Journal of the Balkan Tribological Association *Vol. 26, No 4, 637–652 (2020)*

Fundamentals of friction and wear

EFFECTS OF NANOMODIFIERS ON THE WEAR RESISTANCE OF ALUMINUM-SILICON ALLOY ALSI18 IN TRIBOSYSTEMS IN CASE OF REVERSIVE FRICTION AND LUBRICATION

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ABSTRACT

The paper represents comparative tribological studies of a hypereutectic aluminum-silicon alloy AlSi18 without any modifiers and with modifiers – a standard P modifier, nanomodifiers SiC and ND and combinations of them – in a mode of reversive friction and lubrication. Results, concerning the mass wear, wear intensity and wear resistance when using two types of oil for lubrication – engine oil 15W40 and engine oil 15W40 with addition of 9% oil-soluble metal-plating graft AMP9V, have been obtained. Comparative analysis has been drawn, of the relationship between the wear resistance of the individual samples, and of the tribosystem as a whole, with the hardness, the microstructure of the samples and the influence of the graft presence in the oil.

Keywords: tribology, wear resistance, aluminum-silicon alloys, nanomodifiers, friction lubrication.

AIMS AND BACKGROUND

Increasing industrial capacity brings new high demands on the quality and life cycle of modern machinery and equipment. They are associated with the development of new materials with reduced weight, high mechanical and tribological

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properties[1–10]. Aluminum alloys and composites with aluminum matrix are relatively new materials and have a number of good features such as low density, good thermal conductivity and corrosion resistance, relatively low production cost and good recycling capability. These qualities make them unique for applications in the aviation, aerospace, military and automotive industries. They are used for the production of engine blocks, cylindrical sheaths, crankshafts, camshafts, cardan shafts, helicopter blades, as well as for the production of brake discs and drums of cars and trains[11–23].

The improvement of the mechanical and tribological properties of aluminum composites is accomplished by the addition of suitable modifiers, of which the most commonly used are carbides, borides, nitrates and oxides, i. e. Al_2O_3, SiC, TiC, TiO_2, B_4C, TiB_2, WC and others. The choice of the type, size and amount of additives depends on the manufacturing process, the conditions of operation and on the practical application of the composite materials. In recent years, there has been a trend of using nanoscale modifiers of diamond, silicon carbide, borides, etc.[24–31]

Nanomodifiers are ultrafine nanopowders with a particle size of 4–100 nm and high melting point (~2273–3273 K depending on the composition), which are obtained by self-propagating high-temperature synthesis (SHS)[25] or by plasma-chemical synthesis (PCB) – for the preparation of nitrides, carbides, oxides, oxycarbides, etc.[25–27], as well as by means of detonation technology, for the production of nanodiamonds (ND)[28]. Most of the existing studies have been performed on sub-eutectic aluminum-silicon alloys, eutectic aluminum-silicon alloys, as well as on certain grades of cast iron and steel[29–31].

The aim of this work is to conduct a comparative study of the effect of three types of modifiers (standard P phosphorus, ND nanodiamond and SiC nanosilicon carbide (and combinations of them) on the microstructure, mechanical properties and wear properties of AlSi18 aluminum-silicon alloy in tribosystems with reversive fiction and lubrication. Two types of engine oil are used: only 15W40; and the same oil with the addition of a metal plating additive AMP9V.

MATERIALS

DESCRIPTION

Six samples of AlSi18 aluminum-silicon alloy with no modifier and with three types of modifiers, individually and in combinations were examined as it follows: classical (P) modifier introduced into the melt by CuP10 ligature; nanomodifiers SiC and ND nanodiamond at a concentration of 0,1% by weight; a combination of a classical modifier P and a nanomodifier ND; and a combination of a classical modifier P and a nanomodifier SiC. The chemical composition of the hypereutectic aluminum-silicon alloy AlSi18 is listed in Table 1.

Table 1 Chemical composition of alloy AlSi18, wt.%

Si	Fe	Cu	Mn	Mg	Cr	Ni	Al
17.55	0.120	0.025	0.047	0.001	0.001	0.005	Balance

All the experiments were carried out under the same metallurgical conditions: the melting of the alloy was carried out in an electrical resistance laboratory furnace with a graphite crucible under a layer of refining flux in an amount of 0.5 w% from the amount of the charge material; the degassing of the alloy was carried out at 760°C by purging with argon for 3min.; the modification of the AlSi18 alloy by a standard modifier P and nanomodifiers SiC and ND was carried out at 760°C. The nanomodifiers were introduced near the bottom of the crucible and then mechanically shaken for 3 min at a low number of revolutions per minute (120–130 min^{-1}), aiming at an uniform dispersion of the nanomodifier particles throughout the volume of the melt. When combining a standard P and a nanomodifier, a characteristic feature is that the standard modifier is first introduced into the melt, then the alloy is degassed and the nanomodifier is introduced immediately before pouring. Sample bodies were cast in all the experiments, from which samples for mechanical testing, microstructural analysis and tribological testing were made. Metal equipment at 210°C temperature was used for the casting of the sample bodies.

