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Şcoala Doctorală de Studii Inginereşti

Research of cavitation erosion resistance of some aluminum base alloys with artificial aging heat treatment

Doctoral Thesis - Summary
for obtaining the scientific title of doctor at
Polytechnic University of Timisoara
in the doctoral field of Mechanical Engineering

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Content
(excerpt)

Introduction

Cavitational erosion is one of the three known effects of cavitation, due to the impact of the surface with shock waves and microjets generated by the rapid implosion of bubbles filled with gases and/or vapors at high pressures, formed by the mechanism of emergence and development when the static pressure decreases below that of vaporization. This erosion phenomenon causes changes in the geometry and structure of the surfaces, leading to the equipment being taken out of service during repairs, or through the total or partial replacement of damaged components.

Among the areas, where resistance to cavitation erosion is extensively studied, is that of marine or river ship propellers and hydraulic machine rotors. By understanding the way the equipment works, as well as the mechanisms of evolution and development of cavitation, innovative solutions can be devised regarding the reduction of the destructive intensity of cavitation, in order to optimize the performance and increase the life span of these equipments.

The development of equipment that works in cavitation, of various destructive intensities, determined, worldwide, a deep research of the causes, with the aim of creating material, or structures, that can resist as much as possible the erosive effect of cavitation. Known for extensive studies of behavior and resistance to cavitation are laboratories in the USA, China, France, England, India, Poland, Japan.

In Romania, the best-known laboratory for studying/researching cavitation erosion is the Cavitation Erosion Research Laboratory from the Politehnica University of Timișoara, which has research activity for over 60 years. By purpose and objectives, the doctoral thesis highlights the behavior and resistance to cavitation of three aluminum-based alloys (7075, 2017A and 6082) in delivered states and states resulting from the application of volumetric thermal treatments of artificial aging at a temperature of 180oC, with three holding times (one hour, 12 hours and 24 hours). The content of the thesis is structured in 8 chapters as follows: the first one is intended for the brief presentation of the state of use of aluminum-based alloys; the second is intended to present the three aluminum-based alloys, the third is intended to present the research procedures and apparatus used. The following three chapters are intended to present the results of experimental research, analyzed based on the curves and parameters specific to the behavior and resistance to vibratory cavitation (according to the provisions of ASTM G32-2016 and the laboratory's custom) and the macro and microscopic images of the degraded surfaces. Chapter 7 is dedicated to the evaluation of cavitation resistance by correlating it with the mechanical properties of the investigated material states. The last chapter is intended for the synthesis of general conclusions, personal contributions and the description of future research directions.

The results of this thesis are a continuation of those carried out in the Cavitation Erosion Research Laboratory of the Politehnica University of Timișoara, they are on the wave of current research on the creation of aluminum alloy structures that can satisfy the requirements of operation in low and medium intensity cavitation conditions and constitutes a basis for future research on other categories of aluminum alloys.

Chapter 1
The current state of research and applications of aluminum and its alloys

Aluminum and aluminum-based alloys are among the most important and common engineering materials with a wide spectrum of applications. This practical superiority stems from the intrinsic capacity of aluminum-based alloys for the desired combination of physico-mechanical properties [113]. They benefit from superior corrosion resistance, excellent machinability, high strength-to-density ratio, and adequate electrical and thermal conductivities. These superior properties make this class of metal alloys suitable for the manufacture of structural and industrial components such as automotive parts (pistons, steering boxes, engine blocks and wheels) and military equipment.

Although the use of aluminum and its alloys is ancient, knowledge of their cavitation erosion behavior and resistance to make them usable for boat/ship propeller type parts. valve components or pump casings and impellers, started much later.

From the documentation carried out it is found that the first studies of resistance to cavitation erosion are carried out on aluminum with a purity of 99%, or alloys with a low alloyed aluminum base, carried out in the Knapp type hydrodynamic tunnel, where the intensity destructive cavitation is the smallest of the three devices (tunnel with a choked working chamber, rotating disc and vibrating device) [1-3 , 25, 24, 53, 54, 68, 69]. To highlight the effect of the structure and mechanical properties of aluminum alloys, at first Hobbs [68], then Hammitt [181], respectively Hammitt & collaborators [185] carry out studies on aluminum alloys 1100-0 and 2024-T4 in hydrodynamic tunnel and vibrating device and shows the dependence of the maximum value of the average rate of penetration of erosion MDPRmax (notation in this thesis with MDERmax), defined by the curve of averaging the experimental values on the ultimate resilience (UR) and on the Brinnell hardness, establishing analytical forms of type:

$$1/MDPR \approx C1 \cdot UR^n \qquad \text{or} \qquad 1/MDPR \approx C2 \cdot HB^n \qquad (1.1)$$

Where:
n = 0.7...0.98 - depending on the type of material
C1, C2 = 0.8...1.8- depending on the type and material and surface hardness
UR = (R_m- mechanical breaking strength and E-longitudinal modulus of elasticity longitudinal)

Obviously, there are many forms of correlation between the physical-mechanical properties of the materials and the cavitation erosion parameters, depending on the apparatus/stand where the erosion process was carried out. However, none of the relationships predict cavitation resistance with a very high degree of confidence. For this reason, the purpose of this work is to prove the necessity of applying heat treatment regimes of artificial improvement to aluminum alloys, in order to expand their use in the manufacture of parts working in various cavitation regimes (cylinders and pistons of thermal engines, propellers of boats, pump impellers, etc.).

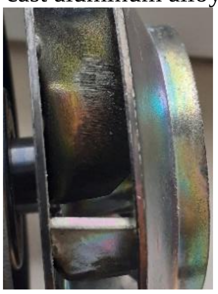
As a result of the effect of the alloying elements and the one brought by the traditional methods of improving the mechanical properties, through microstructural changes, aluminum alloys began to be more intensively researched from the point of view of increasing the resistance to cavitation erosion. The natural reason is to extend their use to parts that work in cavitational hydrodynamic conditions, such as: valves, pistons and cylinders of thermal engines, pump rotors, ship propellers, airplane ogives , and not only.

The analyzes of these rotors and propellers, after certain periods of operation, show areas affected by cavitation erosion, fig. 1.1, a fact that determined, in the last 30 years, the amplification of the study of the structure resistance of existing aluminum-based alloys, simultaneously with the use of technologies that lead to changes in structure and properties with which the resistance to cavitation erosion is increased


a)

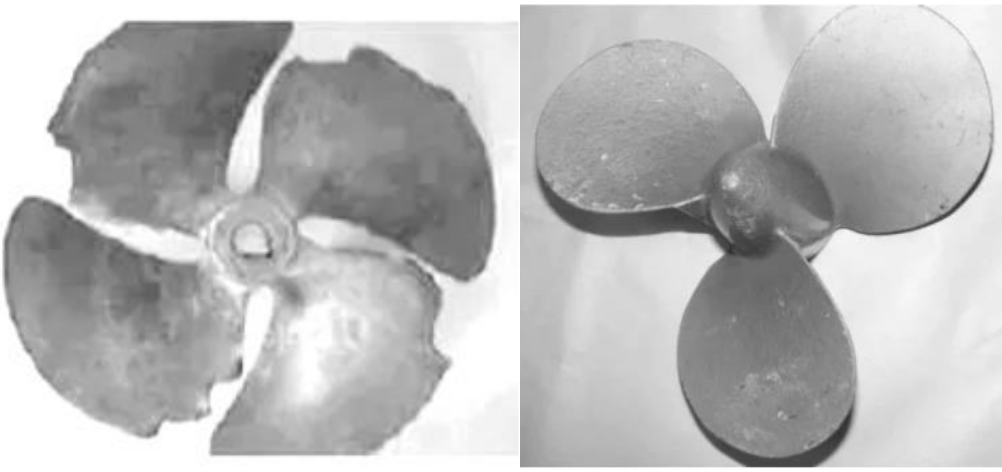

b)

household pump impellers: a) cast aluminum alloy impeller [172], b) cavitation destroyed impeller [179]


c)


d)

c, d) rotor affected by cavitation erosion (component of the cooling pump of the Mercedez bus engine - supplied by the company SC. DUCODAN SRL)



e) motor boat propeller affected by cavitation erosion

Fig.1.1 Cavitation erosions in rotors and propellers made of aluminum-based alloys

Therefore, the erosive effect produced by shock waves and microjets generated by the hydrodynamic cavitation mechanism on the structures of various aluminum alloys has become the object of scientific research and the concern of builders in using them for hydrodynamically stressed parts, beyond that used as resistance structures for the automotive, naval, aviation, sports or military fields.

