INVESTIGATIONS OF STRENGTH, THERMAL EXPANSION AND ENGINE OF NOVEL PISTONS FOR COMBUSTION ENGINES

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Abstract

Pistons of internal-combustion engines work in the conditions of high mechanical and thermal loads. The typical alloy materials applied on pistons of internal-combustion engines have inadequate parameters for such applications. It mainly refers to the fatigue strength of the mechanical and thermal character and to the thermal shocks. In relation with fact that the piston of internal-combustion engine has unsymmetrical shape, that in every case of the piston temperature increase the unequal deformations appear and stresses related with this, what causes fatigue loads of the piston structure. The paper presents special demands, which pistons of contemporary of internal-combustion engines must fulfil with respect to strength, thermal and useful properties, mirrored in the engine work parameters, like engine oil consumption, fuel consumption, noise, gas blowbys to the crankcase and the emission of toxic exhaust elements, mainly hydrocarbons. One turned attention on the new material that can be used in manufacture of pistons for the internal-combustion engines, which is the carbon material. In the article the results of research for the mechanical, thermal and engine properties are submitted for the pistons manufactured from a new material. On the emphasis deserve fact, that the application of new materials permits on the obtainment of the small difference in the coefficient of linear thermal expansion during the heating and the cooling, that will bring many profitable effects of both functional and useful nature.

Keywords*: combustion engine, engine pistons, novel alloys, novel materials, thermal expansion*

1. Introduction

Intensive development of internal-combustion engines taking place in the last time period is concentrating on the electronization of the new technologies encompassing designs for computer control of engine performance processes for the improvement of thermodynamic and combustion cycles, what includes both spark and compression ignition engines. The latest solutions encompass self learning itself systems, which adapt for example individual performance styles directed on the strategies of economy in the fuel consumption. From the new solutions the special attention deserves the direct fuel injection, which is utilized with respect to both types of engines – with the compression or spark ignition. At the same time, primordially two different performance strategies are applied for relative small engine loads, larger and larger loads and the full engine load. On the emphasis deserves inlet variable geometry of turbo-compressors and inter stage cooling. Variable geometry of induction systems adapted to the conditions of the engine work and the variable angles of the valve timing are the additional methods of the engine performance improvement. At last variable compression ratio and the universal application of catalytic reactors throws conditions for neuralgic elements of internal-combustion engine, by what sort are the pistons.

Pistons of internal-combustion engines work in the conditions of high mechanical and thermal loads. The requirements, which the pistons of internal-combustion engines must fulfil are particularly essential with respect to the highly loaded engines. The typical, common piston materials have inadequate parameters for such applications. Principally this refers to the fatigue strength with mechanical and thermal character and to the thermal shocks. In the relation with fact, that the piston of internal-combustion engine has unsymmetrical shape, than in every case of the increase of temperature, the unequal deformations and stresses related with this step out, what causes the fatigue loads of the piston structure. Additional mechanical piston loads from the gas pressure forces and from the inertia forces cause synergy effect and enlarge the influence of fatigue from thermal and mechanical loads. If the changes of temperature will be sufficiently fast, the additional effect of thermal shocks will step out. Pistons work in the wide range of temperature values, if it goes for pistons manufactured from aluminium alloys the maximum work temperature cannot goes over 650 K, but therefore requirements are, in order to the piston material strength properties will be appropriate to the task in the wide range of temperatures, both with static loads and with high-frequency loads, loads generating the large stresses gradients included. Because of the high mechanical and thermal loads the design of pistons to the compression ignition engines is characterized by the larger geometric dimensions and the larger mass. However the value of temperature in the particular places of the piston, in the whole range of the engine performance, they cannot be too large, both with respect to the spark and compression ignition engines. On the values of this temperatures, the properties of materials for pistons and the properties of the fuels and of the lubricating oils decide. The piston temperature cannot in any place reach the melting temperature, but even the temperature in which strength of the material becomes too small, but from a second side, in the points where oil contacts with the piston structure, its temperature must be lower from the oil or fuel decomposition temperature. The step over these temperature values can be the harmful not only for the piston structure, but also can lead to the soot and toxic matter in exhaust formation. Thus in pistons of highly loaded internal-combustion engines often the introduction of cooling becomes necessary, in order to hold temperature in the piston different points on the assumed level.

