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DESIGN OF A NEW ALLOY FOR INTERNAL COMBUSTION ENGINES PISTONS

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ABSTRACT

The results of the work on the development of a new composite alloy pistons designed for internal combustion engines are presented in the article. Tests of alloy crystallization, metallographic tests, tensile strength and hardness tests, coefficient of thermal expansion and tests for seizure resistance as well as the engine tests were performed. Tests of dimensional stability of the pistons in the thermal chamber was carried out and found that permanent deformations of the piston diameter do not exceed 2 μm. The engine with new pistons showed a lower consumption of lubricating oil, lower levels of exhaust emissions and lower noise levels in comparison to the standard engine.

Keywords: combustion engines, engine pistons composite aluminum alloys, engine piston testing, material testing.

INTRODUCTION

The design and materials used for the pistons exert a significant influence on the value of the clearance of the piston-cylinder assembly. Clearances have an impact on the lubricating oil consumption, blow-up into the crankcase, exhaust gases toxicity and noise of engine operation [Tinaut et al.].

Hysteresis of pistons dimensions due to changes in temperature distribution and stress has a major impact on the value of the clearances. In the most internal combustion engines, the pistons are made of alloys based on aluminum, whereas the cylinder liners are made of cast iron, which has different expansion coefficient than the aluminum alloys expansion. Therefore, the attempts of the steel pistons application are investigated [Birch].

However, these pistons have a much larger mass, which increases the load of the crank mechanism and reduces the nominal speed of the engine. Moreover, the implementation of steel pistons requires new and expensive production methods. Therefore, the use of composite pistons of the aluminum is a better solution. It allows to increase the strength of the material at elevated temperature and to reduce the changes in the piston dimensions. Furthermore, the use of a new alloy allows the use of smaller assembling clearances between the piston and the cylinder.

The composite alloy is obtained by adding to the base material (aluminum) of the refractory elements such as chromium, molybdenum, nickel, tungsten. These elements form the intercrystalline compounds, which are located on the grain boundaries. Moreover, the fibres, such as silicon carbide are added, which strengthens the structure of the alloy. As a result, strength of the alloy and dimensional stability is increased, and the deformations of the pistons are reduced [Jankowski Jankowska, Slawinski].

OPERATING CONDITIONS OF THE COMBUSTION ENGINE PISTONS

Pistons in internal combustion engines operate under permanent changes in their temperature and structural stresses distribution, due to changes in engine external loads and engine speed. The materials of the pistons must therefore have appropriate properties not only at the room temperature but also at the operating temperature of the pistons. The maximum temperature of the pistons, which are present on the piston crown, can reach 320-350^{o}C. In the lower part of the piston, at the piston skirt, the temperature reaches a value of 100-140^{o}C. Very important is the temperature in the region of the piston ring grooves, which is determined and limited by the properties of the lubricating oil, it should be a maximum of 230-240^{o}C. If the temperature in this area exceeds this value, the piston must be internally cooled. Large temperature differences in the piston cause the occurrence of high thermal stresses, which superimpose to the mechanical stresses. Large differences in the piston stresses and temperature gradients cause deformation of the pistons, which should disappear after the withdrawal of stresses and temperature. The presence of pistons permanent dimensional changes, because of pistons permanent heating and cooling, known as hysteresis, is a serious problem that needs to be taken into account in the pistons design process. The value of these distortions, determine in fact the dimension of the clearance in a piston-cylinder liner assembly, which affect on piston seizure, lubricating oil consumption, exhaust gases blowby into the crankcase and harmful emissions, mainly unburned hydrocarbons. The value of the pistons hysteresis can be limited, primarily by proper selection of the pistons chemical composition and by selection of the appropriate piston manufacturing processes, including the piston heat treatment processes. The long experience in the pistons manufacturing and testing led to the selection of different aluminum alloys, which is used in the pistons mass production. Specific designs and the usage of the engines, however, require the introduction of the additional requirements that result, that it is necessary to correct the chemical composition of the piston alloys. The most commonly used piston aluminum alloys are Al-Si alloys, containing about 12% Si. They are near eutectic alloys, further more comprising a number of alloying additives.

THE SCOPE OF THE TESTING

The work aim was to replace pistons of the military applications engines, which were produced by forging a wrought aluminum alloy PA12. The pistons produced by casting a near eutectic Al-Si alloy should be characterized by similar strength properties and improved functional properties, which are primarily enabled by reducing the clearances between the piston and the cylinder.

Table 1− Chemical composition of near eutectic alloys for engine piston, at % wt

	Si	Cu	Mg	Ni	Fe	Ti	Cr	Mo	W	V	Mn	Zn	Other
1	10.5-12.5	0.5-1.5	0.8-1.8	0.5-1.5	≤0.7	≤0.1	–	–	–	–	<0.2	<0.2	≤0.15
2	11.5-12.5	3.0-4.0	0.3-06	4.0-5.0	0.05	–	0.05-0.8	0.05-0.8	0.05-0.8	0.05-0.8	0.2-0.35	–	
3	9.5-13.0	0.5-4.0	0.4-1.7	0.5-4.0	0.5-0.7	0.1-1.2	–	–	–	–	0.2-0.6	0.05-0.2	≤0.15

1. PA12 alloy for forget pistons
2. Tested composite silumin alloy
3. Generalised composition of the near eutectic Al-Si alloys

The research program contained large range of metallographic research, the strength testing of materials in terms of the influence of various alloying elements on the strength of the final material, mathematical modelling of temperature distributions and stresses in the pistons and engine brake testing of the new pistons. As a basic alloy to manufacture the test samples, the near-eutectic Al-Si alloy, labelled AK12 was taken.

