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EVALUATION OF FUNCTIONAL PROPERTIES OF THE RAPIDLY SOLIDIFIED CAST AlSi30 ALLOY AS A MATERIAL FOR TRANSPORT APPLICATIONS

Bogusław Augustyn[1], Marcin Szymanek[1], Dawid Kapinos[1], Marek Nowak[1], Wojciech Pakieła[2]
[1]Institute of Non Ferrous Metals in Gliwice Light Metals Division in Skawina, Pilsudskiego Street 19; 32-050 Skawina, Poland
[2]Institute of Engineering Materials and Biomaterials, Department of Mechanical Engineering, Silesian University of Technology
Konarskiego Street 18a; 44-100 Gliwice, Poland

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Abstract

The AlSi30 alloy obtained by melt spinning in the Rapid Solidification process, after fragmentation and consolidation, was subjected to plastic forming. As a result, extrusions in the form of 18 mm rods were obtained, and after forging and heat treatment (T6) were tested for selected functional properties. Mechanical properties, corrosion resistance and tribological properties were determined. Finally, a material with unconventional chemical composition was obtained, which confirmed its applicability for, among others, components operating in the transport industry, mainly pistons.

Introduction

The requirements imposed onto modern light metal constructions propel constant search of materials with always higher properties, both mechanical and functional, tailored, moreover, to the working conditions that the products made of them should withstand. In many cases, achieving this goal by the traditional method of manufacture and using common alloy varieties is simply impossible. Modern materials science through the use of new techniques, such as thixoforming or consolidation of rapidly solidifying materials in the form of powders or ribbons, offers the possibility of producing new alloy varieties [1-5]. These alloys are often based on standard chemical compositions, but are characterized by ultra-fine crystal microstructure, which changes in a quite substantial manner their mechanical and functional properties as well as the properties of components made from them. The unconventional methods of manufacture also allow obtaining alloys with the chemical composition impossible to obtain by the use of common methods only.

In the case of materials designed for use at elevated temperatures, they should possess sufficiently high tensile strength and hardness for the temperature ranges within which the components made of them will be operating. The important parameters distinguishing these materials are: low coefficient of thermal expansion and the associated dimensional stability, and high resistance to abrasion and corrosion [6-9].

In this study an attempt was made to characterize the functional properties of an AlSi30 alloy obtained by melt spinning and plastic forming in the context of its potential future application in the automotive industry, mainly for pistons. Here, only the results of functional tests are discussed. They form a fragment in the wide spectrum of studies of the properties of this material, including metallographic examinations of final products, i.e. ribbons and forgings produced in the initial stage of the casting process combined with Rapid Solidification.

Methodology

The test material was AlSi30 alloy. Final analysis of the alloy chemical composition (main elements) was done by mass spectrometry, and the results are compared in Table 1.

Table 1. Chemical composition of AlSi30 alloy

Element	**Si**	**Fe**	**Cu**	**Mg**	**Mn**	**Ni**	**Ti**
[wt %]	30.8	0.89	1.31	1.12	0.01	1.58	0.02

The alloy was cast by Rapid Solidification in a melt spinner. The casting temperature was 820 - 830^{0}C. As a result of the immediate solidification process, thin ribbons were produced (Fig. 1), and were next reduced to the form of fine flakes (Fig. 2) in a high-speed mill.

Fig. 1 AlSi30 alloy ribbon cast by RS

Fig. 2 AlSi30 alloy ribbon after fragmentation

Thus processed material was subjected to the next step of treatment, which was preliminary consolidation, followed by direct extrusion on a T-500 press (Fig. 3). The extrusion process was carried out in the range of temperatures from 500 to 520^{0}C. The result was a rod with 18 mm diameter, characterized by proper surface quality free from the tears, cracks and structural defects.

Fig. 3 The process of Ø 18 mm rod extrusion from AlSi30 alloy

The extruded rod was subjected to hot forging on a semi-industrial stand using a 250 ton vertical press and special tooling. Forging was carried out in the temperature range from 460°C to 510°C.

The end result of the entire manufacturing cycle was a model forging (Fig. 4). Its task was to simulate the industrial forging process.

Fig. 4 A forging made from AlSi30 alloy

The stock extruded and forged after the heat treatment to the T6 condition (Solution 480°C / 2h and Ageing 150°C / 8h) was subjected to mechanical testing (static tensile test), dilatometric studies (heating and cooling), abrasion resistance test at ambient temperature and at elevated temperatures without lubricants and with mineral oil, and also to corrosion testing and electrochemical studies.