2. Development of pistons to the internal-combustion engines

Engines pistons fulfil many different functions and work in extremely heavy conditions of variable loads, they have constant contact with the liquid and gas environment. The principal demands in relation to pistons refer to their small mass, a small coefficient of thermal expansion, a high coefficient of thermal conductivity, high hardness and strength in elevated temperature, high corrosion resistance, but the particularly the high thermal stability permitting on support of stable piston geometrical dimensions during the work in the engine and in time of the long exploitation. In the last period the tests step out for the application of carbon materials as materials for pistons. The special source materials synthesized from coal tar elements or from crude oil tar serve as the raw material for the production of carbon pistons. Because of their liquid crystalline structure these materials carry the name of mesophase materials. Separated from tar, stabilized chemically and thermally, they are used to the production of the carbon materials with the perfect physical and mechanical properties. Elementary carbon cannot be melted or sintered. Therefore carbon materials are in principle produced within the framework of the pottery materials processes. In these processes basic carbon powder, with the high carbon consent is mixed with binder (prevailing they are the coal tar products - coal tar pitch). Then, after this mixture forming process, binder would be thermally decomposed as a result of the carbonization process to the elementary carbon in the temperature up to 1000 °C to create the form for the basic carbons next. The further thermal processing, graphitization in the temperature up to 3000 °C leads to the obtainment of carbon with properties respondent to the graphite, which are useful to many applications, not only to pistons of internal-combustion engines. Porosity of material can be decreased as a result of the impregnation process, that permits on obtainment of a appropriate specific density, and as a consequence - of the material mechanical strength. Source material to the production of pistons from carbon material is then processed as a result of the sintering. Therefore, it is possible to manufacture parts from the carbon material with the high values of the specific density and of a proper strength without binder usage. Considering the properties of raw material and the manufacturing process, the parts made of the carbon materials can be very homogeneous and have dense structure, but that goes for this - the high mechanical strength. Parts from carbon materials are marked off also by perfect tribology properties because of their isotropic graphite structure, but moreover they prove the very high values of thermal conduction and the oxidation and corrosive environment resistance. Therefore they are the perfect future materials on pistons of internal-combustion engines and not only. Some parameters of typical carbon materials are shown in Table. 1.

Tab. 1. Some parameters of typical carbon material

Parameter		Composite Carbon Material
Density	[g/cm^3]	1.9
Young's Modulus	[MPa]	15000
Bending Strength	[MPa]	100 - 120
Compressive Strength	[MPa]	250
Coefficient of Thermal Expansion	1x10^{-6}	7
Thermal Conductivity	[W/mK]	60

3. Pistons of the internal-combustion engines made from materials based on silumin alloys

The most essential strength parameters for the estimate of the piston design is the tensile strength R_m, relative elongation prior to breaking A_m and hardness. In the relation with the fact that pistons work in the wide temperature range, the physical properties of pistons materials in the work temperature are important above all.

The material tensile strength and relative elongation are essential for the piston from the point of view of its maximum loads, which in general step out for the short period of time or in emergency situations. Therefore in general, this refers to the strength in occurrence of the maximum piston temperature conditions 600-650°K. The hardness of material decides above all on the wear of ring grooves and piston bushings, but this hardness value refer to temperatures in the working engine, which with respect to the ring grooves ought not to be higher, than 230°C.

Moreover from the point of view of the pistons quality, essential is the fatigue strength, and this both thermal and mechanical, and creeping strength. The piston of internal-combustion engine is submitted to variable in the wide range loads, as and prolonged static character large loads. Therefore the pistons material ought to be characterized by eligibly high properties in normal conditions, as in the work conditions with the high temperatures prevailing in the engine combustion chamber.

