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Selected tribological parameters for silumin alloy used for engine piston

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ABSTRACT

Purpose: The conducted tests were aimed at determining whether the tested material meets the requirements for wear resistance in modern turbocharged combustion engines where there is an increased temperature and higher pressure.

Design/methodology/approach: The tests were performed in a pin-on-disc system, according to the ASTM G 99 standard.

Findings: The article presents the results of the coefficient of friction, the amount of wear, chemical analysis and surface profile of the tested material A390.0 in combination with EN GJL-350 cast iron.

Research limitations/implications: The tested materials are used in the construction of pistons for internal combustion engines, therefore the test parameters were selected to take into account the operating conditions in a turbocharged engine with a power of up to 100 kW.

Practical implications: After analysing the properties of the A390.0 alloy at elevated temperatures, it was found that without additional modifications, the alloy cannot be used in modern combustion engines, in particular with turbocharging.

Originality/value: Presents the results of research concerning mechanical properties (HB, HV, R_m) and yield properties ($R_{0.2}$, A_5, Z) of the examined alloy.

Keywords: Tribology, Piston engines, Coefficients of friction

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PROPERTIES

1. Introduction

At present, changes in the design of internal combustion engines used in means of transport are taking place dynamically. Every year, new technologies appear which are dictated by new material or electronic possibilities, e.g. new software, etc. Increasingly ecological solutions are introduced, e.g. hybrid or electric vehicles, which concern not only passenger cars but also buses, trucks or delivery vehicles. For example, buses with hybrid engines (internal combustion engine + electric motor) or electric buses are increasingly used both in public transport and at airports to deliver passengers [1,2]. The main changes related to the improvement of the environmental friendliness of the means of transport are associated with the reduction of weight, the use of new technologies in internal combustion engines or the use of modern materials – light and at the same time very durable such as magnesium alloys or plastics. It should be remembered that the safety of drivers, pilots, passengers or cargo remains first and only after that we can talk about improving the environmental performance of a given means of transport. Eco-friendliness is not only the emission of exhaust gases and meeting increasingly more stringent EURO standards by vehicles, but also the reduction of noise emission through an appropriate aerodynamic structure or reduction of toxicity of dusts emitted in brake pads and discs by limiting materials containing elements or materials hazardous to the environment and man. However, in the case of other types of pollution, it is possible to use other solutions to reduce pollution, such as the construction of acoustic screens or settling tanks for dust pollution on roads, and therefore it is the emission of exhaust gases in means of transport that is still the main source of problems faced by designers [3].

At present, there are changes being made to constructions of engines, mainly those with spark ignition (petrol engines). There are changes being made by installation of turbo-compressors as well as systems increasing the eco-friendliness of the engines such as start-stop systems. Until quite recently, the turbo-compressors had been installed solely in diesel self-ignition engines and that was why the requirements for the material were different depending on the type of engine power supply. Technological changes caused that in petrol engines there was an increase of combustion level from 9 MPa to 13 MPa with immediate downsizing which meant the decrease of engine cubic capacity. Decrease of engine capacities caused the decrease of their weight and the improvement of the performance, but at the same time reduced the ability of heat dissipation [4]. That is why, in modern combustion engines, it is really important to use materials which maintain their properties at elevated temperatures. Moreover, the systems supporting ecological solutions in cars, such as start-stop systems cause the emergence of unfavourable working conditions, especially during city traffic rides where the engine is constantly started and stopped. On the one hand, such system allows for limiting the fuel consumption and at the same time the reduction of exhaust gases emission, but, on the other hand it causes difficulties with lubrication and cooling of the engine [4,5].

The constant attempts to increase the mechanical and tribological properties of materials made from Al-Si alloys forced experts to review the analysis of the notions concerning modification, improvement and upgrading the liquid metal as well as its manufacturing process. For hypereutectic alloys Al-Si the main modifier is phosphorus. The alloys Al-Si with hypereutectic silicon content are mainly applied as materials for pistons for combustion engines (Fig. 1). However, the construction changes of machines and devices where those alloys are used such as, for example, combustion engines, it is necessary to search for new technological solutions in order to meet the high material requirements. Conducted material modifications, even the slightest made, have their correspondence in the properties of the material [6]. One of the main factors which determines the suitability of the Al-Si for use are the tribological properties. That is why the tribological tests are one of the significant elements in gaining knowledge about the materials applied in various friction pairs of machines. The process of friction and wear is dependent on many factors of the process which take into account the mechanical properties of material matchings, the porosity of the surface, plastic deformations, ambient temperature and the presence of lubricant [7].

