Journal of KONES Powertrain and Transport, Vol. 15, No. 2 2008

COMPLEX CRITERION OF DIMENSIONAL STABILITY DISCUSSED ON THE EXAMPLE OF PISTON SILUMINS

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Abstract

The article discusses the use of a quality polygon method in complex evaluation of the dimensional stability of a newly developed AK12 E piston silumin of the Lo-Ex (Low-Expansion) type with around-eutectic silicon content. According to PN-EN 1706:2001, the reference material was standard aluminium piston alloy designated as EN AC-48000 (EN AC-AlSi12CuNiMg). It is an analogue of the well-known and commonly used in production of pistons AK12 alloy according to PN-76/H-88027, withdrawn now from use. Basing on the analysis of Polish and foreign reference literature and on the authors' own knowledge and experience, five parameters of the reversible and irreversible (permanent) dimensional changes in AK12 E and AK12 S alloys (designations adopted for standard alloys) were chosen. The obtained quantitative evaluations, referred to individual parameters, enabled the values of complex (synthetic) parameters of the dimensional stability to be finally determined. From the numerical and geometrical analysis it follows that AK12 E alloy offers the dimensional stability definitely superior to that of AK12 S, but this is on the cost of the tensile strength R_m reduced at room temperature. The obtained experimental results and computations were checked on pistons during the stand engine tests.

Keywords: *piston silumins, dimensional stability, complex criterion, polygon method*

1. Introduction

The study [1] describes the, supported by mathematical and statistical modelling and computer-aided numerical optimising, development of a new family of piston alloys, viz. AK12 E AlSi12.25Cu2.2Mg0.625Ni2.3), AK15 E (AlSi15Cu1.3Mg0.575Ni2.1) and AK18 E (AlSi18-Cu1.37Mg0.75Ni1.95), capable of satisfying the high requirements of dimensional stability, preserving at the same time the standard (normative) requirements of basic mechanical properties.

Polish leading piston manufacturer, Federal Mogul Gorzyce S.A. (former WSK „PZL-Gorzyce"), has become vividly interested in the AK12 E piston silumin, mainly because of a very promising combination of the typical technological properties it can offer. Therefore this alloy was selected for detailed analysis and tests, including engine tests.

The ranges and mean concentrations of the main alloying elements and impurities present in AK12 E alloy (obtained by optimising procedures described in [1]) and in AK12 S alloy are given in Tab. 1.

The developed AK12 E alloy differs from the standard AK12 (AK12 S) alloy in increased content of copper and nickel and also in this that the manganese in amounts of 0.3-0.6 wt % belongs to the most desired alloying elements. It is also characterised by lower Mg concentration, usually kept at the level of 0.625 wt%, i.e. at a level practically two times lower than the Mg concentration in AK12 S alloys.

AK12 E belongs to the group of advanced piston silumins of the Lo-Ex type. Similar silumins have been successfully used for several decades by Federal Mogul Gorzyce S.A., and also by other piston manufacturers in Poland and abroad.

Permanent rise of unit power (above 60 kW/l) and ignition pressure to a level of 180-190 hPa in petrol and diesel engines permanently rises also the mechanical and thermal loads to which the main structural parts of an engine, i.e. the combustion chamber and pistons, are exposed, leaving overall dimensions of these parts practically unchanged (for example, a light model of Mahle Ecoform®-Kolben Design, developed still at the close of the 20th century) [2-4]. The beginning of the 21st century witnessed the development of new materials and their successful implementation in production, with obvious tendency to a wide-spread application of around-eutectic piston silumins of the new generation and Lo-Ex type, characterised by high copper and nickel content [2] (Tab. 2).