The materials most widely used on pistons are neareutectic piston silumin alloys with about 11 - 13% silicon inclusive and overeutectic silumin alloys with about 17 - 24% silicon inclusive. The fault of standard piston aluminium alloys is the relatively fast fall of tensile strength and hardness in the function of temperature. The neareutectic silumin alloys in temperature of 400°K have about 10% smaller strength, in temperature of 500°K the fall of strength is already 40 - 50%, but in temperature of 570°K alloy has only about 35% of strength, which it had in temperature 293°K. With respect to overeutectic silumin alloys, the fall of strength in the function of temperature is smaller (for about 5%) but particularly this is observable in the highest temperatures, higher than 520°K. Relative to hardness, the piston silumin alloys prove much faster fall in the function of temperature. Already in temperature of 420°K the hardness of neareutectic silumin alloys is smaller for about 25%, than in temperature 293°K, whereas in temperature of 520°K hardness is smaller for about 70%, whereas in temperature of 620 K about 80% smaller than in temperature

293°K. In overeutectic silumin alloys this fall is slower, but principally with the values of the temperature higher than 470°K but therefore in the range of temperatures nearing to a maximum temperature of ring grooves and nearing to a piston crown maximum temperature. The values of tensile strength and hardness observed on graphs in the different temperatures permit on the expression of opinion how important are piston material strength parameters, particularly with the temperature values nearing to a maximum work temperature.

4. Investigations of the new pistons

Within the framework of the research tasks, the investigations were carried out of durability properties for different compositions of the tests alloys in the conditions of the surroundings and at the high temperature, the investigations of the linear thermal expansion coefficient with the application of a precise dilatometer which enables the recording of the changes in specimen dimensions relative to temperature in the straight and differential systems and which realizes temperature program controlled with the utilization of the computer, also the test stand engine research directed on the opinion on the new pistons solution in the range of exhaust emission, the fuel expenditure and the engine oil consumption.

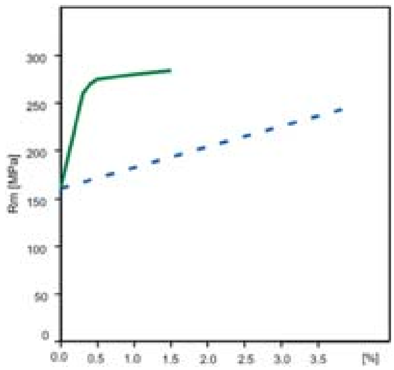

Fig. 1. Influence of Mg (above) and Cu contents on tensile strength of alloy for piston of combustion engines

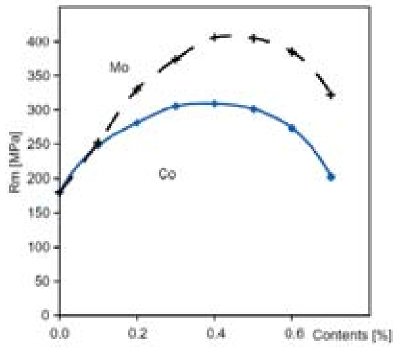

Fig. 2. Influence of Co and Mo on tensile strength of hypereutectic silumins for combustion engine pistons

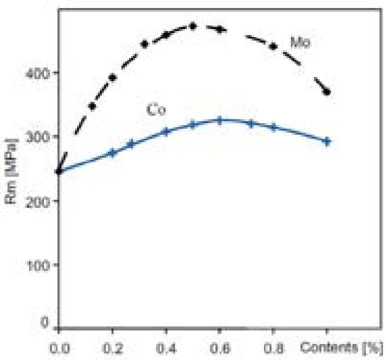

Fig. 3. Influence of Co and Mo on tensile strength of eutectic silumins for combustion engine pistons

