MECHANICAL STRENGTH AND HARDNESS FOR ALUMINIUM ALLOYS USED FOR HEAT ENGINE PISTONS

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***Abstract**: Aluminum alloys are used for building heat engine pistons. Were developed and studied four types of alloy from Al-Si and Al-Cu systems. To determine the influence of temperature on the properties and states in alloys studied. (continuous heating to 300^{0}C) and keeping time at higher temperatures to reproduce as accurate posible the real operating cycles for pistons engine have been determinations of mechanical strength R_m [daN/mm^2] and hardness HB [daN/mm^2]. Was varied maintaining times a certain temperature in the heat treatments to achieve stabilization of the mechanical characteristics. Heat treatment applied consisted in a hardening and a return at hot. Discuss the usefulness of heat treatment relative to the piston engine operating temperature.*
***Key-words:** aluminium alloys, engine pistons, heat treatment, hardness HB, stabilization time*

1. INTRODUCTION

Aluminum alloy are used for the heat engines pistons. A series of heat treatments are used in different situations to modify the structure and improve mechanical properties of cast aluminum alloys.

In study [1] is presented on the heat treatment effect of aluminum alloy 7050. Zn is the main component of alloy and is used in aviation industry. For heat treatment of 7000 series alloys T6 heat treatment provides good strength but poor corrosion resistance. With over aging improves corrosion resistance but decreases the mechanical strength. It requires obtaining the mechanical strength of T6 and corrosion resistance of the T73 heat treatment. Aging heat treatments are proposed in three steps, the aging treatment, and recovery and re-aging. The authors show that a return rate of 57°C/min is favorable to increase mechanical properties. Hardening phases in the matrix are mainly precipitated phases η', GP zones, boundaries of the grains and localized precipitation and discontinuous phases η.

The effect of heat-treatment on the mechanical properties of aluminum-based piston alloys has been investigated by [2] AlCu4MgNi alloys and AlSiCuMgNi alloys with 10.5%, 12%, 18% and 24% Si were utilized for this purpose. After melting, alloys have been cast in the metal mold at 800°C and solidified. The solution treatment has been performed at 500 °C for 5 h and then quenched. The samples have been aged at 180 °C for 9 h to observe the effect of aging on hardness properties.

The response to T6 heat treatment of extruded thixoformed 2014 aluminum alloy was investigated by [3]. Peak hardness is attained after 16h at an ageing temperature of 160 ^{o}C following a solution heat treatment at 500 ^{o}C. While the time-to peak hardness is the same in extruded and thixoformed 2014 alloys, the peak hardness obtained with the latter is higher, suggesting a superior age hardening capacity for the latter. The favourable impact of thixoforming process is attributed to the change in grain boundary chemistry upon thixoforming. The segregation of Si , as well as of Cu, to the grain boundaries during soaking prior to thixoforming facilitates the formation of the ternary Al-Si-Cu eutectic with relatively lower melting point at the grain boundaries. It is easier to dissolve the eutectic network at the grain boundaries and triple junctions than coarse Al_2Cu particles entrapped insaide the grains. The tixoformed alloy thus enjoys a higher amount of solute Cu after the solution heat treatment and higher age hardening capacity.

The paper [4] presents images of the structure of aluminum alloys before and after heat treatments.

The study [5] presents applications of heat treatments (RRA) (retogresion and re-aging) which aimed to improve corrosion resistance while maintaining mechanical properties due by T6 heat treatment. It was shown that the first stage of recovery re-dissolving GP zones and η' phase lower mechanical strength is followed by an increase in the volume of phases η and η' leading to a further increase in mechanical strength but overall there is a decrease of the mechanical properties. Structure and chemical composition of heat treated aluminum alloys was analyzed in the paper (Svenningsen, 2006) [6]