Tab. 1. Ranges and mean values of the content of the main alloying elements and impurities present in the tested AK12 E alloy and in standard AK12 S piston silumin

Alloy designation	Chemical composition [wt %], remainder Al							
	Main alloying elements				Impurities and admixtures			
	Si	Cu	Mg	Ni	Mn	Fe	Zn	Ti + Zr
AK12 E	11.50 - 13.00	2.10 - 2.30	0.55 - 0.70	2.20 - 2.40	0.30 - 0.60	≤ 0.70	≤ 0,06	0.10 - 0.14
			Mean values					
	12.25	2.20	0.625	2.30	0.45	0.35	0.03	0.12
AK12 S	11.50 - 13.00	0.80 - 1.50	0.80 - 1.50	0.80 - 1.30	≤ 0.20	≤ 0.80	≤ 0.20	≤ 0.10
			Mean values					
	12.25	1.15	1.15	1.05	0.10	0.45	0.10	0.05

Tab. 2. Chemical composition of modern aluminium alloys assigned for heavy-duty engine pistons [2]

Alloy designation	Chemical composition [wt%], remainder Al							
	Si	Cu	Ni	Mg	Fe	Zn	Mn	Others
M142	11.0 - 13.0	2.5 - 4.0	1.75 - 3.0	0.8 - 1.2	≤ 0.7	≤ 0.3	≤ 0.3	≤ 0.2
M174	12.0 - 14.0	4.0 - 6.0	1.75 - 3.0	0.5 - 1.2	≤ 0.37	≤ 0.3	≤ 0.3	≤ 0.2

Similar silumins were developed and patented at the close of the past century, also in Poland. According to a patent application from 1998 [5], an alloy claimed in the invention has the following chemical composition (wt%): 2-27 Si; 0.1-5.00 Cu; 0.10-2.0 Mg; 0.10-4.00 Ni; ≤ 1.50 Fe; ≤ 1.00 Mn; ≤ 0.40 Ti; ≤ 4.00 Zn; ≤ 0.60 Cr; ≤ 1.20 Co; ≤ 0.20 Sn; its typical feature is an additional content of 0.01-2.00 V; 0.01-2.00 W; ≤ 2.00 Mo; ≤ 1.50 Nb; remainder aluminium.

Earlier, i.e. in 80-ties of the past century, alloys of this type were objects of patents and publications outside Europe - mainly in USA [6] and Australia [7]. They are characterised not only by high creep resistance and good short-term mechanical properties (Rm, Rp0,2, HB) at room temperature and at high temperatures (up to 350-4000ºC), but also by improved abrasion wear resistance [6] and high dimensional stability (this is true specially in the case of 3HA alloy [7]). Additionally, they also offer good engineering properties.

2. Parameters of dimensional stability

In the technical literature on metal science [8-16] it is proposed to divide the dimensional changes in piston silumins operating under the conditions of thermal loads into two types:

a) the reversible changes caused by thermal expansion,
b) the irreversible changes caused by permanent changes of structure.

The mechanisms responsible for the dimensional changes of both types taking place in piston silumins were discussed in detail by one of the authors in [1].

Basing on foreign [9-11] and Polish [1, 8, 12-16] reference literature, for further tests and studies the following parameters were selected and used in the evaluation of the dimensional stability of piston silumins:

A. Parameters of reversible dimensional changes:

- the technical linear coefficient of thermal expansion $\alpha_{\text{tech.}}^{20...300\,^{\circ}\mathrm{C}}$ [K^{-1}] of alloys (designated further as AT - an abbreviated form of Polish „Alfa Techniczne" - Alpha Technical), assuming mean values within the temperature range of 20-300ºC, regarded as most faithfully corresponding to the true ranges of piston operation and quoted most frequently by the reference literature on engines and piston alloys. It has been assumed that the lower is the value of this coefficient, the better is the partial quality index of piston alloy dimensional stability,
- the physical linear coefficient of thermal expansion $\alpha_{\text{fiz.}}^{300\,^{\circ}\mathrm{C}}$ [K^{-1}] (designated further as AF - an abbreviated form of Polish „Alfa Fizyczne" - Alpha Physical) at the temperature of 300ºC. As follows from the Polish technical literature [12, 17] and from foreign sources [18, 19] as well as own investigations [1], in many cases, the dilatometric curves of piston silumins reveal suddenly growing peaks of linear expansion within the temperature range of 250-350ºC. As in the previous case, also now it is assumed that the quality of piston alloy examined in terms of its dimensional stability will be improving with the decreasing value of AF.

