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Use of the Precipitation Hardening to Improve the Properties of Combustion Engine Pistons Made of Eutectic Silumins

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Abstract

The study presents methods to be used for improving the performance parameters of car engine pistons made of EN AC-AlSi12CuNiMg alloy according to the PN-EN 1706: 2011. Pistons of slow sucking and turbocharged engines were researched. A solution heat and ageing treatments were applied according to four variants. Temperatures of the solution heat treatment were: 550 ±5°C; 510°C ±5°C; and alternate: 276 ±5°C/510 ±5°C. The solution time ranged from 6 min to 4 h. Temperatures of the ageing heat treatment were 20°C and 250°C, while the ageing time ranged from 1,5 to 3h. Natural ageing was performed in 5 days. Measurements of hardness HRB and the piston diameters were performed. An improvement in the performance parameters of combustion engines was observed. Three solution heat treatment and ageing variants, allowed to obtain the pistons with hardness equal/higher than pistons of the turbocharged engines. The test results confirmed the possibility of providing a piston with properties exceeding the high load parameters specified by the manufacturer. Further studies will make it possible to improve the effects of the proposed solutions.

Keywords: Precipitation hardening, Silumins, Heat treatment, Hardness

1. Introduction

Internal combustion engines are the most common type of engines that allow to generate energy from easily available and transportable fuels. Actually, the main structure of combustion engines has not changed and still consists of shafts, pistons, cylinders, and heads [1-4]. Theoretically, an engine can obtain efficiency at the level of 63% [5]. Thanks to the application of different kinds of charging, controlling the mixture combustion, raising the compression levels, and other possibilities, the engine efficiency has constantly been increased. New geometries of the engine elements are being used, particularly, in the most loaded elements – pistons [6]. In addition, alloys with better performance parameters and with better processing possibilities are being used. Lightweight, durable, easy to machine, high performance, and naturally cheap alloys are being searched for. New methods of treatment, casting, and content modification are being applied.

When choosing a material to be used for pistons one should focus on its good properties in ambient and high temperatures that accompany combustion in the combustion chamber. Eutectic silumins are alloys that are commonly used in pistons. Standard aluminum alloys used in pistons are characterized by a sudden drop in tensile strength and hardness in a function of temperature [5,6]. Therefore, it is recommended to perform a heat treatment to improve the properties of aluminum alloys [6-8]. Precipitation hardening is one of the methods to be used (solution combined with artificial or natural ageing) [9-12]. Solution heat treatment of silumins involves melting of intermetallic phases in the boundary solution and its homogenization followed by fast cooling down to ambient temperature. After solution, eutectic silumins have a homogeneous structure made up of crystals of saturated solid solution α. Silicon crystals of eutectics undergo fragmentation and spheroidization, and the amount of Si in phase α increases. Since the saturated solid solution lacks durability, ageing is applied. Thanks to supplied heat energy, the alloy undergoes change to achieve higher stability (durability). Due to variable temperature, the time of ageing procedures is different. Artificial ageing usually lasts 6 hours, whereas natural ageing may last up to several days [9-12].

Based on the results of the research presented in work [13], it has been found that performed T6 heat treatment influences the change of mechanical properties of EN AC-AlSi12CuNiMg alloy. The growth of tensile strength and hardness HB is determined by the selection of adequate temperatures, times of solution heat, and ageing treatments. Usage of increased temperatures of the ageing treatment results in the decrease of the hardness of the examined alloy [13]. It was confirmed in [14] that short-lived (1-6 min) annealing in ultra-high temperature ranges has a positive effect on spheroidization of eutectic silicon and other intermetallic phases, causing significant and desirable changes of mechanical properties. Works [15-25] also include interesting tests results concerning the impact of heat treatment on the properties of silumins.