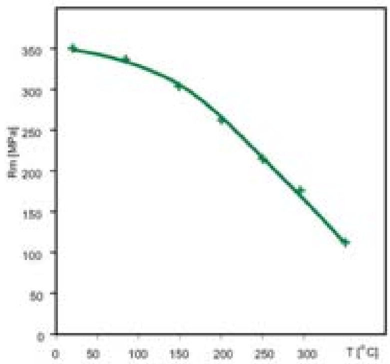

Fig. 4. Tensile strength of eutectic silumins with Ni versus temperature

The results of the strength parameters research in the function of chemical composition and temperature for standard and the new piston materials, based on the standard silumin piston alloys, to which the alloy additives were introduced. These additives were: chrome, cobalt, molybdenum, tungsten and nickel. The influence of separate alloy additives, and also synergic influence of several alloy additives was examined. The results of investigations show on the possibility of the essential increase of strength of alloys containing these additives, both in the temperature of the surroundings, and in the work temperature, till to 620°K, at the same time more beneficial effects were obtained with the simultaneous introduction of several alloy additives.

On Figs. 1 - 6 the exemplary results of the strength research are submitted. Fig. 1 presents the influence of cooper and magnesium additives contents on the tensile strength and Fig. 5 presents influence of cobalt and molybdenum additives on the tensile strength. Fig. 6 presents the influence of cobalt and molybdenum additives contents in silumin overeutectic alloy on its tensile strength. Fig. 7 presents the influence of temperature on the neareutectic silumin alloy strength. Fig. 8 presents the influence of temperature on the neareutectic silumin alloy strength. Fig.13 presents change of alloy hardness in the function of temperature. Figs. 7 and 8 presents the change of a coefficient of linear thermal expansion α in the function of temperature during the heating and cooling of the standard piston and the piston of a new type, respectively.

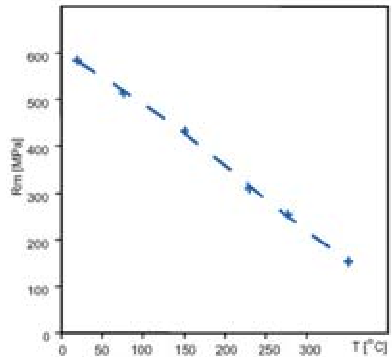

Fig. 5. Tensile strength of eutectic silumins with Mo versus temperature

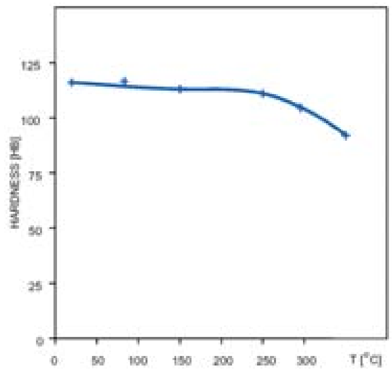

Fig. 6. Hardness of silumin versus temperature for silumin with 0.5% Co

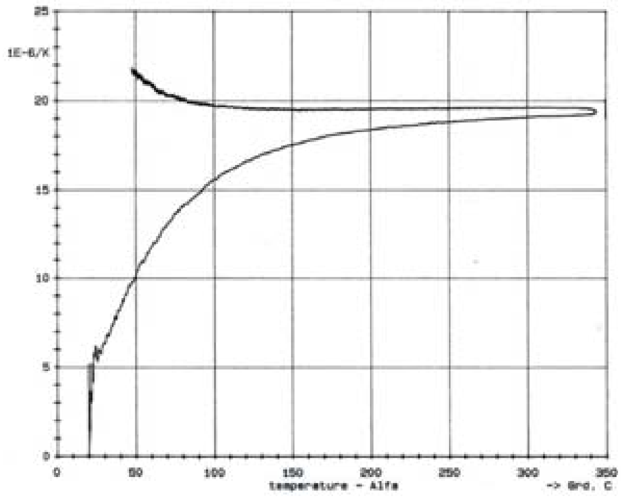

Fig. 7. Dependence of lineal coefficient of thermal expansion versus temperature for standard piston