Table 1 shows the PA12 alloy chemical composition, a global average of the near-eutectic alloys composition, and the alloy composite, which is the final result of the work carried out, and which was selected to make the new pistons.

It should be noted that the results of materials tests have been used in the processes of mathematical modelling. Modelling make possible to determine the outer contour of the piston, whereby space between the piston and the cylinder has been reduced, which had a beneficial effect on the limitation exhaust emissions limitation, fuel economy, also reducing the noise of the engine.

In this article, the main attention has been devoted to metallographic research, the strength research and engine research.

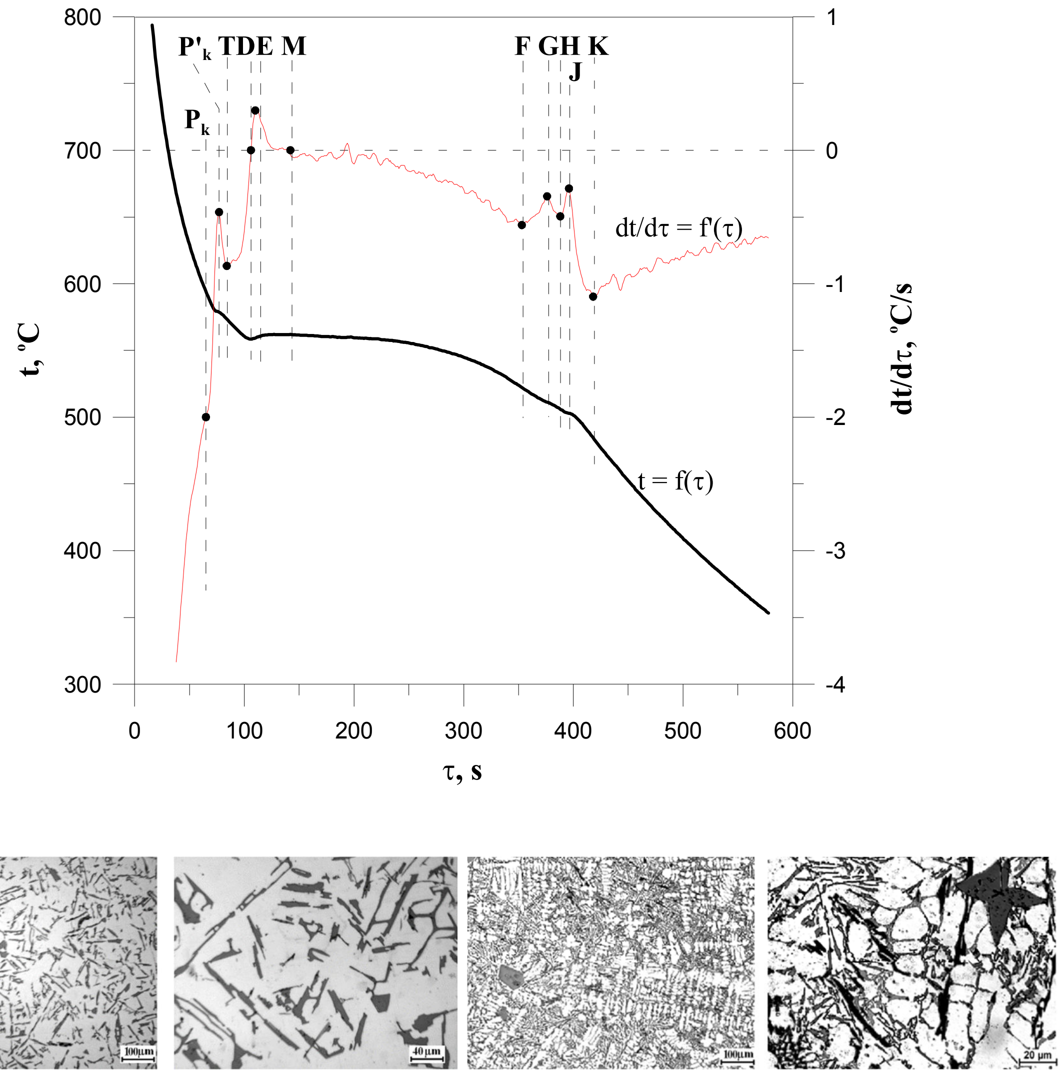

Fig. 1 − Curves of the alloy AlSi12Cu4Ni4MgCrMoVW (Mg 0.5% sample; Cr, Mo, W and V 0.05%) cooling in the tested alloy modified with Sb, Ti, B

Table 2− Distinctive temperature points for cooling curve (Fig. 1)

