RESEARCH RESULTS OF NOVEL COMPOSITE MATERIALS WITH LOW HYSTERESIS DURING HEATING AND COOLING FOR PISTONS OF COMBUSTION ENGINES

Barbara Sieminska

Institute of Aviation
Krakowska Av. 110/114, 02-256 Warsaw, Poland
tel.: +48 22 8460011, fax: +48 22 846 4432
e-mail: barbara.sieminska@ilot.edu.pl

Abstract

Research results of novel silumi ns on pist ons for c ombustion engines, which have high mechanical properties within the range of pist on higher operating temperatures, 100-300°C, are prese nted in the paper. Silumins contain enlarging concentration of the nickel and copper alloy additives up to 4.0, and chrome and molybdenum alloy additives up to 1.0%. Occurrence of given microstr ucture in piston-silumins results in almo st the same values of the coefficient thermal expansi on during the heating up to t he 300°C temperature and during the next cooling i nto the ambient temperature. Small values of the coefficient of expansion of thermal and small differences between values of the coefficient of thermal expansi on during heating and cooling enabl e on application of small values of worki ng clearances between piston and the cylinder liner. As a consequence they make possible, the low exhaust emission level, and the low noise level. The pist ons from alloys with small values of the coefficient of thermal expansion, small differences of this coefficient during heating and cooling are novel aspects presented in paper. Research results of strength and metallographic parameters, research results of the coefficient of thermal expansion, comparative engine research results are represented in the paper. In particular representative chemical components for a standard alloy and novel alloy, mechanical properties investigated alloys after solution heat treatment, wear resistance of novel alloy compared with two cast irons, ATD curves, fibrous construction, silicon construction, microstructure of novel alloy, courses of changes of the coefficient of the rmal expansion in the functi on of the temperature duri ng heating and cooling are presented in the paper.

Keywords: *internal combustion engines, engine piston, thermal expansion, emissions*

1. Introduction

An object of the paper is a research of new composite aluminium alloys designed for high load elements of combustion engines. These elements have to make functional requirements concerning working clearances and transmission of mechanical loads and resistances on periodical mechanical and thermal loads in conditions of high temperatures. For materials that are isotropic (i.e. uniform in all directions), the material undergoes thermal expansion as a whole: that is its volume expands. For materials that are not isotropic such as an asymmetric crystal for example, the thermal expansion can have different values in different directions. Thermal expansion can also vary somewhat with temperature so that the degree of expansion depends not only on the magnitude of the temperature change, but on the absolute temperature as well. Piston alloys, especially composite alloys are not isotropic, so the thermal expansion can have different values in different directions. For an isotropic material, α will be the same in all directions, so we can measure α simply by measuring the change in length of a rod of the material. The values obtained for the coefficient of linear thermal expansion will be compared with commonly accepted values to determine the composition of each rod. Thermal expansion coefficient of piston alloys should be measured in different directions and different places. Most load elements of combustion engines are pistons which have to realize growing functional and of durability requirements. Novel alloy allows on a design of novel generation pistons with high proprieties in high temperatures referring to difference reducing in the thermal expansion during heating and cooling. This increases the resistance of piston design on fatigue damages both mechanical and thermal, and increases the resistance of pistons on thermal shocks [1-9]. Formation of novel generation alloys composite on pistons is the occurrence in them multiple intermetallic phases crystallizing in high temperature before the crystallization of α+ (Al+Si) eutectic. Multiple intermetallic phases, crystallizing as first in process of the solidification piston cast, cause formation of the natural composite material (in situ) of the best functional proprieties. Novel pistons will make possible application of solutions of low clearances, constant sizes during working of vehicles (dimension stability), improving of functional parameters of engines in the aspect of the fuel consumption, emission of toxic components of combustion gases, blow-through to the crank case. Standard and applied nowadays materials on pistons are piston-silumins having the following chemical constitution: 11.0-20.0% Si, 0.7-1.5% Mg, 0.5-1.5% Ni, 0.5-1.5% Cu, 0.2-0.5% Mn, 0.3-0.5% Fe. Alloy-additives Mg, Ni, Cu, Mn and Fe create in silumins following intermetallic phases: Mg2Si, Al3Ni, Al2Cu, and AlFeMnSi. These phases crystallize after finished process of crystallization α+ (Al+Si) eutectic. They cause hardening of the silumin. The mentioned intermetallic phases occurring in the microstructure of piston-silumins are not stable. During piston heating in an engine the intermetallic phases are subject to the partial dissolution to α stable solution, and in process of cooling they emit again. As a consequence the partial plastic piston deformation takes place which is a result the gradual increment of difference between its expansion during heating and a contraction in process of cooling („hysteresis”). On comparatively low functional proprieties pistons performed from standard silumins in the temperature of their work, the essential influence has also size silicon of both primary (overeutectic silumins) and eutectic one. Size primary silicon is contained in interval of 30-50 μm, and eutectic one - in 15-20 μm.

2. Idea of novel alloys

The development objectives of composite alloys are:

- increase in yield strength and tensile strength at room temperature and high temperature,
- increase in creep resistance at higher temperatures compared to that of conventional alloys,
- improvement of thermal shock resistance,
- improvement of corrosion resistance,
- increase in Young’s modulus,
- reduction of thermal elongation,
- while maintaining the minimum ductility or rather toughness.

