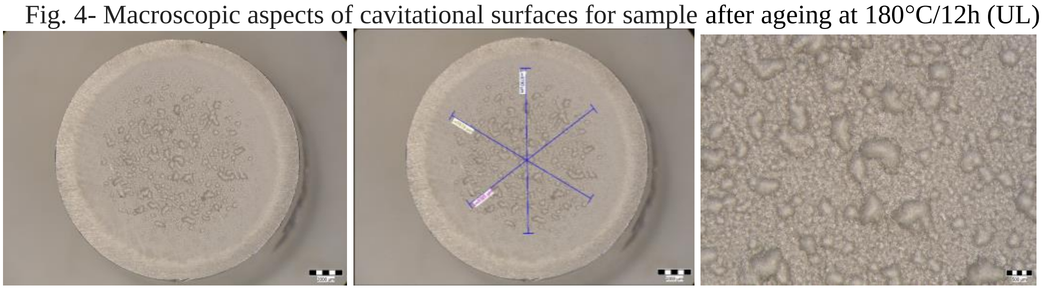


Fig. 5- Macroscopic aspects of cavitational surfaces for sample after ageing at 180°C/24h (UI)

The microscopic investigations performed on the transversal cross sectioned samples, presented in Figs. 6-9, revealed the degradation of the material in different treatment conditions. In each image there are given the results either after stereomicroscopic analysis (as in given in base image), or after quantitative metallographic analysis (as is given in top right image). These images put in evidence the reproducibility of the results given by different structural analysis, both stereomicroscopy and the metallography.

The material in the delivery state (Fig. 6) shows eroded areas accentuated both in surface and in depth, with the maximum depth about 490µm, characterized by extensive caverns formed, as a result of the massive expulsion of material following the propagation of cracks between small caverns and pitting. These cracks propagate mainly in the particles of intermetallic compounds found in the material in the delivery state, particles with a high degree of fragility [2], [11].

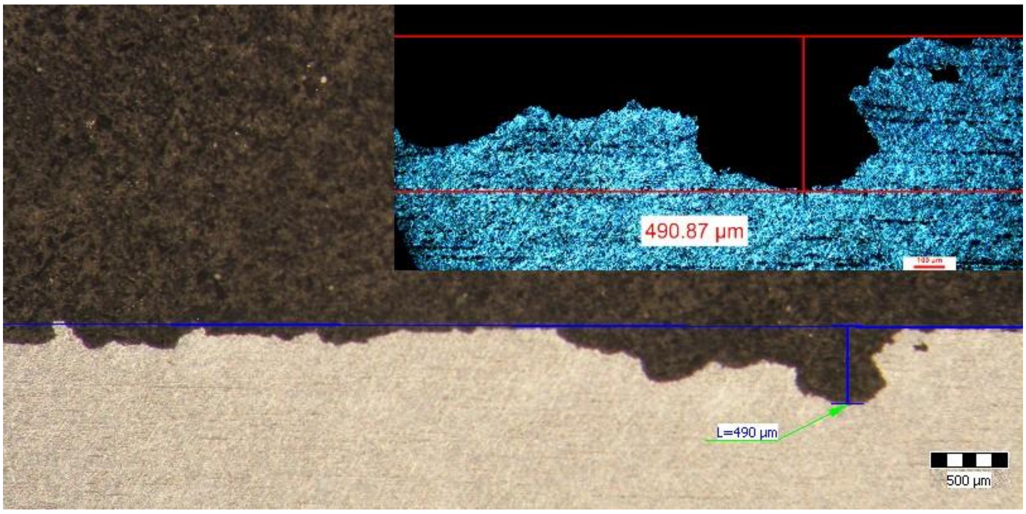


Fig. 6. Microstructural aspect of eroded surfaces of samples in delivery state (U)revealed by stereomicroscopic analysis (base image) and metallographic analysis (right top image)

The UP samples subjected to the ageing treatment at 180°C with maintenance for 1 hour (Fig. 7) show a preponderant degradation on depth, characterized by a significant number of deep and isolated caverns, with the maximum depth about 341µm, smaller in comparison with delivery state sample.