In order to improve the cavitation erosion behavior, with the increase in the strength of these aluminum alloys, it is absolutely necessary to apply appropriate technologies that contribute to obtaining favorable physical-mechanical structures and properties. Among them, voluminous thermal treatments, such as artificial aging, continue to be preferred.

The objectives of the thesis

The objectives of the doctoral thesis are:

- research on the behavior and resistance to vibrating cavitation of aluminum-based alloys 7075 state T651, 6082 state T651 and 2017A state 451, with destination in the manufacture of working parts in cavitation such as: propeller blades of motor boats and sailboats, pump rotors in the system cooling of thermal engines and used for household use;
- the deepening of the degradation mechanism through cavitation erosion, produced in the structure of the surfaces of the three aluminum alloys for four states: delivery state (laminated semi-finished product - referred to as control), states resulting from the volume thermal treatment of artificial aging at 180 0C, with three holding times (one hour, 12 hours, 24 hours);
- investigation of the morphology and mechanism of the generation and propagation of cracks, ruptures, caverns, as well as the macro and microstructural characterization of the surface structure;
- evaluation of the results obtained, based on the comparative method, with similar results obtained on other brands and states of aluminum alloy, using the curves and specific parameters recommended by the ASTM G32-2016 norms and used in the custom of the Cavitation Erosion Research Laboratory of the University Timisoara Polytechnic.

The novelty of the doctoral thesis

The novelty of the doctoral thesis consists in expanding the use of aluminum alloys 7075, 6082 and 2017A in the manufacture of parts that work in cavitation with moderate destructive intensity, specific to motor boat propellers and sails and pump rotors in the cooling system of thermal engines. For this, the effect of the artificial aging heat treatment regime on the behavior and resistance of the structure of the three alloys to the cyclic stresses of shock waves and microjets resulting from the implosion of the cloud of cavitational bubbles, as a result of the change in the values of the mechanical properties, of the dispersion of brittle intermetallic compounds and the degree of microstructural fineness.

Chapter 2
Researched materials

In the research that is the objective of this thesis, three categories of precipitation-hardenable aluminum alloys were used: alloy 2017 A state 451, alloy 6082 state T651 and alloy type 7075 state T651, all taken from rolled semi-finished products from S.C. ALRO S.A. The samples for the cavitation tests were received from the National Polytechnic University of Engineering Sciences in Bucharest - the Metallic Materials Science and Physical Metallurgy Laboratory of the Special Materials Expertise Center (CEMS). From each type of alloy, samples taken directly from the state of the rolled ***semi-finished product were tested by vibrating cavitation, samples subjected to the thermal treatment of artificial aging at 180 ^{0}C with three holding times (one hour, 12 hours and 24 hours)*** after the related tempering treatments for solution. To facilitate the discussions, due to the behavior and resistance of the surface structure required by the vibrating cavitation, a symbolization was used to identify the experimental samples, as indicated in table 2.1, without using the names of the states.

The chemical composition of the three alloys is given in table 2.2, compared to that provided in the related standard, and the mechanical properties, determined in the CEMS laboratory, are shown in table 2.3. The data in table 2.2 show that the alloys selected for the experiments have the appropriate chemical composition, falling within the brand prescriptions.

Table 2.1 Symbolization of experimental samples

Series / Alloy	Sample code	Solution quenching treatment and/or artificial aging (T6)
7075	**Delivery state**	**Control sample (delivery state) -** Laminate
	180/1h	Laminated and aged at 180°C/1h/air
	180/12h	Laminated and aged at 180°C/12/air
	180/24h	Laminated and aged at 180°C/24h/air

6082	**Delivery state**	**Control sample (delivery state) -** Laminate
	180/1h	Laminated and aged at 180°C/1h/air
	180/12h	Laminated and aged at 180°C/12/air
	180/24h	Laminated and aged at 180°C/24h/air
2017A	**Delivery state**	**Control sample (delivery state) -** Laminate
	180/1h	Laminated and aged at 180°C/1h/air
	180/12h	Laminated and aged at 180°C/12/air
	180/24h	Laminated and aged at 180°C/24h/air

Table 2.2 The chemical composition of the experimental samples

Alloy	**Chemical composition, %gr**										
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Pb	Al
Experimental 7075	0.68	0.107	1.58	0.076	2.05	0.19	5.76	0.2	0.023	0.15	Rest
EN AW-7075	≤0.4	≤0.5	1,2-2,0	≤0.3	2,1-2,9	0,18-0,28	5,1-6,1	≤0.2	-	-	Rest
Experimental 6082	0,85	-	-	0,57	0,67	-	-	-	-	-	Rest
EN AW-6082	≤1	-	-	≤0,65	≤0,85	-	-	-	-	-	Rest
Experimental 2017A	0,35	0,002	4,1	0,65	0,56	-	-	-	-	-	Rest
EN AW-2017	≤0,5	-	≤4	≤0,7	≤0,6	-	-	-	-	-	Rest

Table 2.3 The values of the mechanical characteristics of the experimental samples

Alloy	State	Mechanical characteristics				
		Rm MPa	$Rp_{0.2}$ MPa	A_5, %	HB daN/cm^2	KCU J/cm^2
7075	ISO EN AW7075	410-530	300-460	2-6	119-160	10
	Delivery state	531,841	424.82	6	140	12.8
	Aging at 180°C/1h	549,549	410.55	5	157	14.1
	Aging at 180°C/12h	339,459	203.66	5	91.3	7.8
	Aging at 180°C/24h	570,921	417.51	4,5	140	12.7
6082	ISO EN AW 6082	295 – 310	240 – 260	7 – 10	89 – 94	
	Delivery state (state T651)	226,05	161,71	13,58	67,00	25,9
	Aging at 180°C/1h	328,98	155,21	11,88	67,00	8
	Aging at 180°C/12h	249,81	181,87	20,37	67,00	24
	Aging at 180°C/24h	406,52	331,97	16,04	81,30	16,3
2017 A	ISO EN AW 2017	360-390	240-260	10-12	105-110	
	Delivery state (state T451)	291,16	225,01	19,43	121,0	29,10
	Aging at 180°C/1h	274,22	126,4	24,26	84,90	25,3
	Aging at 180°C/12h	281,11	135,68	14,49	80,00	14,3
	Aging at 180°C/24h	281,11	140,09	12,58	74,90	14,5

The heat treatments were carried out in a Nabertherm oven, within the Laboratory of Metallic Materials Science and Physical Metallurgy of the National University of Science and Technology Politehnica Bucharest. For each type of heat treatment, six tests were performed to determine the mechanical properties: mechanical breaking strength (Rm), yield strength (Rp0.2), elongation (A5), toughness/resilience (KCU), Brinnell hardness (HB)/microhardness HV0.5.

The determination of the mechanical characteristics of the experimental samples subjected to different thermal aging treatments was carried out on a universal testing machine Walter + Bai AD Switzerland model LFV 300. The impact resistance was carried out by determining the KCU values on the Pendulum Charpy hammer type Walter Bai with 300J.