Additional targets of usage of composite materials are increase in strength of conducting materials while maintaining the high conductivity, improvement of burnout behaviour, improvement of wear behaviour - sliding contact.

Metal composite alloys have found application in many areas of daily life for quite some time. Often it is not realized that the application makes use of composite alloys. These alloys are produced in situ from the conventional production and processing of metals. Alloys like cast iron with graphite or steel with high carbide content, as well as tungsten carbides, consisting of carbides and metallic binders, also belong to this group of composite alloys. The term metal matrix composites is often equated with the term light metal matrix composites (MMCs). Substantial progress in the development of light metal matrix composites has so that they could be introduced into the most important applications. These innovative alloys open up unlimited possibilities for modern material science and development; the characteristics of MMCs can be designed into the material, custom-made, dependent on the application. This material group becomes interesting for use as constructional and functional alloys, if the property profile of conventional alloys either does not reach the increased standards of specific demands, or is the solution of the problem. The advantages of the composite alloys are only realized when there is a reasonable cost – performance relationship in the component production. The use of a composite material is obligatory if a special property profile can only be achieved by application of these alloys. The possibility of combining various material systems (metal - ceramic – non-metal) gives the opportunity for unlimited variation. The following demands for composite alloys for combustion engine pistons are: low density, mechanical compatibility e.g. a thermal expansion coefficient which is low but adapted to the matrix, chemical compatibility, thermal stability, high Young's modulus, high compression and tensile strength, good processability [10-14].

The aim of the composite material of the minimum-difference of the thermal expansion during heating and cooling for piston engine is increase piston resistance on fatigue damages and on thermal shocks. When the heated piston is subject of temperature gradient or when is composed from two or more materials (e.g. ring insert) with different thermal expansion coefficients then different elements piston component tend to expand into the different manner depend on instantaneous temperature and thermal expansion coefficient proper of given material. To make possible the maintenance of piston continuity, thermal strains and united with them stresses have to appear. They are dependent from the shape of the element and temperature distribution. The problem of the thermal stresses is very important for present development combustion engines, especially turbocharged engines. On the other hand high temperature conditions need application of novel alloys resistant to these temperatures. However the characteristic propriety of these alloys is the smaller elasticity. This is the next reason for searching novel materials. For this reason the thermal stress is one of most important criteria of design in applying of resistant materials on high temperatures, including materials on pistons for heavy duty combustion engines. This problem becomes more essential, when along with cyclical changes of the temperature, changes of the coefficient of thermal expansion will also appear. Research data show that changes of the coefficient of thermal expansion can be very large during heating and cooling, as well during following cycles of heating and cooling of the combustion engine piston with reference to standard alloys on pistons.

3. Material research methods

Representative chemical composition for a standard alloy and novel alloy are presented in Tab. 1.

Tab. 1. Representative chemical components for a standard alloy and novel alloy

No.	Chemical Components, %					
	Si	Mg	Cu	Ni	Cr	Mo
Standard Alloy	12.5	0.37	5.0	4.15	-	-
Novel Alloy	12.5	0.43	5.2	4.15	0.32	0.54

Novel alloy was modified with TiB5 and AlSr10 in the quantity properly 0.2 % and 0.3 % from the mass of the liquid metal of the temperature of 780°C. Test specimens were separation strengthened in conditions of the solution heat treatment at the 520°C during 8 hours and cooling in water, and then were aged at the temperature of 160°C during 8 hours and cooled in environment air. The wear resistance adhesion during the friction was investigated on samples of the diameter d = 18.5mm and length l = 40mm. Research results of mechanical properties after the solution heat treatment are presented in Tab. 2.

Tab. 2. Mechanical properties investigated alloys after solution heat treatment

No.	Mechanical Properties			
	R_m MPa	$R_{p0.2}$ MPa	A_5 %	HB
Standard Alloy	240	190	1.5	80
Novel Alloy	480	400	1.5	148

The wear resistance of novel alloy comparatively for two cast irons is represented in Fig. 1. After 10 hours of friction test, the mass loss of novel alloy was less of 0.8 mg. Wear of the AlSi12.5.Mg standard alloy was about four times greater than novel alloy wear of AlSi12.5MgCr0.3Mo0.5Ni4Cu5.