MECHANICAL CHARACTERISTICS

To determine the mechanical performance of the AlSi18 aluminum-silicon alloy under study, standard short test samples are fabricated and tested on a Zwick/Roell Z 250 tensile tester for measuring the tensile strength Rm and the relative elongation A_5. Metallographic sections are made for a microstructural analysis. Samples of equal size and contact surface roughness are prepared for tribological testing. The tests are carried out under the same friction modes (the same material of the counterbody, normal loading, sliding speed, friction path (time), ambient temperature, lubricant). The results from the mechanical tests of the materials are shown in Table 2.

Table 2. Results from the mechanical tests of AlSi18 alloy without and with a modifier

Sample	Alloy	Rm/Mpa	Re/ Mpa	A_5 /%	HB2,5/62,5/30
1	AlSi18-ND	130	85	1.5	61
2	AlSi18-SiC	82		0.8	65
3	AlSi18-P	128		1.6	64
4	AlSi18-ND + P	116		1.4	66
5	AlSi18-SiC+ P	133		1.2	69
6	AlSi18	108		1.4	65

MICROSTRUCTURAL ANALYSIS

Metallographic sections are made for the microstructure examination. In the microstructural analysis, the arbitrary average diameter of the primary silicon crystals and the sizes of the silicon crystals in the eutectic composition of the AlSi18 alloy, both unmodified and modified with the described modifiers and combinations of them, were.

Table 3. Results from a microstructural analysis of AlSi18 alloy

Sample	Alloy	Arbitrary average diameter of the primary Si crystals D, µm	Size of the Si crystals in the eutectic composition, µm
1	AlSi18-ND	54	15-16
2	AlSi18-SiC	-	4-5
3	AlSi18-P	55.7	115-135
4	AlSi18-ND + P	60	17-18
5	AlSi18-SiC+ P	45.18	57-59
6	AlSi18	92.4	250-260

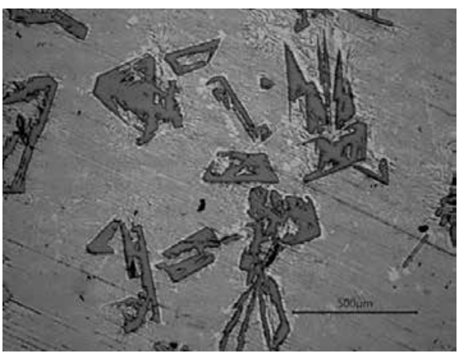


Fig. 1. Unmodified Si crystals

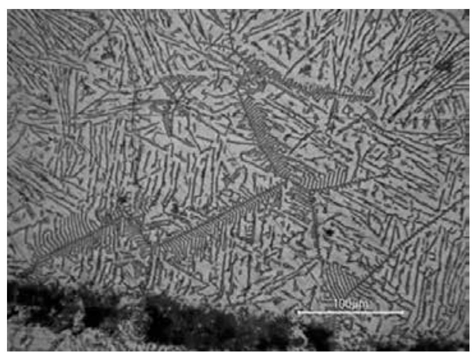


Fig. 2. Unmodified eutectic of AlSi18

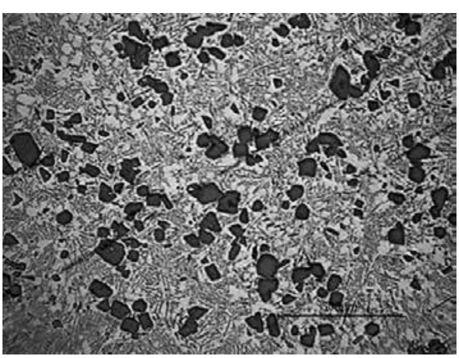


Fig. 3. Modified Si crystals

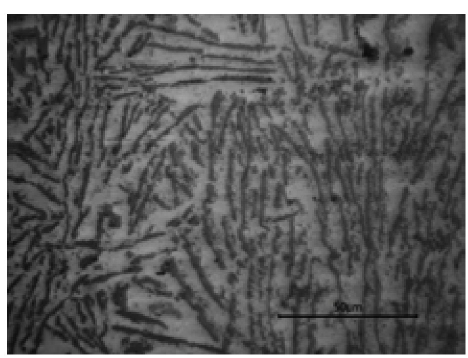


Fig. 4. Modified eutectic of AlSi18

Figure 1 shows unmodified primary silicon crystals in the structure of the AlSi18 alloy, and Figure 2 shows unmodified eutectic matrix of the AlSi18 alloy. Figure 3 shows modified crystals of primary silicon and Figure 4 shows modified silicon crystals in the eutectic composition of an AlSi18 alloy.