Point	τ, s	t, °C	dt/dτ, °C/s	Z, °C/s^2
P_k	65	594	-2.00	0.018
P'_k	77	579	-0.46	-0.054
T	84	574	-0.87	0.006
D	106	558	0.00	0.119
E	110	559	0.30	0.018
M	142	562	0.00	-0.010
F	353	522	-0.56	0.002
G	376	511	-0.34	-0.004
H	388	506	-0.50	-0.017
J	396	503	-0.29	-0.028
K	418	485	-1.10	-0.005

METALLOGRAPHIC TESTING

In a study of casting pistons processes and preparing samples for the strength tests, the derivative thermal method of analysis was used (Derivative Thermo Analysis − DTA), which allows one to track the process of the alloy crystallization and the setting temperatures of phase transitions. This also facilitates suitable design of the casting moulds, to obtain a desired speed of creation for specific structural components. On the other hand, from the alloy-cooling graph, the changes in the microstructure of the alloy can be predicted.

Fig. 1 shows the alloy cooling curve and the derivation curve of the silumin composite alloy AlSi12Cu4Ni4MgCrMoVW (Mg 0.5%, Cr, Mo, W and V, 0.05%) modified with Sb, Ti, B and comparison of microstructure of novel alloy (left) and standard one. Table 2 shows the characteristic temperatures, corresponding to the markings on the cooling curve. The DTA curve, in conjunction with graphs of phase equilibrium and metallographic tests and X-rays tests, allows the interpretation of type and sequence of crystallization of the individual phases in the alloy.

STRENGTH TESTS

High demands on the tensile strength and hardness of the piston material resulted in this that was necessary to increase the strength of the basic, near-eutectic Al-Si alloy, by adding suitable alloying additives. It was also necessary to obtain an alloy, characterized by high dimensional stability in an environment of continuously changing thermal and mechanical loads. Such additives as chromium, molybdenum, tungsten, nickel, and copper were specifically evaluated for their influence. There were tested: tensile strength R_m, yield strength $R_{0.2}$, relative elongation A_5, the Brinell hardness HB. The tests were carried out using a strength-testing machine with a hydraulic drive. Static tensile test was performed at a constant loading rate of 5 mm / min. In studying the effect of temperature on the material strength, the thermal chamber was used.

Fig. 2 - Climatic chamber installed on strength testing machine

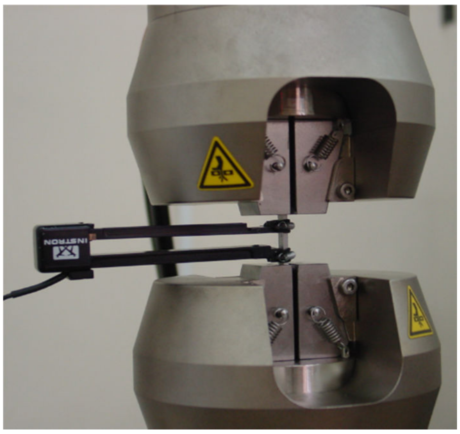

Fig. 3 − Extensometer fixed on the sample

The testing machine view is shown in Fig. 2, and the view of the sample (on which the extensometer is installed) in the machine head is shown in Fig. 3. Test samples were cast in a chill mould and then heat-treated and machined. Investigations of the effect of chromium content in near-eutectic silumin on its strength were carried out in the range from 0% to 1.75% of chromium.

It has been found, that in the case of increasing the chromium content ranging from 0% to 0.6%, the strength increased from 200 MPa to 490 MPa. After crossing the Cr content of 0.6%, the strength rapidly decreased until 110 MPa with Cr content of 1.75%. At the same time, with the alloy chromium content increase, elongation of 0.95% at zero chromium level was reduced to the relative elongation equal zero at the chromium level of 1.2%. With further increase of the chromium content, the silumin sample acted like a fragile body.

Fig. 4 shows the changes of the strength as the function of temperature and Fig. 5 the changes of elongation as the function of temperature, in relation to the silumin alloy, containing 0.6% Cr. As can be seen, during heating of the sample to a temperature of 350°C, the strength of the material systematically decreased and the elongation increased. To reach a temperature of 150°C the rate of change was small, but there has been a sharp rise above a temperature of 150°C.

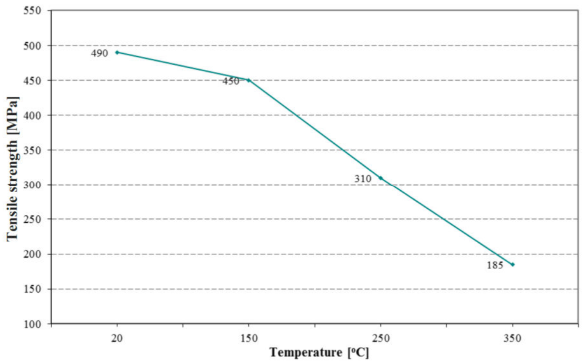

Fig. 4 - Influence of aluminum contents in near-eutectic silumin on tensile strength as a temperature function