The paper [7] investigated the effect of a two-step solution heat treatment on mechanical proprieties and silicon-rich phase of 332 aluminium alloy. Traditional single-step T6 solution (495 ^{o}C /6h) increases the hardness value of the alloy by 5.96%, increased the tensile strength by 20.4% and reduced the elongation by 3.9%. Two step solution treatment of the alloy (495 ^{o}C/ 2h, followed by 514 ^{o}C/4h) increased the hardness value of the alloy by 6.64%, increased the tensile strength by 16.01%, and reduced the elongation by 4.67% compared to as-cast samples. Both solution treatments were followed by hot water quenching (75-90^{o}C) and artificial aging at 250 ^{o}C for 4h. The diference in mechanical proprieties after heat treatment can be linked to the refinement and spheroidasation of silicon-rich phase in the alloy.

It has been demonstrated [8] that the strength of an Al-Si-Cu alloy is maximized by high temperature solution (807-273) ^{o}C which is approximately 16^{o}C higher than the ternary eutectic temperature. The dual-energy K-edge subtraction imaging technique has been employed to obtain the spatial distribution of copper and change during its solution treatment in three dimensions quantitatively, providing interpretation of the improved mechanical proprieties in terms of age-hardenability an its spatial variation. It has been also confirmed that the occurrence of incipient local melting and the accompanying growth of micropores adjacent to melt regions lead to fractures caused by these defects. However, it can be inferred that the positive effects can outweigh the negative effects even above the eutectic temperature, thereby realizing strength at such relative high temperature levels.

In the paper [9] was studied T7 heat treatment on thermal properties forming and hardening of A319 alloy microstructure and break proprieties due accumulation of internal cracks. In work [10] were investigated different types of heat treatment of aluminum alloy 6063. Has been shown time and temperature used in heat treatment improves the mechanical properties but decreases plasticity. In work [11] were studied three aging treatments for aluminum alloy 7010. They also studied presence of cracks in the material.

In work [12] were presented studies of heat treatments applied on AA2618 alloy. This alloy contains Cu and Mg. These alloys are used in automotive pistons, pieces that are working at temperatures up to 300^{0}C. The aging treatment increases the mechanical strength using solution treatment followed by aging treatment. Solution Treatment is made from 530 °C for a period may be extended up to 24 hours for thick sections of material. For the resulting material has been a limited annealing at 385 ° C for 4 h followed by a slight cooling. Aging treatment (T61) is achieved by solution treatment, followed by heating in water at 200 °C for minimum 5h.

It was observed that the temperature at which the solution treatment has an effect on hardness. Increasing the temperature for solution treatment leads to a significant reduction in hardness.

Work [13] presents experiments on aluminum alloys heat treated T6 and then covered with layer of TiN 3μm thickness by physical vapor deposition method (PVD). From this is intended to improve mechanical strength and reduce the risk of fatigue fracture for studied alloys.

In work [14] was studied the influence of heat treatment on the 2024 aluminum alloys cylindrical samples in and plates of the same material with 0.3mm thickness.

In work [15] presents a study on the effects of heat treatment on microstructure and alloy stability for aluminum alloy ZL114A. The alloy belongs to Al-Si-Mg system, obtained by adding a certain amount of Mg in the alloy ZL101A. The alloy contains α solid solution and eutectic phase Mg_2Si and compounds with iron.

In [16] presented homogenization treatment of Al alloys to investigate the deformation and re-crystallization from cold. Were applied annealing treatment at 450 °C, 500 °C and 550 °C .It shows the structure of obtained alloys.

In work [17] was studied the effect of heat treatment on microstructure of A356 alloy (Al-7% Si-0.3mg). In alloy was added strontium. Was applied heat treatment T6 (solution treatment at 535 °C for 4 h and aging treatment at 150 °C for 15h). The other heat treatment was solution treatment at 550°C for 2h and aging at 170 ° C for 2h). They studied the effect of heat treatment on the microstructure and mechanical properties.

