

ADVANTAGES OF USING COMPOSITE ALLOYS FOR INTERNAL COMBUSTION ENGINE PISTONS

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Abstract:

Combustion engine pistons are subject to variable mechanical and thermal loads, and to variable deformations. The article presents the possibilities of using novel composite alloys for the construction of pistons for combustion engines. The novel alloys make it possible to meet high demands, especially for highly load designs, which practically cannot be met by conventional alloys used so far. These high requirements relate to the weight of the pistons, high temperature strength, alloy crystalline structure, abrasive wear resistance, dimensional stability. The requirements for pistons have an impact on the durability of the engine's operation, the level of noise emissions; exhaust gas blow-by into the crankcase, the level of emitted toxic exhaust components, mainly hydrocarbons. The research covered metallography (chemical composition, microstructure), material strength, abrasive wear, and thermal expansion. Investigations of the alloy crystallization process during casting were carried out using the Differential Thermal Analysis (DTA) method. The castings were used for metallographic tests. The strength of the samples was tested at room temperature (20° C) and elevated temperature (up to 350° C) on a testing machine equipped with a special climatic chamber. In particular, the article presents Thermal Derivative Analysis curves and representative microstructures of conventional AlSi12 alloy and the novel composite alloy; dependence of the tensile strength versus temperature for the samples of the novel alloy with various nickel content 2% and 4%; comparison of the tensile strength for conventional alloy and the novel alloy at ambient and 250° C temperature; comparison of abrasive wear of samples, made of novel aluminium alloy and different cast iron; course of the linear expansion coefficient versus temperature for the conventional AlSi12 alloy with incorrect heat treatment; course of the linear expansion coefficient versus temperature for one of tested silumin alloy which expansion coefficient during sample cooling is smaller than during sample heating; course of the linear expansion coefficient versus temperature for the novel composite silumin alloy, after correct heat treatment. The great benefits of using this novel alloy and the introduction of novel alloying elements (in-Situ) have been confirmed in engine research.

Keywords: internal combustion engine pistons, novel silumins, composite materials

To cite this article:

Kowalski, M., Jankowski, A., 2020. Advantages of using composite alloys for internal combustion engine pistons. *Archives of Transport*, 55(3), 85-94. DOI: <https://doi.org/10.5604/01.3001.0014.4236>



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1. Introduction

Permanent increase in work parameters, related to increases in engine performance, requires the development of novel materials that could perform in much more difficult conditions (Singh, J., 2016). This applies in particular to materials used in the production of internal combustion engines, in aviation and aerospace industries. Higher temperature values, higher pressures in which various components of engines and machines operate, become more and more challenging for researchers, working on novel materials (Kowalski et. al., 2017). Particularly interesting is the use of composite materials, which make it possible to meet often very diverse requirements, which are practically impossible to meet for conventional materials (Mistry J. M., et. al., 2017). Composite metal materials are obtained by introducing novel elements or chemicals into the base material during the manufacturing process, which results in increased properties such as alloy strength, heat resistance, abrasion resistance and dimensional stability (Dinaharan I. et. al., 2018). Silicon aluminum alloys (silumins) are widely used in motor designs. Almost all internal combustion engine pistons are manufactured using silumins. The research works presented in this paper deal with the silumins, used in the manufacturing of engine pistons and plain bearings. The requirements relate primarily to high strength values at operating temperatures, thermal shock resistance, high hardness, abrasion resistance and dimensional stability when operating under varying temperature conditions. The results of the investigations presented in this paper cover novel composite silumins with novel alloying additives, such as chromium and molybdenum (not yet used in this type of silumin) and increased content of nickel and copper Zhang W., et. al. (2019).

2. Literature review

Focusing on the work (Siva Prasad G. et al., 2016), who in his work uses two pistons of different materials Al 4032 and alloy steel AISI 4340 in his research using PRO-E software and analyzing the piston using ANSYS software. The structural analysis shows that the maximum stress intensity occurs on the lower surface of the piston.

Another work (Sundaram K. and Palanikumar N., 2016) concerns research on material composition and hardness testing of composite coatings. SiC composites were deposited on aluminum in the

casting process. Three different materials were tested (Al with 10% SiC, AL with 20% SiC and AL with 30% SiC), and the results obtained in the Ansys software show that aluminum with 10% SiC material has a better temperature distribution both in steady-state thermal analysis as well as in transient thermal analysis, hence aluminum with 10% SiC material is better than aluminum alloy material.