Fig. 1. Piston of the combustion v16 engine

To sum up, the changes in engine technologies that have occurred for the last 10 years which include the increase of pressure in combustion chamber and at the same time the reduction of piston size, have forced the producers of materials to make changes. The changes being made, however, must take into account one significant aspect which is the cost. Development of the totally new materials and technologies of manufacturing would be very expensive and that is why there are tests made on the improvement of existing materials [8]. In addition, new materials require detailed research and verification of their operation on real objects. While in the case of motor vehicles, such tests are relatively cheap and as fast as possible to carry out, e.g. in aviation, the use of new materials requires considerable time and financial outlays. Of course, it is possible to carry out simulation tests using computer techniques, but they are not able to show all the details and thus highlight problems that may arise during use. Therefore, it was decided to carry out additional tests that will determine whether it is possible to continue using these types of alloys in modern internal combustion engines. The article presents chosen tribological properties at elevated temperature for A390.0 alloy commonly used for pistons for internal combustion engines up to 100 kW.

2. Material

One of the most commonly used alloys for the construction of pistons of combustion engines are Al-Si casting alloys. The basic criterion determining their properties is their structure, with particular emphasis on the morphology of eutectics and the distribution of intermetallic phases in the matrix. In the case of hypereutectic Al-Si alloys, the morphology of the primary silicon crystals is important, and in particular their appropriate - even distribution in the matrix [9]. The most common forms of primary silicon in hypereutectic silumin, which are used in the construction of highly loaded engine pistons, are: polyhedral, star-shaped, ornaments and dendritic ones (which are formed when cooling down quickly). The unfavourable structure of silicon crystals may change, among others as a result of modification with single or combined reference alloys based on titanium, phosphorus or boron [10]. The factor that reduces the operational properties of silumin are iron admixtures, especially for recycled materials. Then, structures resembling, among others, radial plates, needles, polyhedrons, long-edged stars are unfavourable from the point of view of the efficiency and workability of hypereutectic silumin. It is necessary to use appropriate alloying additives, e.g. manganese or magnesium, to change the unfavourable structure. This material works very well for piston materials for internal combustion engines without turbochargers. In theoretical considerations in terms of mechanical properties, this material should meet the requirements for engines with a turbocharger. The problem, however, is the temperature range at which this material can work properly. Theoretically, its range of use is up to 150°C which would allow its use in modern engines. However, no studies have been conducted so far for such a high temperature range, so it is necessary to analyse the possibility of use of this material [11].

Such modifications are carried out to inhibit the nucleation of silicon crystals, which limits their growth. They are also intended to increase the density of heterogeneous bases. However, the grinding of primary silicon crystals alone is often insufficient. They should be given appropriate shapes, preferably close to spheroidization. An example may be a structure with fine-grained but sharp-edged silicon crystals, which has a negative impact, in particular, on the operational properties, including tribological ones [12,13]. Therefore, an important aspect is the development of silumin modification processes that enable multidirectional optimization. In this study, A390.0 silumin was tested, the chemical composition of which is presented in Table 1. This alloy was modified with phosphorus (0.05% by weight) with the addition of CuP10 masterbatch. The silumin was refined with Rafglin-3 (0.3 wt.%).

Table 1.
Chemical composition of the A390.0 alloy

Alloy	Chemical composition, mass %						
	Si	Fe	Cu	Mn	Mg	Zn	Al
A390.0	16.8	0.573	4.95	0.189	1.001	0.145	rest

The mechanical properties of the tested material were determined in accordance with PN-EN ISO 6892-1:2011 and PN-EN ISO 6892-2:2011 at a temperature of 100°C and were as follows: tensile strength R_m = 183 MPa, the yield strength $R_{0.2}$ = 132 MPa and relative elongation A_5 = 3.1%; at temperature 150°C tensile strength R_m = 168 MPa, the yield strength $R_{0.2}$ = 105 MPa and relative elongation A_5 = 3.4%. The hardness of the test material was 135 HBS [13].