In work [18] was presented homogenization treatment on microstructure of 7B04 aluminum alloy. It starts from the primary eutectic melting temperature of 470°C. A heating with to 10°C/h and 64h and then maintaining at 500°C, after that a heating with 1°C/h were applied. Melting of eutectic phase was followed.

In work [19] was presented heat treatment with the alloy annealed at 413°C for 2.5 h, to study problems of tension and relaxation in the alloy. Stress-strain curve was determined at room temperature. It was shown that the maximum intrinsic energy barrier is 2.3 eV for dislocations movement which also is the specific magnitude for recovery processes.

The work [20] presented effects of heat treatment DAT (aging Treatment deformation) on the microstructure and mechanical properties of alloy 2618.

Heat treatment includes solution treatment to 535°C, quenching in water at room temperature and 1% plastic deformation followed by aging to reach maximum hardness at 200 °C.

In work [21] were presented heat treatment for aluminum deformed cold, roling aluminum plates. The practice of annealing treatment takes place at low temperature 200°C for 1h. Were analyzed theoretically and experimentally the mechanical strength and elongation.

In this paper we present heat treatments applied to aluminum alloys. Their properties were determined on two situations, in hot state and cold state. Running the engine makes aluminum alloys to work prolonged times at high temperatures. Hot Therefore their behavior in hot state is more important than in cold state.

The refractoriness of alloys refers to the degree of resistance to long-term joint action of high temperatures and stresses during operation. Refractoriness is determined by the sum of a lot of factors: physical, chemical, operational, technological and structural and others whose influence is manifested simultaneously, as a rule, these factors are interrelated to each other and have the connections. Dependence of alloys refractory of by chemical composition, structure and type of equilibrium diagram was rendered for the type Al-Mg alloys. The drawback of this research is that the tensile tests were conducted only for short-term resistance (R_m) at high temperatures. So, judging the influence of phase composition refractoriness of alloys was often wrong. These concerns mainly the Al-Mg alloys with a low creep resistance compared to high resistance for short durations.

In general it was found that alloying additions (It) which strongly deformed lattice but leads to a substantial increase in the bond between atoms.

Hence the conclusion: The long-term action of high temperature and load, the greater resistance to plastic deformation will be for solid solution that has a high strength of inter-atomic bond and a minimum lattice deformation. For example, as the high temperature that will be work the Al alloy for long time, the stronger will be the link between the base lattice of alloy and alloying elements that have a low diffusion coefficient in solid aluminum.

The refractoriness increases strongly with the group of transition elements, elements that provide: increases inter-atomic bonding with aluminum atoms, setting Ghinie-Preston zones of meta-stable phases (for example in alloys Al-Cu-Mn-Ce) and increase of coagulation for stable phases. All these phenomena lead to increased braking of oscillations movement, leading to increase the refractivity. As main factors influencing refractivity of aluminum alloys are: physic and chemical, structural, nature, quantity, form and distribution of eutectics and the secondary phases, technology, speed of crystallization of the melt, thermal treatments for aging and coagulation.

2. EXPERIMENTAL PROCEDURE

Selection criteria for studies of aluminum alloys has been determined to satisfy conditions to the engine pistons to ensure thermal refractory properties, friction at hot and cold, (under variable flow condition), low specific weight, but and good technological properties for molding and cutting.

Alloys were developed ATCu4Ni2Mg (1), ATSi13Cu2Mg (2), ATCu5MnTi (3), ATSi9Cu3MgMnB (4) .Alloys 1 and 3 have solution and alloys 2 and 4 have the predominant type eutectic structure.

The four types of complex aluminum alloys used to manufacture piston engines with internal combustion were developed in the Mechanical Factory Timisoara (U.M.T). Batches for each type of alloy were 100 kg. For the tests were cast in diecast for tensile test specimens according to STAS 200-61, on which were measured breaking strength and elongation values. Brinell hardness test samples were performed on broken tensile specimen ends. During the preparation conditions have been kept condition for change, purification and protection of metal bath.To test was provided an adequate number of samples for each point, taking into account here by providing the conditions for establishing a restricted area of dispersion of results.Thus the number of tests to determine his R_m and was at least three, making use of repeated measurements, where there were deviations accidental.