DEVICE AND METHODOLOGY

The wear of the contact system (tribosystem) is investigated in a mode of boundary lubrication at a reverse reciprocating motion using the RT16 tribo-tester presented schematically in Fig. 5. The contact is realized between a vertical sample 10 and a horizontal counterbody 9. The counterbody 9 is secured in the carriage 8, which performs reciprocating motion. The torque from the motor 1 is transmitted through a clutch 2 to a worm gear reducer 3. Disk 5 with a crank mechanism attached to it, is mounted to the output shaft 4 of the worm gear reducer 3. To the connecting rod 6 is attached by hinges the trolley 7, which transmits the reciprocating motion to the carriage 8 with the counterbody 9 mounted on it (Fig. 5). The trolley, the hinge joint and the cylindrical shape of the guide rod provide resistance to the two-way movement of the carriage by self-adjusting the samples and, accordingly, by reducing the friction and vibration in the other contacts of the device.

The sample 10 is cylindrical in shape with a contact diameter of 3 mm. The counterbody 9 is a plate of dimensions: 107 mm long, 43 mm wide and 2 mm thick. The normal load on the sample 10 is set by a lever system, which includes a dynamometric beam 11 with a leverage ratio of 1: 3.2 and reference weights 12. The maximal load of the device is 160 N. The vertical displacement indicator 13 allows measurement of the relative change in the height of the sample during the friction process, i. e. its height wear to the nearest 1 μm. Lubrication is carried out by supplying oil near the contact area of the drip lubrication system 14 at a rate of 40 drops/minute. The kinematic parameters of the device are: frequency 28

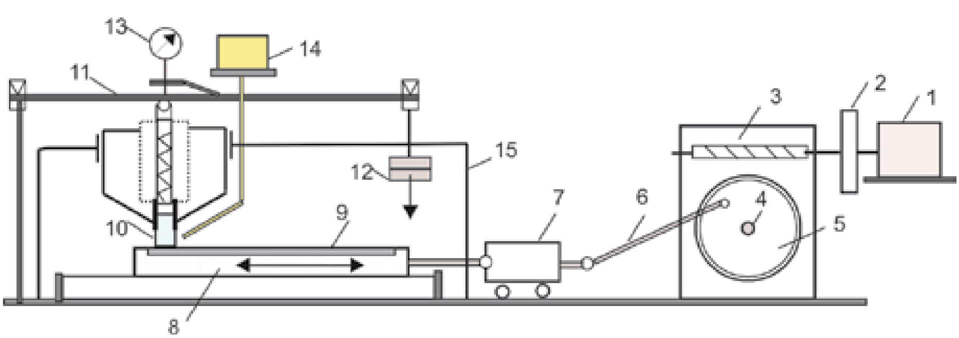


Fig. 5. Device RT16 for studying the wear during reciprocating motion

Table 4. Composition and hardness of samples of steel ASt3 (BDS 5292-61)

Element	C	Si	Mn	S	P	Cr	Fe
wt. %	0.18	0.25	0.52	0.02	0.03	0.28	rest
Hardness	$HB.10^{-1}$ = 131 MPa						

cycles/min; friction path S = 0.14x28 = 3.92 m/min at a sliding speed of 6.8 cm/s. The plate 9 is made of AC3 steel (BDS 5292-61) having a chemical composition and hardness shown in Table 4.

The methodology of the study consists in measuring the mass wear of the tribosystem elements – samples and counterbody – after a certain path/time of friction under specified constant conditions – load, sliding speed, friction path/ friction time, and type of oil. Then the wear characteristics are calculated - mass wear, wear intensity and wear resistance.