When reviewing the literature (Darwai M., Kulshrestha A., 2017) - it is concluded that Al-Si-based alloys are used in automotive and other technical applications due to their light construction and good mechanical and thermal properties. However, the use of basic Al-Si alloys, which may not meet basic requirements, becomes problematic. The authors recognize that in this type of research, spatial and temporal averaging is the most beneficial and appropriate method to improve engineering research for this type of problems.

Kumar G. et al., 2016 based their research on three different materials, Gray cast iron, Aluminum alloy and Al-Ni-graphite. The piston was reported to SolidWorks and the static pressure test was 13.65 MPa. The article presents the thermal analysis and lists the stresses and strains in a tabular form. The research clearly shows that Al-Ni-graphite gives the best results.

From the results of the work (Prasada Rao B. V. V. and Siva Kumar B., 2016) carried out on three types of material Al-6061, Al-6082 and Al-7075, it can be concluded that the deformation stress and deformation of Al-7075 is the lowest among the three materials. Hence, the inertia forces are smaller, which improves engine performance. The mechanical properties of this material were also good compared to the other two, so it is possible to further develop a high-powered motor using this material.

In the article (Sathish Kumar K., 2016), he conducted a finite element analysis under static and dynamic conditions of an engine piston made of various materials. From the results, it was concluded that the SiC reinforced ZrB2 piston has lower deflection, while the aluminum gray cast iron piston has greater deflections for the temperatures and pressures used. It was also observed that the stress for all materials is within the acceptable limits of the respective material. From the modal analysis, it can be seen that the aluminum alloy piston has a lower geometrical stiffness, while the ZrB2 SiC composite piston has a higher geometrical stiffness. Thus, it was found that

the SiC body ZrB2 piston is the best choice for the production of the piston.

The authors of the article (Stepanenko, D., Kneba, Z. 2019) point out that the mathematical description of the combustion process in internal combustion engines is a very difficult task due to the variety of phenomena occurring in the engine from the moment of ignition of the fuel-air mixture to the moment of opening the intake valves and exhaust. Combustion modeling plays an important role in engine simulation, allowing you to predict combustion cylinder pressure, engine performance and environmental impact with high accuracy.

As it results from the literature analysis, there is no comprehensive approach in the area of the case in question, taking into account admixtures of other materials presented in this article.

3. Experimental

3.1. Materials

The subject matter of the study was the novel composite Al-Si alloy for of the internal combustion engines pistons, which parameters were compared to the conventional silumin alloy AlSi12. The chemical composition of both alloys is shown in Table 1.

Tab. 1 Chemical composition of tested alloys, %

	Si	Mg	Cu	Ni	Fe	Mo	Cr
Conventional	12.5	0.37	1.4	1.3	≤0.7	-	-
Composite alloy	12.5*	0.43	5.2	4.1	≤0.5	0.25	0.28

During the study, the content of the different alloying elements was varied to determine the effect of the content of the individual component on the strength of the alloy and its dimensional stability, which was the main objective of the researches.

3.2. Apparatus and procedures

The studies involved both casting process and post-cast material testing. The research included metallography (chemical composition, microstructure), material strength, abrasive wear, thermal expansion (Belmonte M.A.R, et. al., 2015) and (Zurek J. et. al., 2015). Research of the alloy crystallization process during casting was carried out, using the differential thermal derivative analysis (DTA) method (Dhansakaran S, et. al., 2016). Samples were cast in the ATD-10 chill, Fig. 1. The chill was equipped with a thermocouple and an instrument for recording

course of metal solidification, and a heat flow analyser.

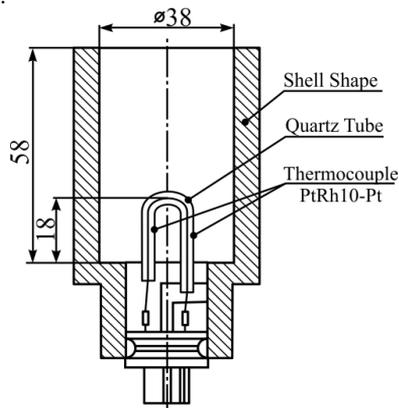


Fig. 1. Chill for casting process testing of aluminium alloy samples

The cast samples were used for metallographic studies.

The samples strength tests were performed at room temperature (20°C) and at elevated temperatures (up to 350°C), and were carried out using the Instron 8802 strength machine, equipped with the Instron 3119-406-222 special climate chamber (Fig. 2.).