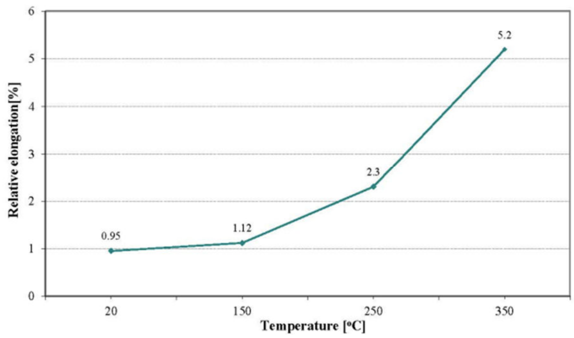

Fig. 5 - Influence of chromium contents in near-eutectic silumin on elongation as a temperature function

When adding molybdenum to eutectic silumin, the strength increased with increasing molybdenum content up to 0.5% Mo, from 200 MPa to 480 MPa. After exceeding the 0.5% molybdenum content, the strength decreased to 200 MPa at a content of 1.4% Mo. In contrast, the relative elongation value at the increased molybdenum content, decreased from the value 0.95 with 0.0% Mo content to the relative elongation value of zero at the content of 1.04% Mo. The hardness of the alloy increased with a molybdenum content increase, from hardness of 98 HB with a molybdenum content of zero to 139 HB with a content of 1.8% Mo. In studying the effect of temperature on the strength, in the range from 20°C to 350°C, two silumin alloys, one containing 0.2% Mo and the other one containing 1.1% Mo, the silumin alloy containing 0.2% Mo, reduced its strength to the value of about one-sixth, and silumin alloy containing 1.1% Mo, the strength decreased by the value of about 40%.

The effect of addition of tungsten to near-eutectic silumin was similar as in the case of molybdenum. Strength of the alloy increased with a tungsten content, ranging from the 210 MPa with zero tungsten content to 460 MPa with a tungsten content of 0.65%. Then the strength decreased, reaching a value of 215 MPa with a tungsten content of 1.4%. Elongation reached zero with tungsten content of 1.4% and grew linearly to the value of 0.96 when the content of tungsten in alloy was reduced to the value of 0.05%. Silumin hardness increased with the increase in tungsten content, from 98 HB with a content of 0.05% W to 139 HB with a content of 1.4% W.

Tests were also carried on impact of other alloying elements to the near-eutectic silumin on the strength of the alloy, wherein on these samples the metallographic examination and thermal expansion and dimensional stability testing were also conducted. Based on the analysis of the test results, it was found that the most promising appears to be silumin alloy, containing 4% Ni and 4% Cu and small additives of other refractory elements, such as Cr, Co, Mo, W, and V. For testing, samples were prepared containing 2% Ni, also 4% Ni and 4% Cu and varying amounts of Co, Cr, Mo, W. Fig. 6 shows the tests results of strength as a function of temperature for these two silumin alloys.

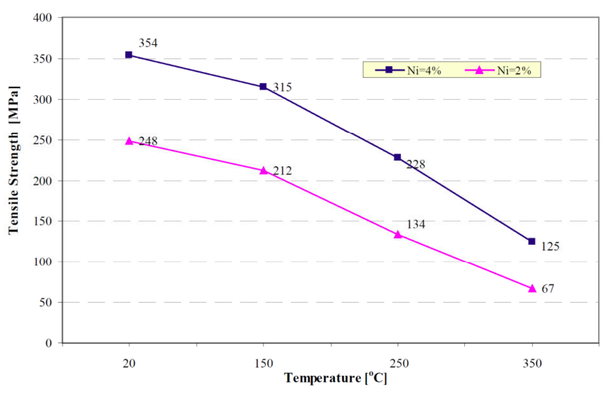

Fig. 6 - Tensile strength versus temperature for novel alloy

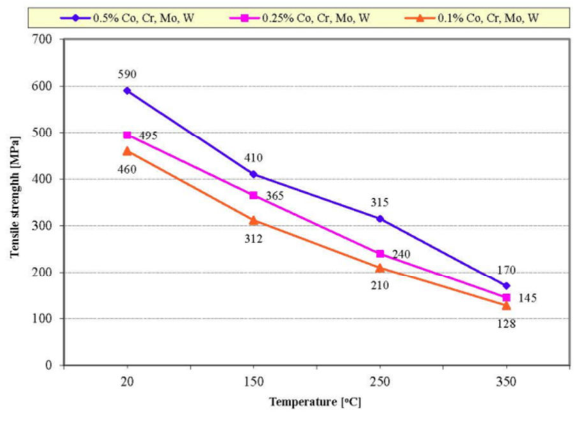

Fig. 7 - Tensile strength of near-eutectic silumin with different Co, Cr, Mo contents as a temperature function (4% Ni and 4.5% Cu)

The drawing shows, that increasing alloy nickel content from 2% to 4% caused a 65% increase in strength at room temperature, while at temperature of 350°C, the strength of alloy containing 4% Ni was higher by 91%.

Fig. 7 shows the dependence of the tensile strength of silumins, containing 4% Ni, 4.5% Cu and the different content of alloying elements, such as Co, Cr, Mo, W: 0.5%, 0.25% and 0.1%. Fig. 8 shows the dependence of elongation versus temperature for these alloys. In turn, Fig. 9 shows the dependence of the hardness on temperature with regard to alloys, such as before.