The procedure involves the following sequential operations: preparation of 6 identical samples and 6 identical counterbodies having the same contact surface roughness (the roughness is measured with a "TESA Rugosurf 10-10G" profilometer); measuring the mass m_0 of the sample and the counterbody using an electronic scale WPS 180/C/2 to the nearest 0,1mg. Before each measurement the sample is cleaned of mechanical and organic impurities and dried in a drying chamber for 15 minutes at a temperature of 150°C in order to evaporate the oily molecules remained in the pores of the material. The sample 10 is fixed rigidly in a holder and the plate 9 is mounted on the carriage 8. A certain normal load is set by the loads 12 and the tank is filled with the lubricant under study. The motor 1 is switched on and a certain friction path is realized, while reading the friction time interval by a chronometer with 1 s precision. The samples are removed, cleaned from the oil by means of a degreaser, dried in a drying chamber and their mass measured again on the same weighing scales.

The following wear characteristics are calculated:

Mass wear *m* as the difference between the mass of the sample before friction and after a specified friction path *S* = const, i. e.

$$\boldsymbol{m = m_0 - m_i} \qquad (1)$$

Mass wear intensity, represented as the ratio between the mass wear per unit of friction path *S* = 1 m and load *P* = 1 N:

$$i_m = \frac{m}{S.P} \qquad (2)$$

Mass wear resistance, the reciprocal value of the wear rate, ie.

$$I_m = \frac{1}{i_m} = \frac{S.P}{m} \qquad (3)$$

Table 5. Experiment parameters

Parameter	Value
Normal load	20 N
Nominal contact area	7.07 mm^2
Nominal contact pressure	2.83x10^4 N/cm^2
Sliding speed	6.8 cm/s
Friction time	15 min
Friction path	58.8 m
Ambient temperature	27^{o}C

All the experiments were performed under the same friction conditions as indicated in Table 5.

EXPERIMENTAL RESULTS

LUBRICATION WITH OIL 15W40

Tables 6 and 7 summarize the results for the mass wear, wear intensity, and wear resistance of each sample, counterbody, or a whole tribosystem as determined by the methodology described above.

Figures 6, 7 and 8 show diagrams of the mass wear of each sample and counterbody, as well as of the tribosystem as a whole, in case of boundary lubrication with 15W40 oil.

Figures 9, 10 and 11 show diagrams of the wear resistance of the elements and the tribosystems for boundary lubrication with 15W40 oil.

Table 6. Mass loss of the elements and the tribosystem when lubricated with oil 15W40.

No	Elements of tribosystem	Mass of elements before wear, g	Mass of elements after wear, g	Mass loss of elements and tribosystem, mg	
1	AlSi18+ND	2.7592	2.7583	0.9	21.9
	Counterbody	34.7507	34.7297	21.0	
2	AlSi18+SiC	2.7421	2.7402	1.9	5.5
	Counterbody	34.7297	34.7261	3.6	
3	AlSi18+P	2.6367	2.6357	1.0	13.9
	Counterbody	33.2337	33.2208	12.9	
4	AlSi18+ND+P	2.7017	2.7007	1.0	4.2
	Counterbody	33.2208	33.2176	3.2	
5	AlSi18+SiC+P	2.7002	2.6998	0.4	1.9
	Counterbody	35.0506	35.0491	1.5	
6	AlSi18	2.7482	2.7474	0.8	2.9
	Counterbody	35.0527	35.0506	2.1	

Table 7. Mass loss, wear rate and wear resistance of the elements and the tribosystem when lubricated with oil 15W40

Elements of tribosystem	Mass loss, mg	Wear rate, mg/m.N	Wear resistance m.N/mg	For tribosystem		
				mg	mg/mN	mN/mg
AlSi18+ND	0.9	0.72×10^{-4}	1.4×10^4	21.9	17.5×10^{-4}	0.06×10^4
Counterbody	21.0	16.8×10^{-4}	0.06×10^4			
AlSi18+SiC	1.9	1.5×10^{-4}	0.7×10^4	5.5	4.4×10^{-4}	0.23×10^4
Counterbody	3.6	2.9×10^{-4}	0.34×10^4			
AlSi18+P	1.0	0.8×10^{-4}	1.3×10^4	13.9	11.1×10^{-4}	0.09×10^4
Counterbody	12.9	10.3×10^{-4}	0.1×10^4			
AlSi18+ND+P	1.0	0.8×10^{-4}	1.3×10^4	4.2	3.4×10^{-4}	0.29×10^4
Counterbody	3.2	2.6×10^{-4}	0.4×10^4			
AlSi18+SiC+P	0.4	0.32×10^{-4}	3.2×10^4	1.9	1.5×10^{-4}	0.66×10^4
Counterbody	1.5	1.2×10^{-4}	0.8×10^4			
AlSi18	0.8	0.64×10^{-4}	1.6×10^4	2.9	2.3×10^{-4}	0.43×10^4
Counterbody	2.1	1.7×10^{-4}	0.6×10^4			