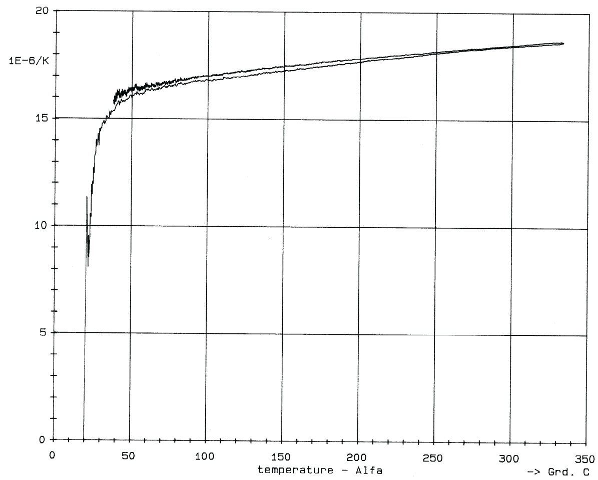

Fig. 8. Dependence of lineal coefficient of thermal expansion versus temperature for novel piston

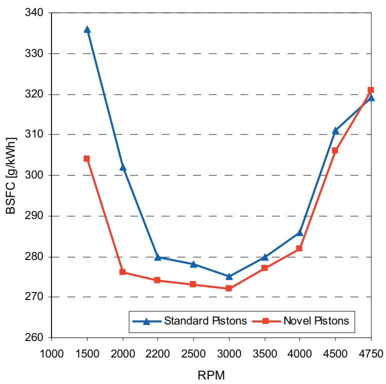

Fig. 9. Specific break fuel consumption versus engine speed at full load (rated power)

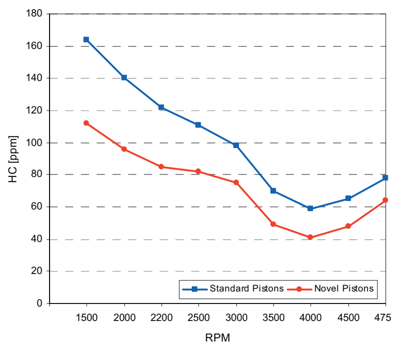

Fig. 10. Dependence of content of hydrocarbons versus rotational engine speed at full throttle opening (full load, rated power)

Engine investigations were performed on the research test engine with the spark ignition. Figs. 7 - 14 present the results of engine investigations, at the same time in the engine by this applied standard pistons and new pistons from the material, which temperature characteristics is shown on the Fig. 8.

Fig. 9 presents specific brake fuel consumption versus engine speed at full load (rated power) for standard piston set an the novel one. Fig. 10 presents dependence of content of hydrocarbons versus rotational engine speed at full throttle opening (full load, rated power) for standard piston set and the novel one.

Fig. 11. presents dependence of content of nitrogen oxides versus rotational engine speed at full throttle opening (full load, rated power) for standard piston set and novel one. Fig. 12. presents specific break fuel consumption versus torque for two engines with novel pistons and standard (load performance) for standard piston set and novel one.

Fig. 13. Courses of changes of the content of hydrocarbons in exhaust gases versus engine torque at constant rotational speed (load performance 3900 rpm) for standard piston set and the novel one.

F ig. 14. Hydrocarbons emission (HC) for standard engine and engine with novel pistons versus engine speed at full load or standard piston set and novel one.

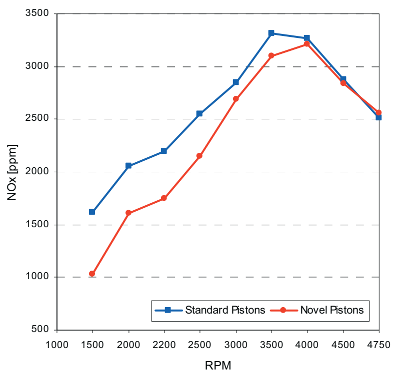

Fig. 11. Dependence of content of nitrogen oxides versus rotational engine speed at full throttle opening (full load, rated power)

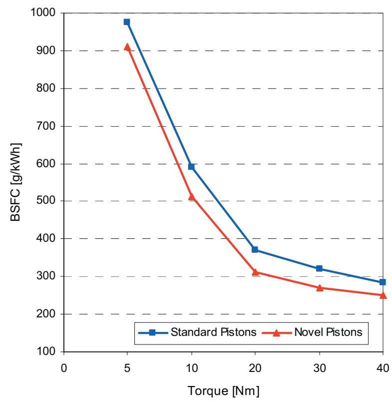

Fig. 12. Specific break fuel consumption versus torque for two engines with novel pistons and standard (load performance)

