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DESIGN OF NOVEL COMPOSITE PISTONS FOR DIESEL ENGINE

Antoni Jankowski

Institute of Aviation (Aeronautics)
Al. Krakowska 110/114, 02-256 Warsaw, Poland
tel.: +48228460011, fax: +48228463244
e-mail: ajank@ilt.edu.pl

Abstract

The paper presents the requirements to be met by diesel engines and their components, in particular pistons for engines of military vehicles. These requirements are related to the mass of modern military vehicles, which has greatly increased. Materials for the piston should have a good strength properties and low hysteresis of thermal expansion coefficient α across the range of operating temperatures, good resistance to galling, low abrasion, low coefficient of friction and good functional properties. On the clearance of the piston in the cylinder, the coefficient of thermal expansion α and its hysteresis has a decisive influence. The paper includes information on the piston working clearances, the requirements for pistons materials, their chemical composition, standard materials for the forged pistons, for the cast pistons (silumin alloys) and for the composite pistons. The paper presents the changes in coefficient of thermal expansion for the alloy in the raw state and after heat treatment and pistons made of new composite material prior to motor testing and after these tests. The completed new pistons have a lower coefficient of thermal expansion and lower hysteresis α, which allows reducing the running piston and cylinder clearances with the resulting effects.

Keywords: *internal combustion engine, Diesel engine, piston engine, composite alloy, combustion engine performance*

1. Introduction

The requirements that pistons for diesel engines must met are particularly important for heavily loaded ones, the structures of which were formed because of the modernization of the basic types. This occurs in a relation to the PZL WOLA SA Mechanical Plant products. Mass of modern military vehicles, including tanks mass is significantly increased, which is associated with the use of additional equipment to improve efficiency, the use of shields increasing armour resistance, usage of shields against improvised charges and mine, the usage of additional reactive armour and screens for armour protection against shaped charges. In addition, modern military vehicles, tanks must have greater manoeuvrability on the battlefield. These two factors mentioned above: increased weight and increased demands on the manoeuvrability make it necessary to increase the power of internal combustion engines, used in military vehicles and so usage of highly loaded engines, both mechanically and thermally. Since the pistons of the new generation the high strength properties at high temperature and functional properties are required, involving mainly on minimizing the difference in thermal expansion during heating and cooling, what increases resistance to damage of the piston structure, both the mechanical and thermal one, and increases the pistons thermal shock resistance [7, 12]. Materials for the piston should have a good strength properties and low hysteresis of thermal expansion coefficient across the range of operating temperatures, good resistance to galling, low abrasion, low coefficient of friction, good functional properties [15]. Typical materials for the pistons, the silumin aluminum alloys have insufficient performance of parameters for such engine solutions. This relates primarily to the mechanical and thermal fatigue strength and thermal shock resistance. Due to the fact that the piston of internal combustion engine has an asymmetrical shape, it is in any case of increase of the piston temperature, i.e. typical situation of engine piston operation, the uneven strains and stresses appear, causing fatigue loads of the piston structure. Additional mechanical loads of the piston coming from pressure forces occurring in the engine cycle and the inertial forces produce synergy effect and deepen the fatigue impact derived from thermal and mechanical loads. If the temperature changes are sufficiently fast, which could occur significantly, especially in relation to military vehicles operated under different conditions, the additional effect of thermal shocks occurs.

2 Operating clearances between Diesel engine cylinder and piston

Due to the fact, that the pistons must meet high requirements in terms of functional properties related to the maintenance of proper dimensions, clearances, under elevated and high temperatures, both the mechanical properties and thermal stability of alloys have to ensure the durability and reliability of their operation. In addition, they must meet the high demands of resistance to changing mechanical and thermal loads at elevated temperatures. On the clearance of the piston in the cylinder, the coefficient of thermal expansion α and its hysteresis has a decisive influence. The pistons are typically made of aluminum alloys, and cylinders from the cast iron, whose thermal expansion coefficient is about twice less, than the coefficient of thermal expansion of aluminum alloys. The temperature in particular points of the piston during engine operation is significantly higher than the temperature of the cylinder. Temperature rise on the piston is greater than on the cylinder, so the share of the piston material in reduction of the clearance between the piston and the cylinder is greater than the cylinder material. Due to the complex shape of the piston and high and different temperature gradients in different parts of the piston, the strains develop which may cause uneven distortion of the piston, leading to deformation. Deformations can cause local or total reduction of clearances and may even lead to seizure. Value of the clearance between the piston and the cylinder should, therefore be optimized, so that on one side there is sufficient clearance for the free deformation of the piston-cylinder assembly over the entire range of thermal and mechanical deformation (including deformation of the piston shape), on the other side, that it is not too large, which could adversely affect engine ecological parameters, such as the exhaust gases toxicity (mainly the presence of hydrocarbons), noise emissions, oil and fuel consumption. Deformation of the piston, by which the distortion in this case should be understood, due to uneven distribution of asymmetric thermal and mechanical strains and the occurrence of hysteresis of the piston material. As a result of its continuous heating and cooling, the hysteresis especially reveals in engine load and rotational speed transient conditions [13].