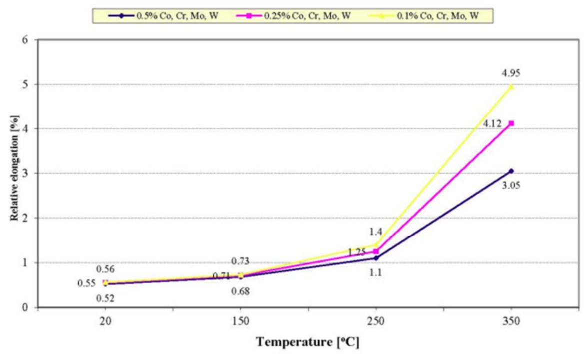

Fig. 8 - Elongation of near-eutectic silumin with different Co, Cr, Mo contents as a temperature function (4% Ni and 4.5% Cu)

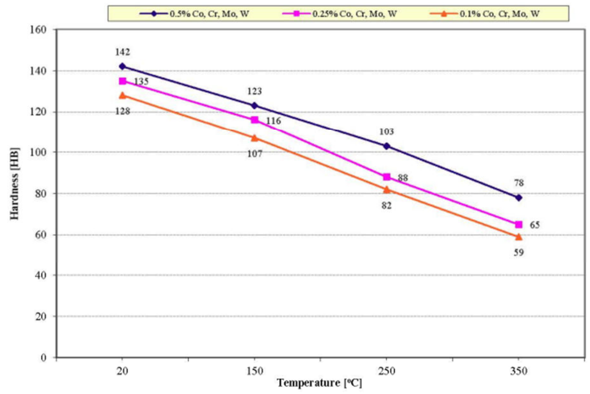

Fig. 9 − of near-eutectic silumin with different Co, Cr, Mo contents as a temperature function (4% Ni and 4.5% Cu)

The results show, that with the increase in temperature, almost linear decrease in tensile strength and hardness appears. Interestingly, samples containing more alloying elements have higher strength and hardness than those containing less alloying additives but in contrast, as the temperature increases, the strength of the samples containing more alloying elements decreases faster than samples containing smaller amounts of alloying elements.

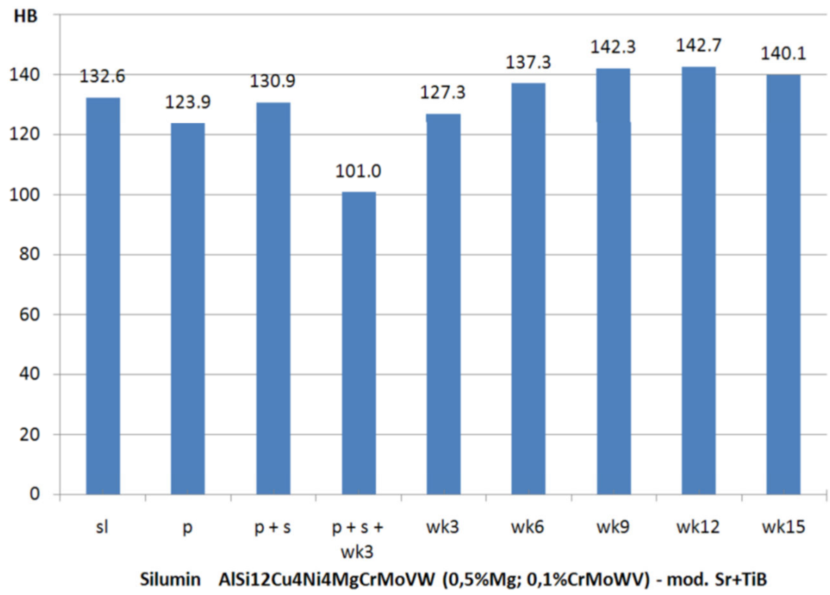

Fig. 10 − Results of a hardness of near-eutectic silumin, containing 4% Ni, 4% Cu and 0.1% Cr, Mo, W, V modified with Sr, Ti, B

Nevertheless, at any temperature up to 350°C, the strength of the samples will be greater the more alloying elements comprised silumin. As for elongation, its value increased with increasing temperature. The increase was small up to 250°C and rapidly increased after the temperature exceeds 250°C, reaching, in the case containing 0.5% Co, Cr, Mo, W − 2.8 times, in the case containing 0.25% Co, Cr, Mo, W −3,3 times, and in the case containing 0.1 Co, Cr, Mo, W − 3.5 times. Fig. 10 presents the results of a hardness of near-eutectic silumin, containing 4% Ni, 4% Cu and 0.1% Cr, Mo, W, V modified with strontium, titanium and boron: in the rough-cast state, after various heat treatment methods, including a multi-stage methods. Differences in hardness for each sample approach the 40%.

The results of strength and the hardness tests carried out of the cast samples at ambient temperature and at increased temperatures up to 350°C, show that the higher strength and hardness values were obtained for silumin, comprising high amounts of alloying elements. The strength of such silumin alloys was comparable to the strength of low alloy steels. This however required the use of large amounts of alloying elements. In selected to manufacture piston alloy, the content of alloying elements reached 22% (including the Si element content). Based on the effect of alloying element content on the alloy strength at room and elevated temperatures and the results of metallographic and the dimensional stability research was decided to choose the chemical composition and manufacturing technology of the research pistons.

