Journal of the Balkan Tribological Association *Vol. 26, No 4, 661–673* (*2020*)

Abrasive wear – tribotechnics and tribomechanics

ABRASIVE WEAR OF A HYPEREUTECTIC ALLOY ALSI18, MODIFIED BY DIFFERENT MODIFIERS

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ABSTRACT

This paper represents comparative tribological studies of a hypereutectic aluminum-silicon alloy AlSi18, without or with different types of modifiers – a standard modifier P, nanomodifiers SiC and diamond ND, as well as combinations of them – under the mode of dry friction on a surface with rigidly fixed abrasive particles. Results have been obtained concerning the wear characteristics – mass wear, wear intensity and wear resistance for different number of friction cycles. Results about the microstructure and the mechanical characteristics of the studied samples have been represented.

Keywords: tribology, abrasive wear, wear resistance, hypereutectic aluminium-silicon alloy.

AIMS AND BACKGROUND

The main tasks of tribology are related to increasing energy efficiency and reducing the material consumption of machines and mechanisms in various fields of industry. It is known that 30% of the world's energy losses are due to friction in the contact joints. Wear is the cause of over 90% of machine failures and the cost of spare parts materials, human resources to repair and maintain their operation.

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These issues are directly related to the problems of natural resources depletion and environment pollution by solid, liquid, gaseous, acoustic, thermal emissions related to the tribo-systems' functioning[1–3].

One of the trends in tribology and tribo-technology related to solving wear problems is to develop new and/or to enhance the functional properties of the conventional tribological materials. In the last 10 years, there has been a great deal of interest in improving the tribological properties of aluminum alloys and composites for application in various fields of the industry – mechanical engineering, transportation, space and military techniques[4–7]. The advances in nanotechnology open up new possibilities for obtaining materials with unique mechanical and tribological characteristics. Modification of aluminum alloys with nanoparticles of different nature – diamond, silicon carbide, boron, tungsten and other nitrides, etc. lead to changes in the tribological characteristics, though ambiguously[8–13].

Wear intensity in tribosystems depends not only on the composition, structure and physical and mechanical properties of the contacting surface layers, but also on a number of other factors – loading, sliding speeds, composition and properties of the lubricant, on the wear products, the presence of vibrations, strikes, etc. Most often, these factors have a synergistic effect with the dominant action of one or two wear mechanisms. Numerous experimental studies in tribology have refuted the notion that an increase in the mechanical properties of materials necessarily leads to an increase in the wear resistance of tribosystems.

The authors of this work conducted systematic tribological studies of the AlSi18 hypereutectic aluminum-silicon alloy without and with various modifiers – a standard modifier P, nanomodifiers SiC and ND diamond, as well as their combinations under different conditions and friction modes. In the present work, comparative results are represented for the wear and abrasion resistance of these alloys in the dry friction mode on a surface with rigidly fixed abrasive particles.

EXPERIMENTAL

Materials. Six samples of aluminum alloy without and with nanomodifiers were examined. The nanomodifiers have a particle size of 4-100 nm and a high melting point depending on their composition. The methods for their preparation are self-propagating high-temperature synthesis (SPS)[8] or plasma-chemical synthesis (PCS) for the preparation of nitrides, carbides, oxides, oxycarbides and the like[9,10]. The nano-modifier nanodiamond (ND) is obtained through detonation technology[9,10]. The designations and descriptions of the samples are represented in Table 1.

Table 1. Designation

Sample	Designation	Description
1	AlSi18-ND	AlSi18 with a nanomodifier nanodiamond (ND)
2	AlSi18-SiC	AlSi18 with a nanomodifier silicon carbide (SiC)
3	AlSi18-P	AlSi18 with a standard modifier (P) without nanomodifiers nanodiamond (ND) and silicon carbide (SiC)
4	AlSi18-ND+P	AlSi18 with a nanomodifier nanodiamond (ND) and a standard modifier (P)
5	AlSi18-SiC+P	AlSi18 with a nanomodifier silicon carbide (SiC) and a standard modifier (P)
6	AlSi18	AlSi18 without a nanomodifier

Wear abrasive test. The methodology for studying the characteristics of the abrasive wear consists in measuring the mass wear of the samples for a given friction path under a constant set dynamic mode and friction conditions – load, sliding speed, type of abrasive material, sample sizes. The mass of the samples before and after friction is measured by an electronic scale WPS 180/C/2 to the nearest 0.1 mg. Before each measurement, the sample is cleaned of mechanical and organic impurities and dried up with ethyl alcohol to prevent the electrostatic effects. Then the wear characteristics are calculated – wear rate, wear intensity, absolute and relative wear resistance.