3 Requirements for materials for pistons for internal combustion engines

Deformation can be prevented by ensuring that the chemical composition of the materials and the design of a suitable technological process of both materials and pistons themselves. When the piston is subjected to a temperature gradient, or when it is composed of two or more materials (piston skirt insert) having different coefficients of thermal expansion and will be subsequently uniformly or non-homogeneously heated, so the various components of the piston have a tendency to expand in different ways, depending on the instantaneous temperature and the thermal expansion coefficient of the appropriate material. In order to allow continuity of the piston structure, the thermal deformations and the associated strains must occur. They are dependent on the element shape and temperature distribution. Brittle and ductile materials react differently on the thermal loads. Brittle materials can transfer only very small deformations before rupture, and the ductile materials can carry much greater deformations. The most important strength parameters of materials for pistons are the tensile strength, relative elongation at fracture, hardness and fatigue strength. This applies to properties over the pistons operating temperature range. Tensile strength and relative elongation determine the piston maximum load, or they must be tailored to these maximum loads. It is essential, therefore the strength of the piston material not at ambient temperature, but in terms of the maximum pistons operating temperature, which is 300-350°C.

The hardness of materials on the pistons is essential for the abrasive wear that occurs mainly in relation to the ring grooves and partly with respect to the pistons skirt. Within the ring grooves, in the maximum engine load conditions the temperature may reach a value up to 230°C. The temperature in the ring grooves is limited mainly by the properties of lubricating oils, but under these conditions, the hardness of the standard piston silumin alloys strongly decreases, which causes the occurrence of heavy abrasive wear. Thus, the piston material should have high hardness, in the range from ambient temperature up to temperature of 250°C [14].

4. Materials for pistons of internal combustion engines

The standard and currently used materials for the piston are the silumin piston alloys, which have the following chemical composition: 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 in silumin alloys form following intermetallic phases: Mg2Si, Al3Ni, Al2Cu, AlFeMnSi. These phases crystallize after the completion of the process of eutectic crystallization α + β (Al + Si). They cause the strengthening of the silumin alloy. Mechanical properties at ambient temperature of silumin piston alloys are in the following ranges: R_m = 200-360 MPa, $R_{p0.2}$ = 160-320 MPa, A_5 = 0.2-2.5%, HB = 80-100 and E = 80-85 GPa. For example, at a temperature of 250°C they are as follows: R_m = 120-140 MPa, $R_{p0.2}$ = 95-85 MPa, A_5 = 0.9-8.5%, HB = 40-50 and E = 73-75 GPa. The above-mentioned intermetallic phases present in the microstructure of silumin piston alloys are not stable. During the heating of the piston in the engine, they are partially dissolved in a solid solution α, and in its cooling process, they are released again. Consequently, a partial plastic deformation of the piston occurs, which results in a gradual increase in the difference between its expansion during heating and contraction in the cooling process (it is called hysteresis). On the relatively low functional properties of pistons made of presented silumin alloys at their work temperature, are significantly affected by the size of the silicon, both the primary (hypereutectic silumin alloys) and eutectic. Size of the primary silicon is in the range 30-50 µm, a eutectic in the range of 15-20 µm. The essence of the new generation of pistons composite [1, 2, 4] materials is the occurrence in them of the intermetallic compound, crystallizing at high temperatures prior to crystallization of the eutectic α + β (Al + Si). Multi component inter metallic phases, crystallizing as the first in the process of the piston casting solidification results in the natural (in situ) composite material, with the best functional properties. To produce hypoeutectic phases, the chromium and molybdenum will be introduced into silumin, and for obtaining their multicomponentity, the nickel and copper concentrations are increased and magnesium content is reduced. Along with the new composite material, the modern technology to strengthen the surface of the piston head with the laser pulse will be introduced. Multi-phase of the microstructure and lack of the dissolvability of alloys component elements in aluminum causes the crystallization of compound phases with the high fragmentation, because the place of nucleation and subsequent growth phase is the interphase border of previously crystallized phase and liquid. Multiphaseability of microstructure, its considerable fragmentation and presence of Si in some phases causes the decrease of its liberation quantities, and as a consequence obtainment of high useful properties. The highest friction coefficient values were obtained for samples of materials, which have a high hardness, which, however have the form of a brittle body with very low value of relative elongation at a relatively high value of the force. These materials also show improved properties under conditions of elevated temperature, when with increasing temperature the material elongation grew [5, 7].