B. Parameters of irreversible (permanent) dimensional changes:

- permanent dimensional changes ΔV/V0 [%] in piston alloys observed after 100 cycles of temperature changes according to the sequence: 500 → 20 → 100^0C (designated as NZ1). Most desired is the zero permanent increase in volume (or in the corresponding linear dimension) under given conditions of thermal loading, i.e. when |NZ1| → 0,
- permanent dimensional changes ΔV/V0 observed after 100 cycles of temperature changes according to the sequence: 500 → 20ºC (designated as NZ2). As in the case of NZ1, in terms of the dimensional stability, the absolute value of these changes should tend to zero (i.e. |NZ2| → 0),
- permanent dimensional changes ΔV/V0 after 100 hours of quasi-static (isothermal) holding at the temperature of 500ºC (designated as NZ3). As in the previous two cases (NZ1 and NZ2), also now the best is considered the piston alloy of zero irreversible increment in absolute values under the conditions of given thermal loads (i.e. | NZ3| → 0).

The thermal expansion behaviour was investigated on an electronic NETZSCH 402ES dilatometer, using cylindrical specimens of Ø 4 x 30 mm dimensions.

The relative permanent (irreversible) dimensional changes were determined on cylindrical specimens of Ø 10 x 15 mm dimensions, measuring their volume before and after the predetermined model of thermal loading (parameters: NZ1, NZ2 and NZ3). In the examined cases, the principle of thermal acceleration of the test was used [20]. It consisted in increasing the upper thermal loading limit to a level of 500ºC, i.e. to a level higher by approximately 100-150ºC than the maximum operating temperature of pistons made from aluminium alloys [1]. The variable thermal loads (NZ1 and NZ2) were obtained by relatively rapid (about 5 minutes) heating of the specimens up to the temperature of 500ºC (in a KS 1350/25-15-10/1 laboratory furnace), holding under these conditions for 15 minutes, followed by quick cooling in water at room temperature. According to the thermal loading regime designated as NZ1, the specimens were additionally held for about 10 minutes in boiling water, which was supposed to raise to maximum the subsurface content of hydrogen in the examined piston silumins (and - as suggested by the British researchers - to make them „swell") [21]. The volume of the investigated samples was determined at an accuracy of ± 0,0001 g by the method of hydrostatic weighing on an analytical E42 S scales made by GIBERTINI.

3. The method of quality polygon

In terms of their chemical composition, piston silumins from the Al-Si-Cu-Mg-(Ni)-(Mn)-(Fe)-(Zn) system, where in brackets the typical impurities and/or the recommended alloying elements are given, are considered the group of most complex cast alloys. However, the regime of piston operation is also very complex, and various - often contradictory - requirements are imposed onto the materials from which pistons are cast. So, quite obviously, both quality control and multi-faceted evaluation of materials of this type must result very difficult, too. In such cases the use of synthetic multiplicative indices of quality is possible and frequently practised [22-24], though it still fails an intuitive interpretation.

In this situation a solution may be the use of a, well-known in quality engineering, model polygon [25-28]. In the specific case of complex evaluation of piston silumins in terms of their dimensional stability, a pentagon of quality will be taken into consideration.

The method of quality polygon presented below, though referring in this article to a specific problem, is not deprived of the features of versatility which make it equally applicable also in other cases.

Speaking in most general terms, the idea of using a model polygon in quality evaluation (of materials, products, processes, etc.) consists in comparing the true (examined) quality feature (the dimensional stability of piston alloys in this particular case) with an ideal (reference) quality of the examined alloys (most often regarded as a theoretical concept only). This is done by comparing the field P′ of a convex scalene polygon (e.g. the polygon a′b′c′d′e′ of equal central angles α) with the field P of an entirely regular equilateral polygon abcde (Fig. 1).