All presented values of mechanical properties are the average of 15 measurements. They comply with the requirements for piston materials in turbocharged combustion engines up to 100 kW. Table 1 presented the chemical composition of A390.0 alloy and Figure 2 shows the microstructure of the tested material.

3. Testing method

The tests of the friction coefficient were carried out in the pin-on-disc system, according to the ASTM G 99 standard. During the test, the determination of the friction coefficient is possible only and exclusively when the entire surface of the pin shows signs of wear [15]. Otherwise, it is necessary to repeat the test. The adopted test parameters reflecting the conditions prevailing in modern engines,

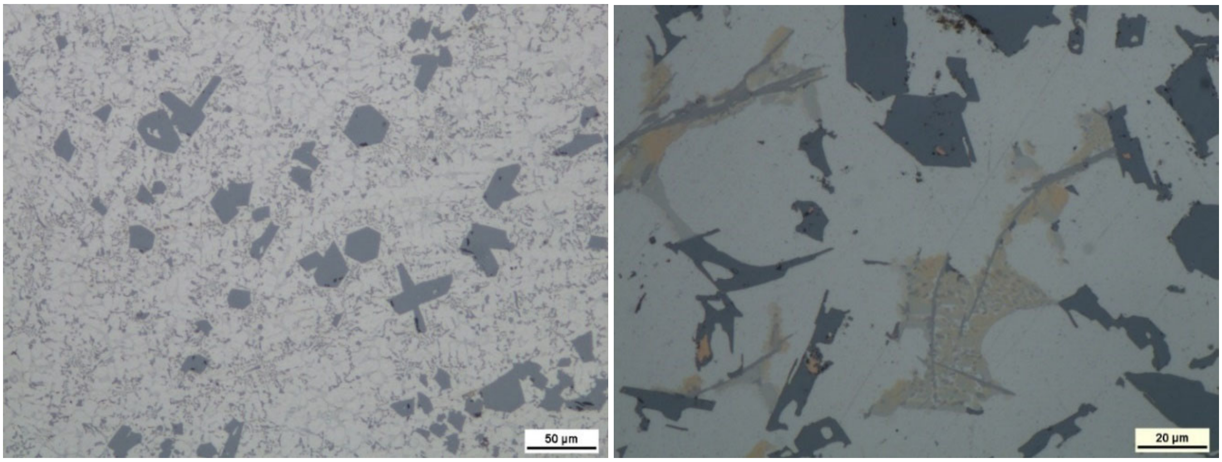

Fig. 2. Microstructure of A390.0 alloy

which are currently very high, meant that there was no need to repeat the test. In the tests carried out, the disc was made of EN GJL-350 cast iron, while the pin was made of the tested alloy A390.0. The adopted combination of materials is used in older types of engines. All tests were carried out under dry friction conditions with a load of 1.3 MPa and a velocity of v = 1.2 m/s, at three temperatures of 100ºC, 125ºC and 150ºC. The total sliding distance for all tests was 1000 m. The test parameters were set to correspond to the conditions of a 100 kW spark-ignition turbocharged internal combustion engine with direct fuel injection. Due to the heavy load, wear marks were visible on the entire surface of the pin in all cases. 12 tests were performed for each temperature. Changes in the weight of the tested material pairs were determined using the Radwag AS 220/C/2 balance with an accuracy of 0.1 mg. The friction marks were observed using an Olympus SZX9/8X stereoscopic microscope and a Hitachi S-3400N scanning microscope.