Fig. 2. Instron 8802 strength testing machine with climatic chamber Instron 3119-406-222

Samples for strength testing were cast in metal chill in the form of rods of diameter and 185 mm length. Abrasive wear testing was performed using samples of diameter $d = 18.5$ mm and length $L = 40$ mm. The counter sample was a C45 steel disc with a hardness of 56 HRC: a diameter of $D = 100$ mm and a thickness of $s = 10$ mm. The disc rotational speed of $n = 100$ rpm. The specimen pressures on the disc are 4 MPa. The sample was lubricated with engine oil. The sample wear was determined hourly, and the abrasive wear test time for the one sample was 10 hours. The results of abrasive wear tests for the novel aluminum alloy were compared with the results of abrasive wear tests of various types of cast iron specimens.

The dimensional stability of the novel aluminum alloy was investigated using the Bahr 802/801 precision dilatometer. This device allows one to register

and record the sample dimensions as a function of temperature, during sample heating and cooling. Measurements can be conducted in a comparative system (with pure aluminum or platinum samples) or by direct measurement. The results of measurements are very precise. The device operates according to a special temperature program which is a computer controlled.

4. Test results and discussion

During the DTA crystallization process investigations, derivative curves have been determined, that allows the analysis of the solidification process and the analysis of the heat transfer process in the sample structure and phase transformations. Fig. 3 shows the derivative curve for the conventional AlSi12 alloy and representative microstructures, and characteristic temperatures.

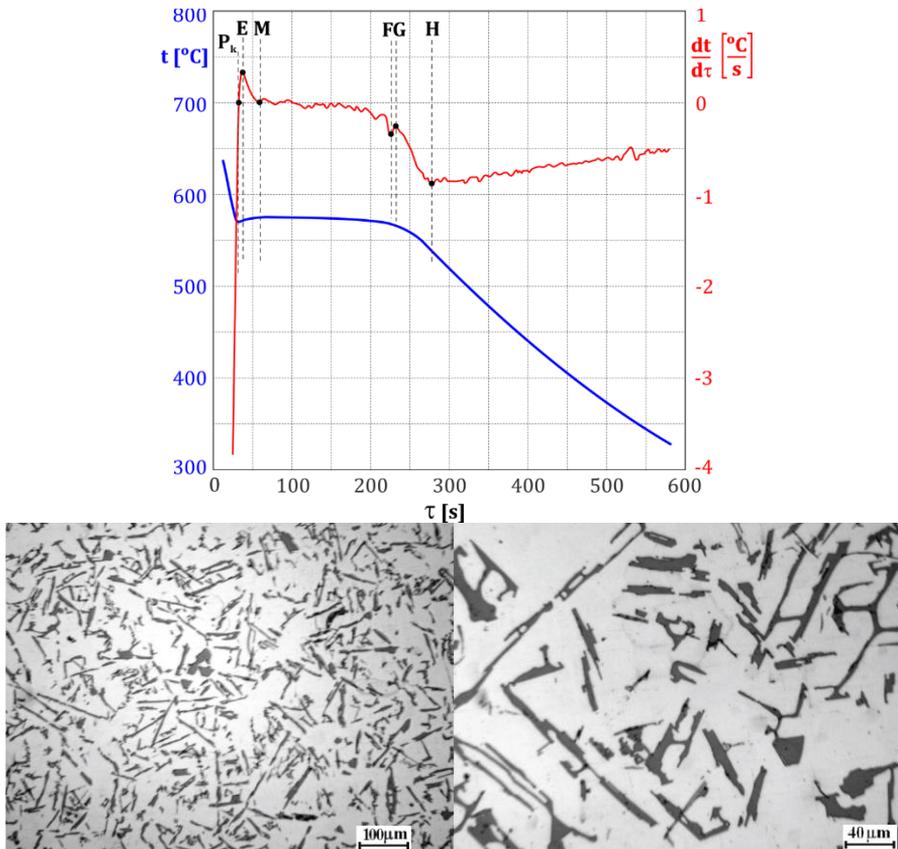


Fig. 3. The DTA curves and representative microstructures of conventional AlSi12 alloy

Fig. 4 shows the derivative curve for the novel composite aluminum alloy and the representative microstructures and characteristic temperatures.