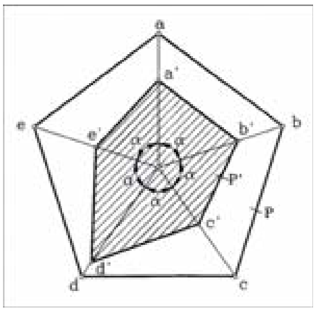
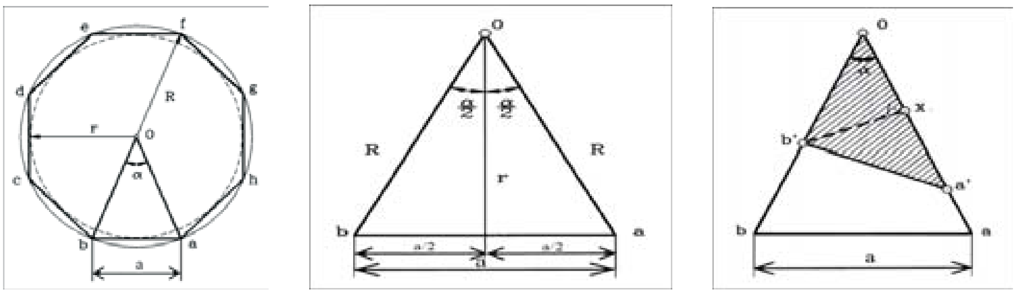


Fig. 1. Geometrical interpretation - on the example of a pentagon - of the true (examined) quality with an ideal (reference) quality

If we consider a regular polygon abcdefgh of an n number of sides and the central angle α = 360/n (Fig. 2 a), then the total field of the polygon can be calculated from the relationships given below (1-6), where the field of one component triangle P0ab (e.g. 0ab in the schematic diagrams in Fig. 2a and 2b) is determined from an elementary relationship (1):

$$P_{0ab} = \frac{1}{2}\overline{ab}\,r = \frac{1}{2}a\,r. \tag{1}$$



a) *b)* *c)*

Fig. 2. Geometric schemas for the determination of: a) and b) the field of a regular polygon, and c) the field of an irregular polygon; r and R - the radii of the inscribed and circumscribed circles, respectively, a - the side of a regular polygon

From simple trigonometric relationships (Fig. 1b) we derive relationship (2) for $\overline{0a}$ and r in function of the central angle α and radius R:

$$a = 2R\sin\left(\frac{1}{2}\alpha\right),\quad \mathrm{r} = \mathrm{R}\cos\left(\frac{1}{2}\alpha\right). \tag{2}$$

Having introduced the quantities present in (2) to equation (1) and having made the respective transformations, we obtain [1]:

$$\mathrm{P}_{0ab} = \frac{1}{2}\sin\alpha\,\mathrm{R}^2. \tag{3}$$

Hence it follows that the field P of an arbitrary regular equilateral polygon of n sides and the central angle α will be equal to:

$$\mathrm{P} = \mathrm{nP}_{0ab} = \mathrm{n}\frac{1}{2}\sin\alpha\,\mathrm{R}^2. \tag{4}$$

Assuming R = 1 and n = 5, the field of the whole pentagon of quality abcde (α = 3600/5 = 720) will be calculated and expressed in conventional surface units [c.s.u.]:

$$\mathrm{P}_{abcde} = \mathrm{n}\frac{1}{2}\sin\alpha\,\mathrm{R}^2,\ P_{abcde} = 5\frac{1}{2}si72^0\,1^2 \cong 2.378\ [\mathrm{c.s.u.}]. \tag{5}$$

The obtained numerical value P is the maximum size of a given polygon (a pentagon in this case), and it expresses a complex (synthetic, collective) ideal quality of product (e.g. alloy), characterised by the five examined parameters (diagnostic variables) [29]).