To determine hardness for each point have been a number of 12 prints. Two prints each of the six ends of the broken specimens. Of the total number of around 400 samples for each of the four types of alloy, half were treated heat, and half were tested after a minimum of 15 days from casting shell, without initial treatment.

During preparation for casting chemical analysis were performed, taking three samples namely early to mid-casting foundry and its end.

Samples from groups receiving heat treatment applied, were complied with the conditions imposed. (parameters for heating and heat treatment followed by the obtaining solution of artificial aging) from references.Treatment heating for obtaining solution was carried out in a Heraeus oven type with forced air circulation, ensuring a change in heating temperature of $\pm$ 5°C. The samples were mounted in a specially constructed grid, which provides a vertical position and also for abundant ventilation achieved a transmission assets as heat.Measurement characteristics Rm, A and HB on the four alloys in the two states (heat treated and untreated) was performed at 20^{0}C ambient temperature in continuous heating at temperatures of 60^{0}C, 100^{0}C, 140^{0}C,

For temperatures from above 220^{0}C namely, 220^{0}C, 260^{0}C şi 300^{0}C measurements were performed after prior thermal stress at the same temperature for samples 2, 6, 10, 14, 18 and 22 hours of maintenance. Time period 22 hours is time to maintain at temperature for that appears stabilized measured values of parameters, mechanical proprieties. Also after those thermal tretments were determined mechanical properties regained at cold. Breaking samples was performed on an Amsler type traction machine. Brinell hardness was measured on a device type Balanta Sibiu.

Tests at hot were performed in a furnace mounted vertically on traction machine, taking into account the conditions of temperature mixing by maintaining proper temperature. Specimen temperature was measured along the specimen with a Fe-Constantan thermocouple.

Hardness values at hot were measured in a tank heater unit mounted on Brinell device. The piece was immersed in a fusible alloy. Temperature was determined

180^{0}C, 220^{0}C, 260^{0}C, 300^{0}C.

by placing a thermocouple in hole with 3 mm diameter charged in the body of specimen.

The main study was aimed to carrying out mechanical tests on cast aluminum alloys in hot state without heat treatment and with heat treatment.

Heat treatment consisted in a hardening and a return at hot. Samples submitted for determining hardness were introduced in the melt alloy Wood, the hardness values depending on temperature are showed in Figure 1 for alloys no. 1 and no. 3 in for heat treated and untreated states. Temperature of 300 ° C was chosen from fact that engine pistons work at temperatures that not exceed this temperature. Testing was repeated for alloys with the eutectic structure (Figure 2), alloys no 2 and no. 4.

From Figures 1 and 2 is noted that the values of Rm and HB (considered minimum) at temperature of 300 ° C after heating continues, are very close, regardless of chemical composition and state of alloys and there is a small variation between values.