RESEARCH OF STRENGTH AND HARDNESS OF PISTON TEST SPECIMENS

The chemical composition of the material, from which the new pistons were manufactured, is shown in Table 1. After determining the chemical composition of the composite silumin and the pistons manufacturing process, the experimental batch of the pistons was manufactured, from which the pistons for the strength tests were selected. Due to the specific dimensions of the pistons, the specimens could not be manufactured to the standard dimensions. Specimens were cut from the piston crown and piston skirt, from pistons made of the new composite silumin and from the old pistons, manufactured of PA12 alloy. The study allowed us to compare the strength properties of the new piston material and the old pistons alloy PA12.

The tests determined tensile strength R_m, yield strength $R_{0.2}$, relative elongation A_5 and Brinell hardness HB at ambient temperature and at 250°C. Fig. 11 shows a sketch of a piston with marked sites from which specimens were cut out for the strength tests. Fig. 12 shows the specimen drawing, on which the tests were performed. Five specimens of each piston crown and 3 specimens of each piston skirt were conducted.

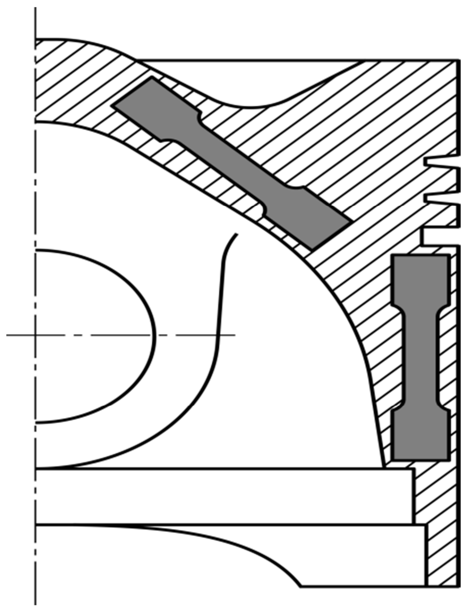

Fig. 11 - Sketch of piston with marked sites for cut of the specimens

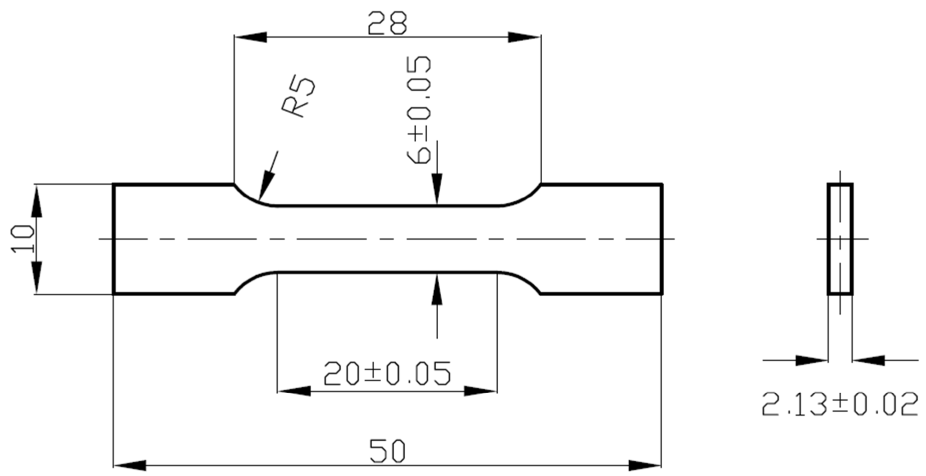

Fig. 12 - Sample for strength tests

The averaged results of pistons material strength are shown in Table 3.

Table 3 − Results of the strength tests at room and 250°C temperatures (mean values)

Alloy	R_m **[MPa]**	$R_{p0.2}$ **[MPa]**	A_5 **[%]**
PA12	371.0	320.8	3.7
PA12 (250°C)	250.2	215.7	11.4
Composite alloy	451	385	3.7
Composite alloy at 250°C	364	299	5.7

As shown by the test results, the pistons of the new material have a higher strength than pistons of PA12 alloy. These differences at room temperature are about 22% and at a temperature of 250°C about 45%. The decrease in the strength with heating specimens from 20°C to 250°C has reached about 24% with respect to the composite material and about 48% for PA12 alloy. It should be emphasized that the spread of the results of the examinations in respect of tensile strength was small and at room temperature was about 9% for samples from new material and about 3% for samples from PA12 material. As regards elongation, its values at room temperature were the same for both materials (3.7%). At a temperature of 250°C, elongation of samples made from PA12 material was about two times greater than the samples made with the new material. Young's modulus of the new material was higher by about 5% since the PA12 Young's modulus. The hardness of the new material was approximately 10% higher than that of the PA12 material.