4. Results

Tests were conducted on 12 samples for each tested temperature. From one casting of alloy A390.0 there were 3 samples (pins) taken for tests on tribological tester in order to achieve the most reliable results. Prepared test samples were observed under scanning microscope each time with the immediate tests of chemical composition. During the tests there were no significant differences found between the castings. Counter-sample made of cast iron (EN GJL-350) in form of a disc was prepared from cylinder with diameter of 30 mm cut from bought material from iron-foundry with certificate. The pin had a diameter of 4 mm and a length of 20 mm, while the disk had a diameter of 25 mm with a thickness of 6 mm. Before testing, both the pin and the disk were subjected to grinding on 300 grams, 600 grams and 1200 grams of abrasive paper. Then the samples were mechanically polished with a 3 µm diamond suspension and 0.05 µm oxide suspension. After polishing, they were washed with acetone and washed in an ultrasonic cleaner. After completion of the test, the samples were also washed and only then weighed. The T-11 tribological tester was subjected to a verification of correct functioning before each start-up (Fig. 3).

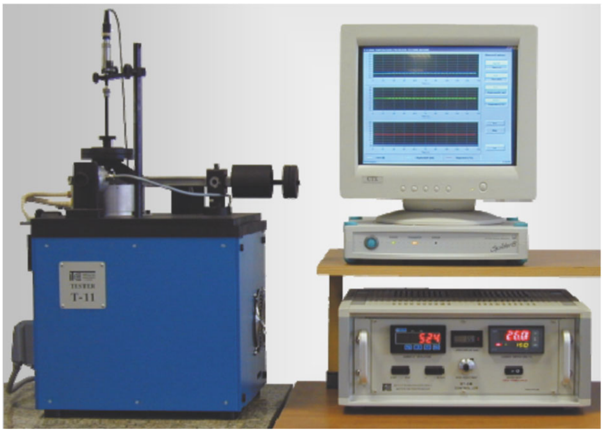

Fig. 3. Tribological tester T-11

Figure 4 presents the pin (A.390.0) and the disc (EN GJL-350) after testing in temperature of 100ºC. Visually, on a light microscope, all samples after testing for each temperature looked similar. Differences between individual samples were only visible when using scanning microscopy. Figure 5 presents the surface of the disc and the pin after applying friction at 125ºC. The Figure 6 shows the side view of the pin after friction at temperature 150ºC.