Macroscopic structural analysis was performed on an OLYMPUS SZX stereomicroscope, equipped with QuickMicroPhoto 2.2 software, and microscopic metallographic analysis on a REICHERT UnivaR optical microscope equipped with Image Pro Plus software,

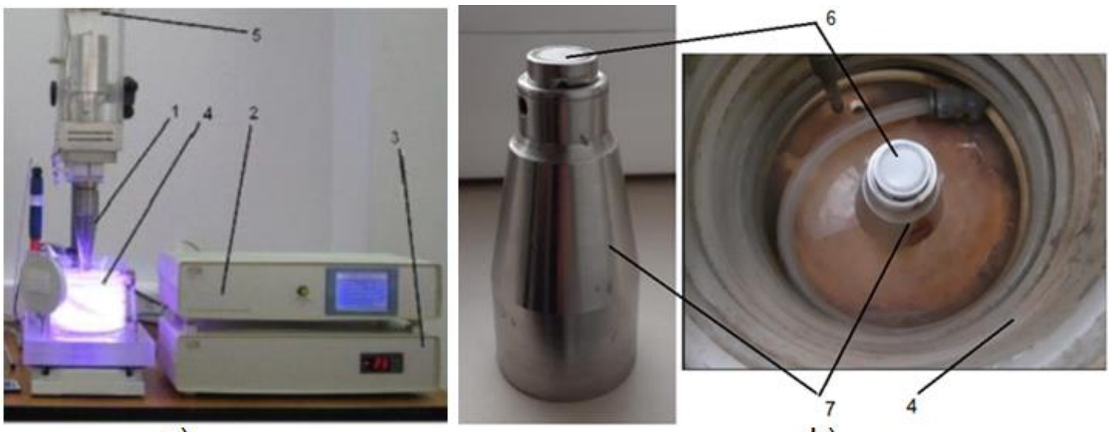
Scanning electron microscopy analysis was performed on a scanning electron microscope, the most widely used being the Thermophischer Quattro S model.

Chapter 3
Laboratory equipment. Cavitation Test Method.
Processing procedure and interpretation of experimental results

The experimental program of cavitation testing, of the structure's resistance, took place in the Cavitation Erosion Research Laboratory of the Polytechnic University of Timişoara, on the vibrating device with piezoceramic crystals (fig. 3.1) [12, 15, 59, 122, 125, 192].
The functional parameters of the vibrator, which determine the hydrodynamics of the cavitation, respectively the intensity of destruction, were rigorously controlled by a special software implemented in the computer connected to the vibrator [121, 122, 165]. Their values, according to ASTM G32 standards, are:

- Double vibration amplitude = 50 µm
- Vibration frequency = 20000 ± 1 % Hz
- The power of the electric ultrasound generator = 500 W
- Liquid medium = double distilled water
- Liquid temperature = 22 ± 1 ^{0}C

<u>Clarification</u>: because the construction of the vibrating mechanical system is for the DIRECT TESTING METHOD *(with vibrating sample caught in the mechanical system*), for metallic and non-metallic samples with a diameter of 15.8 mm and a length of 18 mm and with masses of 16..17.5 g. For the generation erosion by vibrating cavitation, for light alloy samples, such as aluminum, due to the very low mass, even if the sample complies with the required geometric dimensions, the INDIRECT TESTING METHOD *(stationary sample method*) was used. In this sense, a special sample fixation system was built, as can be seen in fig. 3.1 b.



a) b)

Fig.3.1 The vibrating device with piezoceramic crystals

a) vibratory device; b) sample fixture for testing by the indirect method
1- sonotrode; 2- the electronic ultrasound generator; 3- electronic device for regulating the water temperature; 4- the container with liquid and the cooling coil; 5- the piezoceramic transducer of 20 KHz and 500 W; 6- sample for cavity testing (d= 15.8 mm, length = 18 mm); 7- sample fixing device for carrying out the experimental test

In order to follow and analyze the behavior of structures during cavitation attacks, specific diagrams are built, containing the experimental values of the cumulative eroded mass Mi and the average erosion penetration speed vi, as well as the variations of the averaging curves M(t) and v(t) of these values . The relations used have the following forms:

- for the cumulative eroded mass:

$$Mi = \sum_{i=1}^{i=13} \Delta m_i \quad = \; [mg] \qquad (3.1)$$

- for the analytical curve averaging the experimental values of the cumulative eroded mass [12]

$$M(t) = A \cdot t \cdot (1-e^{-B \cdot t}) \text{ sau } M(t) = A \cdot t \cdot (1+e^{-B \cdot t}) \qquad (3.2)$$

- for the average erosion speed:

$$v_i = \Delta m_i / \Delta t_i \qquad [mg/min] \qquad (3.3)$$

- for the analytical curve averaging the experimental values obtained for the average erosion velocities [12]

$$v(t) = A\cdot(1-e^{-B\cdot t}) + A\cdot B\cdot t\cdot e^{-B\cdot t} \quad (3.4)$$

where:

for i = 1, $\Delta t_i = 0$, $M_i = 0$

i - represents the number of the test period;

Δm_i - is the mass of material lost through erosion in period i, in grams

Δt_i – the duration of the intermediate period "i" of cavitation (of 5, 10 and 15), in minutes;

A - is the scale parameter, statistically established on the basis of experimental values, for constructing their approximation/averaging curve, provided that their deviations from it are minimal;

B - is the shape parameter of the curve, established statistically based on experimental values.

The values of parameters A and B were obtained in the Matchad program, following a model built in the Cavitation Erosion Research Laboratory [12].

Because cavitation, as a hydrodynamic phenomenon, whose destructive effect, through cavitation erosion, is strongly dependent on the microstructure (with constituents, phases, defects, intermetallic compounds, etc.), the physical-mechanical properties of the material and the values of the device parameters that determine the hydrodynamics of cavitation vibrators, in the diagrams expressing the variations of the average erosion depths, a legend is given with the values of the average standard deviation that intervenes in the relations of the upper (S) and lower (I) limits of the range of dispersion of the experimental values (called in statistics as the degree of precision or tolerance range), which shows the accuracy of the experiment. For a hydrodynamic process, of the complexity of cavitation, the data provided by the specialized literature [1-3, 12, 52, 54] show that the values of the tolerance interval, for a test correctly driven with the parameters of the hydrodynamic regime rigorously controlled, it can have values up to 90 % (approximation error of ± 10 %).

The relations used to determine the average standard deviation σ and the limits S and I, according to the literature [12, 77], have the following forms:

- for the average standard deviation

$$\sigma = \left[\frac{\sum_{i=0}^{13}\left(M_i - M(t)_i\right)^2}{n-1}\right]^{\frac{1}{2}}, \; n = 13 \quad (3.5)$$

- for the 99% tolerance interval:

$$S99(t) = M(t) + 1\cdot \sigma \; ; \; I99(t) = M(t) - 1\cdot \sigma \quad (3.6)$$

- for the 90% tolerance interval:

$$S90(t) = M(t) + 10\cdot \sigma ; \; I90(t) = M(t) - 10\cdot \sigma \quad (3.7)$$

*Also, to assess the resistance of the structure, at various moments of the cavitation, through the deformations and caverns produced, the photographic images of the eroded surface, taken with the **Canon Power Shot A 480** device, as well as those obtained with the help of optical and electronic microscopes, are used.*

The thermal treatments of artificial aging at 180 ^{0}C (applied after those of tempering for placing in solution) were carried out at the Polytechnic University of Bucharest, Faculty of Materials Science and Engineering, according to the cycle diagram fig. 3.2 using the Etuva Thermo SCIENTIFIC-THERMOLYNE thermal treatment oven.