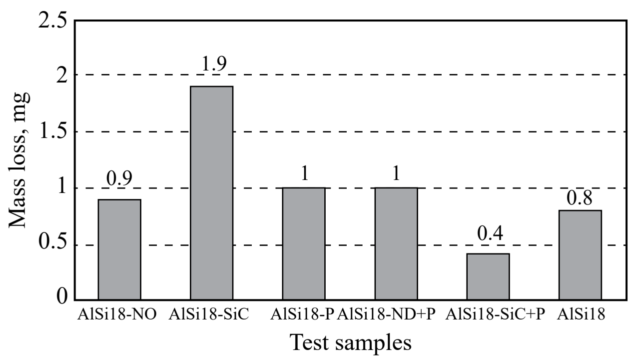


Fig. 6. Diagram of the mass loss of the test samples when lubricated with oil 15W40

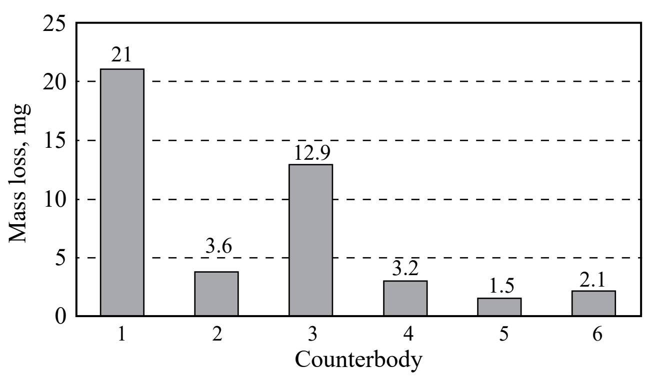


Fig. 7. Diagram of the mass loss of the counterbody when lubricated with oil 15W40

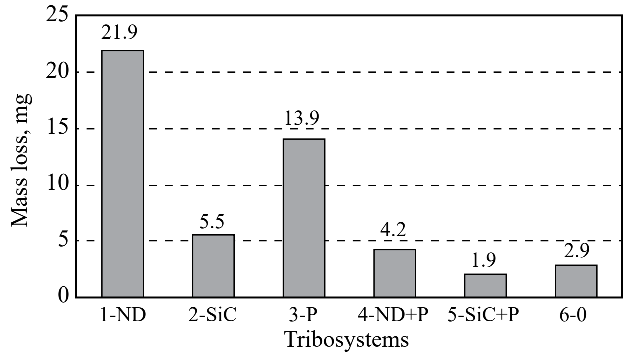


Fig. 8. Diagram of the mass loss of tribosystems when lubricated with oil 15W40

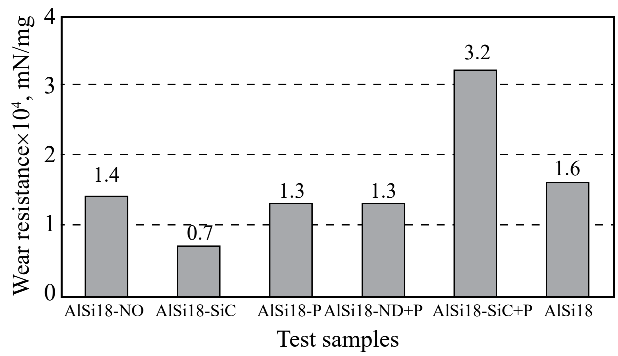


Fig. 9. Diagram of the wear resistance of test samples when lubricated with oil 15W40

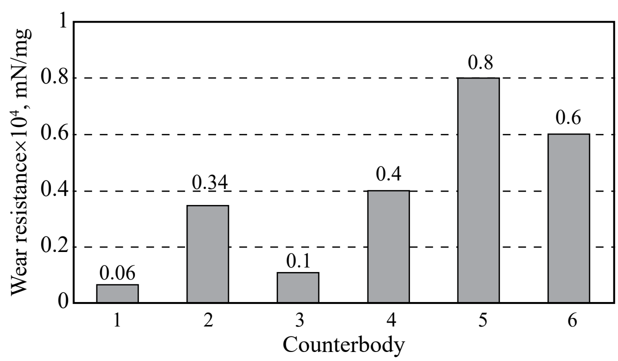


Fig. 10. Diagram of the wear resistance of a counterbody when lubricated with oil 15W40