Results

Testing of mechanical properties

Thinking of the potential future use of the newly developed material, mechanical tests were carried out at temperatures from -50 to 300°C. Testing was performed on an INSTRON 5582 machine equipped with a chamber for high and low temperature tests. The results are shown in Table 2 and in Figure 5.

Table 2 Changes in AlSi30 alloy properties in relation to temperature

Temperature [°C]	$Rp_{0.2}$ [MPa]	Rm [MPa]	A_5 [%]
-50	380	412	0.1
-20	365	379	0.2
20	362	372	0.2
100	351	360	0.5
200	307	330	1.5
300	144	181	3.5

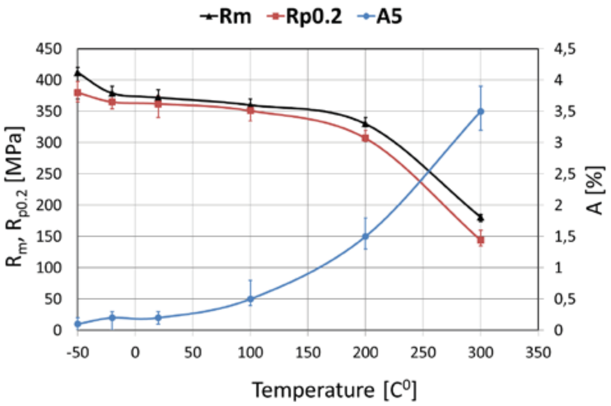

Fig. 5 Graph showing changes in AlSi30 alloy properties

The AlSi30 alloy has proved to be resistant to the effect of elevated temperatures. The strength at 300°C decreased to approximately 50% of the value obtained at ambient temperature, and only to about 20% at 200°C.

Dilatometric examinations

Changes in dimensions under the influence of temperature are a typical physical property of materials. Yet, in the case of components operating at elevated temperatures, they can cause very serious problems. Therefore it is recommended to know in advance the physical properties of the alloy from which a component will be made and use these data in practice at the stage of design and construction. This is particularly important in the case of mate parts made of different materials (such as the engine piston and cylinder). Systems of this type require the use of materials with physical properties as similar as possible.

The dilatometric studies were carried out on an AlSi30 alloy in the T6 condition. The use of the dilatometer enabled determination of the alloy characteristics during heating and cooling within the predictable range of operating temperatures, i.e. from 20^{o}C to 300^{o}C, in both transverse and longitudinal direction of the sample. Some examples of the results of investigations are shown in Figures 6 and 7. Dashed line on the graph shows the curves of thermal expansion α. The heating and cooling of samples was conducted each time in an argon protective atmosphere.

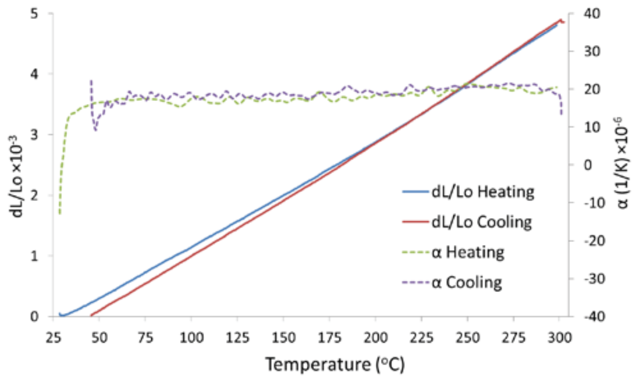

Fig. 6 The results of dilatometric studies of the AlSi30 alloy (longitudinal direction)

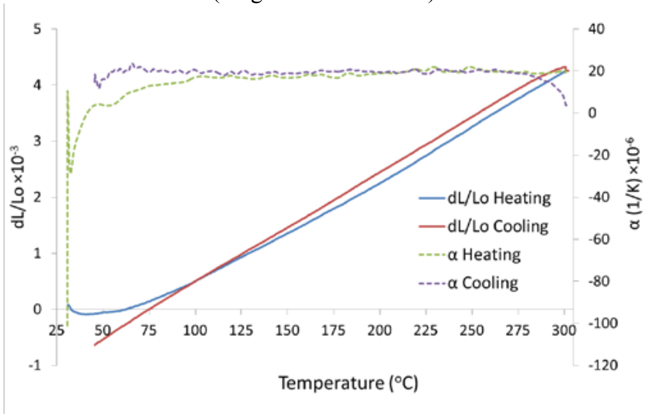

Fig. 7 The results of dilatometric studies of the AlSi30 alloy (transverse direction)