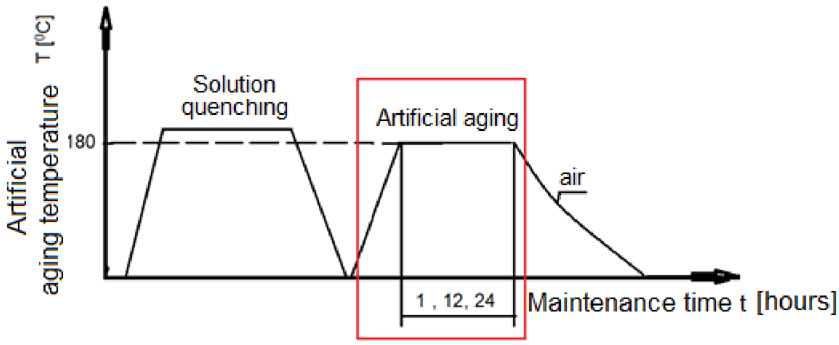


Fig. 3.2 Cyclogram of thermal treatment of artificial aging

The macroscopic structural analysis was performed on an OLYMPUS SYX57 stereomicroscope, equipped with QuickMicroPhoto 2.2 software, equipped with a variety of eyepieces, objectives and lighting techniques, which allow large zooms, depending on the purpose of the investigation. For the microscopic metallographic analysis, the REICHERT UnivaR type optical microscope equipped with Image Pro Plus software was used.

Chapter 4
Investigation of cavitation resistance of 7075 alloy

The results of the test of resistance and behavior to the erosion of vibrating cavitation, of the structures of this alloy, in the rolled state (of semi-finished product) and in the states resulting from the thermal treatment of artificial aging at 180 0C with three durations (one hour, 12 hours and 24 hours), are rendered through specific diagrams, photographic and microscopic images.

The determination of the experimental values of the cumulative eroded mass M_i and of the erosion velocities v_i was carried out with the relations (3.1) and (3.4) based on the mass losses (Δm_i), , and the analytical averaging curves M(t) and v(t) were constructed with relations (3.2) and (3.3).

Comparison of results

To determine the differences in cavitation resistance between the 4 states, as a result of the values of the mechanical properties and microstructures, the histogram in fig. 4.1 was constructed.

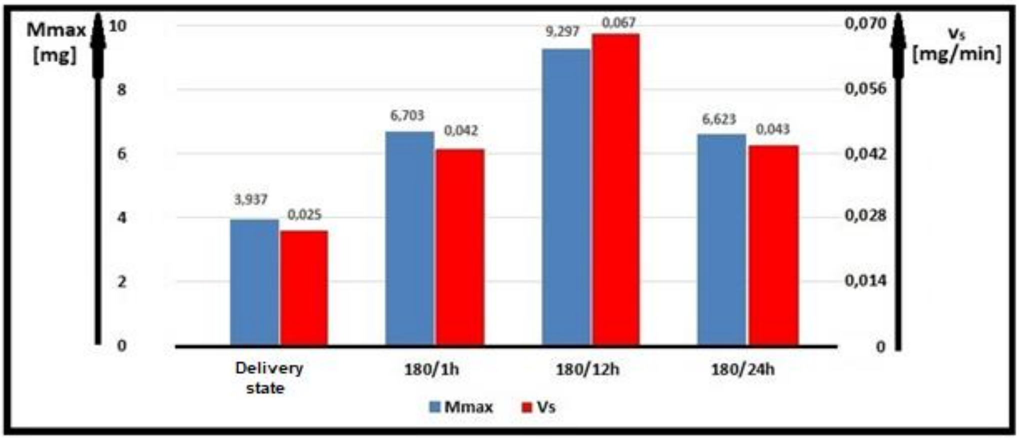


Fig.4.1 Histogram of the comparison of resistance to erosion by vibrating cavity (7075)

From the point of view of the resistance of the structure to the erosion of the vibrating cavitation, the data in the histogram show that the greatest resistance is that conferred by the Control sample, taken directly from the semi-finished product in a laminated state of delivery.

The thermal treatments 180/1h and 180/24h led to structures with cavitation erosion resistance of the same order, the differences between the values of the parameters Mmax and vs being insignificant, due to the small differences between the values of the mechanical properties (R_m and $R_{p0.2}$ - see table 2.3), as well as reducing the effect of the higher hardness of the alloy with 180/1h treatment (HB = 157) compared to that obtained with the 180/2h treatment (HB = 140), by the higher level of resilience (KCU= 14.1 J/cm^2 for the 180/1h treatment, compared to KCU = 12.9 J/cm^2 for the 180/12h treatment).

Chapter conclusions

1. The photographic, microscopic images and the values of the reference parameters (Mmax and vs) show that the structure of the MARTOR alloy (laminated semi-finished product - without heat treatment) has the highest resistance to the cyclic stresses of the vibrating cavitation, and the weakest is that of the structure results from the 12-hour treatment;

2. The fact that the structures of the three treatments led to mechanical properties with different values and to different behaviors/strengths justifies the importance of the volume heat treatment of artificial aging at 180^{0}C, as a technological solution for application to parts made of aluminum alloy 7075 working in cavitation regime, such as boat/ship propellers, household pump rotors and the cooling system of thermal engines.

3. Images obtained with optical, stereo and scanning electron microscopes show caverns of various sizes, created by breaks in the base material and by expulsions of intermetallic compounds, which confirm the differences in the resistance of the structure to the cyclic stresses of cavitational microjets.

4. The exponential evolutions on the first part, with the tendency of linearization on the second part of the cavitation, of the averaging curves of the M(t) results and of increasing towards a maximum value, with a

decrease towards the stabilization value, of the v(t) curves confirm the hardening of the layer required by the shock waves and the cavitational microjets, as well as the damping effect created by the air/water penetrated into the caverns during the compression phase of the oscillatory mechanical system.

5. The high accuracy of the vibration cavitation erosion test experiment and the processing of the results, for all 4 states of the alloy, is proven by the low values of the standard deviations σ = 0.176 ...0.251 and the high values of the tolerance interval of 97 %.

Chapter 5
Investigation of cavitation resistance of 6082 alloy

The results of the test of resistance and behavior to the erosion of vibrating cavitation, of the structures of this alloy, in the rolled state (of semi-finished product) and in the states resulting from the thermal treatment of artificial aging at 180 ^{0}C with three durations (one hour, 12 hours and 24 hours), are rendered through specific diagrams, photographic and microscopic images.

Comparison of results

To highlight the differences in resistance to cavitation, between the 4 states, the histogram from fig. 5.1 was constructed.

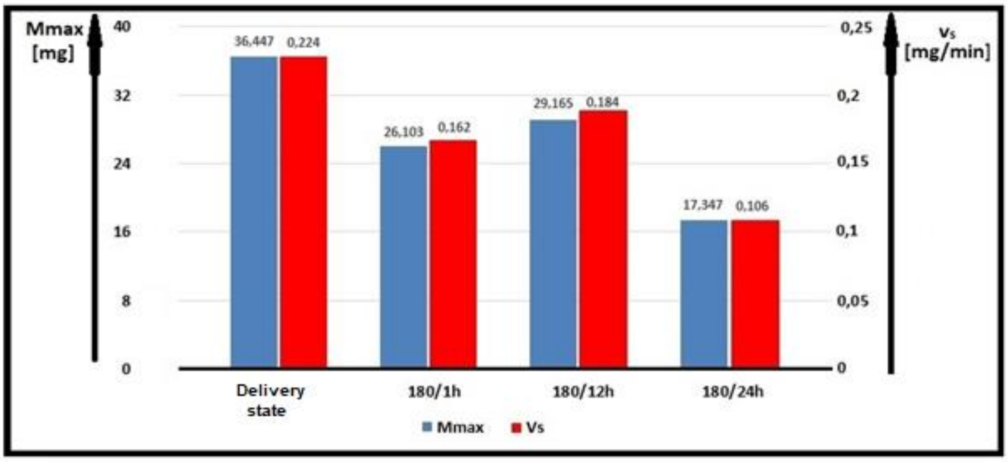


Fig.5.1 Histogram of the comparison of resistance to erosion by vibrating cavity (6082)

From the point of view of the resistance of the structure to the erosion of vibrating cavitation, the data from the histogram show that the highest resistance is that conferred by the structure of the sample obtained through the 180/24h heat treatment regime, of artificial aging at 180 ^{0}C lasting 24 hours, in the first row due to the highest values of the mechanical strength properties (R_m = 406.52 MPa, $R_{p0.2}$ = 331.97 MPa, HB =81.30 daN/cm^2) which, according to the values of the parameters M_{max} and v_s , compared to the structure of the alloy in the semi-finished state (Control) is about 2 times higher, and the face obtained by the thermal aging treatment 180/1h is by (50..52) % and compared to the one obtained by the thermal aging treatment 180/12h is higher by (68...73)%.