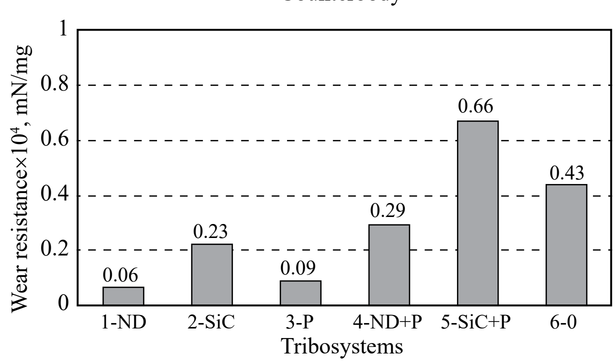


Fig. 11. Diagram of the wear resistance of tribosystems when lubricated with oil 15W40

LUBRICATION WITH OIL 15W40 WITH A METAL PLATING ADDITIVE AMP9V

The results about the tribosystem wear resistance, presented in Figure 11 indicate that the 1-ND and 3-P tribosystems have the lowest wear resistance. These tribosystems were tested under lubrication conditions with the same 15W40 oil, but a 9% AMP9V metal plating additive was added to the oil. The AMP9V graft is copper-based and oil-soluble. The aim is to investigate the effect of the presence of the graft in the lubricant.

Tables 8 and 9 summarize the results obtained for the mass wear, the wear intensity, and the wear resistance of the two tribological systems AlSi18-ND and AlSi18-P when lubricated with 15W40 oil, in which an AMP9V metal plating has been added.

The results, given in Tables 8 and 9, are presented in the form of diagrams in Figures 12, 13 and 14.

Table 8. Mass loss of the elements and the tribosystem when lubricated with oil 15W40 with a metal plating additive AMP9V in it for samples No 1 (AlSi18-ND) and No 3 (AlSi18-P)

No	Elements and tribosystem	Mass before wear, g	Mass after wear, g	Mass loss, mg	
1	AlSi18+ND	2.7583	2.7576	0.7	8.8
	Counterbody	35.7535	35.7454	8.1	
3	AlSi18+P	2.6357	2.6349	0.8	5.8
	Counterbody	35.7454	35.7404	5.0	

Table 9. Mass loss, wear rate and wear resistance of the elements and the tribosystem when lubricated with oil 15W40 with a metal plating additive AMP9V in it for samples No 1 (AlSi18-ND) and No 3 (AlSi18-P)

Tribosystems	Mass loss, mg		Wear rate, mg/mN		Wear resistance, mN/mg			
	15W40	15W40 +AMP9V	15W40	15W40 +AMP9V	15W40	15W40 +AMP9V	For tribosystem 15W40	For tribosystem 15W40 +AMP9V
AlSi18+ND	0.9	0.7	0.7×10^{-4}	0.5×10^{-4}	1.4×10^{4}	1.78×10^{4}	1.5×10^{4}	1.95×10^{4}
Counterbody	21	8.1	16.8×10^{-4}	6.5×10^{-4}	0.06×10^{4}	0.15×10^{4}		
AlSi18+P	1.0	0.8	0.8×10^{-4}	0.6×10^{-4}	1.3×10^{4}	1.56×10^{4}	1.3×10^{4}	1.81×10^{4}
Counterbody	12.9	5.0	10.3×10^{-4}	4.0×10^{-4}	$0.\times10^{4}$	0.25×10^{4}		

Fig. 12. Diagram of the mass loss of the test samples AlSi18-ND and AlSi18-ND when lubricated without and with a metal plating additive AMP9V in the oil