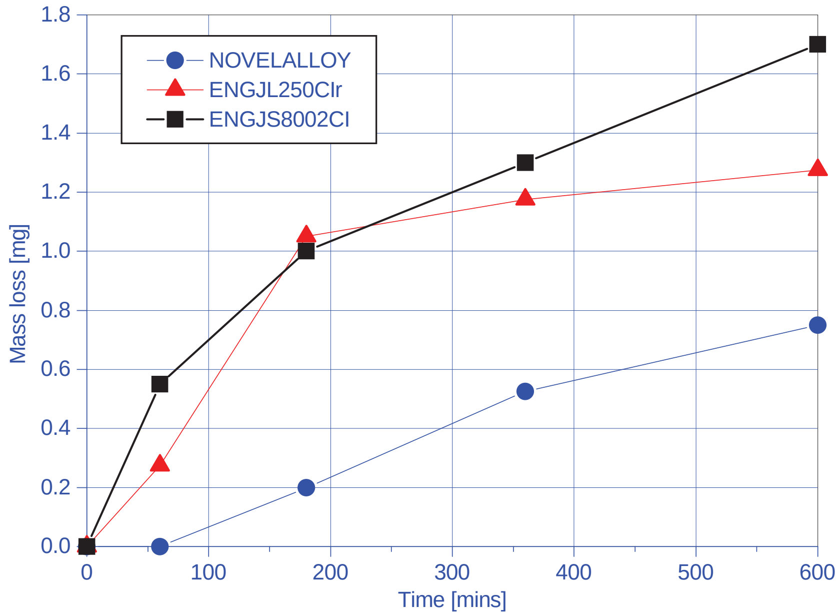


Fig. 1. Wear resistance of novel alloy compared with two cast irons (EN-GJS-800-2 spheroi dal perlite cast iron and EN-GJL-250 grey-iron)

4. Test results

Main research concerning novel pistons included, except research of mechanical proprieties and research of wear resistance, ATD research, microstructure, the microanalysis with X-ray and dilatometric research, whereat dilatometric research were basic research for the determination of the propriety of functional pistons in reference to noise and exhaust gases emission levels.

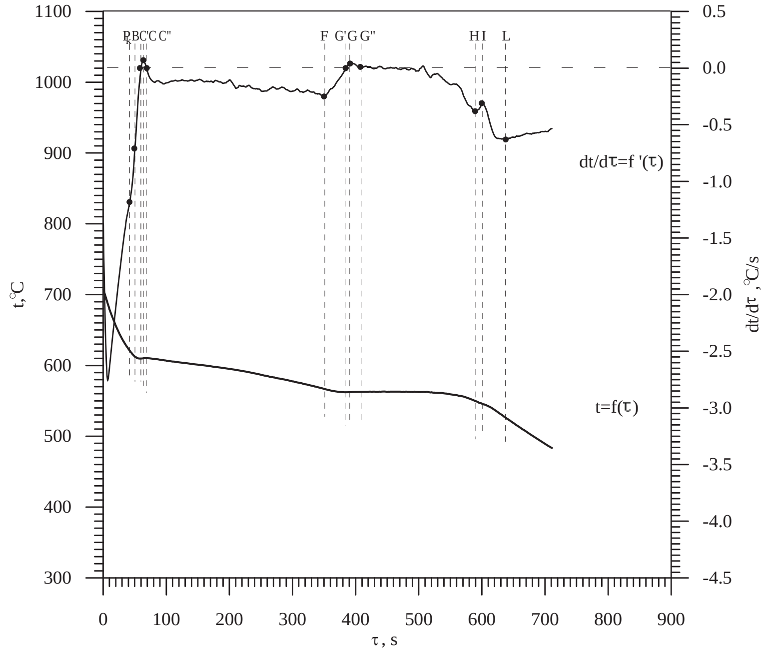
ATD curve of the AlSi12.5Mg standard piston alloy and its microstructure are presented in Fig. 2.

Construction of silicon is fibrous, with very large fragmentation what is represented in Fig. 3.

The finest fragmentation of microstructure for novel alloy is obtained after introduction of Cr and Mo additives within the range of 0.2-0.3 %. In Fig. 4 the ATD curve of the novel piston alloy and its microstructure are presented. Thereby on derivation curve the P_KAB thermal effect is due with crystallization of this phase in the temperature of tPK = 647°C up to tB = 605°C. In this temperature the partial peritectic transformation of L+Al12.5MoCrNiSiCuFe → L+α+Al12.5MoCrNiSiCuFe happens which is ended at the temperature of tD = 556°C. It is the beginning temperature of crystallization of the Al_3NiCu phase. It finishes crystallization at the temperature of tF = 548°C. From this temperature the crystallization of α+β eutectic begins up to the temperature of tH = 541°C. It is beginning of the crystallization of the Mg_2Si phase which happens up to the temperature of tJ = 514°C. In the final stage solidifications of novel alloy, the phase Al_2Cu crystallizes within the range temperatures up to tL = 490°C. Identification of the AlSiMoCr phase with the X-ray micro analyser is represented in Fig. 5.

After the solution heat treatment of silumins at the temperature of 520°C during 8 hours and cooling in water, with the next aging at the temperature of 160°C during 8 hours and cooling in environment air, the fragmentation and the coagulation of silicon and the phase Al_2Cu follows. For example in Fig. 6 separations of silicon after the separation consolidation is represented. Separations have spherical, compact and plate form of size of 0.1-3.0 μm.

a)



Points	τ, s	t, °C	dt/dτ, °C/s	$dt^2/d\tau^2$, °C/s^2
P_k	40	623	-1.24	21.7
B	52	611	-0.56	91.2
C’	63	609	0.06	0.97
C	67	610	0.02	-3.63
C”	80	609	-0.12	0.42
F	351	566	-0.24	-2.45
G’	385	561	0.00	9.07
G	392	562	0.04	1.95
G”	409	562	0.00	2.93
H	591	549	-0.38	-1.72
I	601	545	-0.31	0.87
L	637	526	-0.63	-1.27

b) c)