Chapter conclusions

1. The photographic, microscopic images and the values of the reference parameters (M_{max} and v_s) show that the structure of the alloy subjected to the improvement heat treatment at 180 ^{0}C for 24 hours has the highest resistance to the cyclic stresses of vibrating cavitation, due to the high values of the mechanical resistance to breaking R_m, the yield strength R_{p02} and HB hardness, and the weakest is that of the control sample structure (semi-finished state).

2. Images obtained with optical, stereo and scanning electron microscopes show caverns of various medium and large sizes, such as pits and trenches, created by breaks in the base material and by expulsions of intermetallic compounds, which confirm the differences in the resistance of the structure to cyclic stresses of cavitational microjets.

3. the increase in the resistance of the structure to cavitation stresses is strongly dependent on the values of hardness (HB), yield strength (R_{p02}) and mechanical resistance to rupture (R_m) - in that order.

4. The high accuracy of the vibration cavitation erosion test experiment and the processing of the results, for all 4 states of the alloy, is proven by the high values of the standard deviation σ = 1.093 ...2.215 and the high tolerance interval of 98 %.

Chapter 6
Investigation of cavitation resistance of 2017A alloy

The results of the research are presented through experimental values, analytical curves approximating these values, photographic images from the most suggestive cavitation durations and microscopic images of the eroded structure.

The determination of the experimental values of the cumulative eroded mass M_i and of the erosion velocities v_i was carried out with the relations (3.1) and (3.4) based on the mass losses (Δm_i), and the analytical averaging curves M(t) and v(t) have were constructed with relations (3.2) and (3.3).

Comparison of results

. Highlighting the differences in cavitation resistance between the 4 states is achieved by comparing the values of the two characteristic parameters displayed in the histogram from fig.6.1.

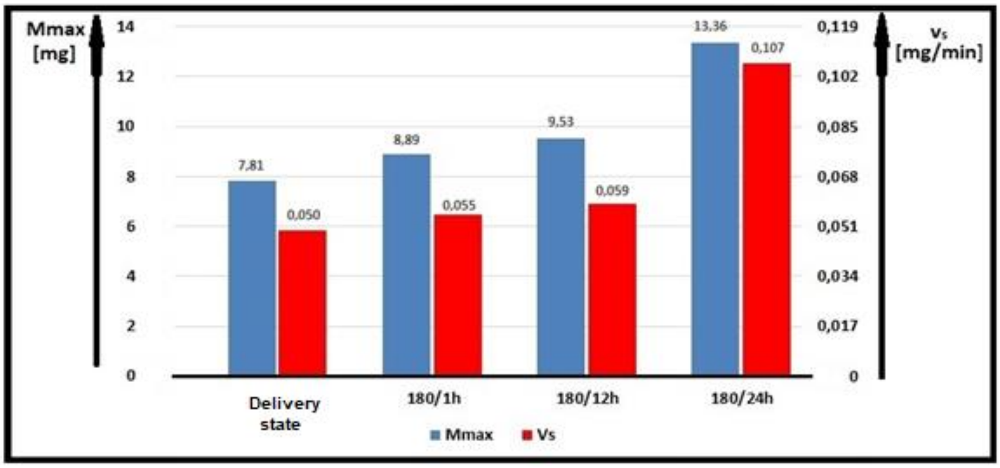


Fig. 6.1 Histogram of the comparison of resistance to erosion by vibrating cavity (2017A)

Datele din histogramă, prin compararea valorilor celor doi parametrii, arată că cea mai mare rezistență este ce conferită de structura probei martor, prelevată direct din starea de semifabricat laminat, iar cea mai slabă este cea a probei 180/24, pentru care durata de menținere la 180 ^{0}C a fost de 24 ore.

6.6 Chapter conclusions

1. The photographic, microscopic images and the data contained in the diagrams specific to the behavior and resistance to cavitation of the structures of the 2017A alloy samples, in 4 different states (laminated semi-finished product, with artificial aging treatments at 180 ^{0}C with holding times of one hour, 12 hours and 12 hours), shows that;

- the structure of the laminated semi-finished product has the highest resistance to the cyclic stresses of the vibrating cavitation (the MARTOR sample), and the weakest is that of the structure resulting from the 180/24h treatment;
- the structures resulting from thermal treatments with durations of one hour (180/1h) and 12 hours (180/12h), have very close cavitation resistances, with small differences visible also through the microcavities formed and the parameter values (M_{max} and v_s).

2. The research carried out on the 2017A alloy must continue for other values of the holding time at the aging temperature of 180 ^{0}C until a structure is obtained whose resistance to cavitation is higher than that of the semi-finished product (WITTER sample).

3. Macro and microscopic images show the effect of brittle intermetallic compounds and mechanical properties (some that aid cavitation resistance (R_m, $R_{p0.2}$ and HB) and others that decrease cavitation resistance (A5 and KCU)), through caverns of various sizes created by tearings from the base material and by expulsions of intermetallic compounds.

4. Cavern shapes from microcraters to craters with various shapes and sizes are determined by the sizes and geometric shapes of intermetallic compounds and base metal grains.

5. Corroborated with similar results obtained in other laboratories, on other brands of aluminum alloy, it follows that, in this case, the increase in the resistance of the structure to cavitation stresses is strongly dependent on the hardness values (HB).

6. Exponential evolutions on the first part, with the tendency of linearization on the second part of the cavitation, of the averaging curves of the M(t) results and of an increase towards a maximum value of the v(t)

curves, with a decrease or not towards the stabilization value v_s, reconfirms the mechanical hardening and damping mechanism of air and water entering the caverns.

7. The correct execution of the cavitation test program, on all samples, regardless of the condition, as well as the accuracy of the results obtained, are proven by the low values of the standard deviations σ = 0.173...0.712 and high values of the tolerance interval of 97 %.

Chapter 7
Evaluation of the strength of structures by comparing the values of the reference parameters

In this chapter, the cavitation resistance of the three aluminum alloys will be analyzed, with four states (rolled semi-finished product and volume thermal treatment of artificial aging at 180^{0}C with durations of one hour, 12 hours and 24 hours), by comparing the values of the parameters of reference recommended by the ASTM G32-2016 standards and used in laboratory practice [12, 25].

Correlation of mechanical properties with cavitation resistance

In order to be able to make a relevant analysis on the causes that led to certain cavitation behaviors, of the structures of the studied alloys, with thermal treatment of artificial aging at 180 ^{0}C with three holding times (1 hour, 12 hours and 24 hours), and taking into account due to the fact that, from a microstructural point of view, the changes are insignificant, the diagrams related to this subchapter show the correlations of the five mechanical properties with the resistance to cavitation (R_{cav}), the defining parameter for the structure's resistance to cavitation stress [122].