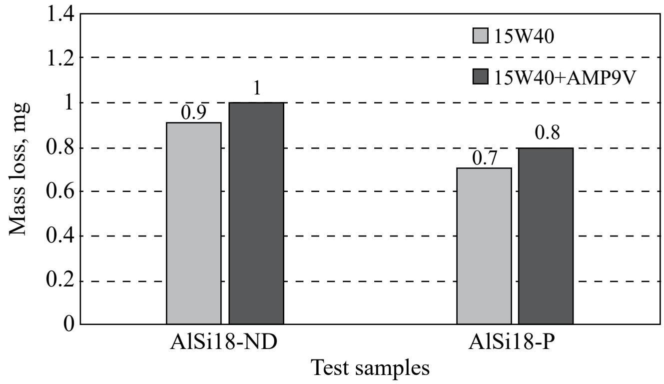
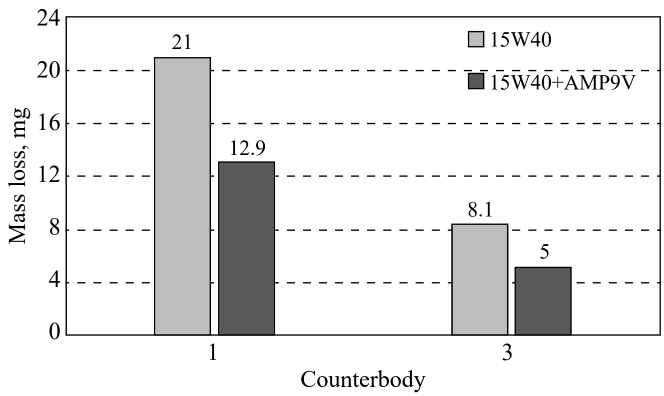
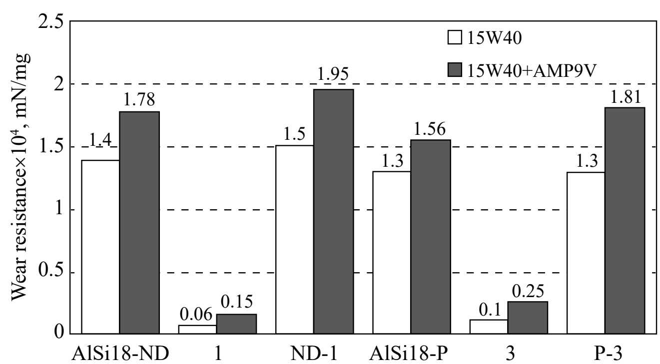


Fig. 13. Diagram of the mass loss of the counterbody in tribosystems №1 and №3 when lubricated without and with a metal plating additive AMP9V in the oil



Fig, 14. Diagram of the wear resistance of a sample, a counterbody and tribosystems №1 and №3 when lubricated without and with a metal plating additive AMP9V in the oil



The relative wear resistance of the samples, counterbodies and tribosystems under the action of an AMP9V metal plating graft in the oil is the ratio of the test samples, counterbody and tribosystem wear resistance, I_a(15W40+AMP9V) when lubricated by oil with a graft, to the wear resistance of the same samples, counterbody and tribosystem when lubricated by oil without a graft I_a(15W40) I_s

(15W40), obtained under the same friction modes, i.e.,

$$R = \frac{I(15W40 + AMP9V)}{I(15W40)} \tag{4}$$

Table 10 shows the results for the relative wear resistance R of each sample, counterbody and tribosystem. The results are presented in the form of a diagram in Fig. 15.

Table 10. Relative wear resistance for elements of tribosystems and for tribosystems AlSi18+ND and AlSi18+P in case of lubrication with oil 15W40 without and with a metal plating additive AMP09V

Tribosystems		Wear resistance and relative wear resistance R for elements of tribosystems			Wear resistance and relative wear resistance R for tribosystems		
		15W40	15W40+AMP9V	R	15W40	15W40+AMP9V	R
1	AlSi18+ND	1.4×10^4	1.78×10^4	R_s=1.3	1.5×10^4	1.95×10^4	R_1=1.3
	Counterbody	0.06×10^4	0.15×10^4	R_c=2.5			
3	AlSi18+P	1.3×10^4	1.56×10^4	R_s=1.2	1.3×10^4	1.81×10^4	R_3=1.4
	Counterbody	0.1×10^4	0.25×10^4	R_c=2.5			

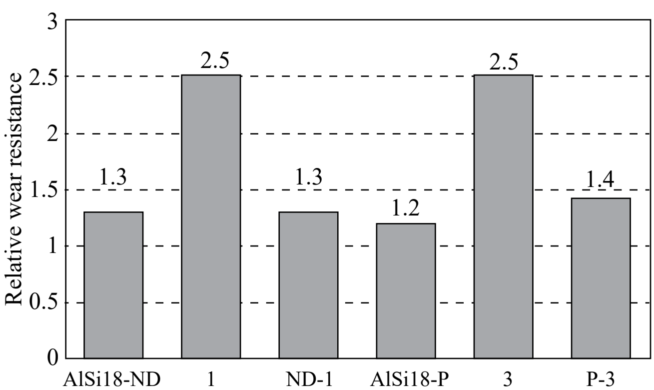


Fig. 15. Diagram of the relative wear resistance of a sample, a counterbody and tribosystems No 1 and No 3 when lubricated without and with a metal plating additive AMP9V

ANALYSIS OF THE RESULTS AND CONCLUSIONS

The effect of the different types of modifiers and the combinations of them on the structure and properties of the hypereutectic aluminum-silicon alloy AlSi18 has been discussed in detail in other published materials of ours [32, 33].