The UL samples subjected to ageing treatment at 180°C with maintenance for 12 hours (Fig. 8) show a predominant degradation on the surface, characterized by extensive caverns but of shallower depths. The maximum depth of the cavern is about 335µm, smaller than pervious state.

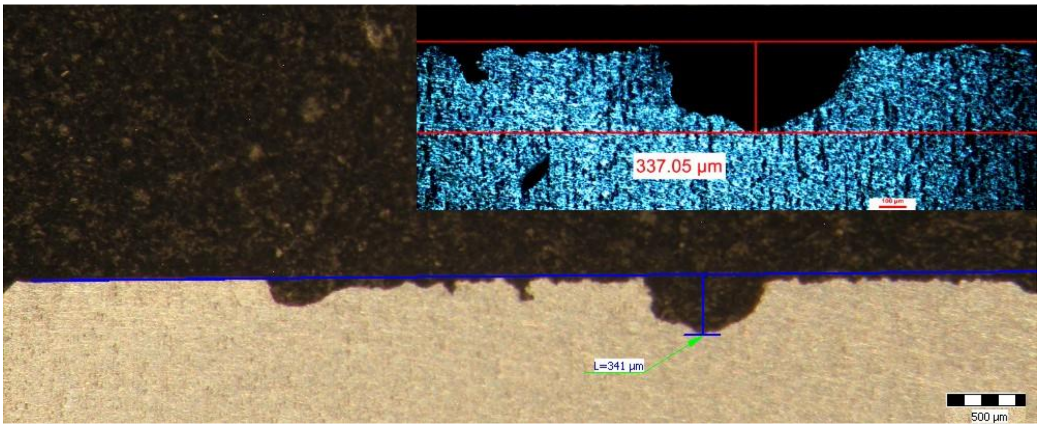


Fig. 7. Appearance of eroded surfaces samples after ageing at 180°C/1h (UP) revealed by stereomicroscopic analysis (base image) and metallographic analysis (right top image)

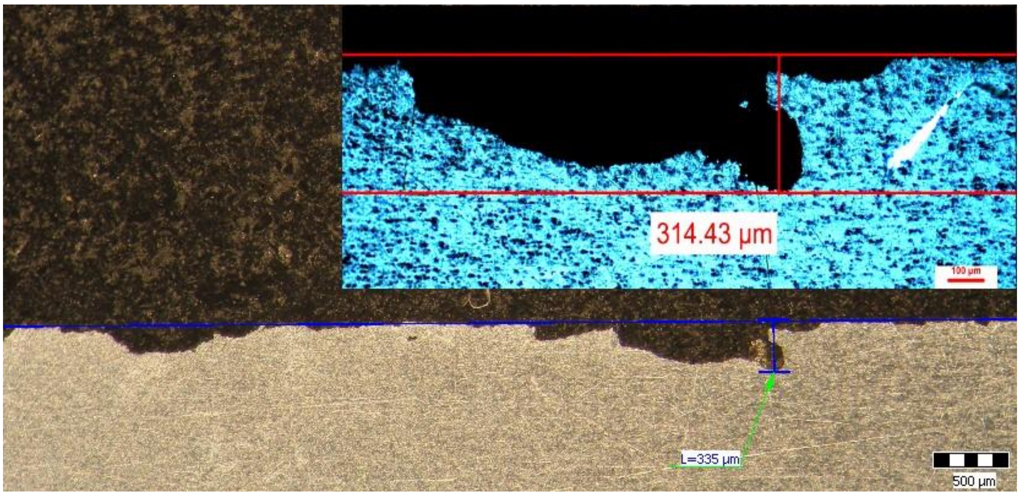


Fig. 8. Appearance of eroded surfaces samples after ageing at 180°C/12h (UL) revealed by stereomicroscopic analysis (base image) and metallographic analysis (right top image)

The UI samples subjected to the ageing treatment at 180°C with maintenance for 24 hours (Fig. 9) show the slightest degradation of the tested surface, with the smallest value for the maximum depth about 267μm. The effect is mainly due to the precipitation of intermetallic compounds due to the long holding time and the increase in the values of the mechanical properties of the material after treatment.

