NEW RESULTS REGARDING THE INFLUENCE OF ARTIFICIAL AGING HEAT TREATMENT AT 140°C ON THE CAVITATION RESISTANCE OF THE 2017 A ALUMINUM ALLOY STRUCTURE

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The 2017 A aluminum alloy is known for its mechanical properties, which make it applicable to the improve of high-strength structures in the aviation, military and other fields. As a series of aircraft components (noses, wings, fuselage) and military equipment (structures of fast river boats) are hydrodynamically stressed, specialists have determined to direct their studies towards its use in components that work in cavitational environments with a moderate and increased degree of destruction by erosion. In order to increase the resistance to the stresses of the cavitational microjets, studies of the behavior of the structure of this alloy are in full research, resulting from the application of various types of technologies and volumetric or/and surface heat treatments. The paper presents sme studies on the behavior of the structure of the 2017 A alloy, resulting from the volumetric heat treatment of artificial aging at 140 °C, with a holding time of 12 hours, also fall into this direction. The use of macro and microstructural images, as well as a novel way

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of analysis, based on the results of the cavitation test and the values of specific parameters, by comparing them with regimes with other holding times, brings new elements, compared to those already obtained on the same brand of steel and with the same heat treatment regime. The results presented are of real use to those who design and build equipment with structures from this alloy and who work in a non-stationary, cavitational hydrodynamic regime.

Keywords: aluminum alloy type 2017A, cavitation erosion, mass loss, mean erosion rate, microstructure.

1. Introduction

The expansion of the use of aluminum alloys in parts working in currents with various intensities of cavitation erosion has led scientists to find methods by which their structure can have the highest possible resistance to the cyclic stresses of shock waves and cavitational microjets. The targeted areas are naval (propellers of engines for pleasure boats), automotive (valves, pistons, rotors of cooling pumps of thermal engines), water supply (domestic pumps) [1-7]. Literature [8-14] shows that research is pursuing the effect of various heat treatments (volume or surface) as well as new technologies for hardening the surface exposed to cavitation, by remelting or coatings with hard composites. Thus, Mitelea et al. [14] study the effect of TIG reheating on alloy 6082 and find that it led to the refinement of the grain size and microstructure of the alloy and to an increase in the strength of the reheated structure compared to the structure resulting from the specific solution hardening treatment followed by artificial aging.

Istrate et al. [15] studied the effects of artificial aging heat treatments, at various temperatures and holding times of the artificial aging heat treatment, on the structural strength of 5083 aluminum alloys, in cast and rolled states. The results of their research show that from a microstructural point of view and from the dispersion of intermetallic compounds, no spectacular changes are obtained, and the values of mechanical strength and plasticity properties, resulting from the heat treatments, vary, without being able to establish a clear rule regarding the effects of temperature or holding time. Similar conclusions are obtained from the results of cavitation tests carried out by Bordeasu [16] and Ghera [17] on alloy 6082, by Odagiu [18] on alloy 7075, in cast and rolled semi-finished states, all with artificial aging heat treatments with different values of temperatures and holding times. Cheng-Cheng in [13] analyzes the mechanism of fracture of alloy 7050 by vibratory cavitation in distilled water and in with3.5 wt% NaCl solution solution and finds the effect of reducing mass losses in NaCl solution as a result of the creation of the oxide film. Tomlinson and Matthews in [7] investigate the behavior and resistance to cavitation erosion of pure aluminum and 8 other of its alloys and finds, according to the values of the incubation times of erosion and the value of the velocity in the stabilization zone, that the cavitation resistance of the structure, of the nine metals, is different and is dependent on the main alloying element and the type of semi-finished product. From the above, it follows that research must continue, in order to deepen the mechanism of the influence of the duration and temperature of the aging treatment on the resistance of the aluminum alloy structure to the cyclic stresses of cavitational microjets, in order to increase the lifespan of the parts stressed by cavitation. As the easiest method of modifying the values of mechanical properties, on large surfaces, with complex geometric configurations (such as pump rotor blades and boat propellers), is volumetric heat treatment, research in this direction is increasingly intense and carried out through doctoral theses [4, 11, 18, 19].