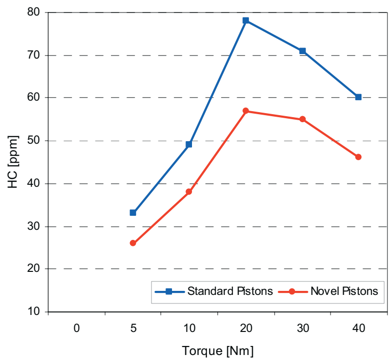

Fig. 13. Courses of changes of the content of hydrocarbons in exhaust gases versus engine torque at constant rotational speed (load performance 3900 rpm)

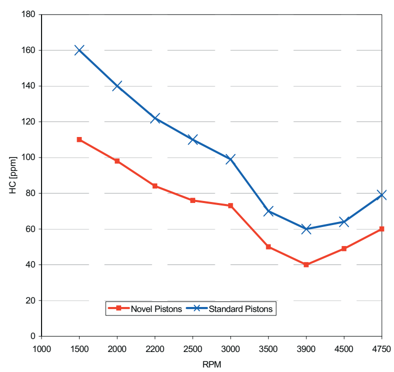

Fig. 14. Hydrocarbons emission (HC) for standard engine and engine with novel pistons versus engine speed at full load

Tab. 2 presents the results of research for the specific consumption of oil and fuel in reference to two solutions of piston assembly: the standard solution and solution with the new pistons.

Tab. 2. Test results of Brake Specific Oil Lubricant Consumption and Brake Specific Fuel Consumption for two piston sets: novel piston set and standard

	Brake Specific Oil Lubricant Consumption	Brake Specific Fuel Consumption	Rate of Brake Specific Fuel Consumption to Brake Specific Oil Lubricant Consumption	Notes
	g/kWh	g/kWh		
1	0.43	266	618	Novel pistons
2	0.48	281	585	
3	0.42	292	695	
4	0.46	275	597	
5	0.99	277	279	Standard
6	1.21	281	232	
7	1.12	280	250	
8	0.98	282	285	

4. Conclusions

1. The results of research of the influence of temperature on the strength of new materials, containing alloy additives like: chrome, cobalt, copper, molybdenum, nickel, tungsten proved, that the fall of the strength of silumin alloys in the function of temperature was smaller in the comparison with silumin alloys generally used to the pistons manufacture.
2. The highest value of the silumin alloys strength in temperature of 620°K, nearing to a maximum work temperature of pistons, was obtained with the highly synergistic nickel, cooper contents and such molybdenum contents, with which the maximum alloy strength in the normal temperature exists, that is to say 0.5%.
3. Equally important parameter for the opinion on piston materials, as its strength is the coefficient of thermal expansion α and its hysteresis.
4. Silumin alloys containing such additives as cobalt, molybdenum, nickel are characterized not only by the very good strength properties, but also small hysteresis of coefficient α, that permits to apply them with the good effect as piston material.
5. The application of new materials on pistons permits also on the application of smaller working tolerances between piston and cylinder, that beneficially influences on the decrease of engine oil consumption and the decrease of the hydrocarbon emission level in exhaust.
6. The new material characterizing itself by minimal hysteresis creates the possibilities for the obtainment of correct engine performance in the full range of engine rotational speeds and loads.
7. These gives the possibilities for achievement of decrease the emitted noise levels, and also decrease of the mechanical piston loads.
8. The application effect for the pistons manufactured from a new material with minimal hysteresis of thermal expansion coefficient α is, beside the decrease of the oil consumption and the decrease of the hydrocarbon emission in exhaust, the decrease of blowbys to the crankcase, the decrease of the ring grooves and the piston walls wear, decrease of the pistons deformation and increase of durability and reliability of the internal-combustion engine pistons performance.

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