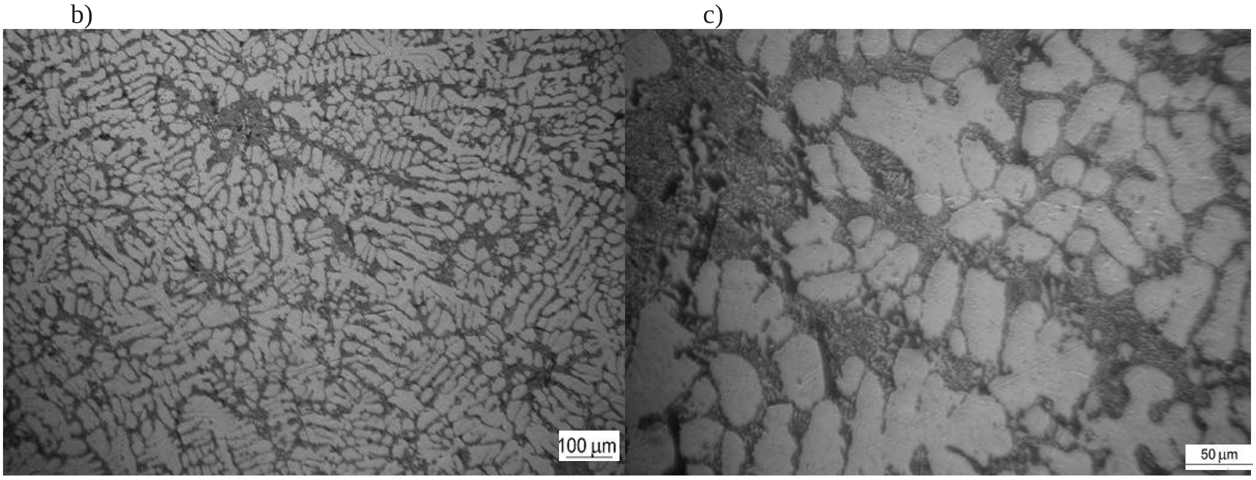


Fig. 2. ATD curve (a) of the AlSi12. 5Mg standard piston alloy and its microstructure (b, c) . Phases: α, Mg_2Si, α+β eutectic

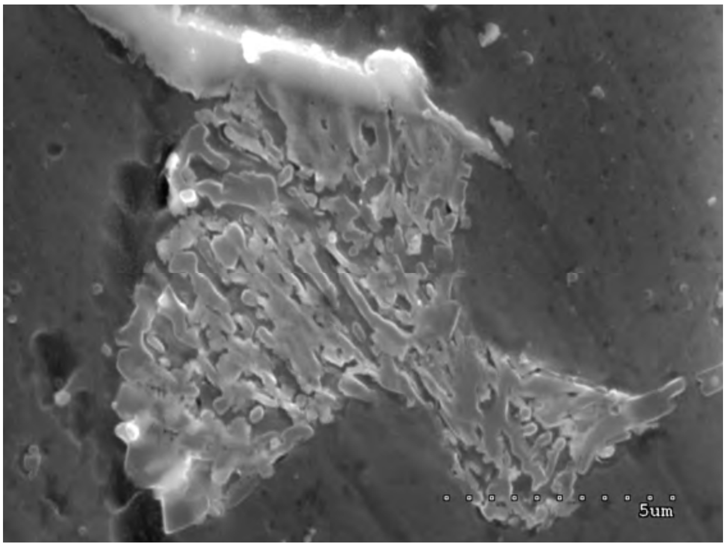
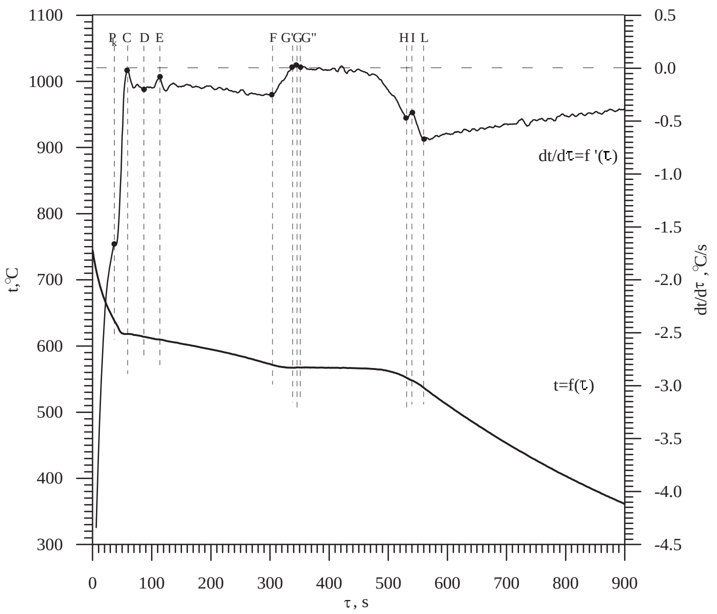