The research carried out on the 2017 A alloy is also in this line, the results of which are presented and analyzed within this work, as they are part of the objectives of the doctoral thesis developed by Luca. [11].

2. Researched material

The material investigated is the 2017 A grade T451 aluminum alloy (AlCu4MgSi (A) - according to EN-AW-2017) [20]. The samples for the cavitation tests and mechanical tests are taken from specimens with dimensions of 50 mm x 50 mm x 150 mm, cast in the specialized laboratory of the National University of Science and Engineering Politehnica Bucharest. Of these, some were heat treated by artificial aging at 140oC with three holding times (1 hour, 12 hours, 24 hours) and cooling in the oven. The three heat treatment regimes were carried out in the Special Materials Expertise Center within the National University of Science and Technology Politehnica Bucharest (UPB) using the Thermo Scientific-Thermolyne Oven type oven. Samples for cavitation tests, mechanical strength and plasticity tests were taken from the heat-treated bars. The chemical composition (see table 1) and mechanical properties (see table 2), for the semi-finished state and those with artificial aging heat treatments were also determined within the Special Materials Expertise Center. The hardness in table 2 is the algebraic average value of 8 measurements.

As the mechanical properties, according to the research of Hobs [21], Garcia a.o [22], have a significant influence on the resistance of the structure to cyclic cavitation stresses, from table 2 it can be seen that, compared to the semi-finished state, the holding times led to significant changes in their values, some higher, others lower, which will be seen in the cavitation test results.

In Table 2, for simplicity, the following abbreviations are used:

- **T0** for the semi-finished state;
- **T1** for the state with artificial aging heat treatment at 140 °C, with a holding time of one hour;

- **T12** for the state with artificial aging heat treatment at 140 ºC, with a holding time of 12 hours;
- **T24** for the state with artificial aging heat treatment at 140 ºC, with a holding time of 24 hours.

Table 1.

The chemical composition of 2017A alloy, state T451

Alloy	Chemichal composition, [% wt]									
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Zr**	**Al**
Standard*	0,2-0,8	≤ 0,7	3,5-4,5	0,40-1,0	0,40-1,0	≤ 0,10	≤ 0,25	≤ 0,15	-	rest
Experimental	0.61	0.3	4.25	0.5	0.97	0.1	0.078	0.08	0.021	rest

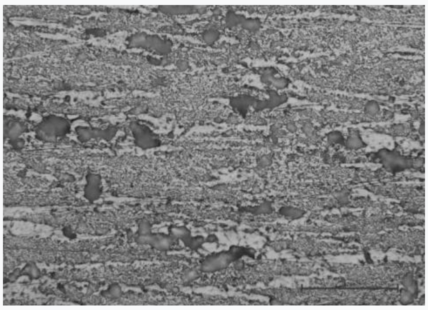
*file:///C:/Users/user/Downloads/node_87_printable_pdf.pdf

Table 2.

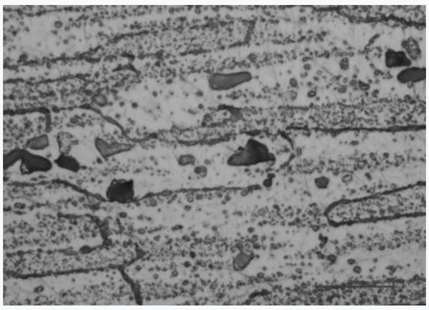
The physical and mechanical properties of 2017A alloy, state T451

State	**R_m MPa**	**$R_{p0.2}$ MPa**	**HB daN/cm^2**	**KCU J/cm^2**
T0	291.16	225.01	121	29.1
T1	239.409	142.87	88	19.5
T12	282.075	156.07	109	10.1
T24	298.114	148.36	87	22

Analysis with the Reichert UnivaR electron microscope of the semi-finished structures (Fig. 1a) and of the one resulting after 24-hour aging does not show significant structural changes, in terms of the dendritic matrix (base metal), but only in terms of the dispersion and dimensions of the intermetallic compounds ($CuMgAl_2$ și $CuAl_2$) which, depending on the duration of maintenance, increase up to 30 µm in length and15 µm in width, Fig. 1b.



a



b

Fig.1 Microstructural images recorded with metallographic microscope: a) Semi-finished state, b) artificially aged state at 140^{0}C for 12 hours