The investigations of pistons material strength were performed at a different material chemical composition, wherein the content of one element in the core material composition was increased, and also changing collectively the several alloying elements. As a result of this action, one can determine the effect of each particular element on the strength of the material at normal temperature and at elevated operating temperatures, up to a temperature of 350°C and the synergic effect of the alloying elements added to the core alloy. The investigation results show, that the increase of the alloying element content in silumin alloys was followed with increase in strength to a certain value, and then as the content increased, it was followed with reduced strength and the material become more brittle [8, 9, 10]. With a certain content of the alloying element, the relative elongation decreased to zero. This is probably due to the fact, that the added alloying elements have much larger lattice parameters. These alloying elements affix on the base material grain boundary and cause the occurrence of internal stresses and at greater quantities are additionally the cause of intergranular cracks, wherein these cracks can increase with increasing amounts of added elements and the formation of increasing intermetallic compounds, which locate on the grain boundary. Therefore, the technological process should be conducted in such a way, that the resulting intermetallic compounds are not present in the form of large crystals with sharp edges, because it will lead to damage of the material microstructure. The investigations results of the strength and thermal expansion coefficient has been used to select the chemical composition of the new piston material. The carried out laboratory tests show the dimensional stability of the new piston material, comprising a non-conventional alloy elements, such as: chromium, molybdenum, tungsten, with increased content of copper and nickel, it will be characterized by very favourable strength properties, both in normal conditions and in maximum temperature conditions. The developed material has a low hysteresis of thermal expansion coefficient α, slightly lower coefficient of thermal expansion than the standard silumin piston alloys, and a high resistance to galling and low friction coefficient. The pistons made of a new material showed the small deformations after the long-term engine tests, in difficult conditions, frequent changes in engine speed and engine load [3], which was probably the reason why they show very little oil consumption, crankcase blow-by, resulting in low hydrocarbons emissions. The result of the performed investigations was development of a composite material for pistons for heavy-duty engines of military vehicles (tanks) with high strength properties, including resistance to both mechanical and thermal fatigue damage and thermal shocks. Developed composite material is characterized by a minimum difference of thermal expansion during heating and cooling, which increases resistance to damage pistons fatigue and thermal shock and allows the use of assemblies with lower clearances, dimensionally stable during the operation of military vehicles (dimensional stability), which allows increase the functional engine parameters in terms of fuel consumption, toxic exhaust emissions, crankcase blow by gases emissions [11]. The chemical composition of the materials for pistons so far produced is shown in Tab. 1, and generalized silumin alloys chemical composition is presented in Table 2. The chemical composition of composite silumin alloys is presented in Tab. 3.

Tab. 1. The chemical composition of the PA12 alloy forged pistons

The chemical composition % Wt.								
Si	Cu	Mg	Ni	Ti	Fe	Zn	Mn	
10.5-12.5	0.5-1.5	0.8-1.8	0.5-1.5	≤ 0.1	≤ 0.7	< 0.2	< 0.2	≤ 0.15

Tab. 2. Generalized chemical composition of silumin piston alloys

The chemical composition % Wt.								
Si	Cu	Mg	Ni	Ti	Fe	Zn	Mn	Other total
9.5-13.0	0.5-4.0	0.4-1.7	0.5-4.0	0.1-1.2	0.5-0.7	0.05-0.20	0.2-0.6	≤ 0.15

Tab. 3. The chemical composition of the tested composite silumin alloys

The chemical composition % Wt.									
Si	Cu	Mg	Ni	Fe	Mn	Cr	Mo	W	V
11.5-12.5	3.0-4.0	0.3-0.6	4.0-5.0	≤ 0.50	0.20-0.35	0.05-0.8	0.05-0.8	0.05-0.8	0.05-0.8

5. Results of the investigations

In Fig. 1 shows the changes in thermal expansion coefficient α during heating and cooling of the silumin alloy in the raw state. From the above figure results, that during the cooling of the silumin alloy, starting from 350°C temperature, the coefficient α is greater, than during the heating of it. The hysteresis of coefficient α forms, it is a very disadvantageous phenomenon to pistons of the internal combustion engine, which can cause piston seizure in the cylinder. Fig. 2 presents the change in thermal expansion coefficient of the silumin alloy, type AlSi12Ni4Cu4Mg0.5CrMoWV, after the heat treatment. The analysis of curves (Fig. 1 and Fig. 2) showed that the precipitation processes start at about 200 ° C and end at 320°C. From the presented data shows, that the aging temperature should correspond to the value of maximum increase of silumin alloy dimensions. After aging at this temperature, the hysteresis of the α coefficient is practically non-existent, as is shown in Fig. 2.