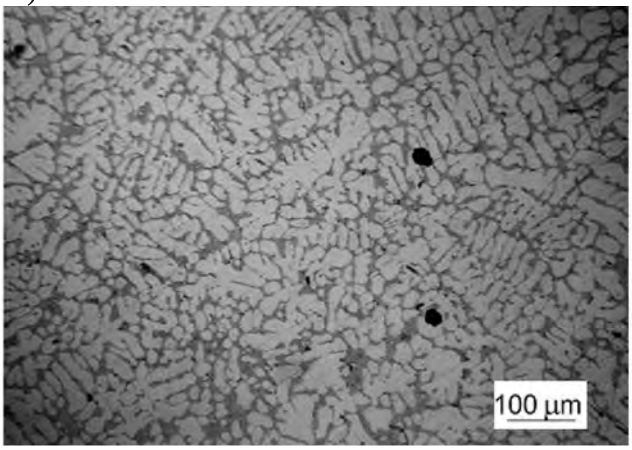
Fig. 3. The fibrous construction with very large fragmentation

a)



Points	τ, s	t, °C	dt/dτ, °C/s	$dt^2/d\tau^2$, °C/s^2
P_k	38	636	-1.66	1.55
C	59	618	-0.01	-2.53
D	94	612	-0.17	4.58
E	102	610	-0.18	-0.95
F	315	568	-0.16	16.4
G’	335	567	-0.01	0.01
G	354	567	0.00	6.47
G”	365	568	-0.00	0.03
H	530	552	-0.47	-9.29
I	540	548	-0.41	-2.15
L	563	535	-0.66	6.84

b)



c)

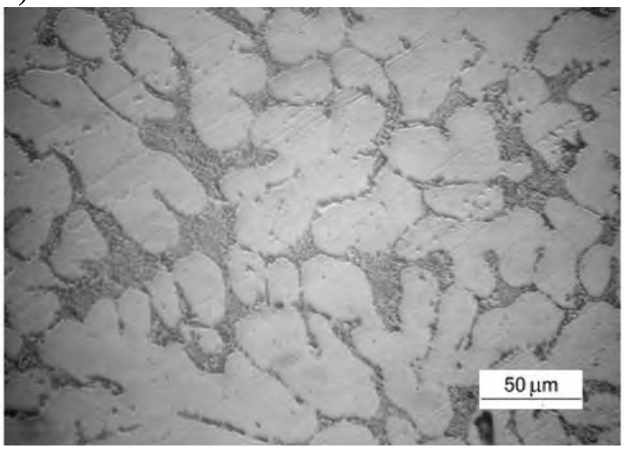
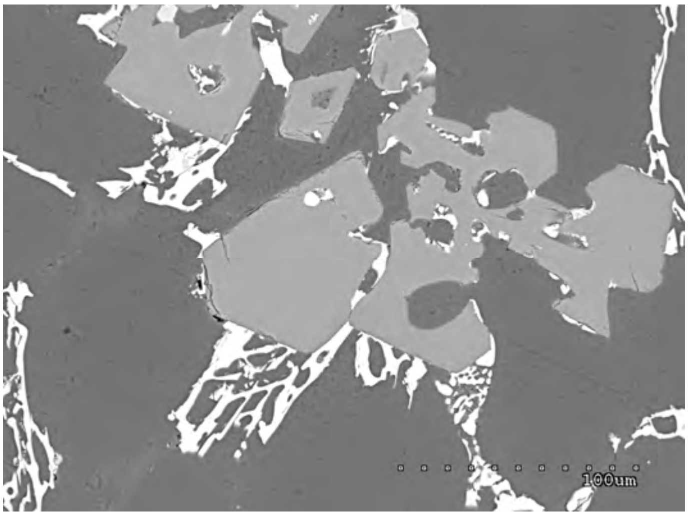
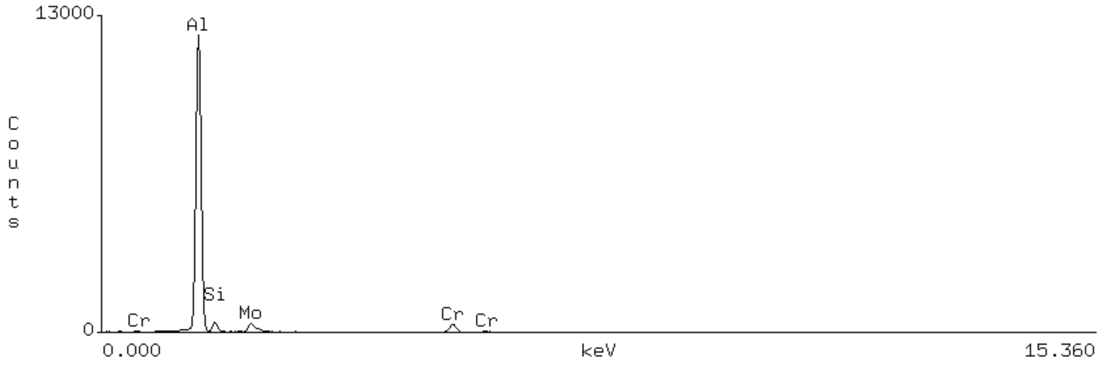