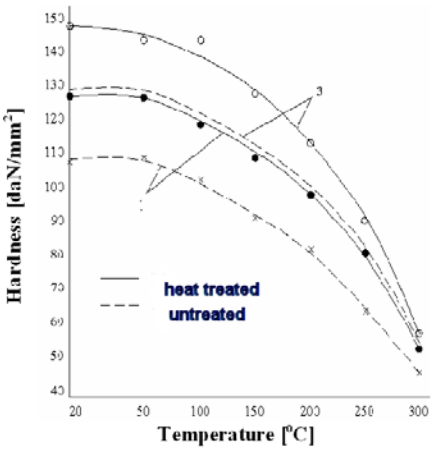


Figure 1. Variation of hardness with temperature for alloys. no.1 and no. 3

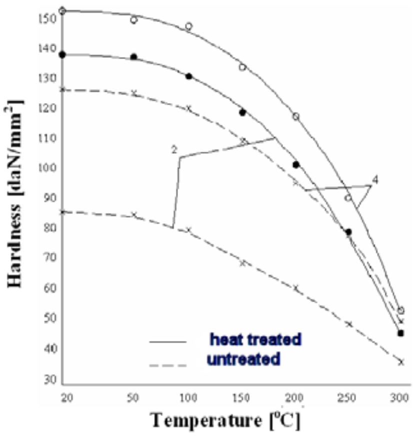
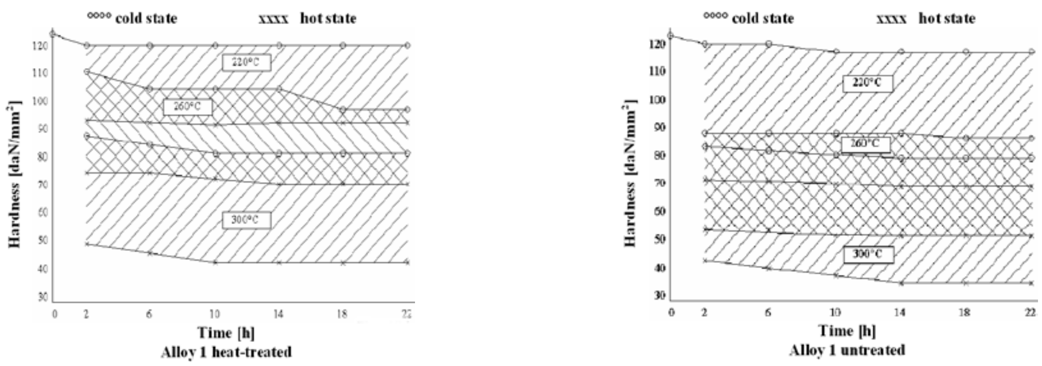


Figure 2. Variation of hardness with temperature for alloys no.2 and no. 4

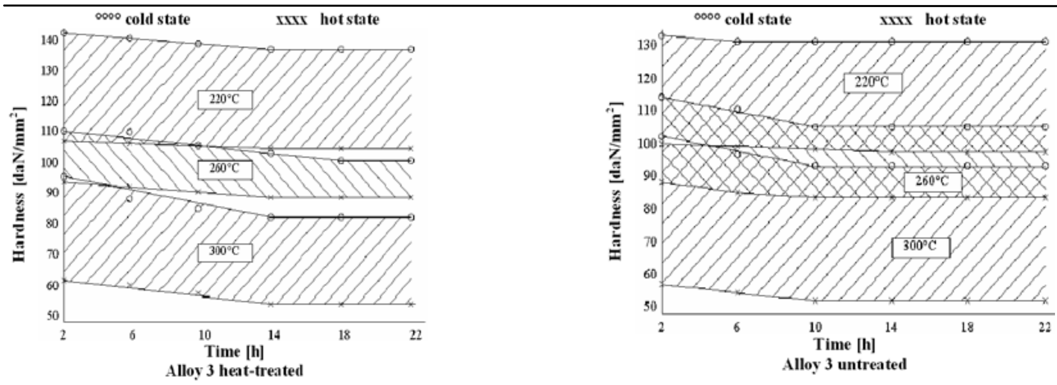


a) *b)*

Figure 3. Influence of retention time to obtain HB = constant, depending the temperature for alloy no.1, a-heat treated, b-untreated