The field P’ of an irregular (scalene) polygon a′b′c′d′e′ (Fig. 1c) expresses the real (true) quality:

$$\mathrm{P}_{0a'b'} = \frac{1}{2}\overline{0a'}\,\overline{b'x}. \tag{6}$$

After trigonometric transformations we obtain relationship (7) for the surface area of the triangle 0a′b′ field [1]:

$$P_{0a'b'} = \frac{1}{2}\sin\alpha\,\overline{0a'}\,\overline{0b'}. \tag{7}$$

A similar formula is obtained for the remaining triangles, wherefrom it follows that the surface area of the pentagon a′b′c′d′e′ field will be equal to:

$$P' = P_{a'b'c'd'e'} = \frac{1}{2}(\overline{0a'}\,\overline{0b'} + \overline{0b'}\,\overline{0c'} + \overline{0c'}\,\overline{0d'} + \overline{0d'}\,\overline{ac'}. \tag{8}$$

Relationships similar to (8) will be obtained in the case of other (n ≠ 5) polygons.

Knowing the field P of a regular (equilateral) polygon and the field P′ of an irregular polygon (scalene, though exceptionally the inner polygon may be equilateral as well), the following (9) relative complex quality index S (e.g. of generally understood dimensional stability) is accepted [1, 25, 27, 28]:

$$S = \frac{P'}{P}, \tag{9}$$

where:

S - assumes values from the range [0, 1],
P′ and P - have the same units, usually expressed in [c.s.u.].

To the value S = 0 is corresponding a zero (minimum) product quality understood in terms of the investigated parameter, whereas S = 1 is the maximum quality.

To express the quantities P′ and P in conventional surface units ([c.s.u.]), it is necessary to transform the absolute variable diagnostic states (features) AT, AF, NZ1, NZ2 and NZ3 (with determined unit) into relative (quotient) quantities εj from the numerical range [0, 1] (Fig. 2). The process of transformation is called relativisation [1, 25], standardisation [22], or normalisation [29]. In reference literature [22, 29] there are many proposals for transformations of this type.

In numerous cases, the quotient transformation, also called min-max (or max-min) normalisation, applies in accordance with the following formula (10) [1, 22, 29]:

$$\varepsilon_j = \left| \frac{|k_z| - |k_m|}{|k_b| - |k_m|} \right|, \tag{10}$$

where:

$0 \le \varepsilon_j \le 1$ - the value of the j - the diagnostic variable,
k_z - the existing (true, real) state of the j-th variable.

Fig. 3 below shows a linear interpretation of the procedure of relativisation of the measurable parameters in accordance with the uniaxial versatile scale of quality states [1, 29].

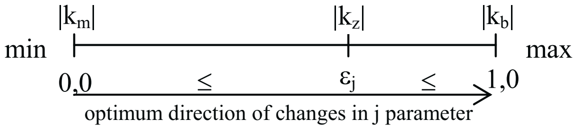


Fig. 3. Geometrical and numerical relationship between absolute and relative states of the j-th examined parameter (diagnostic variable)

Although k_m and k_b are determined by the researchers subjectively, the choice of values is based on the data given in literature and on the knowledge and experience related to the task being solved.

4. Complex quality investigation of AK12 E and AK12 S alloys

The results of an evaluation of the dimensional stability parameters based on mathematical models derived during the experiment planned in [1] for the newly developed AK12 E alloy and for the standard AK12 S alloy are shown in Tab. 3 below (the parameter kz).

From relationship (8) we obtain equation (11) for the field P' (expressed in [c.s.u.]) of an irregular polygon corresponding to the true (actual) complex quality (considered in terms of the dimensional stability) of the examined AK12 E and AK12 S alloys:

$$P' = k(\varepsilon_{AT}\,\varepsilon_{AF} + \varepsilon_{AF}\,\varepsilon_{|NZ1|} + \varepsilon_{|NZ1|}\,\varepsilon_{|NZ2|} + \varepsilon_{|NZ2|}\,\varepsilon_{|NZ3|} + \varepsilon_{|NZ3|}\,\varepsilon_{AT}), \tag{11}$$

where:

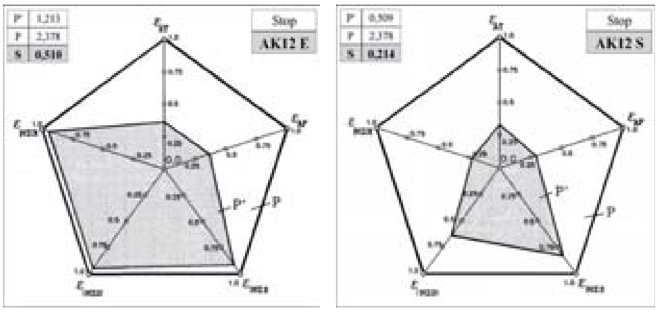
$k = 1/2 \sin 72^0 = 0{,}475528258 \approx 0{,}4755.$

Tab. 3. Values of the dimensional stability parameters (AT, AF, NZ1, NZ2 and NZ3) computed for the absolute (ideal) quality states and for the corresponding relative (true) quality states εj of the examined AK12 E and AK12 S piston silumins and the results of complex (synthetic) calculation of quality indexes S

Alloy designation	DIMENSIONAL STABILITY PARAMETERS [1]															Surface area fields [c.s.u] and alloy quality index
	Reversible dimensional changes						Irreversible dimensional changes									
	Linear coefficient of thermal expansion x10^6, [K^{-1}]						Relative permanent volume changes, [%]									
	$\alpha_{tech.}^{20..300°C}$ / AT		ε_{AT}	$\alpha_{fiz.}^{300°C}$ / AF		ε_{AF}	$\Delta V/V_0$ / NZ1		$\varepsilon_{\lvert NZ1\rvert}$	$\Delta V/V_0$ / NZ2		$\varepsilon_{\lvert NZ2\rvert}$	$\Delta V/V_0$ / NZ3		$\varepsilon_{\lvert NZ3\rvert}$	
AK12 E	k_b	k_m	0.385	k_b	k_m	0.336	k_b	k_m	0,896	k_b	k_m	0,954	k_b	k_m	0.946	P' = 1.213
	18.5	22.5		21.5	26.5		0.00	0.20		0,00	0,10		0.00	0.70		P = 2.378
	k_z=20.959			k_z=24,821			k_z=-0.0207			k_z=-0.0046			k_z=+0.0375			S = 0.510
AK12 S	k_b	k_m	0.310	k_b	k_m	0.257	k_b	k_m	0,824	k_b	k_m	0,654	k_b	k_m	0.245	P' = 0.509
	18.5	22.5		21.5	26.5		0.00	0.20		0.00	0.10		0.00	0.70		P = 2.378
	k_z=21.260			k_z=25.216			k_z=+0,0351			k_z=+0.0342			k_z=+0.5284			S = 0.214

[1] The following mechanical properties were obtained for AK12 E and AK 12 S alloys: Rm: 190.4 and 206.0 [MPa], respectively, and Brinell hardness: 90.1 and 90.2 [HB], respectively

The geometrical interpretation of the obtained results of calculations in the form of quality pentagons is shown in Fig. 4.



a) *b)*

Fig. 4. Pentagons of dimensional stability for: a) tested AK12 E alloy of the Lo-Ex type; b) standard AK12 S alloy

The data in Tab. 3 and Fig. 4 show us that complex dimensional stability of AK12 E alloy has the value much higher than the same index obtained for AK12 S alloy, and that it is mainly due to the irreversible dimensional changes. Analysis of data in Tab. 3 leads to a conclusion that it is possible to improve the dimensional stability of the new alloy but on the cost of some of its mechanical properties (mainly Rm) suffering a drop. Particularly large permanent set was observed in AK12 S alloy subjected to isothermal heating (thermal loading according to NZ3 regime). Now it is worth noting that both the reversible and irreversible dimensional changes taking place in AK12 E alloy and used as starting data for complex evaluation were obtained as a result of heat treatment (artificial ageing) of the parameters used typically for standard AK12 alloy, i.e. temperature - 220ºC, time - 8h [1].