Changes in dimensions under the effect of temperature were evaluated from the coefficient of thermal expansion. Aluminum is included in the group of metals with a high value of the coefficient of linear expansion α (24 x 10^{-6}1/K), while for silicon this value is several times lower (2,5 x 10^{-6}1/K), and therefore it is the silicon which acts as an inhibitor of the thermal expansion and has a major influence on its value [5,6]. For the tested material, the coefficient of thermal expansion approximated the value of 20 x 10^{-6}1/K and was stable within the investigated range of temperatures for both measured directions.

Tribological tests

"Dry" abrasion test in a "Ball-on-Disc" system

The coefficient of friction μ and the wear rate $W_{s(disc)}$ were determined with a UMT-2MT universal tester for tribological studies of materials, provided with the accessories supplied by CETR (USA). Tests were performed in a "dry" "Ball-on-Disc" system. The method involves gradual removal of a volume of material during friction of two samples (ball and disc) loaded with constant force, giving rise to the formation of a toroidal groove on the disc surface (Fig .8).

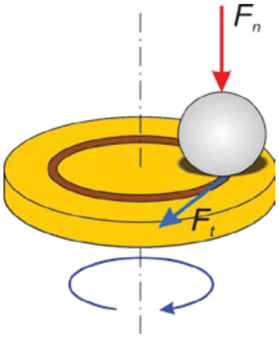

Fig. 8 Schematic representation of the Ball-on-Disc method

The above described test conditions and parameters are shown in Table 3. With the test completed, using a TOPO 01 needle profilometer, wear profiles were measured on the cross-sections at four locations on the circle distant by an equal angle (according to ISO 20808:2004 E). Then, the average cross-section of the worn out areas and the coefficient of wear were calculated. Exemplary profiles are shown in Figures 10 to 12.

Table 3. Test parameters

	Test1	**Test2**	**Test3**
temperature:	RT	100°C	200 °C
ball material:	Al_2O_3	Al_2O_3	Al_2O_3
ball diameter, d and class of accuracy:	3.175 mm (1/8") G5	3.175 mm (1/8") G5	3.175mm (1/8") G5
loading, F_n:	2N	2N	2N
friction radius, r:	5.0 mm	5.0 mm	5.0 mm
linear friction speed, v:	0.1 m/s	0.1 m/s	0.1 m/s
friction path, L:	400 m	400 m	400 m
test duration:	66.7 min	66.7 min	66.7 min

The coefficient of friction of the AlSi30 alloy sample - Al_2O_3 ball friction pair operating at room temperature and at 100°C and 200°C is shown in Figure 9.

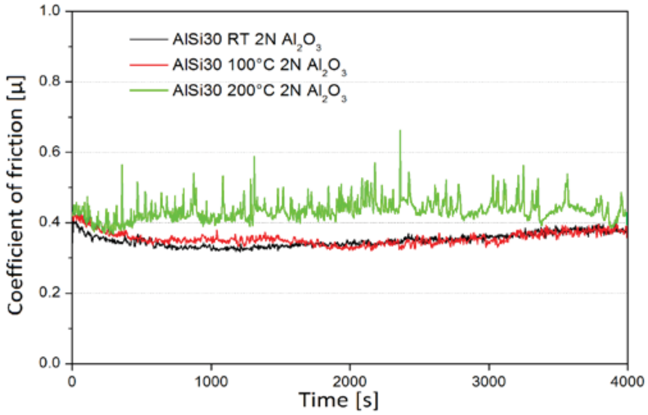

Fig. 9 The coefficient of friction of the AlSi30 alloy sample at room temperature and at 100°C and 200°C