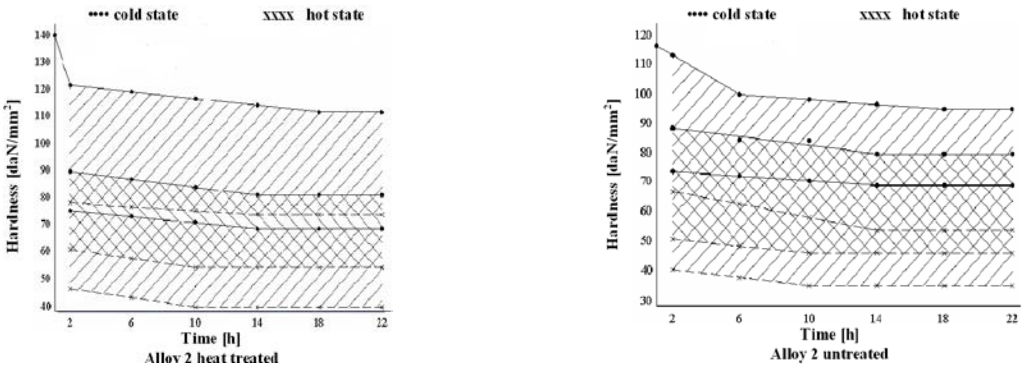
It follows that regardless of chemical composition or condition (heat treated or untreated), aluminum alloy with multiple alloying elements cast into pieces working at high temperatures (like piston motor) obtained after heating and then cooling, not significant differences in mechanical properties.

For castings pieces (aluminum alloys) that are working at higher temperatures the solvus line temperature of Al-Cu equilibrium diagram, will take place phenomena the dissolution of secondary phases in aluminum α solid solution o which then at cooling will be separate from the solution. So the structure is unstable at temperature variations, as is the case of thermal engines pistons, it is necessary to identify which are times required function of temperature, which to lead to stabilization of the structure, can therefore be considered to present a constant values of mechanical the properties in our case for hardness. For tests were admitted as tests temperatures 220, 260 and 300°C, because on the height of piston the temperatures are variable.



a) b)

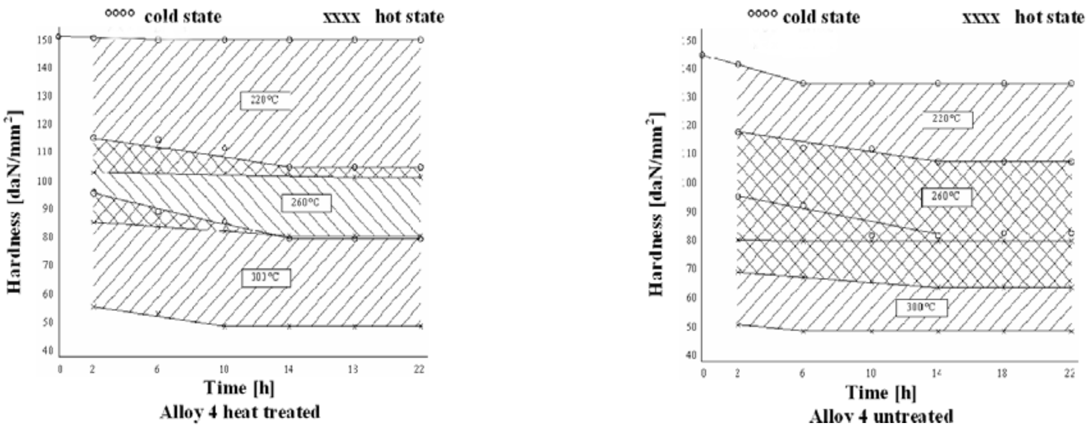
Figure 4. Influence of retention time to obtain HB = constant, depending the temperature for alloy no.3, a-heat treated, b-untreated



a) b)

Figure 5. Influence of retention time to obtain HB = constant, depending the temperature for alloy no.2, a-heat treated, b-untreated

Figures 3-6 showed influences retention times at different temperatures for testing to obtain a constant value of hardness (HB = constant). Hardness were measured in "hot state" at temperatures 220, 260 and 300 °C, then "cold state" after removing samples from Wood alloy and cooling them to ~ 20 °C.



a) b)

Figure 6. Influence of retention time to obtain HB = constant, depending the temperature for alloy no.4, a-heat treated, b-untreated

Table 1 shows the mechanical properties, tensile strength for samples of Φ12.5mm aluminum alloys cast in die, for untreated and heat treated states (improved).