The quantitative results of the measurements for the eroded cavitational surfaces are given in table 4. As one may see that the ageing treatments may diminish either the proportion of the eroded surfaces (from 74% in delivery state, to 71% after ageing at 180°C/1h, to 69% after ageing at 180°C/12h and finally to

66% ageing at 180°C/24h), or the maximum depth of the cavitational attack (from 490μm in delivery state, to 341μm ageing at 180°C/1h, to 335μm ageing at 180°C/12h, and 267 μm ageing at 180°C/24h).

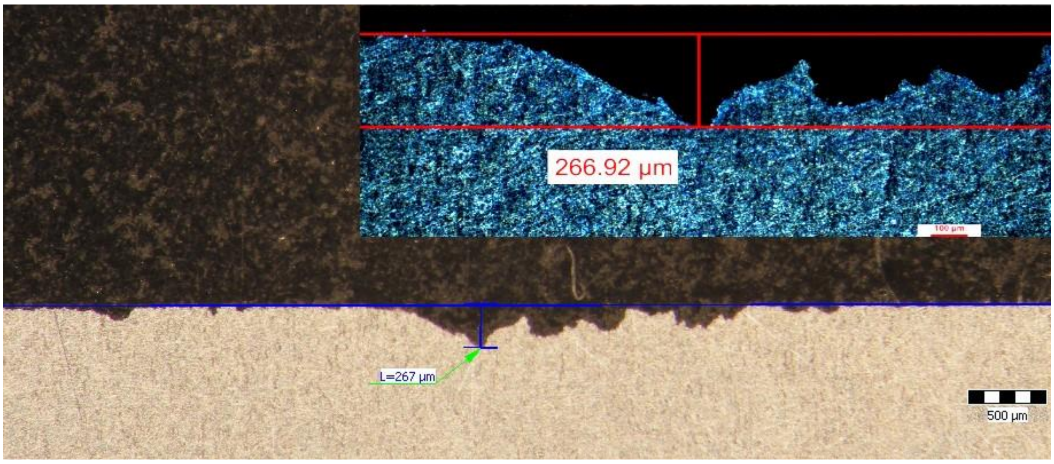


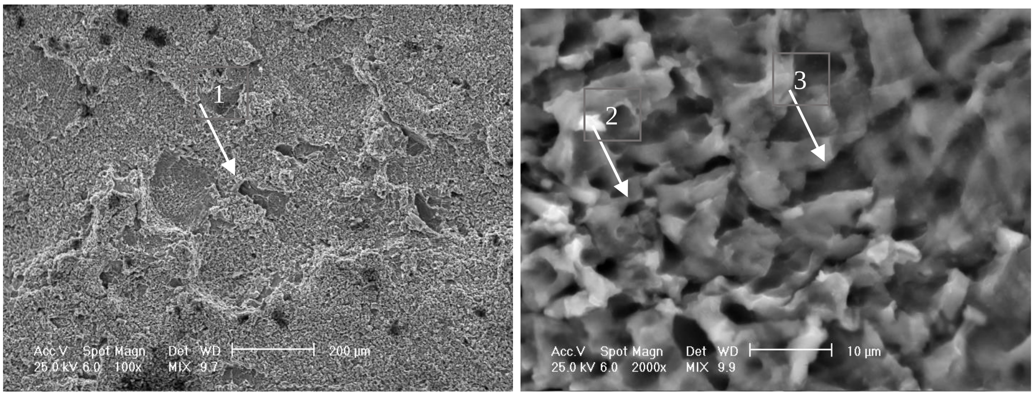
Fig. 9. Appearance of eroded surfaces samples after ageing at 180°C/24h (UI) revealed by stereomicroscopic analysis (base image) and metallographic analysis (right top image)

Table 4

Measurements of the surfaces diameters and the maximum depth of the cavitational attack of the samples in different state