3. The experimental methodology

Cavitation behavior and resistance test on 3 samples from each type of heat treatment regime, on the vibrating apparatus with piezoceramic crystals, in the Cavitation Erosion Research Laboratory of the Polytechnic University of Timişoara [23]. The tests were carried out by the indirect method, with the stationary sample [5, 9, 11, 17, 24], and the procedure and division of the total duration of 165 minutes, in intermediate periods at the end of which mass losses were measured, eroded surfaces were analyzed and photographed, and the steps specific to laboratory custom were followed [23, 25], in compliance with the requirements set forth in ASTM G32-2016 standards [26].

The functional parameters of the device, which dictated the erosive intensity of the vibrating cavitation, were controlled and maintained at the values recommended by ASTM G32-2016 standards, throughout the testing, thanks to the software implemented in the computer with which the experimental program was conducted.

3.1. Experimental results

The experimental results, for each state, are presented through photographic and microscopic images of the surface degraded by erosion and through the specific cavitation curves M(t) and v(t), constructed based on the relationships established within the cavitation laboratory [23, 27, 28], which average the algebraic mean value of the experimental ones, obtained on the three samples.

For each state (semi-finished and with artificial aging heat treatments) the analysis of the evolution of the behavior and resistance to cavitation is carried out based on the diagrams in Fig.2 and 3 in which the experimental values (points) are algebraic means of those obtained on the three tested samples.

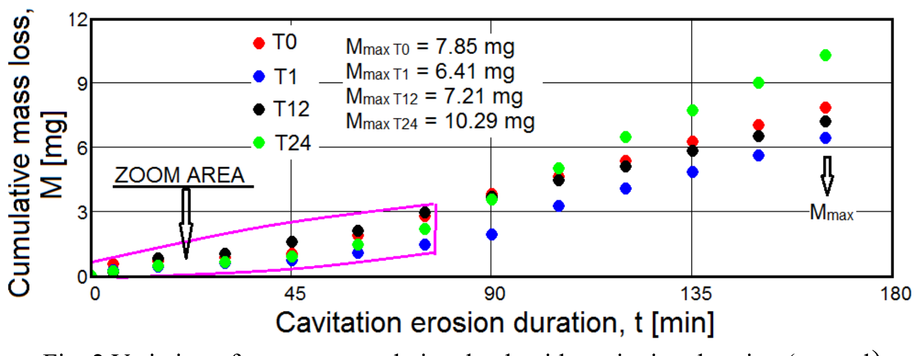


Fig. 2 Variation of average cumulative depth with cavitation duration (control)

From the analysis of the data contained in the diagrams in Fig. 2, conclusions emerge regarding the nature of the alloy (2017A) and differences dictated by the duration of maintenance, as a result of the changes that occurred, more so, on the values of the mechanical properties and less on the changes at the microstructural level.

From the point of view of similarities, it is observed:

- insignificant differences between the mass losses in the first 60 minutes, which leads to the opinion that this mode of behavior is specific to the alloy, regardless of the state (with or without heat treatment), the erosion mechanics (deformations, cracks, creation of microcavities) being identical;

- for all states, the losses in intermediate periods, after 60 minutes, are of a similar order, which leads to an approximately linear increase, reflected in the variations in speeds, through the tendency to horizontalize (see fig.3).

The differences in behavior under cyclic fatigue stresses during cavitation are evident after 60 minutes of attack; the weakest behavior being the T24 state, the semi-finished and T12 states having approximately identical behaviors, and the structure of the T1 state being the most resistant to cavitation.