Fig. 4. ATD curve (a) of the novel piston alloy and its microstructure (b, c). Phases: AlSiMoCr, Mg_2Si, $\alpha+\beta$ eutectic

a)



b)



Element	k-ratio (calc.)	ZAF	Atom %	Element Wt % (1-Sigma)	Wt %	Err.
Al-K	0.6275	1.183	84.92		74.22	+/- 0.34
Si-K	0.0221	2.575	6.26		5.69	+/- 0.12
Mo-L	0.0646	1.768	3.67		11.42	+/- 0.35
Cr-K	0.0754	1.150	5.15		8.67	+/- 0.25
Total			100.00		100.00	

Fig. 5. Analysed microstructure of novel alloy (a) and concentration of elements component in chromic-molybdenic phase (b)

Because silicon comes into composition of chromic-molybdenic phases crystallizing in the first phase of the solidification process of novel alloy, so its concentration decreases in the fluid. Thereby its quantity in eutectic is reduced and its fragmentation is increased.

Novel alloy has good strength propriety, but not only. The course of changes of the coefficient of thermal expansion of in the function of temperature during heating and cooling for the standard-alloy on pistons is presented in Fig. 7. The course is characterized by increasing of the coefficient of thermal expansion during cooling. The course of changes of the coefficient of thermal expansion as a function of the temperature during heating and cooling for other standard-alloy on pistons is shown in Fig. 8. This course is characterized by decreased coefficient of thermal expansion during cooling. One ought to underline that observed changes of the coefficient of expansion of thermal during following cycles surrendered to further changes, and all courses of the coefficient of thermal expansion show differences during heating and cooling.

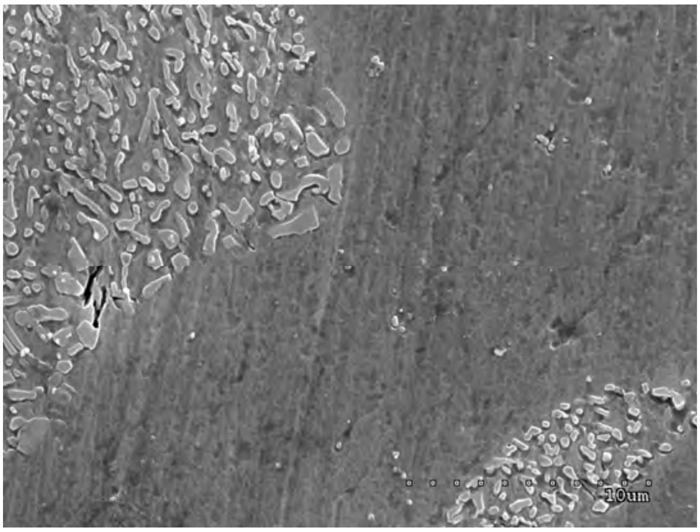


Fig. 6. Construction of silicon after solution heat treatment

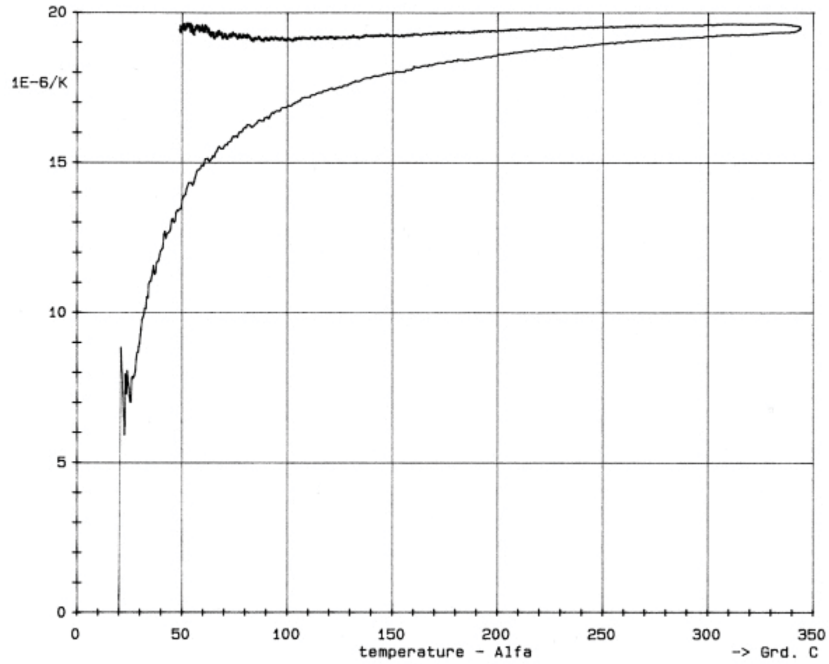


Fig. 7. The course of changes of the coefficient of thermal expansion in t he function of the temperature during heating and cooling for the standard-alloy on pistons being characterized by increasing of the coefficient of thermal expansion during cooling