5. Verification of the results obtained in engine tests

At the former „Kęty” S.A. Light Metals Plant (present ALUMETAL S.A. Group), the AK12 E alloy was ordered and manufactured on semi-industrial scale in an amount of about 500 kg. Its chemical composition (in wt %.) according to the submitted certificate (melt: W 635, Conformity Certificate No. 18/94) was the following: 11.72 Si; 2.15 Cu; 0.63 Mg; 2.26 Ni; 0.39 Mn; 0.19 Fe; 0.05 Zn and 0.11Ti; rest Al.

From the above mentioned AK12 E alloy, test pistons were made by WSK „Gorzyce” S.A. in an amount of about 100 pieces to be used in the engine of a POLONEZ 1500 car (according to Drawing No. 0.33.647). Allowing for the in-plant requirements of dimensional stability determined for pistons at the WSK „Gorzyce” (in accordance with TMT/520/93), and having achieved the normative limits on mechanical properties (Rm and HB) at room temperature, using special program of research [1], the conditions of heat treatment (artificial ageing - T5) were determined for a test batch of pistons made from the AK12 E alloy. The heat treatment conditions were as follows: temperature - 275°C, time - 4.0-4.5 h.

Additionally, at the WSK „Gorzyce” S.A., a batch of 100 pistons of the same design was produced from an AK12 S alloy (from the AK12 family) of the following chemical composition (wt %) [30]: 12.47 Si; 0.90 Cu; 1.11 Mg; 0.88 Ni; 0.12 Mn; 0.70 Fe; 0.03 Zn and 0.02; 0.003 P; rest Al. Pistons made from AK12 S alloy were heat treated to T5 condition applying the heat treatment parameters typically used for this type of piston silumins, i.e. ageing temperature - 220°C, time – 8 h.

The microstructure of both alloys comprised a solid solution αAl, granular and/or granular-striped eutectic (alloys modified with phosphorus), and the precipitates of typical intermetallic compounds of copper, magnesium, iron, manganese and nickel (Al_3Ni) present on the grain boundaries. In AK12 E alloy, numerous precipitates of the intermetallic phases of T(Al_7Cu_4Ni) were also present [30-31].

The performance tests of the pilot pistons were carried out on a stationary engine testing stand equipped with a hydraulic braking system of the SCHENC D630 type. It was a rapid (20 hours) test made in accordance with the H/5/TK3 (WSK „Gorzyce S.A.) in-plant specification.

Pistons from AK12 S alloy were mounted in piston-cylinder sleeve arrangement with mean assembly clearance of 42 μm [30]; for AK12 E alloy the clearance was 35-36 μm [31], and hence – 25-26 μm [32].

All engine tests yielded good results (no failures occurred); oil pressure and its consumption rate were within the standard range of values; the traces of piston/cylinder sleeve mating were wide and without any signs of seizures. The evaluation of the dimensional stability based on the measurements of diameters taken in planes T-T and P-P before and after the engine test has proved that pistons made from AK12 E alloy suffered much smaller permanent (irreversible) deformation [31, 32] than pistons made from AK12 (AK12 S) alloys [30].

6. Final conclusions

The studies and the analysis of results gave the following conclusions:

- piston silumins of the Lo-Ex type and higher in respect of standard alloys content of Cu and Ni are characterised not only by better parameters of thermal expansion but also by lower permanent (irreversible) deformation under quasi-static and dynamic conditions of thermal loading,
- the highest permanent set (especially in the case of AK12 S alloy) was observed to take place during isothermal heating at the temperature of 5000C. Cyclic thermal loading according to NZ1 and NZ2 regime resulted in small positive or negative dimensional changes,
- an improvement of complex dimensional stability parameters in the examined group of alloys is on the cost of mechanical properties reduced at room temperature, but this fact does not mean that obtaining satisfactory performance properties in Lo-Ex type alloys is not possible,

- the method of quality polygon, described in general terms and presented on a specific example, may be used with success in control and optimising of the chemical composition of materials, in quality control of the semi-finished products, final products and casting process parameters.

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Large fragments of this publication have been based on an unpublished study executed under a research project entitled: „Stabilisation of materials and geometry of pistons for I.C. engines", commissioned by the KBN State Committee of Scientific Research, Contract No. KBN Nr: PB 370/S6/92/02 [1].