Mass wear is calculated by the formula:

$$m = m_O - m_i \tag{1}$$

The mass-wear intensity is represented as the lost mass per unit of friction path, i.e.

$$i_m = \frac{m}{S} \tag{2}$$

The friction path is calculated to be $S = 2\pi R.N$, where R = 38.1 mm is the distance from the axis of rotation to the center of the contact area, and N is the number of friction cycles.

The wear resistance is the reciprocal value of the wear rate and is calculated by the formula

$$I_m = \frac{1}{i_m} = \frac{S}{m} \tag{3}$$

The abrasive wear during dry friction is examined by a laboratory device using a kinematic ‘Thumb-disk’ scheme at plane contact (Fig.1).

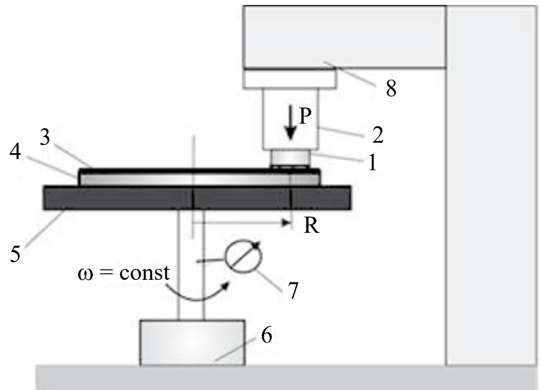

Fig. 1. Scheme tribotester 'Thumb-disk'

The test sample 1 is rigidly fixed in the holder 2 of the load head 8, so that the front surface of the sample contacts the abrasive surface 3, which is immovably fixed to the horizontal disk 4. The disk 4 is driven by the motor 6 and it rotates about its vertical central axis at an angular velocity ω = const. The normal load P is applied to the center of gravity of the contact area between the sample and the abrasive surface and it is secured by means of a lever system in the load head 8. The friction path/number of cycles/ is set by the number of revolutions by the revolution-counter 7. The samples have a cylindrical shape with a cross-section diameter of 8 mm and a height of 32 mm. The abrasive surface 3 is modeled by an impregnated corundum (E) of 9.0 hardness on the Mohs scale, which guarantees the requirement of the standard for at least 60% higher abrasive hardness than that of the surface layer of the test materials. All tests were performed under the same friction conditions as it is indicated in Table 2.

Table 2. Experiment parameters

Parameter	Value
Normal load	4,6 N
Nominal contact area	0.5×10^{-4} m^2
Nominal contact pressure	9.16 N/cm^2
Distance R	36 mm
Speed	212 min^{-1}
Sliding speed	15.5 cm/s
Friction time	15 min
Friction path	от 33 до 132 m
Abrasive surface	Corundum P 320
Ambient temperature	25.6°C

Table 3. Results from the mechanical tests of the alloy AlSi18 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

RESULTS AND DISCUSSION

Table 3 shows the results from the mechanical tests of the hypereutectic aluminum-silicon alloy AlSi18 – unmodified, modified by phosphorus, modified by nanomodifiers and modified by a combination of a standard modifier P and a nanomodifier ND, as well as a combination of a standard modifier P and a nanomodifier SiC.

The structure of the hypereutectic aluminum-silicon alloys is made up of crystals of primary silicon and eutectic. During the microstructural analysis, the arbitrary average diameter of the primary silicon crystals and the sizes of the silicon crystals in the eutectic composition of AlSi18 alloy (unmodified and modified with various types of modifiers and combinations of them) were measured. Table 4 shows the obtained results.