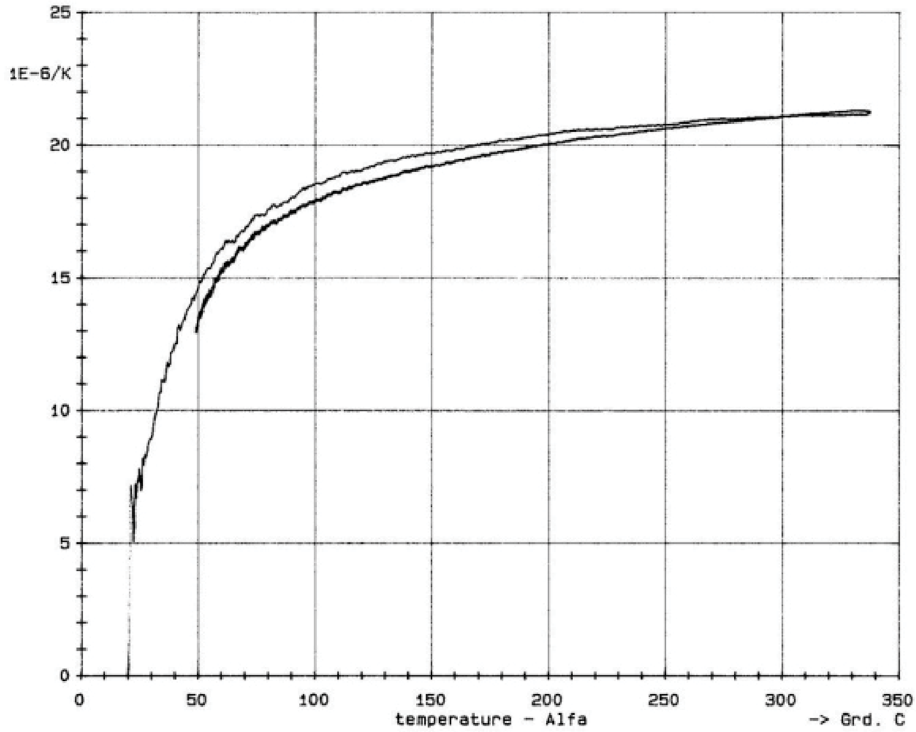


Fig. 8. The course of changes of the coefficient of thermal expansion in the function of the temperature during heating and cooling for the standard- alloy on pistons being characterized by decreasing of the coefficient of thermal expansion during cooling

The course of changes of the coefficient of thermal expansion as a function of temperature during heating and cooling for the novel composite material are presented in Fig. 9. Differences of the coefficient of thermal expansion for this alloy are much lower than for standard alloys. The above-situation causes moreover that for the same thermal loads thermal gradients will be lower for novel alloys in comparison to standard alloys. In connection with of above the thermal loads of novel pistons will be lower than thermal loads of pistons performed with standard alloys working under the same conditions. Characteristics of novel alloys diminish piston clearances and obtainment of the correct work in the full range of rotational speeds of the engine loads.

Such situation is due to a presence of many elements in pre-eutectic phases which causes their considerable strengthen, thereupon functional proprieties of pistons will be enhanced. The occurrence in the microstructure of silumins of pre-eutectic phases will diminish differences of the coefficient of thermal expansion during heating and the cooling (practically „hysteresis absence”) what is confirmed by the presented data on Fig. 9. Performed research showed that except mentioned phases, constituent elements of alloys can create composite multiple phases e.g. Al12CrSiNiTi, Al12MoNiSiCuTi, AlSiMoCr, AlCrMoNiSiFe, Al3NiCu3 and Al3NiCu of the very low fragmentation. Their kind depends on concentrations of each element in the alloy. Multiphases of the microstructure, their considerable fragmentation and the presence of Si in some phases cause decreasing of the quantity of separations, and consequently the obtainment of high useful proprieties.

Multiphases of the microstructure and absence of the dissolubility of constituent elements in alloys in the aluminium cause the crystallization of multiple phases of the low fragmentation, because a place of the nucleation and increment of the following phase is the interphasic border of the previously crystallized phase of and liquid. Thereby the pistons performed with novel alloy have high dimension-stability, high mechanical properties within in the range operating temperatures of pistons (120-340^{o}C), the wear resistance of ring grooves and the piston skirt and the high mechanical and thermal fatigue strength.