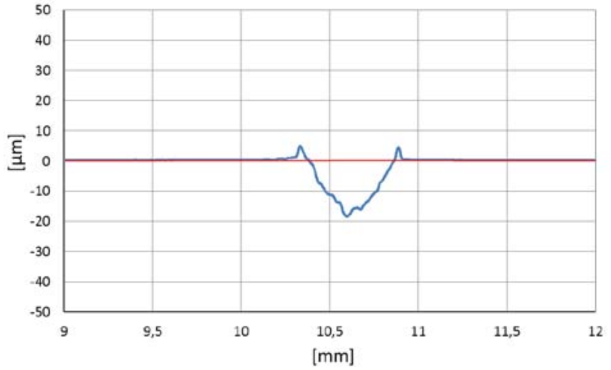

Fig. 10 Wear profile of the AlSi30 alloy in T6 condition at 25°C

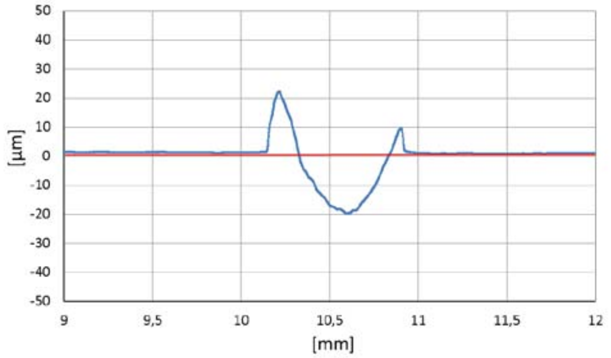

Fig. 11 Wear profile of the AlSi30 alloy in T6 condition at 100°C

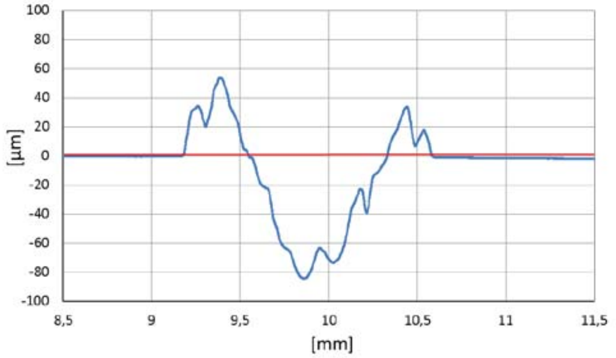

Fig. 12 Wear profile of the AlSi30 alloy in T6 condition at 200°C

“Dry” and "wet" abrasion wear resistance test in "Pin-on-Disc" and "Pin-on-Plate" systems

The coefficient of friction µ was determined with a Tribometer from CSM Instruments. Using a rotating "Pin-on-Disc" system, in addition to "dry" measurements, also a "wet" test with oil lubricant was conducted at 100^0C and 150^0C under different loads. The test in a reciprocating "Pin-on-Plate" sliding system was made only at ambient temperature. To determine the wear profile, after the tribological test, a Sutronic 25 contact profilometer from Taylor Hobson was used. Sample graphs from the measurements taken under variable parameters in the "Pin-on-Disc" test are shown in Figures 13-16. Figures 17 and 18 show the graphs of selected values of the coefficients of friction obtained in the "Pin-on-plate" test.

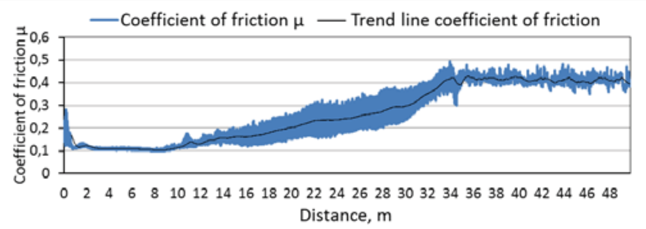

Fig. 13. Plotted values of the coefficient of friction calculated for the AlSi30 alloy, temperature 25˚C, load 5N, distance 50m

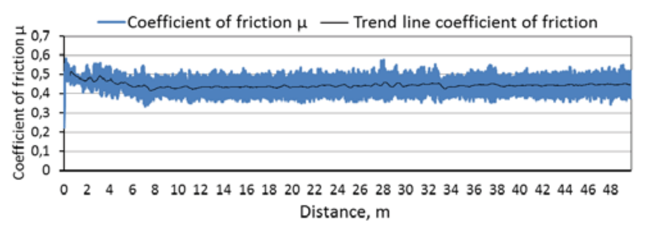

Fig. 14. Plotted values of the coefficient of friction calculated for the AlSi30 alloy, temperature 25˚C, load 15N, distance 50m