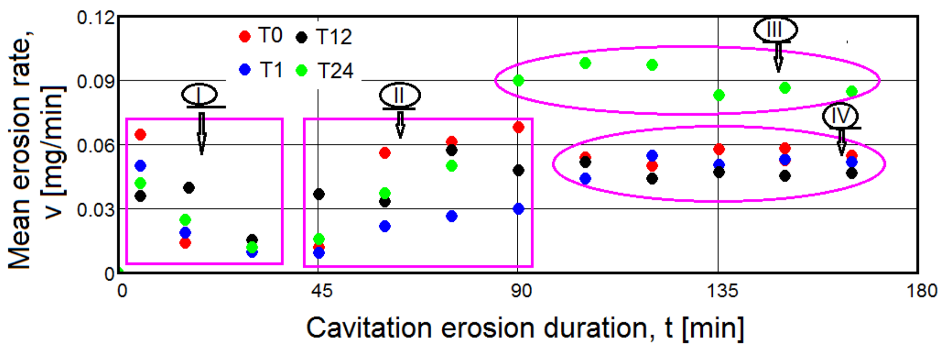
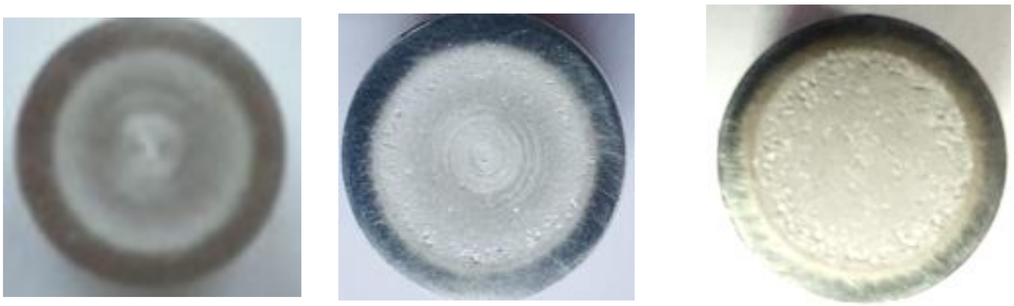


Fig. 3 Variation of the average erosion penetration velocity with cavitation duration (control)

The dispersions of the experimental values, in Fig.3, arată trei zone cu variații dierite ale vitezelor de eroziune (vitezele pierderilor de masă). The first, marked with **I**, corresponds to the interval 0...30 minutes, in which the speed values decrease, those in the first 5 minutes being specific to the elimination of the asperities peak, and the last ones being characteristic of the elasto-plastic deformations and the generation of crack networks in the surface structure. These values are certified by the macroscopic images from minute 15, in Fig. 4. The next period, marked with **II** (45..90 min), is characterized by the increase in the speed values, due to the fact that the pressure forces, resulting from the impact of the surface with the cavitational microjets, produce expulsions of the grains, starting with the brittle intermetallic compounds (CuMgAl2 and CuAl2) and deepen the cracks in the caverns left after the expulsion. The certification of these values is given by the images from minute 60, in Fig. 4. In the last period, denoted by **III** and **IV** (90...165 minutes), the velocity values show small differences between them, which is why it can be considered that the cavitation erosion proceeds with a slight constancy (with mass losses, in the intermediate periods, with insignificant differences), which leads to a tendency for the velocities to linearize. Obviously, according to previous studies [21, 22, 29-31], these values are greatly influenced by the increase in the hardness of the layer affected by cavitation, as well as by the attenuation of the pressure forces by the air and water entering the created caverns.

In order to substantiate what has been stated in the analysis of the evolution of the behavior and resistance to the vibratory cavitation stresses, based on the experimental values in Fig. 2 and Fig. 3, Fig. 4 presents images, taken with the Canon Power Shot A 480 camera, from significant times in the three areas mentioned in Fig. 3, with macrostructural aspects of the erosions produced in the surface structure of the 4 states, exposed to the vibratory cavitation attack. Regardless of the state, the images reflect the destructive intensity of the fatigue cyclic stresses of the shock waves and microjets, developed by the implosion of the bubbles in the cavitation cloud attached to the vibratory sample. As can be seen, the differences are given by the time at which the pinches appear, by their dimensions and number, with increasing duration of exposure to cavitation. Obviously, the shape of the caverns, their dimensions and number are an effect of the resulting structural strength of the sample type (condition), as a result of the microstructure and mechanical properties (see Table 2).