<u>**Note**</u>: The parameter R_{cav} is defined based on the value of the stabilization velocity (v_s) of erosion (toward which the curve v(t) tends to stabilize at 165 minutes - see the legends of the diagrams containing the averaging curves and the experimental values v_i), according to the relation :

$$R_{cav} = \frac{\rho \cdot \pi \cdot d_p^2}{4 \cdot v_s} = [\mu m/min] \qquad (7.1)$$

Unde:

v_s - is the value of the erosion stabilization speed during the period (see the legends in the specific diagrams)

d_p - is the diameter of the surface of the area affected by cavitation (see tables 4.1...4.4-for alloy 7075, 5.1...5.4-for alloy 6082 and 6.1...6.4, for alloy 2017 A)

ρ - density of the aluminum alloy (alloy 7075 = 2.8 g/cm^3, alloy 6082 = 2.7 g/cm^{3}alloy 2017 A= 2.8 g/cm^3)

These diagrams show the trend of influence of the strength of the structure by each property.

The reason for constructing these diagrams is the fact that the relationships of influence of the mechanical properties, centralized by Garcia et al. in [53], and repeated by many researchers in their works, such as Franc et al. in [51], are links of the penetration speed of erosion (MDER), direct or combined, with surface hardness, mechanical resistance to breaking, resilience (see forms (1.1)).

<u>Clarification</u>: In previous analyses, the cumulative effect of the 5 properties was taken into account. The individual effect being decisive only when 4 of the properties are equal in value.

To construct these diagrams, the values from table 7.1 are used.

Table 7.1 Cavitation resistance values and mechanical characteristics

Alloy	State	R_{cav}	Rm	Rp	HB	KCU	A5
		[min/µm]	[MPa]	[MPa]	[daN/cm^2]	[J/cm^2]	[%]
7075 laminate	delivery state	21.27	531.841	424.82	140	12.8	6
	180/1h	12.82	549.549	410.55	157	14.1	5
	180/12h	8.92	339.549	203.66	91.3	7.8	5
	180/24h	12.98	570.921	417.51	140	12.7	4.5
6082	delivery state	2.46	226.05	161.71	67	25.9	13.58
	180/1h	3.39	328.98	155.21	67	8	11.88
	180/12h	4.44	249.81	181.87	67	24	20.37
	180/24h	5.1	406.52	331.97	81.3	16.3	16.04
2017A	delivery state	10.2	291.16	225.01	121	29.1	19.43
	180/1h	9.43	274.22	126.4	84.9	25.3	24.26
	180/12h	9.17	281.11	135.68	80	14.3	14.49
	180/24h	5.58	281.11	140.09	74.9	14.5	12.58

5083 laminate	delivery state	2.08	229.65	122.68	79	4.8	6.3
	180/1h	5.88	276.14	146.6	82.5	5.3	6.5
	180/12h	12.65	317.09	147.51	86.1	5.3	6.5
	180/24h	31.25	324.53	155.43	87.1	5.3	6.5
7075 laminate	140/1h	22.72	344.55	205.94	86.1	5.4	5.6
	140/12h	8.13	355.93	232.27	95.5	9.6	6.3
	140/24h	31.25	595.22	451.37	146	12.8	9.5
	120/1h	9.61	247.17	154.27	89.5	4	5.4
	120/12h	16.39	343.4	210.99	76.5	4.9	5.8
	120/24h	10.41	354.05	210.03	86.1	7.2	6.4
7075 cast	delivery state	4.4	225	175	74.5	6	6

Histograms of comparison of reference parameter values

The following figures show histograms of the comparison of the values of the parameters characterizing the structural resistance to cyclical local fatigue (destruction by erosion). These are according to the condition of the alloy and the technological parameters of the heat treatment to make it artificial at 180 ^{0}C.

In the histogram in fig. 7.1, the cavitation resistances of other structures in the state of laminated semi-finished products are compared. To increase the degree of confidence, data related to the strength of the laminated 5083 alloy structures [77, 188] (R_m = 226.65 MPa, $R_{p0.2}$ = 122.68 MPa , HB = 79 daN/mm^2, A5 =6%, KCU = 4.8 J/cm^2) and of the semi-finished cast 7075 alloy [124] (R_m =225.75 MPa, $R_{p0.2}$ = 175 MPa, HB = 74.5 daN/cm^2, A5 = 6 %, KCU = 9.5 J/cm^2).

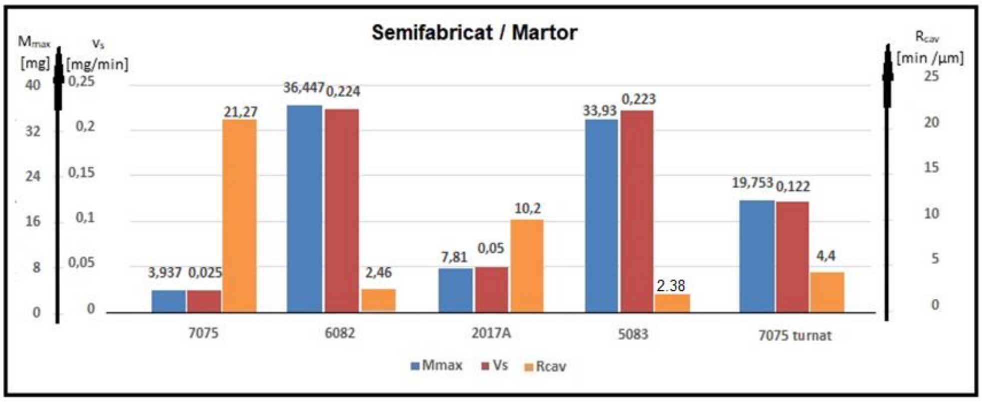


Fig. 7.1   Histogram of the comparison of the parameters of the resistance to erosion by cavitation (semi-finished states –delivery state samples)

The data from the histogram shown in fig. 7.1 shows the highest resistance to cavitation erosion has the structure of alloy 7075 and the weakest has the structure of alloy 6082;

In the histogram in fig.7.2, the cavitation resistances of the investigated alloy structures are compared, with thermal treatments of artificial aging at 180 ^{0}C and with a holding time of one hour. To increase the degree of confidence, the data related to the strength of the laminated 5083 alloy structure was also introduced [77, 188].

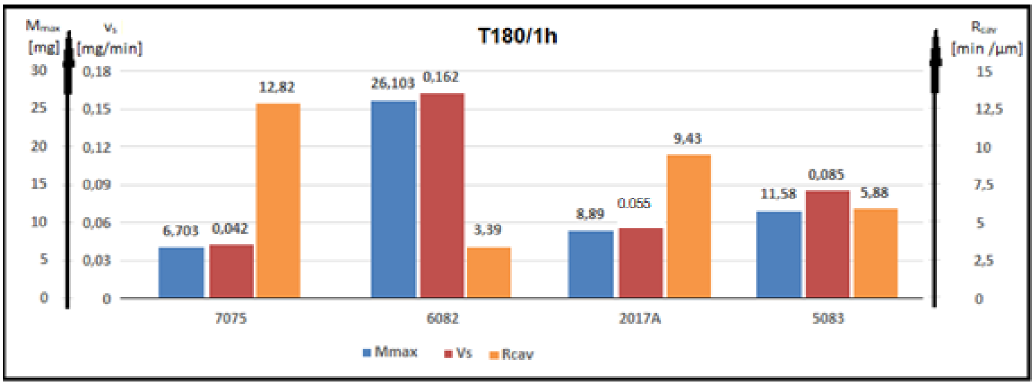


Fig. 7.2   Histogram of the comparison of parameters of resistance to cavitation erosion (treatments 180/1h)

The data from the histogram shown in fig. 7.2 shows that the structure of alloy 7075 has the highest resistance to cavitation erosion and the structure of alloy 6082 has the weakest.

In the histogram in fig.7.3, the cavitation resistances of the alloy structures of the studied alloys are compared, with thermal treatments of artificial aging at 180 ^{0}C and with 12-hour holding times. To increase the degree of confidence, the data related to the strength of the laminated 5083 alloy structure was also introduced [77].