In work [18] heat treatment of the 356.0 (EN AC AlSi7Mg) alloy was performed. This study presents the elaboration of a diagrams and dependencies between the mechanical properties obtained in this treatment and the parameters of dispersion hardening such as: temperatures; times of solutioning and ageing treatments. Obtained results enable full control of dispersion hardening process to programming and achieving a specific technological quality of the alloy (mechanical properties after performed heat treatments). The research [19] uses a micro-jet system of cooling during quenching of hypoeutectic cast silumin EN AC-AlSi7Mg0.3. In work [20] it was found that for a combustion engine cylinder head made of AlSi7Cu3Mg alloy, the optimal process of heat treatment, involves solutioning at a temperature of 500°C for 1 h, and then aging for 2 h at 175°C. The effects of T6 heat treatment (precipitation hardening) of the EN AC-AlSi11(Fe) alloy were presented in [21]. Correct selection of the artificial ageing and solution treatment parameters allows obtaining several dozen percent increases in hardness, elongation, tensile strength, and impact strength compared to the raw alloy. The [22] demonstrate experimentally that decrease in the sizes of the crystals of primary silicon and in the transverse size of the -Al secondary dendrite arms can halve the time of holding for quenching and aging at a guaranteed margin of the strength properties. Hardening T6 [24, 25] (solution annealing 540°C, 12 hours/water 20°C and artificial aging 150°C, 3 hours on the air) was performed on AlSi7Mg0.3 alloy with an addition: constant content of Zr or varying content of Ti. Alloys, characterized by varying Ti content, achieved a more significant improvement in mechanical properties after heat treatment.

The tests conducted as part of the research were supposed to show the efficiency of eutectic silumins parameter improvement and find out the impact of precipitation hardening on the material of an operating piston for its further application. The main risk of this kind of heat treatment includes, apart from mechanical damage (fracture or sinking), its size increase beyond the cylinder fit tolerance.

2. Research material

Eight operational engine pistons were used for the research (Fig.1). Four pistons came from a slow sucking (Subaru) EJ20E engine. For the purpose of the research, they were marked as NA. The next four pistons were taken from a (Subaru) EJ205 turbocharged engine. They were marked as T. All the eight pistons were free from excessive use or defects. Both sets had been in service until they were dismantled for the needs of the experiment. The sets of pistons differed in terms of geometry. They were cleaned from all impurities and polished in the places of chemical composition measurement, that is, the piston bottom.

To determine the chemical composition of the pistons Olympus DP 2000CC spectroscope- equipment of Palfinger Poland sp. z o.o. was used. Measurements were carried out six times for each piston. An analysis showed the chemical composition of the alloy according to PN-EN 1706:2020-10 norm - English version, (PN-EN 1706:2011 Polish version) as EN AC-AlSi12CuNiMg alloy. This alloy also denoted as EN AC-48000, is known to have been widely applied in piston production since the 30s of the 20th century [6, 13, 26]. The chemical composition presented in Table 1 is in compliance with the PN-EN 1706: 2011 standard.

Fig. 1. Image of researched engine pistons

Table 1.
Chemical composition of EN AC-AlSi12CuNiMg alloy, % weight

Elements, wt. %									
Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	other	Al
10.5-13.5	max. 0.7	0.8-1.5	max. 0.35	0.8-1.5	0.7-1.3	max. 0.35	max. 0.25	max. 0.15	remnant