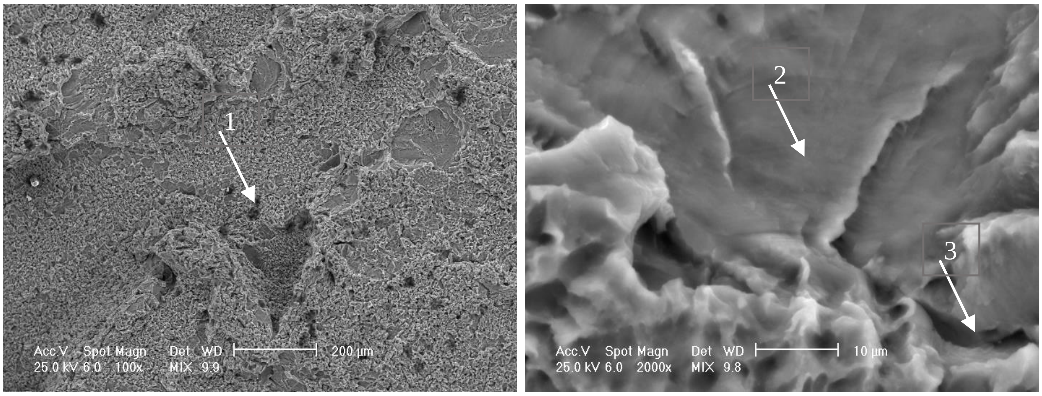
Sample	Cavitational attacked surface			Maximum depth of the cavitational attack, μm	
	Exterior diameter, mm	Interior diameter, mm	%	Stereomicroscopic analysis	Metallographic analysis
Delivery state (U)	14.359	10.593	74	490	490.87
180°C/1h (UP)	15.661	11.167	71	341	337.05
180°C/12h (UL)	14.373	9.988	69	335	314.43
180°C/24h (UI)	14.397	9.574	66	267	266.92

The analysis made on scanning electron microscope reveals the main structural aspects of the cavitational attacked surfaces. So, if in delivery state, as is shown in Fig. 10 the aspect reveals in macro structure many pits (arrow 1 in Fig. 10a), and many pitting (arrow 2 in Fig. 10b) and secondary cracks (arrow 3 in Fig. 10b). After applying an ageing treatments, as is shown in Fig. 11, one may reveal a very attacked surface with numerous pits (arrow 1 in Fig. 11a), zone with flat appearance (arrow 2 in Fig. 11b) and secondary cracks (arrow 3 in Fig. 11b).



a ***b***

Fig. 10- SEM image of the eroded surface of the delivery state sample (U), at different magnification



a ***b***

Fig. 11- SEM image of the eroded surface sample after ageing at 180°C/24h (UI), at different magnification

Analysis based on characteristic cavitation curves

The characteristic cavitation curves shown in Fig. 12 and Fig. 13 were based on the partial mass losses determined on the analytical balance with an accuracy of 10^{-5} g, according to the requirements of the international regulations in the field of ASTM G32-2016 [10].

The mediation curves of the experimental values, MDE(t) and MDER(t), are constructed with the analytical relations established statistically, within the Laboratory [1], [9], [11].

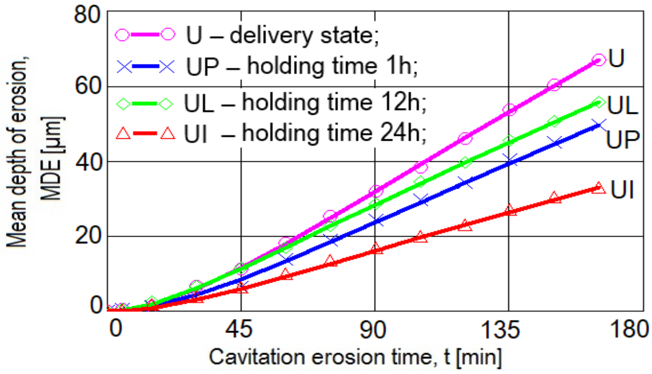


Fig. 12. The variation of the mean depth of erosion MDE with the duration of the cavitation t

The experimental values of the cumulative average depth (Fig. 12) and the related speed of erosion penetration (Fig. 13) are approximated by curves built with analytical relationships, the shapes of which are established in the Cavitation Erosion Research Laboratory [1, 9]:

- for the cumulative average depth:

$$MDE\ (t) = A \cdot t \cdot (1 - e^{-B \cdot t}) \quad (1)$$

- for the rate of erosion penetration (obtained by deriving relation (1) with respect to time):

$$MDER(t) = A \cdot (1 - e^{-B \cdot t}) + A \cdot B \cdot t \cdot e^{-B \cdot t} \quad (2)$$

The standard errors of approximation of the experimental values by the analytical MDE(t) mediation curves, built with relation (1), are: σ_U = 0.273; σ_{UP} = 0.301; σ_{UL} = 0.249; σ_{UI} = 0.264;

For a cavitation intensity process, dependent on the multitude of factors specific to the surface material, but also the hydrodynamics of the vibrating cavitation, as specified in [1, 9, 11, 12], the deviation values confirm the accuracy of the cavitation tests.