Table 1 Breakthrough strength values R_m in hot state 300 °C and cold state 20 ° C for samples of alloys untreated and heat treated

Alloy	state	tensile strength R_m [daN/mm^2] untreated	heat treated
1	cold state	23	32.5
	hot state	16	20
2	cold state	20	27
	hot state	12	16
3	cold state	21	35
	hot state	15	16
4	cold state	37	42
	hot state	17	18

The results obtained for measuring the hardness in hot state and cold state (Table 2) shows that the maintenance at 300 °C until the HB = ct, HB is greatly reduced in both cases (Table 3) to the biggest loss of ΔHB_{abs} stands for alloys No. 2, 4 for hot state and heat treated, and the lowest for alloys the No.1 and No.3. For untreated state the greatest loss occurred for alloys No. 3 and 4.

Absolute values and differences for hardness listed in Table 3 lead us to conclusions very important for industrial practice.

It shows that R_m and HB are almost "leveled" at 300 °C this shows, paradoxically, that the heat treatment for cast aluminum alloys intended to obtain maximum values of mechanical properties at room temperature, called enhancement (quenching + return), is useless if the casting aluminum alloy pieces are used in operation at temperatures exceeding solvus line.

Table 2 Analyze of hardness variation, ΔHB_{abs} is the difference between HB_{max} at the ambient temperature (initial state) and HB_{min} obtained after initial stabilization at 300 ° C. Values for initial state take regardless of presence of heat treatment)

Alloy No.	State	$\Delta HB_{abs} = HB_{max} - HB_{min}$	
		heat treated	untreated
1	hot state	124 – 43 = 81	107 – 38 = 69
	cold state	124 – 77= 47	107 – 75 = 32
2	hot state	138 – 38 = 100	95 – 36 = 59
	cold state	138 – 69 = 69	95 – 69 = 26
3	hot state	148 – 55 =93	129 – 55 = 74
	cold state	148 – 84 = 64	125 = 94 = 35
4	hot state	152 – 50 = 102	127 – 48 = 79
	cold state	152 – 80 = 72	127 – 78 = 49

Heat treatment aimed at obtaining the maximum mechanical properties of aluminum alloys, quenching and tempering, is useless because after heating at a temperature above the temperature solvus line, because the phenomena that occur in solid solution α, these properties are reduced significantly. Actually occurs treatment "annealing or recovery" which is related to the initial state of the cast alloy.

Cast aluminum alloys, regardless of chemical composition and state (cast, heat treated), if are used in pieces working at temperatures exceeding line transformation of α solid solution, solvus line, is recommended to be heat treated at least the temperature at which they work (to stabilize the structure) and function status will be an annealing or recovery.

Figures 3-6 and Tables 3 and 4 show that: the difference Δ between the maximum of the properties acquired before heating tests at various temperatures (up to the constancy of properties) increased more since the test time (engine running) is longer. Heat treated alloys (quenched and tempered) maintain the mean property values around 61.5% for Rm baseline to 44.5% after continuous heating to maintain and stabilize property HB_m = 35 and 29.5% respectively. For the same test conditions for heat-treated alloys have Rm = 71.5 and 58% and HB_m = 39 and 34.2%.

More pronounced loss properties of heat treated alloys is due because at temperature of 300°C and especially warming continues to maintain this temperature-mechanical property values almost leveled while baseline is very different and much higher for heat treated alloys.

Table 3 HB values stabilized after maintaining at temperature of 300 °C

Alloy No.	State	HB initial		Time for stabilization [h]		Stabilized HB Values [daN/mm²]		Diference for HB stabilized values at 300°C $HB_{heat\ treated}-HB_{untreated}$
		heat treated	untreated	heat treated	untreated	heat treated	untreated	
1	hot state	124	107	10	14	43	38	5
	cold state			10	14	77.3	75	2.3
2	hot state	138	95	14	10	38	36	2
	cold state			14	6	68.8	68.8	0
3	hot state	148	129	14	10	55	55	0
	cold state			14	10	84	94	10
4	hot state	152	127	10	10	50	78	2
	cold state			14	14	80	45	2

Consequences of influences for temperatures and the operating time for heat engine pistons, leading to the leveling influence mechanical properties, regardless of chemical composition and state or heat treatment of alloys led to the development of alloys with high technological properties.