TESTING DIMENSIONAL STABILITY OF MATERIALS FOR PISTONS

Pistons for internal combustion engines operate under changes in temperature and stresses, which leads to constant changes in dimensions. Dimensional changes are only possible within the existing clearances between the piston and the cylinder. Therefore does not should be a permanent change in dimensions because of heating and cooling of the piston. Permanent changes in dimensions may cause seizure or increase of the clearances between the piston and the cylinder. The desired dimensional stability may be achieved by appropriate choice of chemical composition of alloys and by a proper heat treatment.

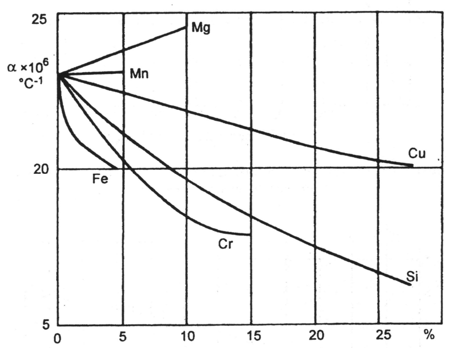

Fig. 13 - Influence of Mg, Mn, Cu, Si, Cr, Fe on the thermal expansion coefficient of aluminum alloy

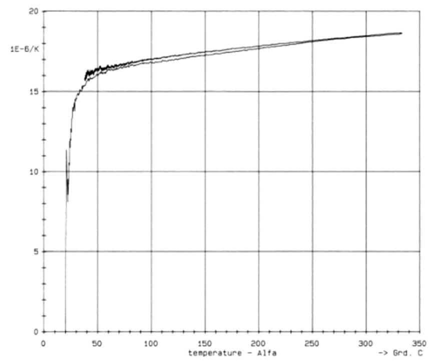

Fig. 14 - Changes of thermal expansion coefficient of AlSi12Ni4Cu4Mg0.5CrMoWV alloy after heat treatment

During the work on the development of the new pistons, one conducted comprehensive dilatometric research on pistons materials. During the test runs changes in dimensions of samples of materials were recorded during heating and cooling, in the engine temperature range, from 20°C to 330°C. Fig. 13 shows the changes of the thermal expansion coefficient and different chemical elements in aluminum alloys. The significant increase of coefficient during cooling can be seen, what leads to permanent dimensional changes of the material.

Fig. 14 shows the changes of the coefficient of thermal expansion of the completely stabilized sample material on the pistons during heating and cooling. It can be seen that the sample coefficient of thermal expansion is identical during heating and cooling. Proper course of the coefficient was achieved by an appropriate choice of chemical composition and heat treatment of alloys.

TESTS OF THE COMBUSTION ENGINE

The final verification of the quality of materials and newly developed pistons were tests of the engines, equipped with new pistons. The investigations were carried out on the engine dynamometer bench, installed in the engine test cell. The pistons have the corrected outline external surface, obtained by mathematical modelling. The results of material and strength research also have been applied.

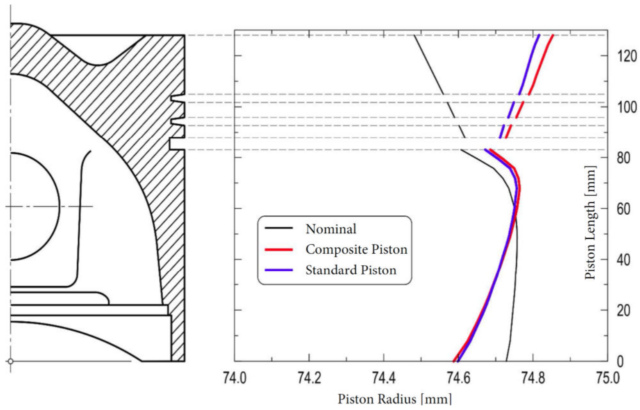

Fig. 15 - Comparison of piston's dimensions for novel piston (right red) and standard piston

On Fig. 15 the shape of the outer contour of the newly developed pistons to the shape of the outer contour of previously used pistons are compared. The performed correction allowed reduction of the clearance between the piston and the cylinder and the space between the piston and the cylinder in the area of the fire threshold by about 10-20%, which should have a positive impact on exhaust emissions of harmful gases.

The view of the novel pistons before engine tests is shown on Fig. 16. The pistons were carefully measured, whereupon one fitted them in the engine. After testing, the pistons were removed and measured to determine the pistons wear and cylinder wall interference signatures.

After reaching the engine and conducting factory acceptance tests, the load characteristics were defined (at constant speeds) and external characteristics (full load for different engine speeds). During the tests were recorded: engine speed, engine load (torque), fuel consumption, oil consumption and characteristic pressure and temperature values at specific measurement points. Fig. 17 presents the engine on the test bench. The test stand was equipped with a set of modern measuring and recording instrumentation.