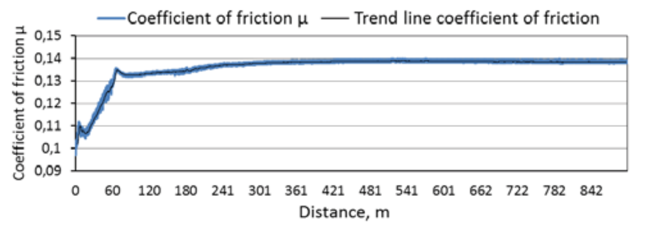

Fig. 15. Plotted values of the coefficient of friction calculated for the AlSi30 alloy, temperature 100˚C, load 5N, distance 900m

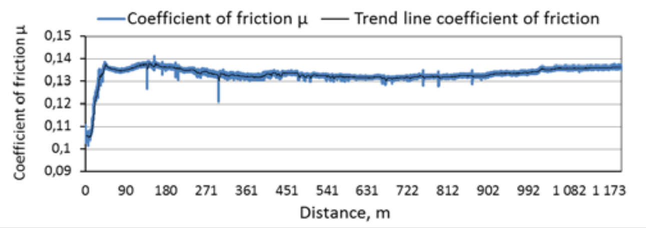

Fig. 16. Plotted values of the coefficient of friction calculated for the AlSi30 alloy, temperature 150˚C, load 5N, distance 1200m

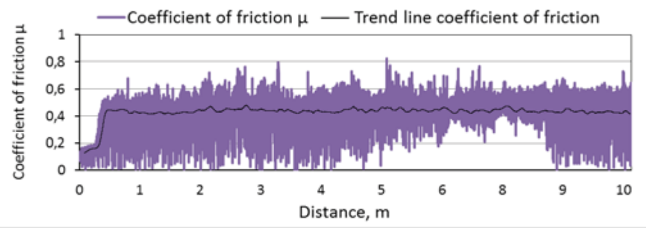

Fig. 17. Plotted values of the coefficient of friction calculated for the AlSi30 alloy, temperature 25˚C, load 5N, distance 10m

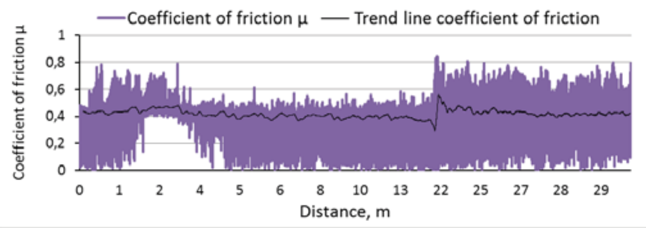

Fig. 18. Plotted values of the coefficient of friction calculated for the AlSi30 alloy, temperature 25˚C, load 15N, distance 30m

Corrosion testing

Corrosion tests were carried out in a DURA's 1000 liter capacity HKT 1000 salt spray chamber. The exposure of samples to the effect of neutral salt spray was 300 hours. The test solution was prepared with NaCl (50 g/l) of analytical grade and deminaralized water with a conductivity of 2.1 μ S/cm and pH of 6.54. Samples were degreased with acetone before testing. The sample multiplicity was 3. The study was conducted in a test chamber at 35°C using a continuous salt spray.

With the study completed, samples were visually evaluated to trace the progress in corrosion. Photographs of sample appearance after the salt spray test are shown in Figures 19 – 20. Figures 21 - 22 show the appearance of samples after the NSS test and removal of corrosion products from the alloy surface. After drying, the samples were tested gravimetrically. The measured results of losses in the sample weight are given in Table 4.

Table 4. The results of gravimetric measurements

Sample designation	Loss [g]	Average loss [g]	Loss [g/m^2]	Average loss [g/m^2]	Loss [%]
AlSi30 RS F condition	0.014 0.013 0.012	0.013	14.2 12.9 11.9	13.0	0.3 0.2 0.2
AlSi30 RS T6 condition	0.006 0.006 0.006	0.006	5.9 5.9 5.9	5.9	0.1 0.1 0.1

Based on the results of studies conducted in a neutral salt spray it can be concluded that heat treatment has a favorable effect on corrosion properties of the tested material. AlSi30 alloy was observed to increase its corrosion resistance two times. Average weight loss in the alloy after the application of heat treatment was 0.006 g, while in the starting material, the average weight loss was at a level of 0.013 g.

Fig. 19 AlSi30 RS alloy in F condition after the salt spray test (300h) with deposited corrosion products

Fig. 20 AlSi30 RS alloy in T6 condition after the salt spray test (300h) with deposited corrosion products

Fig. 21 AlSi30 RS alloy in F condition after the salt spray test (300h) with removed corrosion products

Fig. 22 AlSi30 RS alloy in T6 condition after the salt spray test (300h) with removed corrosion products

Electrochemical testing

Electrochemical measurements were performed using an "Autolab" -potentiostat/galvanostat set made by EcoChemie BV with GPES ver. 4.9 software for the experiment control, data acquisition and analysis of results.