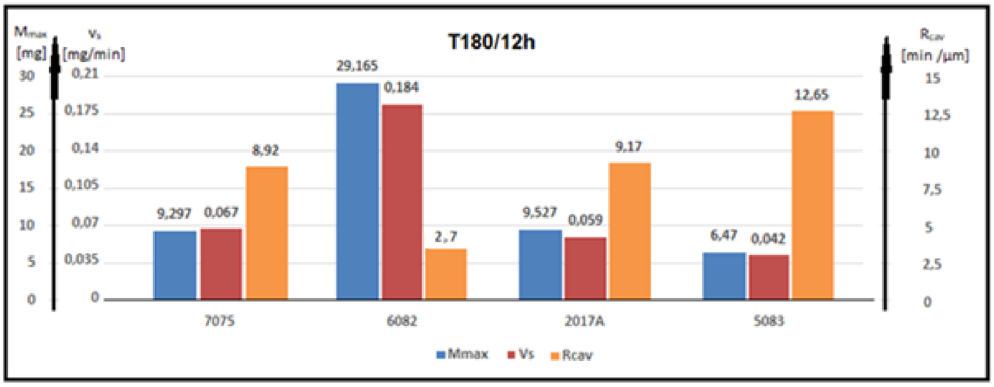


Fig. 7.3 Histogram of the comparison of parameters of resistance to cavitation erosion (treatments 180/12h)

The data from the histogram shown in fig. 7.3 shows that the structure of alloy 5083 has the highest resistance to cavitation erosion and the structure of alloy 6082 has the weakest.

In the histogram in fig. 7.4, the cavitation resistances of the alloy structures of the studied alloys are compared, with thermal treatments of artificial aging at 180 ^{0}C and with maintenance times of 24 hours. To increase the degree of confidence, the data related to the strength of the laminated 5083 alloy structure was also introduced [77, 188].

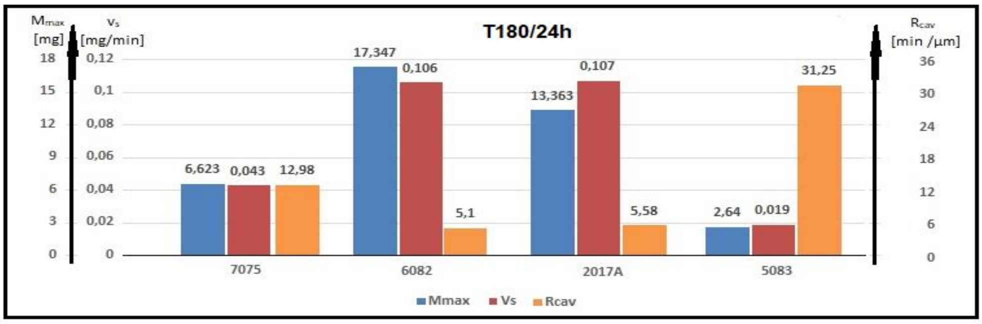


Fig. 7.4 Histogram of the comparison of parameters of resistance to cavitation erosion (180/24h treatments)

The data from the histogram shown in fig. 7.4 shows that the structure of alloy 5083 has the highest resistance to cavitation erosion and the structure of alloy 6082 has the weakest.

In the histogram in fig. 7.5, the cavitation resistances of the 7075 alloy structures are compared, with thermal treatments of artificial aging at 180 ^{0}C, 140 ^{0}C, 120 ^{0}C and with identical holding time of one hour.

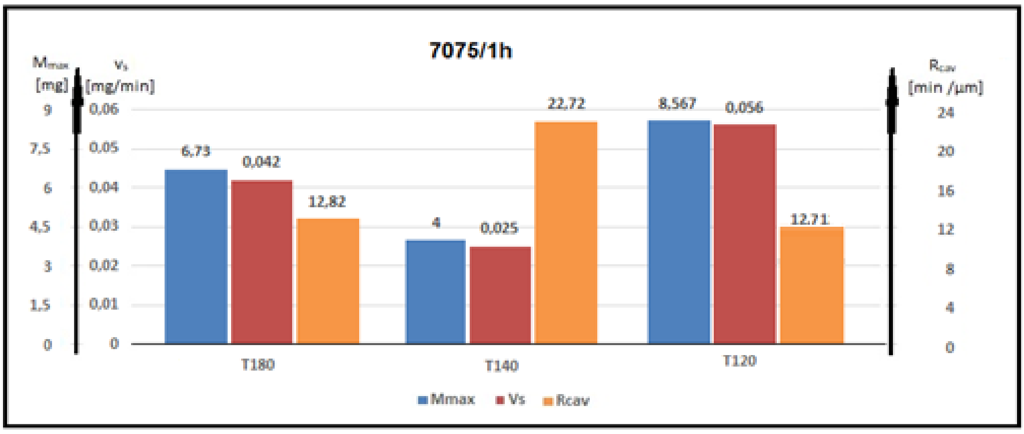


Fig. 7.5 Histogram of comparison of cavitation erosion resistance parameters of alloy 7075 with different artificial aging temperatures (180 ^{0}C, 140 ^{0}C și 120 ^{0}C) and holding time of one hour

The data from the histogram shown in fig. 7.5 shows that the structure of the alloy with T140 treatment has the highest resistance to cavitation erosion, and the structure of the alloy with T120 treatment has the weakest.

In the histogram in fig. 7.6, the cavitation resistances of the 7075 alloy structures are compared, with thermal treatments of artificial aging at 180 ^{0}C, 140 ^{0}C , 120 ^{0}C and with identical holding time of 12 hours.

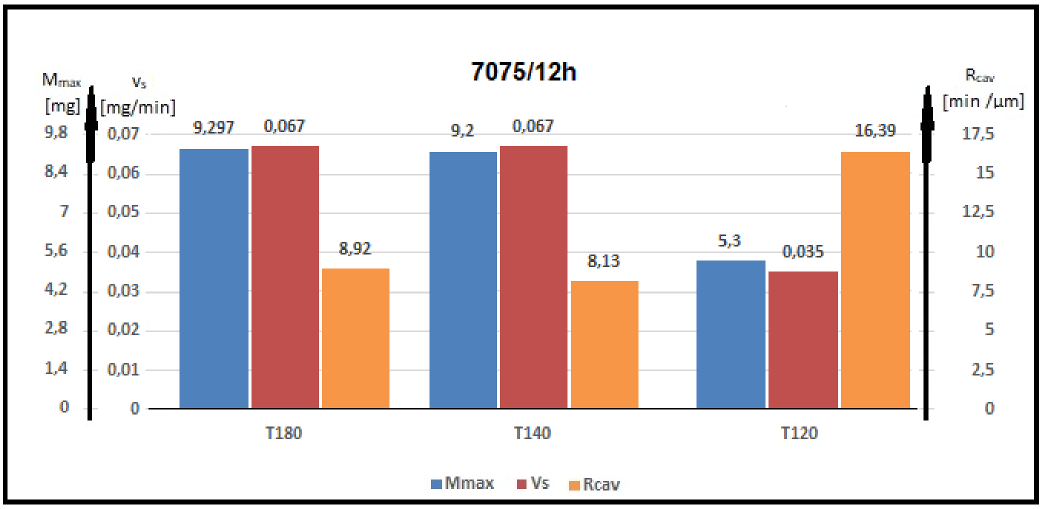


Fig. 7.6 Histogram of comparison of cavitation erosion resistance parameters of alloy 7075 with different artificial aging temperatures (180 ^{0}C, 140 ^{0}C și 120 ^{0}C) and holding time of 12 hours

The data from the histogram shown in fig. 7.6 shows that the alloy structure with T120 treatment has the highest resistance to cavitation erosion, and the alloy structures with T140 and T180 treatments are lower.

In the histogram in fig.7.7, the cavitation resistances of the 7075 alloy structures are compared, with thermal treatments of artificial aging at 180 ^{0}C, 140 ^{0}C , 120 ^{0}C and with the same holding time of 24 hours.