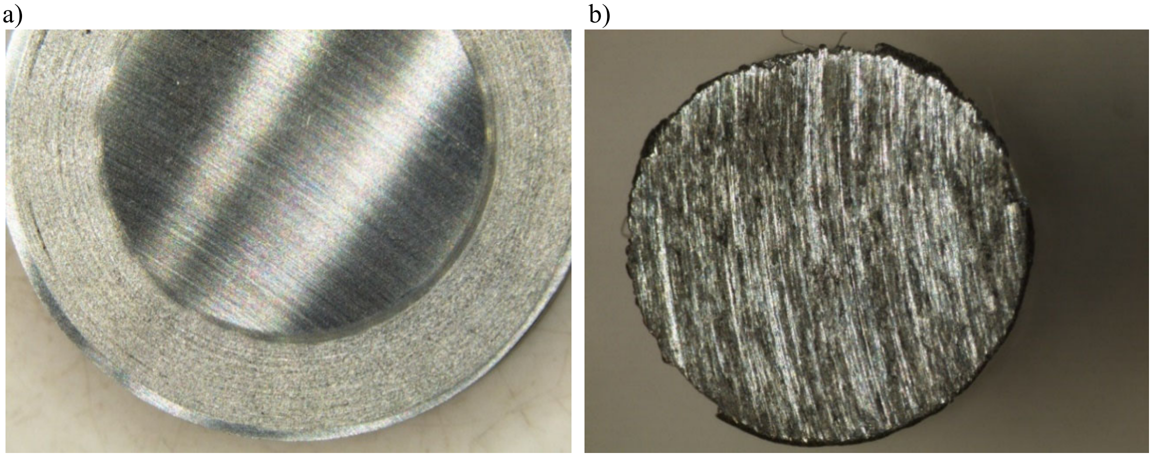

Fig. 4. The surface of the disc (a) and the pin (b) after test at 100ºC

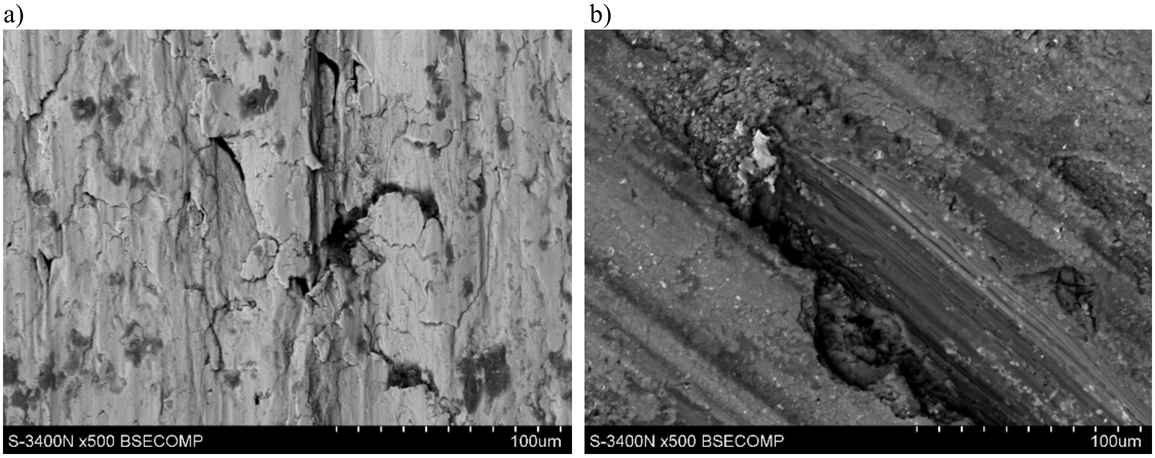

Fig. 5. Material surface after wear test at 125ºC: a) disc, b) pin

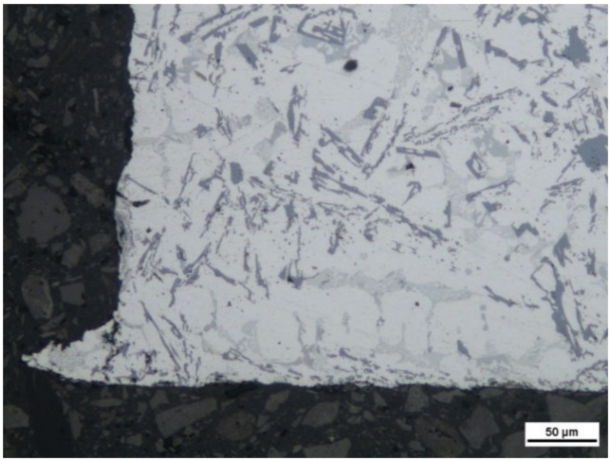

Fig. 6. Side view of the pin after friction at temperature 150ºC

Table 2 presents the results of the coefficient of friction for the tested materials, while Figure 7 shows the results of wear measurements of the pin and the disc. Each sample mass measurement was carried out 3 times before and after the test. The presented results are averaged results. Figures 8 and 9 present a chemical analysis of the surface of pin and disk.

Additionally, the surface profile of the tested material was tested. Tests were performed on the Mitutoyo SJ-500 device based on the PN-ISO 4288: 1998 standard. Figure 10 shows the surface of the tested pin for individual temperatures. In turn, Table 3 presents the obtained results of the surface examination.

The results presented in Table 2 are average values obtained in individual research cycles. The lowest value of the coefficient of friction was obtained at the temperature of 150°C and it was 0.33. At the two remaining temperatures, 100°C and 125°C, the coefficient of friction was the same and amounted to μ = 0.34. However, the differences are visible only during the analysis of the standard deviation, which at the temperature of 125°C was 0.005, while for the temperature of 100°C it was 0.008. The wear analysis showed that the smallest loss of the pin material (A390.0) was obtained during the test at 150°C and it was 2.28 mg, while the highest wear value was observed at 100°C and it was 2.36 mg. In the case of disc wear (EN GJL-350), the highest value, unlike in the case of the pin, was obtained at the temperature of 100°C and was 1.78 mg, while the lowest wear was obtained at the temperature of 150°C and was 1.75 mg.