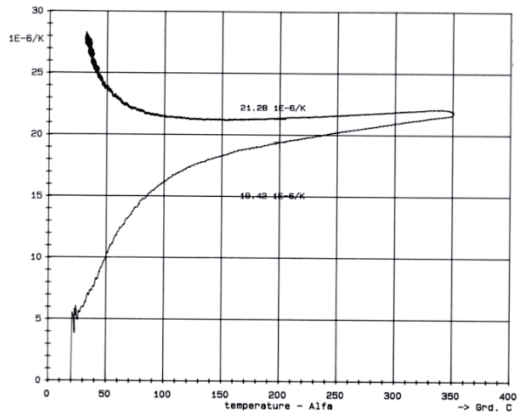

Fig. 1. Changes of thermal expansion coefficient of raw state silumin alloy AlSi12Ni4Cu4Mg0.5CrMoWV during heating and cooling

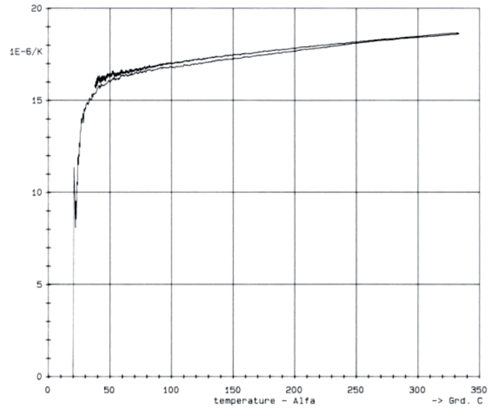

Fig. 2. Changes of thermal expansion coefficient of silumin alloy AlSi12Ni4Cu4Mg0.5CrMoWV after the heat treatment

The analysis of the investigations shows that the introduction of alloying additions to silumin piston alloys does not ensure the low hysteresis of the thermal coefficient α, because during material heating and cooling the intermetallic phases are rebuilding within the material. Only performance of the multi-stage heat treatment interrupts this process, stabilizes phases, which is reflected in the reduction of the coefficient of thermal expansion α variations during piston heating and cooling [16]. Completed research allowed choosing the optimal type of heat treatment, so that the material developed for the pistons meet the established parameters. From the developed composite alloy, the engine pistons were made, which are presented in Fig. 3.

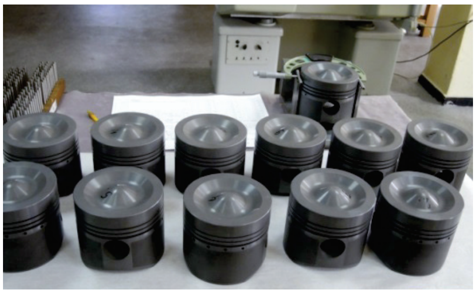

Fig. 3. Diesel engine pistons prior to motor tests

Fig. 4. Diesel engine pistons after the motor tests

The pistons after the engine tests are shown in Fig. 4. The photo of the engine, for which one has developed the new composite pistons, is given in Fig. 5.

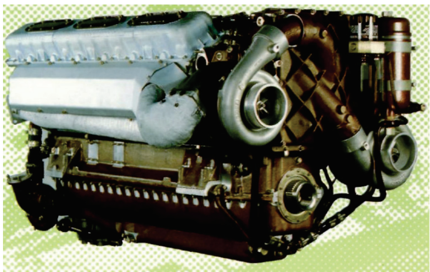

Fig. 5. Photo of the twelve-cylinder Diesel engine, for which one has developed the new composite pistons [6]

7. Conclusions

On the basis of investigations carried out it can be concluded that it is possible to obtain a very low hysteresis of thermal expansion coefficient α during heating and cooling of silumin alloys after artificial aging at 230°C.

The favourable effect of low hysteresis of α coefficient is reflected in improved engine functional parameters, including oil and fuel consumption, engine power, emissions, mainly hydrocarbon ones and engine noise level.

The advantageous parameters obtained with the new composite pistons are acquired after performing of the technological process, comprising a multi-stage thermal treatment.

In order to obtain better functional engine parameters, reducing the mounting clearance between the piston and cylinder, the piston outline changes, including the change of a barrel skirt and oval are necessary. After implementation in the piston design, better results for oil consumption, emission, noise, fuel consumption and engine power were obtained.

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