The tested electrodes were aluminum alloy samples, the electrode used for comparison was a stainless steel electrode in the form of a wire with 2 mm diameter, and the reference electrode was Ag/AgCl 3M KCl electrode.

The resulting numerical values were obtained by analysis of the experimental data done with the GPES ver. 4.9 software attached to the measuring equipment.

Measurement of corrosion potential

Corrosion potential is the difference in potentials measured in the external circuit between the electrode and the reference electrode which is in contact with the same electrolyte.

Studies of corrosion potential were made in accordance with ASTM G 69-97 (2003) on an AUTOLAB device made by Eco Chemie with GPES version 4.9 software. The reference electrode was AglAgCl c(KCl)=3mole/L electrode. The potential of this electrode relative to a standard hydrogen electrode (NEV) was 207 mV. The test time was 60 minutes for each sample. The test solution for studies of the corrosion potential had the following composition: NaCl 58.5 g / l and 30% H_2O_2 9 ml / l. The results of the corrosion potential measurements are shown in Table 5 below.

Table 5 The results of the corrosion potential measurements

	AlSi30 RS F condition	AlSi30 RS T6 condition
Corrosion potential [mV]	- 678	- 661

From the obtained results it follows that heat treatment reduces the corrosion potential.

Potentiodynamic studies

Potentiodynamic method is an electrochemical method during which the potential of the electrode changes continuously at a predetermined speed. During the experiment, the sample was polarized in a wide range of potential values from -1 to 1 V at a rate of potential changes amounting to 0.001 V/sec.

The results of the studies were polarization curves, plotted in a logarithmic system. The relevant values were used to calculate the corrosion potential - E_{corr}, corrosion current - I_{corr} and polarization resistance - R_p. The results of the conducted studies are shown in Figure 23 and Table 6.

Table 6 The results of electrochemical testing

	AlSi30 RS F condition	**AlSi30 RS T6 condition**
i_{corr} [µA/cm^2]	6.86	0.673
R_p [Ω]	1717	3676
$E_{corr, obs}$ [mV]	- 749	- 693
$E_{corr, calc}$ [mV]	- 746	- 688

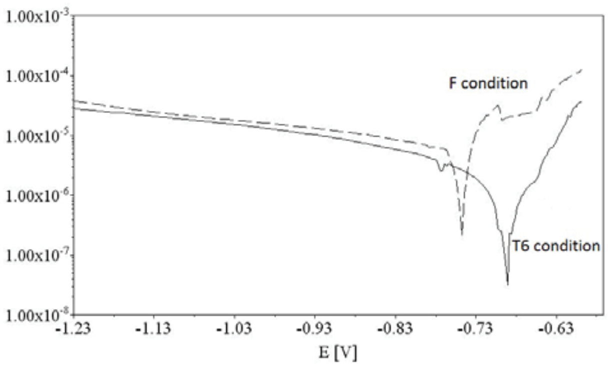

Fig. 23 Polarization curves for the AlSi30 RS alloy

Based on the results of electrochemical studies it can be concluded that heat treatment affected the corrosion potential shifting it towards the cathode.

Summary

The study done in order to explore some alternative solutions in production of materials with properties beyond the standard ones has confirmed that the developments based on rapid solidification are a very promising trend for future applications. Using traditional methods of casting it would never be possible to produce materials with so high content of alloying elements, especially silicon. High silicon content was reflected in the functional properties of the material produced. Comparision of the mechanical properties at elevated temperatures for conventional hypereutectic aluminum alloys with a silicon content 18-24 % ranges between: R_m 125 – 135 MPa, $R_{p0,2}$ 100 – 135 MPa, A_5 1.3 - 4.0 % given for the temperature 250^0 C [7].

The high strength values obtained at elevated temperatures, low and stable coefficient of thermal expansion and high abrasion resistance have proved that the newly developed material can be successfully used for the automotive piston applications. Of course, further studies are necessary to better investigate the technology of making forged pistons, combined with trials conducted under thermal loads in a combustion chamber. The studies of corrosion and electrochemical tests confirmed once again the beneficial impact of heat treatment on the alloy corrosion resistance.

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