The results of the analysis indicate that the microstructure of the novel composite alloy is more finely grained and that many intermetallic compounds can be observed at the grain boundaries. When is analysing the effect of nickel and copper in increased quantity and novel additional additives chromium and molybdenum so they can be beneficial not only for the microstructure fragmentation but also for neutralizing the harmful effects of iron in aluminum alloys. As a result of the increased amount of Ni and Cu and the presence of previously unused chromium

and molybdenum, intermetallic compounds such as: $(CrFe)_4Si_4Al_{13}$, $Al_2(CrSiFe)$, $Al(SiMoFe)$, $Al_{12}(SiWFe)$, $AlSiFeCo$, Al_9Co_2 , $Al(SiMgCuNiFeCo)$ were created. In silumin and other aluminum alloys, containing small amounts of alloying elements and large amounts of iron, an intercrystalline Al_9Fe_2Si compound is formed, which occurs in the form of long, sharp-pointed crystals (Vedrtnam A. et. al., 2017). This has a detrimental effect on the strength of the materials, particularly on the ultimate tensile strength, the relative elongation, the yield strength and the fatigue strength. This has also adversely effects on other alloy properties.

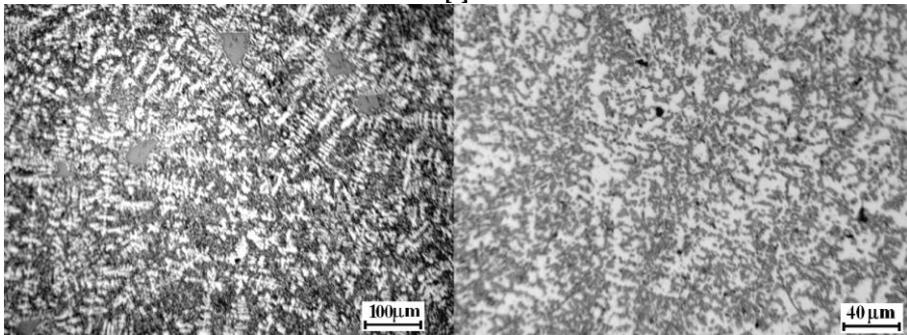
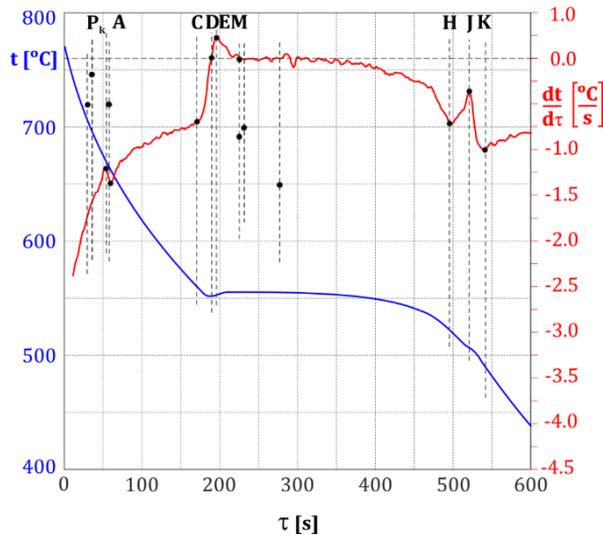


Fig. 4. The DTA curves and representative microstructures of the novel composite alloy

Tests of the samples strength allowed determining the influence of different alloying elements on strength at ambient temperature and at elevated operating temperatures. The increased nickel additive is particularly beneficial. Fig. 5 shows the influence of nickel on alloy strength at various temperatures, with 2% and 4% nickel content in the alloy. The tensile strength of the alloy containing 4% nickel at 20°C was 43% greater than the alloy containing 2% nickel, but at 350°C, tensile strength was greater by as much as 87%. Comparative results of the tensile strength of the novel composite alloy and the conventional AK12 alloy are shown in Tab. 2.

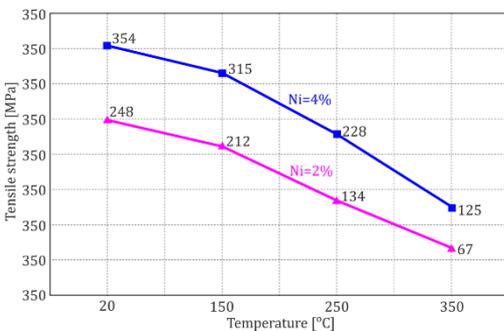


Fig. 5. Dependence of the tensile strength versus temperature for the samples of the novel alloy with various nickel content: 2 % and 4 %

The results of the abrasive wear test of the novel aluminium composite alloy were compared with the samples of different types of pearlite – martensitic microstructure with carbides, ductile cast iron EN-GJS-800-2 and grey cast iron EN-GJL-250.