4. DISCUSSION AND CONCLUSIONS

Analyzing the variation of mean values of mechanical properties of refractory alloys used in casting pistons in untreated and heat treated states, both continuous heating to 300 ° C and to maintain high temperatures (cycles that replicate working mode of the engine) to stabilize the mechanical properties, we draw some conclusions of great importance to industrial practice. We have:

Aluminum alloys for casting parts working at high temperatures, including the pistons engine with internal combustion, regardless of their chemical composition and thermal treatment after casting, with continue increasing temperature to 300 ° C or maintaining temperatures of 220, 260 and 300 °C to obtain stabilization of properties, mechanical properties lose substantial value expressed by R_m and HB. Reduction (loss) mechanical properties is greater (heavy) as these properties have higher values before heating (continuous or maintaining at 220-300 ° C, alloy no. 4 heat-treated condition) as shown in Table 3.

Given the very similar size of proprieties for resistance and hardness values obtained for all alloys after continuous heating up to 300°C, both as absolute values and the differences between the maximum (at 20 °C) and minimum (at 300 °C), consider that the study on hardness only is sufficient to determine the influence of chemical compositions and heat treatments. This simplifies testing method, leading to savings of material, fuel and energy.

Values obtained in studies for influences continuous heating temperature and stabilization time to obtain constancy of properties of complex aluminum alloys, working at high temperatures indicates that alloys that containing alloying elements still that form inter-metallic compounds "stable" at high temperature, fully confirms the previous discussion on the influence on chemical composition and heat of treatments applied to Al alloys on the mechanical properties.

The pistons engine will heat and operate at different times and different temperature regimes, spread over height of piston. In Table 4 are presented influence of maintaining time at temperature to 300 ° C to on HB property values stabilized, the alloys heat treated and untreated (cold state and hot state).Was chosen for presentation only temperature of 300 ° C because at test temperatures T <300 ° C (as shown in Figures 3-6) R_m and HB properties have higher values.

Values of mechanical properties at operating temperature of the pistons are very low compared to the original, for cast alloys. At the operating temperature of the piston (considered to be over 300°C), practically, between the values of mechanical properties of alloys heat treated and untreated, there are no differences, which leads that the heat treatment aimed to obtaining maximum values of mechanical proprieties in cold state before engine running) is useless.

Properties (mechanical or physical) determinate on the piston material in the initial state "heat treated or untreated" is not conclusive and can not draw up a certificate that fairly characterize the functional qualities of the piston. Actual functional properties consider heating temperatures of the piston in the cylinder and the duration of application of these temperatures are lower relate to properties determined initial in cold state. This follows from the dynamic changes in heating aluminum complex alloys studied resulting quantitative and qualitative aspects of structural changes occurred.

Properties regained in cold state when the heating temperature exceeds a certain value, are lower than initial properties determinate in cold state.

Because the changes occurred by heating, thermal expansion coefficient of the material, causing a range of functional rearrange the piston - cylinder thermal game fits. If it is contemplated and that some types of engines to get the pistons reach temperatures regimes is up to 500^{o}C, in this case becomes more than the mandatory reconsideration of the principles underlying the choice of technology-based manufacturing aluminum pistons.

Determining the chemical composition and nature of alloying elements to the aluminum alloys, for casting pistons be considered primarily mechanical strength criterion hot state but not in cold state. This would increase the dimensional stability of the pistons which would reduce radial game fit level from design. These criteria would allow a substantial increase reliability of pistons, reducing fuel consumption and simplified manufacturing technologies.

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