The primary silicon crystals in the structure of the unmodified AlSi18 alloy are different in shapes. Straight-walled polygons and well-shaped plates are observed, but irregularly shaped crystals predominate (Fig. 2). The arbitrary average diameter of the primary silicon crystals in the unmodified AlSi18 alloy is within the range 87.2-97.6 μm. The silicon crystals in the eutectic composition have dimensions reaching a length of 250-260 μm (Fig. 3).

Primary silicon crystals of a hypereutectic aluminum-silicon AlSi18 alloy, modified by phosphorus, differ in shape and size from those of the unmodified AlSi18 alloy (Fig. 4). The arbitrary average diameter of the primary silicon crys-

Table 4. 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. 2. Si crystals AlSi18

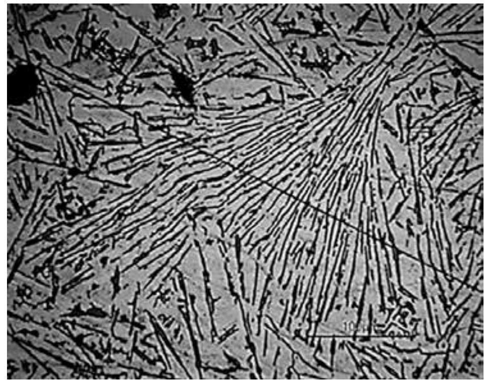

Fig. 3. Si crystals in the eutectic AlSi18

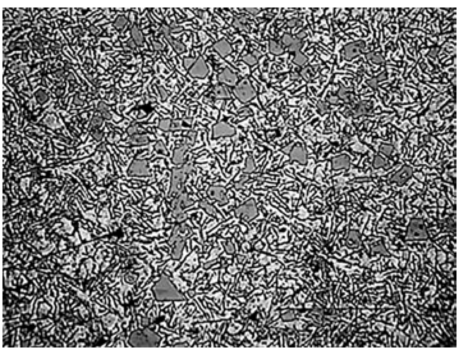

Fig. 4. SI crystals AlSi18+P

Fig. 5. Si crystals in the eutectic AlSi18+P

tals ranges from 52.1-59.2 μm. The silicon crystals in the eutectic composition of the phosphorus-modified hypereutectic aluminum-silicon AlSi18 alloy are also refined, measuring 115-135 μm in size (Fig. 5).

Primary silicon crystals in the structure of a hypereutectic aluminum-silicon AlSi18 alloy, modified by a nanomodifier SiC are of irregular star shape (Fig. 6) and therefore the arbitrary average diameter of the primary silicon crystals is not measured and calculated. In this case, the longest side of the crystal is measured, whose average size is about 250 μm. The silicon crystals in the eutectic composition of the hypereutectic aluminum-silicon AlSi18 alloy are highly refined and their length is not greater than 4–5 μm (Fig. 7).

In the structure of the hypereutectic aluminum-silicon alloy AlSi18, modified by a nanomodifier – nanodiamonds – primary silicon crystals in the form of polygons predominate. The arbitrary average diameter of the primary silicon crystals is 54 μm (Fig. 8). The silicon crystals in the eutectic composition are significantly refined. The amount and the average length of the eutectic plates (needles) is small; their average maximal length is about 15–16 μm (Fig. 9).