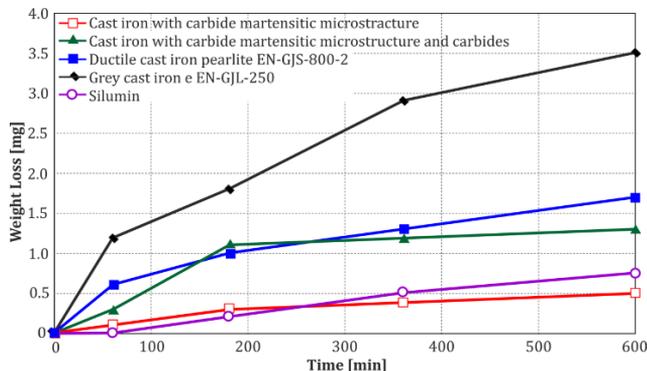


Fig. 6. Comparison of abrasive wear of samples, made of novel aluminium alloy and different cast iron

Diagrams of the wear course over time are presented in Fig. 6.

Table 2. Comparison of the tensile strength for the novel alloy and conventional alloy at ambient and 250°C temperature

Material	Rm [MPa]	R _{p0.2} [MPa]	As [%]
AlSi12	371.0	320.8	3.7
AlSi12, 250°C	250.2	215.7	11.4
Composite alloy	451.0	385.0	3.7
Composite alloy, 250°C	364.0	299.0	6.7

The abrasive wear of the investigated novel aluminium composite alloy, as seen in the figure, is comparable to that of martensitic cast iron with carbide, but is less than all other cast irons, even several times less one.

In the dilatometric researches, a great deal of experience has been gained, regarding the composition of the alloy and its heat treatment. On selected courses of linear expansion and linear expansion coefficients, the quality and operability of a given element at elevated temperatures can be ascertained, especially if the possible thermal deformation of the element can be strictly defined.

Fig. 7 shows the course of changes in thermal expansion coefficient as a function of the temperature for conventional silumin, without heat treatment. There are large differences in the coefficient values during heating and cooling, which is reflected in the deformation increase.

Fig. 8 shows the course of the thermal expansion coefficient as a function of the sample temperature for the novel composite alloy, which exhibited a lower expansion coefficient during sample cooling than for sample heating.

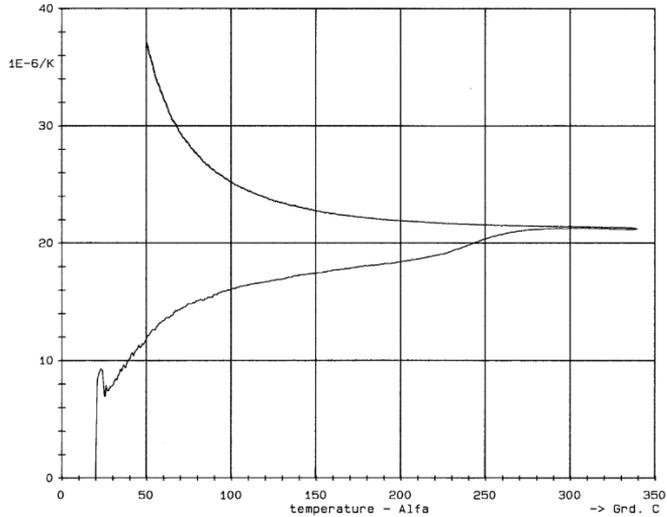


Fig. 7. Course of the linear expansion coefficient versus temperature during heating and cooling for the conventional AlSi12 alloy, with incorrect heat treatment

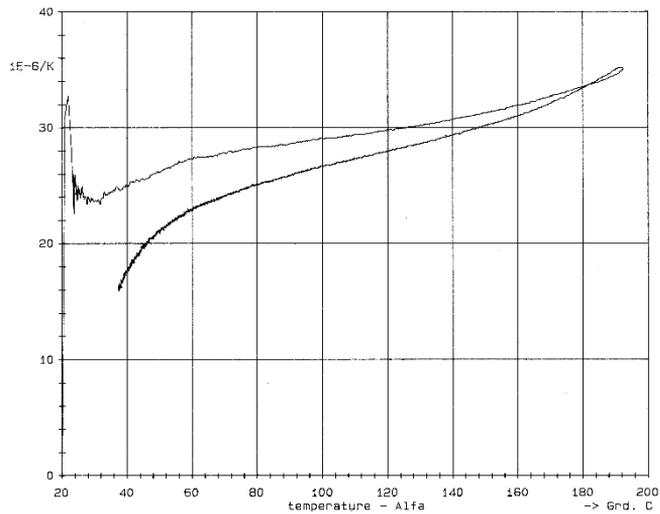


Fig. 8. Course of the linear expansion coefficient versus temperature during sample heating and cooling for one of tested silumin alloy, which expansion coefficient during sample cooling is smaller than during sample heating

Fig. 9 shows the course of the thermal expansion coefficient as a function of the sample temperature, made of the novel composite material during heating and cooling, after properly performed heat treatment.