When lubricating with an engine oil in case of a reverse motion, the results show that AlSi18 alloy samples modified by a standard modifier P and a nanomodifier ND have comparable wear resistance that is insignificantly lower than that of the unmodified alloy. In both cases, the wear resistance of the counterbody is significantly lower than that of the unmodified alloy. The increased wear of the steel counterbody is due to both the modified crystals of the primary silicon, on the one hand, and to the silicon crystals in the eutectic composition of the AlSi18 alloy under study, on the other hand.

The use of an AMP9V metal plating additive in the oil leads to an increase in the wear resistance of both the AlSi18 alloy samples and the steel counterbody, compared to the wear resistance of the same tribosystem when lubricated without the AMP9V metal plating additive.

When studying a tribosystem consisting of a sample of hypereutectic aluminum-silicon alloy AlSi18, modified by a nanomodifier SiC and a steel counterbody, the obtained results show a decrease in the wear resistance of both the sample and the counterbody against the wear resistance of the tribosystem, consisting of an unmodified sample and a steel counterbody. The mass wear of the steel counterbody is due to the significantly refined silicon crystals in the eutectic composition of the studied AlSi18 alloy. The mass wear of the AlSi18 alloy sample with a SiC nanomodifier is due to the removal of the unmodified primary silicon crystals (irregularly sized and large in size) from the eutectic matrix during friction. These crystals, as wear products, act as abrasive particles in the contact and lead to an increase in wear intensity.

In the study of a tribosystem consisting of a sample of the hypereutectic aluminum-silicon AlSi18 alloy modified with a combination of a standard P modifier and a nanomodifier ND, plus a steel counterbody, the results showed an insignificant decrease in the wear resistance of both the sample and the counterbody, compared to a tribosystem with unmodified alloy sample and a steel counterbody. The increased wear of the steel counterbody is due both to the refined primary silicon crystals, and to the refined silicon crystals in the eutectic composition of the AlSi18 alloy under study.

The mass wear of the steel counterbody in a tribosystem, in which the AlSi18 alloy under study is modified with only an ND nanomodifier, is times greater than the mass wear of the counterbody in the tribological system, containing AlSi18 alloy modified by a combination of P and ND modifiers. It is evident that the wear resistance of the counterbody is influenced not only by the size and shape of the primary silicon crystals and the silicon crystals in the eutectic composition of the alloy, but also by the formation of new phases (phosphides along the grain boundaries) that have antifriction properties and favor the reduction of friction in the contact area of the tribosystem.

When studying tribosystems, containing a sample of the hypereutectic aluminum-silicon alloy AlSi18, modified by a combination of a P modifier and a nanomodifier SiC, plus a steel counterbody, the results show an increase in the wear resistance of both the sample and the counterbody with respect to that of a tribosystem, comprising an unmodified sample and a steel counterbody. The results, concerning the wear resistance of such a tribosystem are the best compared to all other conducted experiments. The increased wear resistance of the sample is due to the refined primary silicon crystals in the structure of the studied alloy. Not only the size and shape of the primary silicon crystals and the silicon crystals in the eutectic composition of the alloy have influence on the wear resistance of the counterbody, but also the formation of phosphides along the grain boundaries, which have antifriction properties and contribute to reduction of friction in the contact area of the tribosystem.

The results from all conducted experiments with a hypereutectic aluminum-silicon AlSi18 alloy showed that in case of modification by a combination of a standard modifier (P) and a nanomodifier (SiC), the refinement of the primary silicon crystals was the largest and the highest values of tensile strength and hardness of the alloy were measured, as well as the highest wear resistance of the tribological system when tested for wear resistance by reversive lubrication and friction.

When modifying a hypereutectic aluminum-silicon AlSi18 alloy by a nanodiamond modifier (ND), the size of the primary silicon crystals and of the silicon crystals in the eutectic composition is refined. The mechanical properties of the tested AlSi18 alloy are enhanced. The test results, concerning a tribosystem, containing a sample of the alloy under study and a steel counterbody show an insignificant mass loss of the sample and a large mass wear of the steel counterbody. The obtained results are a prerequisite for investigating the wear resistance of the so modified alloy in a tribosystem with a counterbody of the same or another alloy with a suitable structure that would form a more durable tribological system.

ACKNOWLEDGEMENTS

This study and the results are related to the implementation on tasks: contract: ДН 07/28 'Research and creation of new wear-resistant coatings using composites and nanomaterials', funded by the National Science Fund at the Ministry of Education and Science, Bulgaria.

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

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Received 8 June 2020
Revised 29 August 2020