15 min 60 min 165 min

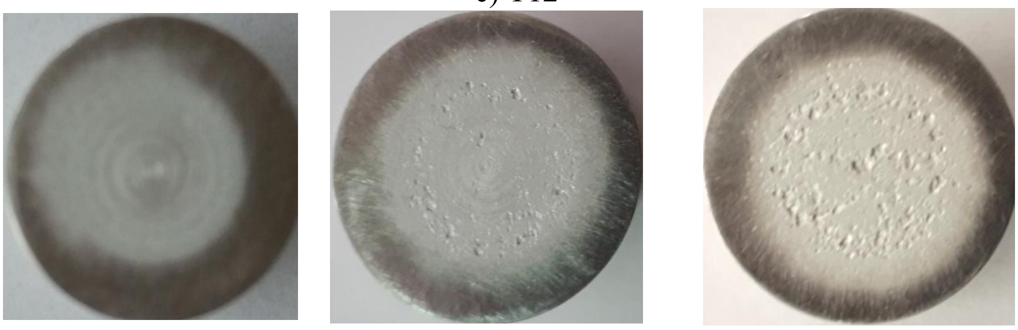
a) T0

15 min 60 min 165 min

b) T1

15 min 60 min 165 min

c) T12



15 min 60 min 165 min

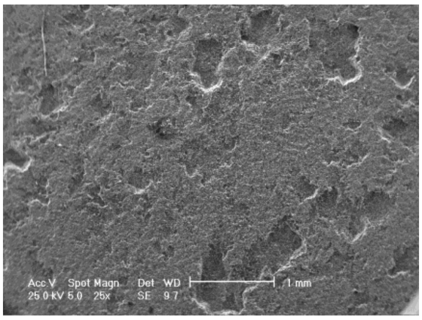
d) T24

Fig. 4. Macroscopic images (photo) of the degradation of the structure, at significant times of cavitation erosion

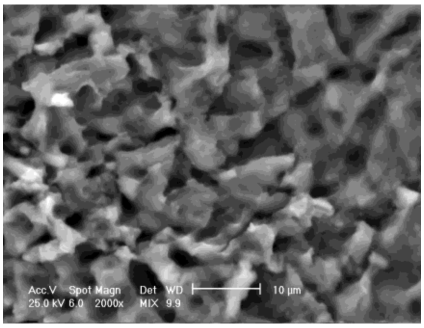
Thus, the images from 15 minutes show frosted areas, characteristic of surfaces with multiple elasto-plastic deformations and crack networks. The images from minute 60 of the cavitation attack show the mechanics of cavitation erosion, by the propagation of cracks, the breaking of bonds between grains and their expulsion. The effects are the multiple caverns generated, especially towards the periphery, in the surface structures of the samples of the T0, T12 and T24 states and very few in the T1 state. The images from minute 165 are instructive regarding the nature of the mechanical stress of cavitation, by the fact that the microjet stresses being typical of local fatigue [22, 24, 29, 30] cause the crack networks, still existing, and the formed caverns to become primed, leading to the amplification of the number of microcavities, with the increase in the size of the formed caverns (see also the SEM images in Fig. 5). The differences between the evolutions of the caverns, in terms of dimensions and geometric shapes, also explain the reduced differences between the losses in the intermediate periods after minute 90, in which the mechanical hardening of the layer in the stressed surface [4, 9, 11, 13, 16, 18, 31] and the existing caverns act as shock absorbers of the pressures produced upon impact with the microjets or shock waves, generated through the hydrodynamic mechanism of vibrating cavitation.

3.2. Structural degradation

For the morphological analysis of structural degradation, the fractographic method was used, being the most widely used by fracture mechanics specialists. The results of this fractographic analysis, obtained on one of the three tested samples of each condition, are suggestively reproduced in the images in Fig.5.