Fig. 16 - Photo of pistons from novel composite alloy before engine tests

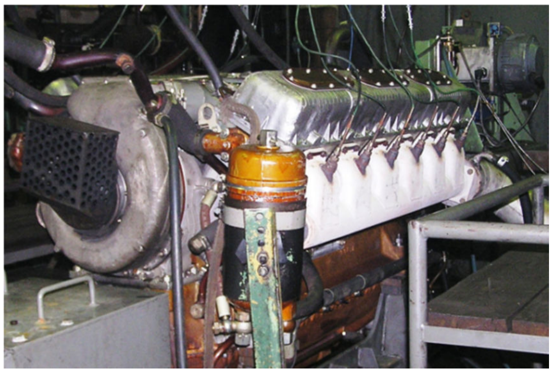

Fig. 17 - The engine on test bench

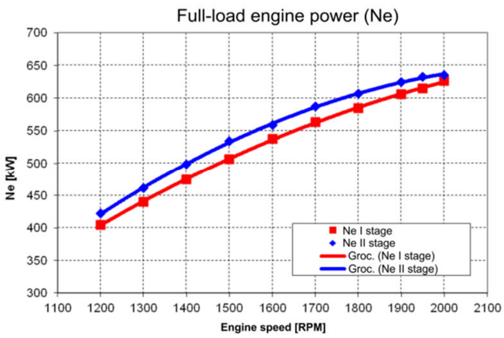

Fig. 18 - Comparisons of full-load power curves for engine with standard and novel (above) pistons

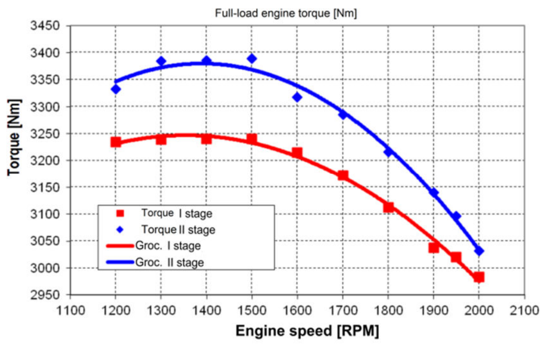

Fig. 19 – Comparisons of full-load torque curves for engine with standard and novel (above) pistons

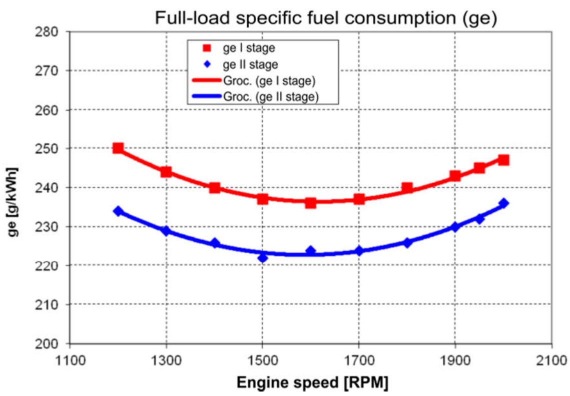

Fig. 20 – Comparisons of full-load specific fuel consumptions curves for engine with standard (above) and novel pistons

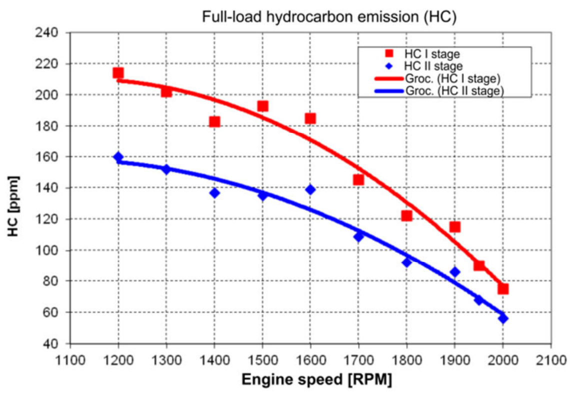

Fig. 21 – Comparisons of full-load HC curves for engine with standard (above) and novel pistons

The course of engine power as a function of engine speed at full load is shown in Fig. 18, Fig. 19 presents the course of engine torque and fuel consumption graph is in Fig. 20. The tests results show, what was achieved because of the new pistons: the increase in power and torque and a reduction in specific fuel consumption, a significant reduction emission of unburned hydrocarbons (HC), as shown in Fig. 21, as well as smoke opacity and exhaust blowby into the crankcase. Oil consumption was reduced by about 17% in comparison to pistons made of the PA12 alloy.

CONCLUSIONS

In the result of development work involving the studies: metallographic, dilatometer, strength, in the field of metallurgy, a new material was developed for the engine pistons - silumin composite.

The new material has a very good dimensional stability and high strength properties and high hardness, both at ambient as well as elevated temperature.

The use of mathematical modelling using experimental research allowed making a shape correction of the contour of piston external surface in the direction of reducing clearance between the piston and the cylinder.

The research confirmed the high quality of the new pistons for engine, resulting in achieved by 2-3% higher engine power, increase in engine torque by 4%, reducing the specific fuel consumption by 4%, reducing HC emissions by 24% and carbon monoxide by 10-20%, reducing oil consumption by 17%, reducing engine exhaust blowby to the crankcase of the 35-45%.

The use of new pistons had the greatest impact on reducing exhaust blowby to the crankcase and reducing oil consumption and what goes with it, the emission of hydrocarbons.

The samples of the pistons have the proper cooperation traces and very little wear of the ring grooves, compared with previously used pistons, due to the higher hardness of the new material and the preferred microstructure.

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