Fig. 6. Si crystals AlSi18+SiC

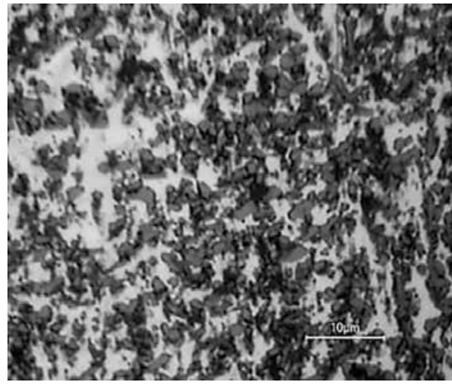

Fig. 7. Si crystals in the eutectic AlSi18+SiC

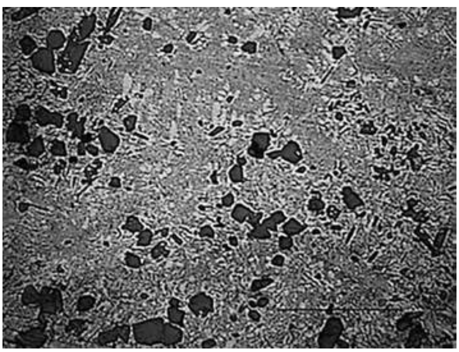

Fig. 8. Si crystals AlSi18+ND

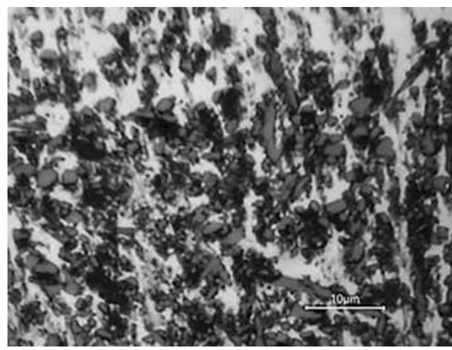

Fig. 9. Si crystals in the eutectic AlSi18+ND

The primary silicon crystals are refined by the modifying treatment of the hypereutectic AlSi18 aluminum-silicon alloy by a standard modifier (P) and nano-modifier (ND). The arbitrary average diameter of the primary silicon crystals is 60 µm (Fig. 10). The silicon crystals in the eutectic composition are also refined and their average maximal length is 17–18 µm (Fig. 11).

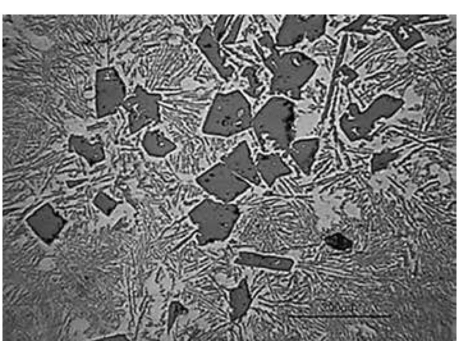

Fig. 10. Si crystals AlSi18+P+ND

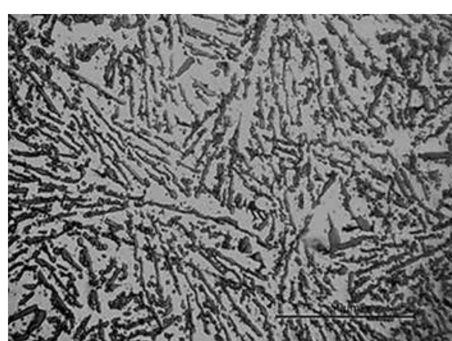

Fig. 11. Si crystals in the eutectic AlSi18+P+ND

The use of a standard modifier phosphorus P and a SiC nanomodifier to modify the hypereutectic aluminum-silicon alloy AlSi18 results in refinement of both the primary silicon crystals and the silicon crystals in the eutectic composition. The arbitrary average diameter of the primary silicon crystals in the AlSi18 alloy, modified by a nanomodifier (SiC) and a standard phosphorus modifier (P), is 45.18 μm (Fig. 12). The average maximal length of the silicon crystals in the eutectic composition is within the range of 57–59 μm (Fig. 13).

The described methodology and device give experimental results for the wear characteristics – mass wear, wear intensity and wear resistance for the tested materials over a number of cycles: N = 300, 600, 900 and 1200, corresponding to a friction path S = 33, 66, 99 and 132 m. The results are represented in Tables 5, 6 and 7 respectively.

Figures 14, 15, 17 and 18 show graphical dependencies of the change in mass wear, wear intensity and wear resistance on the friction path/friction time period, and Figures 16 and 19 show the wear resistance diagrams of the tested materials.