All research results indicate that the novel developed composite aluminum alloy has far better parameters than aluminum alloys used previously for pistons of the internal combustion engines (Kowalski M et. al. 2018) and (Jankowski A. et. al., 2015).

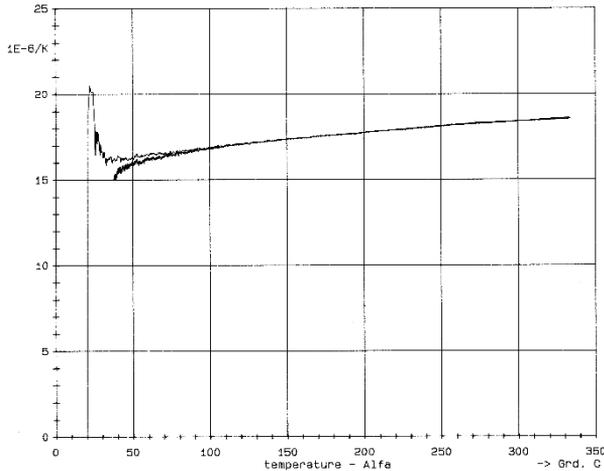


Fig. 9. Course of the linear expansion coefficient versus temperature, during heating and cooling for the novel composite silumin alloy, after correct heat treatment

5. Summary

The article presents the results of research on the implementation of innovative composite alloys for pistons of internal combustion engines.

The aim of the research work was to develop alloys that would meet the requirements for engines with high mechanical and thermal loads that cannot be met by the conventional alloys used so far.

These requirements relate to functional properties (increased power, reduced fuel consumption, reduced oil consumption); ecological properties (reduction of the emission of toxic exhaust components, mainly hydrocarbons and reduction of exhaust gas blow-by into the crankcase) and the durability of internal combustion engines, especially mechanically and thermally highly loaded.

The aim of the research work has been achieved. A novel composite alloy has been developed that meets the assumed increased functional, ecological and durability requirements. The introduction of innovative additives into silumin alloys: Cr, Mo, W, Co and increasing the content of Ni and Cu increases the strength of the alloy, reduces abrasive wear and increases the dimensional stability of the alloy. The alloying elements of hard-melting elements cause the crystallization of the alloy phases before the $\alpha + \beta$ eutectic, which was reflected in the reduction of Si in eutectics and significant fragmentation of Si.

Novel elements also have a beneficial effect on the neutralization of the harmful effects of iron in aluminum alloys, as they contribute to the formation of crystals of intermetallic compounds, the shape of which is more favourable than the shape of compounds formed in the absence of these elements.

By adding innovative elements to silumin, multi-phase microstructures of very fine fragmentation are created, which has a positive effect on increasing the strength of the material and reducing abrasive wear. The method (DTA) can control the type and order of crystallization of the alloy.

In particular, the tests covered the chemical composition, microstructure, material strength, abrasive wear, thermal expansion, and the alloy crystallization process.

The microstructure of the novel composite alloy is finer and there are many intermetallic compounds at the grain boundaries. Analysing the influence of Ni and Cu in increased amounts and the innovative Cr and Mo additions, it can be concluded that they may be beneficial not only for the fragmentation of the microstructure, but also for the neutralization of the harmful effects of Fe.

As a result of the increased amount of Ni and Cu and the presence of previously unused Cr and Mo, intermetallic compounds are formed.

In particular, a large amount of Fe has a detrimental effect on the strength of materials, especially tensile

strength, relative elongation, yield point and fatigue strength. The increased addition of Ni is particularly preferred. The tensile strength of the alloy containing 4% of Ni at 20° C was 43% higher than that of the alloy containing 2% of Ni, while at 350 ° C the tensile strength was higher by 87%. The abrasive wear of the novel aluminum composite alloy under study is comparable to that of martensitic cast iron with carbide.

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