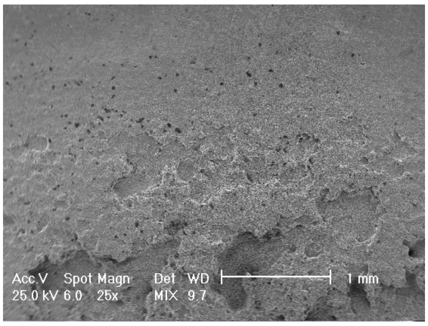


a) x25

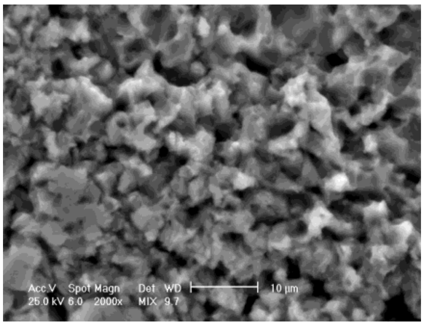


b) x2000

T0

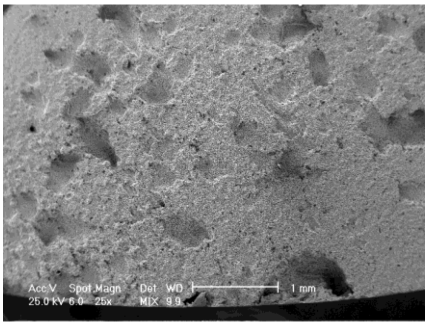


c) x25

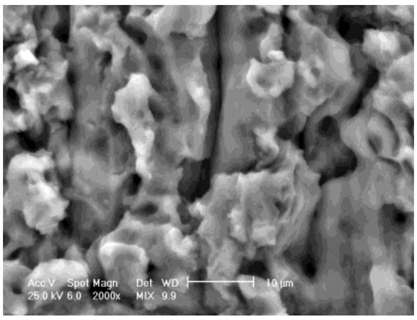


d) 2000

T1

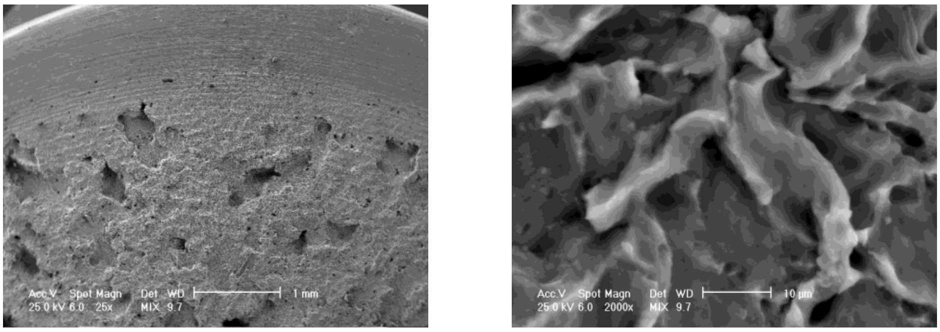


e) x25



f) x2000

T12



g) x25 h) x2000

T24

Fig. 5. SEM images of the eroded surface

SEM analyses, regardless of zoom and sample condition, show the presence of intergranular (along grain boundaries) and transgranular (through grains) cracks, which proves that grain boundaries constituted crack initiators, caused by the presence of impurities, such as the hard and brittle intermetallic compounds CuMgAl2 and CuAl2. Also, SEM images with 25X magnification show shapes of grooves and pits, some few in number, with dimensions of 2..3 mm, with sharp faces, with a brittle appearance of breakage, a sign of intergranular and transgranular pitting corrosion. These pits, with various shapes, are the result of the expulsions of the plastically deformed layer after about 60 minutes of attack, as a result of the resilience effect (see Table 2).

SEM images, with a magnification of 2000 x, of the structures of the samples with heat treatment of aging at 140^0C (states T1, T12 and T24) highlight similar aspects, both macrostructural and microstructural, of a ductile or brittle fracture, where the shapes and dimensions of the caverns are determined, first of all, by the dimensions of the brittle intermetallic compounds, the first broken and expelled from the surface structure under the attack of shock waves and microjets produced by vibrating cavitation. The difference between them and compared to the semi-finished state (T0) consists in the shape, size and distribution of the cavitations on the eroded surface. Thus, for the T0 state the average size of the caverns is 25-30 µm (Fig.5a.b) for the T1 state it is 15-20 µm (Fig.5c.d), for the T12 state it is 15-30 µm (Fig.5e.f), and for the T24 state it is 10-35 µm (Fig.5g.h).

Therefore, from the analysis carried out, according to the shapes and dimensions of the caverns, we believe that, compared to the semi-finished state (without thermal aging treatment), research must continue with other holding times, because the increase result obtained for the one-hour holding time, and the decrease for the 12 and 24-hour durations do not allow a clear opinion to be formed regarding the effect of these durations on the resistance of the structure aged at 140^0C to cavitation erosion.