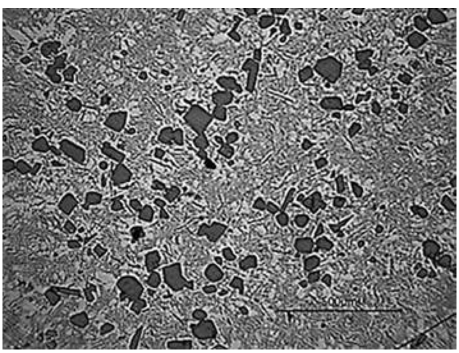

Fig. 12. Si crystals AlSi18+P+SiC

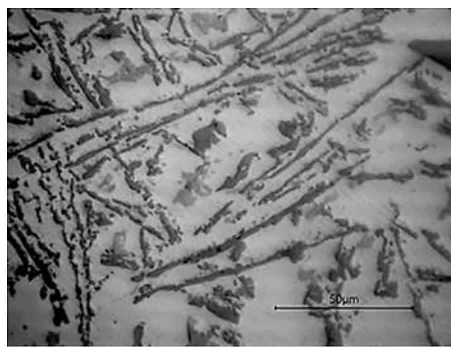

Fig. 13. Si crystals in the eutectic AlSi18+P+ND

Table 5. Abrasive wear of tested materials

Sample	Designation	Number of cycles (N)			
		300	600	900	1200
		Sliding distance, m			
		33	66	99	132
		Mass loss, mg			
1	AlSi18+ND	20.1	26.3	31.6	36.9
2	AlSi18+SiC	28.3	35.8	43.1	48.7
3	AlSi18+P	17.0	25.4	33.8	39.6
4	AlSi18+ND+P	19.1	26.5	34.0	37.9
5	AlSi18+SiC+P	15.1	21.6	26.9	31.6
6	AlSi18	17.2	23.2	28.7	32.7

Table 6. Abrasive wear rate of tested materials

Sample	Designation	Number of cycles (N)			
		300	600	900	1200
		Sliding distance, m			
		33	66	99	132
		Wear rate, mg/m			
1	AlSi18+ND	0.61	0.34	0.32	0.28
2	AlSi18+SiC	0.86	0.54	0.44	0.37
3	AlSi18+P	0.52	0.38	0.34	0.30
4	AlSi18+ND+P	0.58	0.40	0.34	0.29
5	AlSi18+SiC+P	0.46	0.33	0.27	0.24
6	AlSi18	0.52	0.35	0.29	0.25

Table 7. Wear resistance of tested materials

Sample	Designation	Number of cycles (N)			
		300	600	900	1200
		Sliding distance, m			
		33	66	99	132
		Wear resistance, m/mg			
1	AlSi18+ND	1.6	2.9	3.1	3.6
2	AlSi18+SiC	1.2	1.9	2.3	2.7
3	AlSi18+P	1.9	2.6	2.9	3.3
4	AlSi18+ND+P	1.7	2.5	2.9	3.4
5	AlSi18+SiC+P	2.2	3.0	3.7	4.2
6	AlSi18	1.9	2.8	3.4	4.0

Figure 20 presents a general diagram of all tested alloys modified by diamond nanoparticles (ND), silicon carbide (SiC) and a standard modifier (P) at a friction path of 132 m.

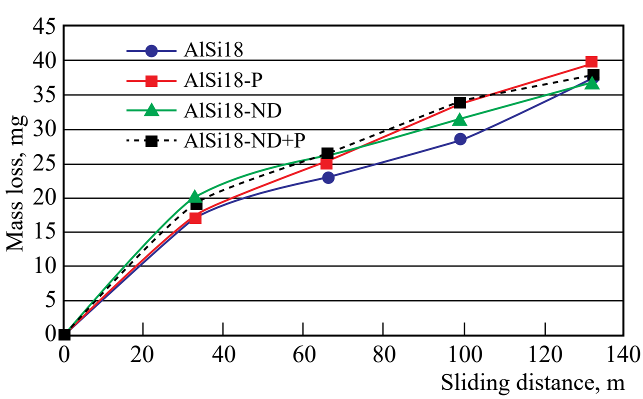

Fig. 14. Mass loss vs. sliding distance for AlSi18 with ND modifier and standard P modifier