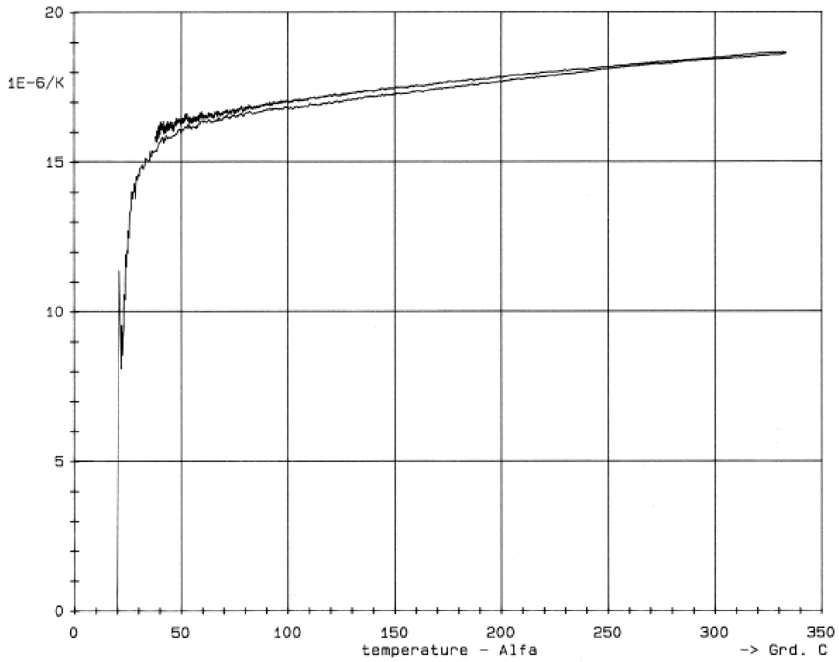


Fig. 9. The course of changes of the coefficient of thermal expansion in the function of the temperature during heating and cooling for the novel all oy which is characterized by very low differences of the coefficient of thermal expansion during heating and cooling

5. Conclusions

Composite alloys have, in automotive engineering, a high application potential in the engine area especially in oscillating construction units: valve train, piston rod, piston and piston pin; covers: cylinder head, crankshaft main bearing; engine block: part-strengthened cylinder blocks.

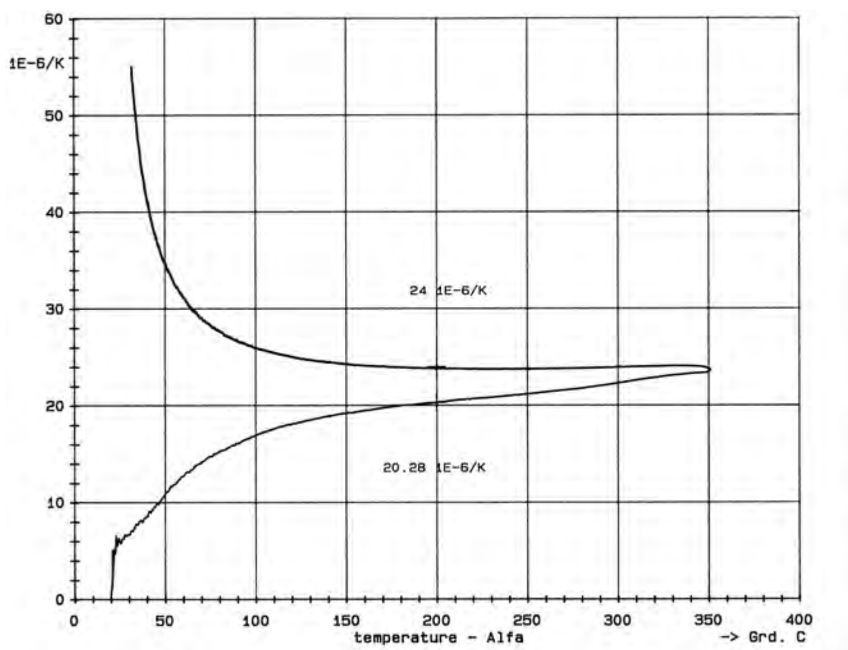


Fig. 10. The course of changes of the coefficient of thermal expansion in t he function of the temperature during heating and cooling for the standard alloy which is characterized by high differences of the coefficient of thermal expansion during heating and cooling

- Changes of the coefficient of thermal expansion can be very large during heating and cooling, as well as during following cycles of the heating and cooling of the piston the combustion engine with reference to the standard alloy applied on pistons.
- Observed changes of the coefficient of thermal expansion during following cycles are subject to further changes and all courses of the coefficient of expansion of thermal show differences during heating and cooling for the standard alloys.
- Differences of the coefficient of thermal expansion during heating and cooling for novel alloy are considerably lower than for the standard alloys.
- The thermal loads of novel pistons are lower than thermal loads of pistons performed with the standard alloys which work in such same conditions.
- Characteristics of novel alloys give possibilities of minimalizing of clearances and obtainment correct work in the full range of rotational engine speeds the loads.
- Novel alloy permits also to obtain greater elasticity together with high strength.
- Low clearances between piston and cylinder liner result in reduction of exhaust gases emission level and noise level.
- The lowest fragmentation of the microstructure for novel alloy may be obtained with introduction additives of Cr and Mo within the range 0.2-0.3 %.
- Because silicon comes into composition of chromic-molybdenic phases crystallizing in the first phase in solidification process of novel alloy, its concentration in liquid is low. Thereby its quantity in eutectic is low and its fragmentation is very fine.
- The occurrence in the microstructure of novel alloy of pre-eutectic phases will decrease the difference in the coefficient of thermal expansion during heating and cooling (hysteresis „absence”).

The thermal expansion coefficient is determined by the previous thermal heat treatment of the composite materials, which results from the production and the application. With the monolithic materials the thermal expansion coefficient increases with increasing temperature. With increasing temperature the difference of thermal expansion coefficient becomes less. After a heat treatment the increment values thermal expansion coefficient, particularly in the temperature range above the ageing temperature decreases.

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