Comparing the values of the cavitation parameters resulting from the ageing process of the aluminum alloy 6082, with those of the alloy in the delivery state, is observed a decrease of them with the increase of the holding time at 180 °C.

Analyzing the curves of variation of the mean depth of erosion MDE (t) Fig. 12, after the 165 minutes of attack, compared to the delivery status, we observe decreases in the values obtained by approximate 50.7% for aged samples with a holding time of 24 hours, approx. 16.9% for aged samples with a holding time of 12 hours, respectively with approximate 20% for aged samples with a holding time of 1 hour.

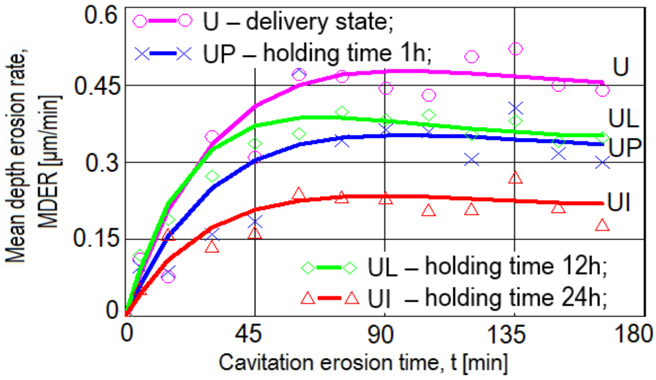


Fig. 13. Variation of mean depth erosion rate MDER with cavitation duration t

The material in the delivery state U presents the highest values of the cavitation parameters: cumulative average penetration depth of MDE erosion, MDER erosion rate. The appearance of the curve MDER (t) (Fig.13) is characteristic of materials with crystalline structure with high granulation and low cavitation resistance [1]. The behavior of UL samples, after ageing at 180°/1h, according to the shape of the curve MDER(t), is characteristic of materials with high plasticity, on the surface may appear the work hardened structures [12]. The UP samples, after ageing at 180°/12h have a similar behavior to those mentioned above. The UI samples, after ageing at 180°/24h show the best behavior at cavitational erosion, being in accordance with the superior mechanical characteristics of the material, obtained after the treatment.

4. Conclusions

The experimental research conducted in our paper on aluminum alloy type 6082 in order to put in evidence the influence of applying different ageing treatment at 180°C, with different time of maintaining reveals the following conclusions:

- By applying the ageing treatment at 180°C, with different periods of maintaining, it resulted a significant increase of the mechanical characteristic values (hardness, yielding strength and ultimate strength) and an improvement of the cavitational behavior, especially at the samples aged at 180°C for 24 hours at temperature;
- In the delivery state the aluminum alloy type 6082 does not fully satisfy the requirements of cavitation erosion resistance;
- A significant correlation between structural characteristics of the eroded sample - measured mass losses- mechanical characteristics and the allure of the characteristic cavitation curves, can be observed, which certifies the correctness of the results;

- The measurements of the maximum depth of the cavitational eroded surfaces made both by stereomicroscopic analysis and metallographic analysis were very close, which show the reproducibility of the results;
- Analyzing the curves of variation of the average depth of penetration of erosion MDE (t), after the 165 minutes of attack, compared to the delivery status, we observe decreases in the values obtained by 50.7% for aged samples with a holding time of 24 hours, 16.9% for aged samples with a holding time of 12 hours, respectively with 20% for aged samples with a holding time of 1 hour;
- The chosen method can be successfully used on a large scale to improve the cavitation erosion behavior of the 6082 aluminum alloy results obtained encourageing further research for other treatment parameters;
- The best results both mechanical and cavitational behaviour were obtained for the samples which were aged at 180°C, with a maintaining of 24h. So, the maximum depth of the eroded surfaces was about 266μm, in comparison with delivery state (about 490μm), or other time of maintaining (12h, with 335μm, or 1h, with 341μm).

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