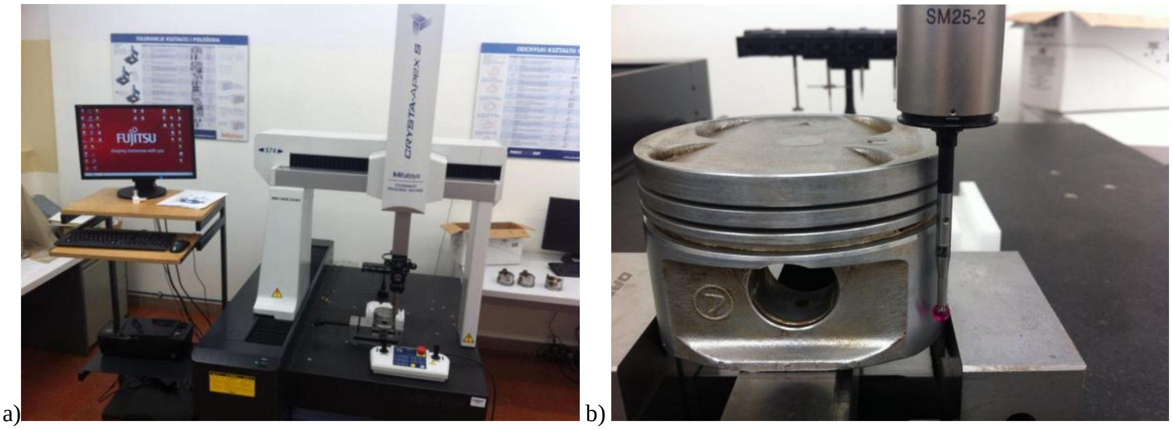

Fig. 2. a) Coordinate measuring machine used for determination of the specimen dimensions, b) spherical measuring tip, made of ruby, during the measurement

3. Research methodology

In order to determine the piston diameter dimensions, a coordinate measuring machine Mitutoyo Crysta-Apex S574 was used (Fig. 2). The measurements were performed in a laboratory of the Department of Manufacturing Techniques - Faculty of Mechanical Engineering, the University of Science and Technology in Bydgoszcz. The measurements were performed in the points indicated by the piston manufacturer to determine the wear degree as well as the piston and cylinder matching degree. Each piston was separately measured, at the same measuring station and by the same method. The result is an extreme, maximal dimension, not an average measurement result. In this case, it is caused by the fact that the average may be within the tolerance range. Whereas even one point beyond the tolerance range results in piston damage.

Based on the literature [13-25] and the author's own experiences, four variants of heat treatments were applied. Cooling after solution heat treatment was always applied in ambient temperature water. Cooling after ageing was applied for five days, always at ambient temperature. Then the hardness and diameter of the pistons were measured. Table 2 shows parameters for each variant of heat treatment.

Variant I involved first heating in temperature 510°C for 180 minutes, then three times, alternate piston heating in temperature 276°C and 510°C for 10 minutes (each time), using two furnaces with a temperature of 276°C and 510°C.

Neoterm NT 1313 laboratory furnaces of the Department of Manufacturing Techniques (UTP) were used for heat treatment. Tolerance of temperature measurement error was set by the manufacturer to be 5°C.

Table 2.
Parameters for four variants of heat treatment

Variant	I		II		III		IV	
	Temp. °C	Time min.	Temp. °C	Time min.	Temp. °C	Time min.	Temp. °C	Time min.
Solution heat treatment	510 276 510 276 510 276 510	180 10 10 10 10 10 10	550	6	510	180	510	180
cooling	20	2	20	2	20	2	20	2
ageing	250	180	250	180	250	90	20	-
cooling	20	-	20	-	20	-	-	-

Prior to tests, each furnace was appropriately heated to obtain the desired temperature and minimize temperature drop while inserting the specimens. To cool hot specimens, they were put on a fireclay.

Measurements of hardness were performed with the use of Łucznik Rockwell hardness tester. The measurements were performed in the laboratory of Department of Manufacturing Techniques. The hardness tester was adjusted to measuring aluminum alloys in HRB scale, that is, by means of a steel ball and for loading of 980N. The bottom of each piston was checked twelve times. The measurements were performed randomly but all over the bottom horizontal surface. After obtaining the twelve results, the mean value was calculated.

4. Research results

Table 3 shows measurements of the piston hardness, whereas in table 4 there are results of the piston diameter measurements. The maximum permissible diameter of the pistons for both series was 91.995 mm.

5. Discussion

Variant I increased the diameter measurement hardness of NA1 and T1 pistons by a very similar value (Tab.3). In the case of T1 piston the growth was minimal–at the level of 0.009 mm. A significant, though within the tolerance range, diameter increase by 0.181 mm was obtained for NA1 piston. Variant I did not provide any significant benefits from the introduction of an indirect procedure.

Table 3.
Presentation of piston hardness measurement results

		Piston hardness, HRB		
Piston no.	Treatment variant	Prior heat treatment	After heat treatment	Difference value hardness
NA1	I	31	40	+9
NA2	II	33	26	-7
NA3	III	33	55	+22
NA4	IV	28	58	+20
T1	I	44	54	+10
T2	II	53	54	+1
T3	III	53	65	+12
T4	IV	53	70	+17

It involved threefold, alternate piston heating in temperature 276°C and 510°C for 10 minutes, each time. There are reasons (literature based) to believe that this indirect procedure has the biggest impact on the properties of the material operating in a raised temperature. Further tests should be conducted under such conditions to confirm this finding.