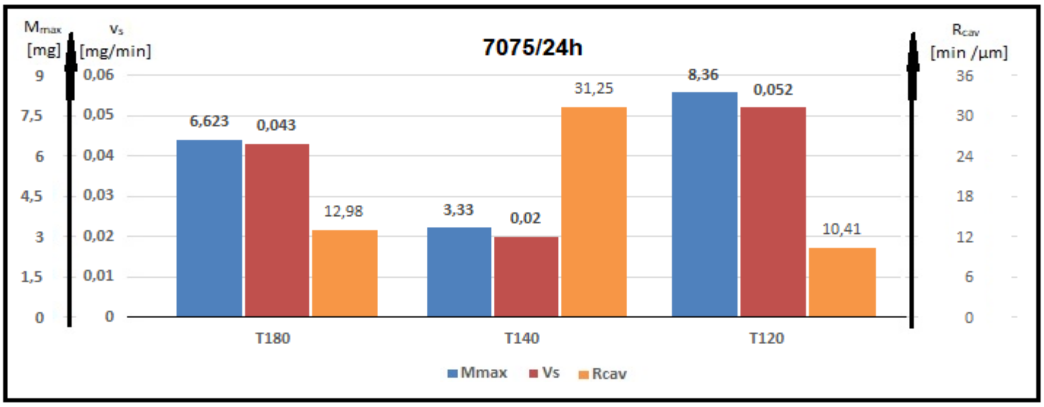


Fig. 7.7 Histogram of comparison of cavitation erosion resistance parameters of alloy 7075 with different artificial aging temperatures (180 ^{0}C, 140 ^{0}C și 120 ^{0}C) and holding time of 24 hours

The data from the histogram shown in fig. 7.7 shows that the structure of the alloy with T140 treatment has the highest resistance to cavitation erosion, and the structure of the alloy with T120 treatment has the weakest.

Conclusions

Strength comparisons show that there is no law by which the strength of the structure of different aluminum-based alloys correlates with the microstructure and mechanical properties, so that it can be predicted with certainty whether or not an increase is obtained, compared to the strength of the semi-finished structure, by using identical heat treatment regimes (temperature and holding time) or different ones (either by temperature or by holding times).

The comparative histograms also show that different alloys can have cavitation resistances of close order, for the same heat treatment regime

Chapter 8
General conclusions. Synthesis of main contributions. Future research directions

8.1 General conclusions (selection)

From the completed documentation, from the results of experimental research and from the analyzes carried out, the following general conclusions can be drawn:

- for many years, after the discovery, aluminum and its alloys were used for household items (dishes), ornaments and resistance structures;
- the modification of the mechanical properties, by alloying with different chemical elements, led to the obtaining of various types of alloys, called duralumin, due to the increase in the values of the mechanical properties, at a level comparable to that of low-alloyed carbon steels, a fact that led to the amplification of the use of these alloys in all fields, among which stand out: automotive, aviation, naval, sports and military equipment;
- the development of bulk and surface thermal treatment technologies, as well as modern ones (such as mechanical hardening using a laser beam and WIG remelting), through which the obtained microstructure acquires modified mechanical properties compared to the semi-finished state, has led specialists to use these technologies for aluminum alloys to be able to use them also for parts that work in cavitational currents, of various destructive intensities;
- although research into the behavior and resistance of aluminum-based alloy structures to cyclic cavitation stresses is in full swing, it has not been possible to elucidate the destruction mechanisms due to the complexity of the hydrodynamics of cavitation, the mechanical behavior and the dependence of this resistance on the mechanical characteristics (R_m, $R_{p0.2}$, A5, HB, KCU), the type and variety of intermetallic compounds;
- the research carried out within this thesis, on the three aluminum alloys, each with four different states, shows that erosion is manifested simultaneously through the mechanisms of ductile fracture and fatigue cracking, forming craters of various sizes, isolated and dispersed throughout surface;
- for the evaluation of the behavior and resistance to cavitation, it is recommended to use the specific diagrams, due to the data contained, regarding the values of the parameters recommended by the ASTM G32-2016 norms (M_{max}, R_{cav}, v_s), to the statistics of experimental data processing (tolerance interval and average standard deviation) and to the shapes of the averaging curves of the experimental values M(t) and v(t);
- the information about the behavior and resistance to cavitation erosion is credible if the analysis based on the curves and parameters specific to cavitation erosion is complemented by the one made on the basis of the macroscopic images from various moments of the cavitation attack and on the basis of the microscopic ones obtained with high-resolution microscopes (stereo , SEM, etc.);
- the use of volumetric heat treatments for artificial aging is a solution to change the resistance to cavitation of aluminum alloys if, through the parameters of the heat treatment regime (temperature and holding time), high values are obtained for R_m, $R_{p0.2}$ and HB and low for A5 and KCU;

8.2 Synthesis of main contributions (selection)

The significant contributions made in this thesis, through documentation and experimental tests, carried out on the 36 samples (3 for each state), beyond those mentioned in each chapter, are:

- highlighting the dependence of the strength and behavior of the structures of aluminum alloys 7075, 6082 and 2017A on the microstructure, chemical composition and mechanical properties, especially hardness, determined by the duration of maintenance at the artificial aging temperature of 180 ^{0}C;
- investigation of the behavior and resistance to cavitation, of aluminum alloys 7075, 6082 and 2017A, in four states: one delivered (rolled semi-finished product) and three differentiated by the holding times (one hour, 12 hours and 12 hours) at the artificial aging temperature of 180 ^{0}C, which showed that only for alloy 6082, for all holding times, a significant increase in resistance to cavitation erosion was obtained. For the 2017 A and 7075 alloys, the strength of the semi-finished structure, without heat treatment, is higher (at most by a small difference) than those obtained by artificial aging heat treatments at 180 ^{0}C, regardless of the holding time;
- carrying out morphological investigations of the structure degraded by cavitation, with the presentation of quantitative data, based on macro and microstructural images, using cameras and microscopes;
- carrying out deep analyzes of the behavior of the structures during cavitation erosion, based on the dispersion of the experimental values, the evolution of the specific curves M(t), v(t) and the values of the characteristic parameters (M_{max}, v_s and R_{cav});
- highlighting the increase in resistance to cavitation, the structures of the three aluminum alloys (7075, 6082 and 2017A) with the increase in the values of hardness (HB), mechanical resistance to breaking (R_m), yield strength ($R_{p0.2}$) and with the decrease in the values for elongation at break (A5) and resilience (KCU);
- the analysis of the causes that led to the differences between the strengths of the structures of the investigated alloys, using the comparative histograms and other results obtained on the same alloy (7075), with different heat treatment regimes (temperature and/or holding times), respectively with the state of the blasted semi-finished product (7075 cast);

- justifying the continuation of research on other types of aluminum alloys, respectively for other regimes of thermal treatment of artificial aging, in order to obtain the resistances necessary for the use of these aluminum-based alloys in parts working in moderate or industrial cavitation conditions);

8.3 Future Research Directions

The results of the research lead to the formulation of new directions of study, which can be carried out on aluminum-based alloys, so that they can be used for cavitationally stressed parts, with intensities above the average (industrial) ones. Below are 4 of them:

1. continuation of the studies on regimes with the same temperature (180 ^{0}C) but other maintenance times;
2. expanding research on other types of aluminum-based alloys, such as those in class 3****, 4**** or 8****;
3. the use of modern technologies for hardening the structure of surfaces exposed to cavitation, such as: mechanical hardening with sonic spots, with balls, with the laser beam, by WIG remelting;
4. finding correlation relationships between mechanical properties and the cavitational erosion parameter ($MDER_s$, R_{cav}, MDE_{max}, etc.), which allow the prediction of resistance to mechanical stresses.

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