Table 2.
The value of the coefficient of friction for the tested materials

Material: A390.0	Temperature, ºC	μ	σ_μ
Test No. 1	100	0.34	0.0078
Test No. 2	125	0.34	0.0051
Test No. 3	150	0.33	0.0019

where: σ_μ – standard deviation, μ – friction coefficient

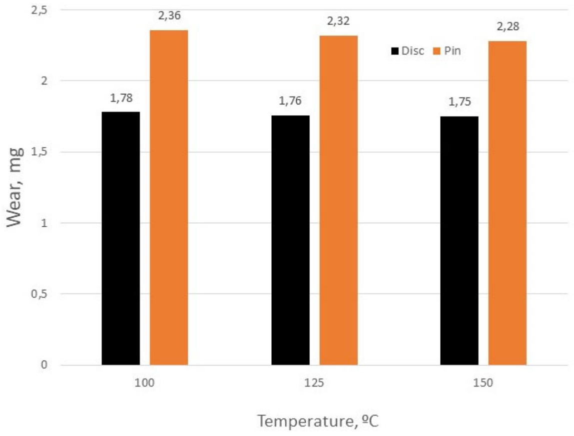

Fig. 7. The mass loss of tested materials

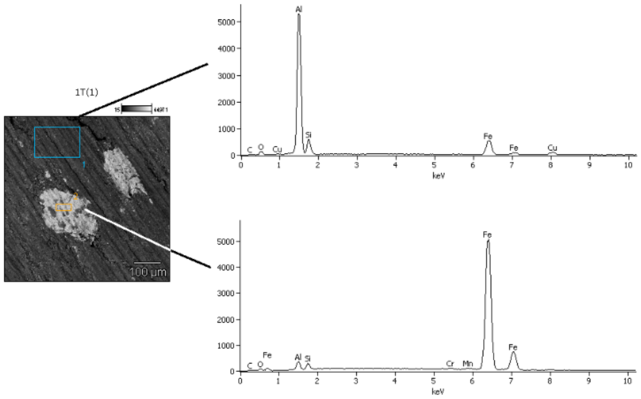

Fig. 8. Chemical analysis of the surface of pin at temperature 125°C

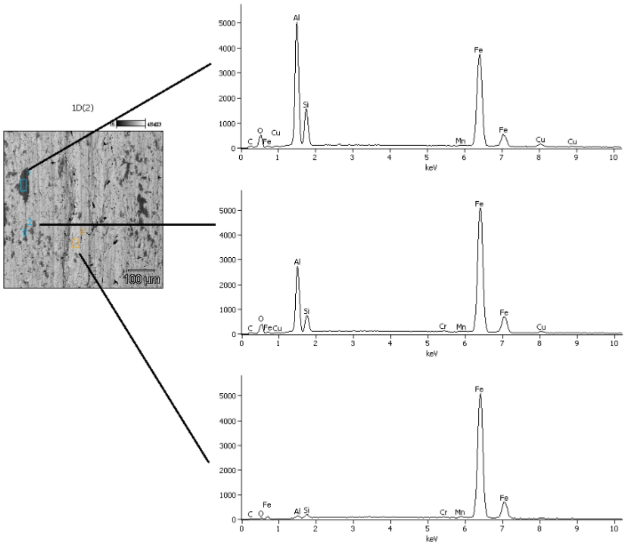

Fig. 9. Chemical analysis of the surface of disk at temperature 125°C

Chemical analysis of the pin surface (Fig. 6) shows that during the friction process particles from the disc appeared on it. This is clearly seen in the white area with concentrated Fe content (Fig. 6). Iron particles due to their hardness were most likely rubbed into the pin matrix (phase α). In turn, when analysing the surface of the disc (Fig. 7) it is noticeable that the pin particles (measuring points 1 and 2 in Fig. 7) have been transferred, most likely into the grooves formed due to silicon friction and then the soft matrix (phase α) was rubbed into the cavities.