To have an idea of the effect of the heat treatment regime on the cavitation resistance, the histogram in Fig.6 compares the values at 165 minutes, maximum mean erosion depths (MDE_{max}) and cavitation resistances R_{cav}.
The calculation relationships of these parameters, recommended by the international standards ASTM G32 [26] and used in the Cavitation Laboratory of Politehnica University Timișoara, are:
- for the depth of erosion:

$$MDE_{max} = \frac{4 \cdot M_{max}}{\rho \cdot \pi \cdot d_p^2} \quad (1)$$

- for the resistance to cavitation (corresponding to the tangent on the area of linear variation of mass losses over the interval 60...165 minutes):

$$R_{cav} = \frac{105}{MDE_{max} - MDE_{60}} \quad (2)$$

Where: M_{max} - the value of the cumulative mass after 165 minutes of erosion (see the notation in Fig. 1); ρ - 2.7 g/cm^3 - is the density of the alloy; d_p - 15.8 mm is the diameter of the sample surface exposed to cavitation; MDE_{max} – the value of the average erosion depth related to the M_{max}; MDE_{60} – the value of the average erosion depth related to the cumulative losses in 60 minutes of cavitation erosion.

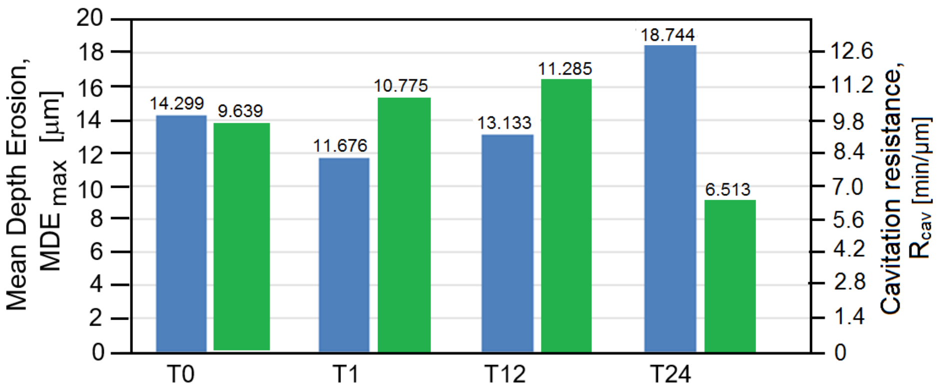


Fig.6 Histogram of cavitation resistance comparison

From the point of view of numbers, the cavitation resistance of the structure of the samples in the T1 state, compared to T0, is higher by about 22%, compared to T12 it is higher by about 12% and compared to T24 it is higher by about 60%.

From the point of view of cavitation resistance, the most resistant structure is that of the alloy corresponding to the T12 state which, compared to T0, is higher by about 17%, compared to T1 it is less significant (by about 5%) and compared to T24 it is higher by about 73%.

4. Conclusions

The heat treatment of cast aluminum alloy 2017A by artificial aging at 140^0C, with holding times of 1, 2 or 24 hours, does not lead to substantial improvements in the behavior and resistance of the surface to erosive cavitation stresses. The mechanical properties, in the volume of the samples, respectively in the cavitated surface, did not undergo essential changes compared to the semi-finished state (state T0), with slight increases or decreases, depending on the holding time.

Of the three heat treatment regimes, only the one with the holding time of one hour led to a significant increase in the surface resistance to erosion; the increases compared to the other 3 states (T0, T12 and T24) were between 12% and 60%.

The fracture has a brittle aspect of the fracture, a sign of intergranular and transgranular pitting corrosion. The 25X magnification images show pits of various shapes on a rough surface, resulting from the expulsions of the plastically deformed layer.

The destruction of the structure by erosion is the effect of a typical local fatigue stress, under cyclic stresses at cavitational microjets, which produces ductile type ruptures, characterized by the formation of microvoids, and brittle type, with very little prior plastic deformation.

Given the results obtained, which do not provide a clear direction of the influence of the holding time at the aging temperature of 140^0C on the resistance to cavitation erosion, of the alloy structure 2017 A. It is necessary to continue research on other volumetric aging heat treatment regimes (temperature, holding time, cooling medium).

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