Untypical hardness decreases by 7 HRB units was found for NA2 piston after variant II of heat treatment (Tab. 3). The smallest hardness increase, only by 1 HRB unit was found for T2 engines in variant II.

Table 4.
Presentation of piston diameter measurement results

		Piston diameter, mm		
Piston no.	Treatment variant	Prior to heat treatment	After heat treatment	Dimension difference
NA1	I	91.794	91.975	0.181
NA2	II	91.832	91.911	0.079
NA3	III	91.826	92.041	0.215
NA4	IV	91.820	91.991	0.171
T1	I	91.901	91.910	0.009
T2	II	91.891	91.922	0.031
T3	III	91.899	91.914	0.015
T4	IV	91.902	91.772	-0.130

Despite the hardness decrease observed for NA2 engine, the piston diameter increased by 0.079 mm, whereas the diameter of piston T2 increased by 0.031 (Tab.4). It can confirm improvement in heat and dimensional stability of the pistons which enables better prediction of the piston behavior in operation and reduction of piston swelling under raising the temperature. The results of hardness and size measurements for variant II can suggest inappropriately matched parameters – particularly those of the solution heat treatment which should last longer, or the temperature should be higher.

Variant IV was carried out without ageing. The highest hardness increase was found for NA4 and T4 pistons (Tab. 3). Hardness higher than that of T pistons in the initial state was found for NA4 piston. Among all heat treatment variants, this was the one for which a single reading of hardness was found to be at the level of 72 HRB. An optimal diameter growth, as compared to the remaining variants, was found for variant IV in the case of NA4 allowing it to fit in the tolerance range. In the case of T4 piston, there was probably a measurement error due to diameter reduction by 0.13 mm. Such measurement would indicate the piston shrinking which seems to be impossible. As for variant IV, despite the highest hardness growth, this value is likely to drastically drop in the piston operational temperatures, due to the lack of stabilization by artificial ageing.

As for slow sucking engines, the largest diameter increase was observed for NA3 piston, after application of variant III and was equal to 0.215 mm (Tab.4). It was accompanied by the highest hardness increase equal to 22 HRB units. Slight diameter growth of 0.015 mm. was found for T3 piston. For NA 3 piston the diameter growth was the largest for NA3 piston, which resulted in exceeding limit values of the tolerance range. Variant III, thanks to the application of artificial ageing, largely contributes to maintaining the values of measurements obtained for ambient temperature. Further tests need to be conducted in order to verify these findings.

6. Conclusions

1) An increase in the piston diameter after precipitation hardening makes its dimension approach the tolerance range, which seems to be beneficial for the piston-cylinder cooperation. A hypothesis can be formulated that such a heat treatment provides excessively worn pistons with some kind of regeneration proving of which, however, needs further tests to be conducted.
2) An increase in the piston diameter does not pose a big problem because it can be decreased by machining. This conclusion needs to be verified.
3) After solution heat treatment and ageing of slow sucking NA engines, the pistons of turbocharged engines T experienced decolorization – with the exception of treatment according to variant II. Initial light silver pistons changed color into dark grey with shiny fragments. It can prove that pistons T have already been subjected to some kind of heat treatment by the manufacturer.
4) Color change in NA pistons into dark grey can make it possible to recognize whether silumins have already been heat treated by the manufacturer (Subaru).

5) The test results indicate that there is a relatively simple way of charging slow-sucking NA engines, originally unsuited to turbocharging. Three out of four solution heat treatment and ageing variants, allowed to provide the pistons with hardness equal/higher than pistons of the turbocharged engines T, which are suited to turbocharging by the manufacturer.

6) Having taken into consideration the geometry of the tested pistons, it can be assumed that after precipitation hardening, a piston of a slow sucking engine NA will accomplish its task significantly better which is the effect of much thicker walls and hardness equal/higher than that of the pistons of a turbocharged engine T.

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