Table 3.
Roughness of the surface results for the pin and disc after friction

Studied alloy	Ra	Rz	Rt
Pin - 100◦C	1.68	9.24	10.23
Disc - 100◦C	1.02	6.35	10.69
Pin - 125◦C	1.57	9.30	9.98
Disc - 125◦C	0.99	6.21	10.63
Pin - 150◦C	1.55	9.14	10.01

Based on the data presented in Table 3 and Figure 10, the parameters of the surface profile of the tested material are not clear. This applies to both the pin and the disc. In the case of the tested material (pin), the highest value of the Ra parameter was at a temperature of 100ºC and was 1.68. The lowest value was obtained at a temperature of 150ºC and it was 1.55. The differences, however, were illusory and were only 0.3 between all the samples tested. In the case of the Rz and Rt parameters, the obtained results were exactly the same as for the Ra parameter. The highest values of the parameters were obtained for the highest for a temperature of 100ºC and the lowest for a temperature of 150ºC. The analysis also showed that on the surface of the pin the maximum indentation was obtained for a temperature of 100ºC and was almost 9 µm.

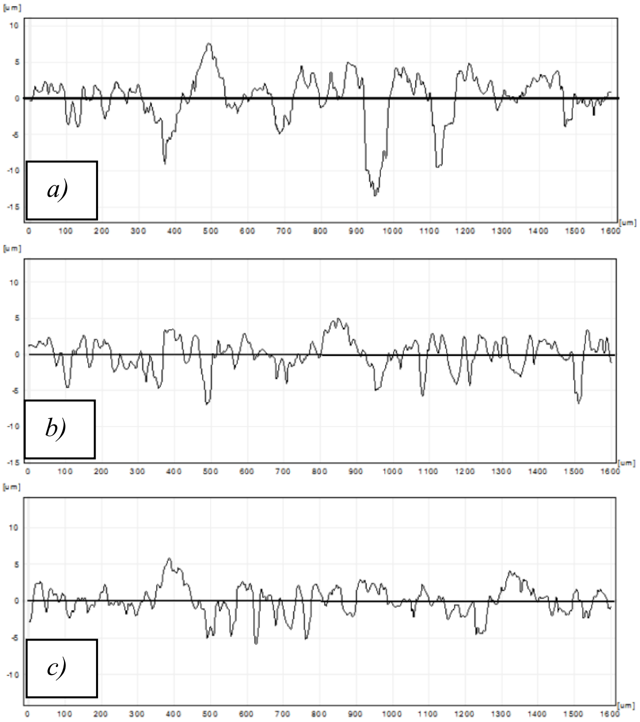

Fig. 10. Surface profile of the pin (A390.0) alloy at temperature: a) 100°C, b) 125°C, c) 150°C

5. Conclusions

Continuous technological changes, construction of combustion chains, driven by the drive to reduce fuel consumption, improve performance or reduce weight, constantly search for new materials or an attempt to use existing materials. The development of new materials entails the need to perform costly simulations as well as subsequent mechanical tests that will give an answer to the usefulness of the material. In addition, it is necessary to develop production technologies, repeatedly modify existing production line to a new type of material which again entails costs. In addition, it is necessary to develop technology for the disposal of new materials, which from now leads to an increase in the cost of new materials. These considerations mean that, at this time, it does not seek to develop completely new materials and attempts to modify existing or attempts to apply existing materials to new design solutions.

The introduction of new technical solutions to spark-ignition (gasoline) engines, such as: direct injection and a turbocharger, with a simultaneous reduction in their size, resulted in a change in the load characteristics that occur during piston operation. This forced the necessity to verify whether the materials used so far meet these exorbitant values. In particular, it is important to check the operation of the material at elevated temperatures. The tests carried out for the A390.0 alloy (modified with CuP - phosphorus) without additional modifications and in the standard production process show that this alloy does not meet the requirements. The obtained value of the friction coefficient for all tested temperatures, i.e. 100, 125 and 150ºC, was high and amounted to 0.34 and 0.33, respectively. In addition, the study of the surface profile indicated significant losses in the tested material, which disqualifies it from being used in modern engines. Therefore, it is necessary to verify whether the application of additional improvements, e.g. increasing the alloying elements (copper) or changes in the production technology, e.g. increased cooling speed, enable the further use of this material.

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