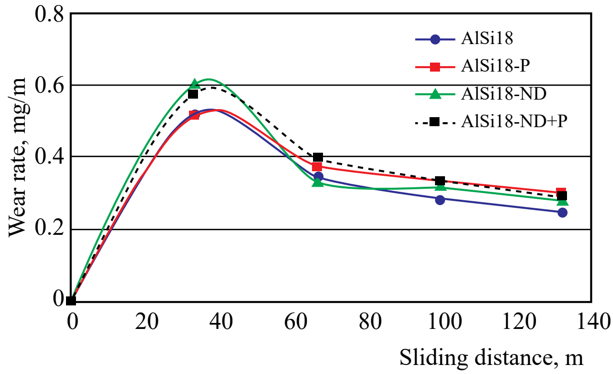

Fig. 15. Wear rate vs. sliding distance for AlSi18 with ND modifier and standard P modifier

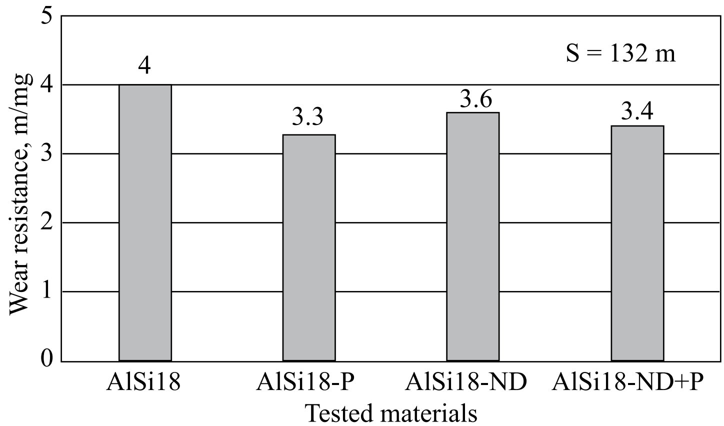

Fig. 16. Wear resistance diagram of a hypereutectic aluminum-silicon AlSi18 alloy modified by ND nanomodifier for a friction path S = 132 m

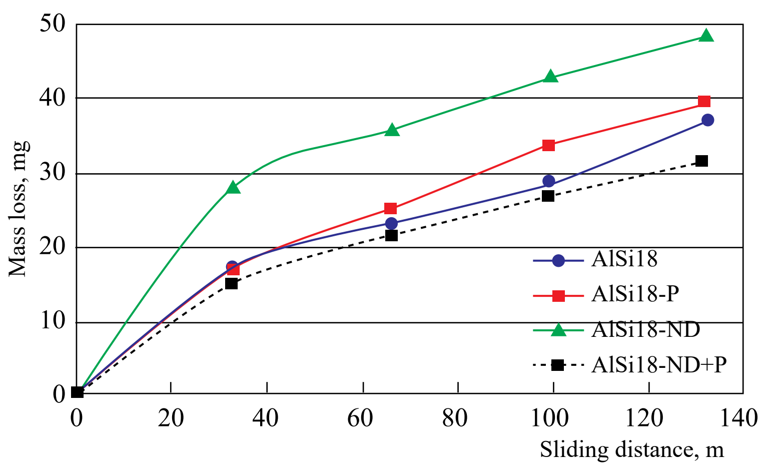

Fig. 17. Mass loss vs. sliding distance for AlSi18 with SiC modifier and standard P modifier

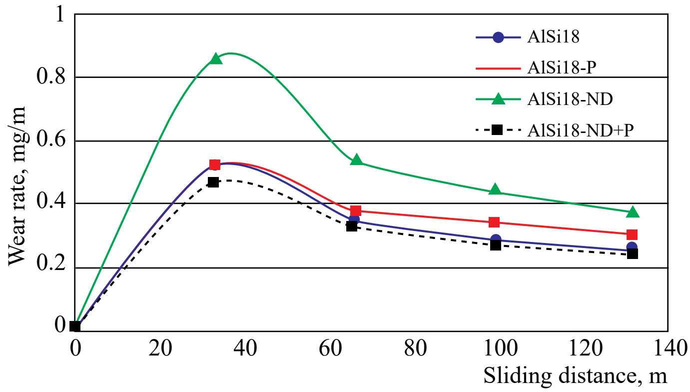

Fig. 18. Wear rate vs. sliding distance for AlSi18 with SiC modifier and standard P modifier

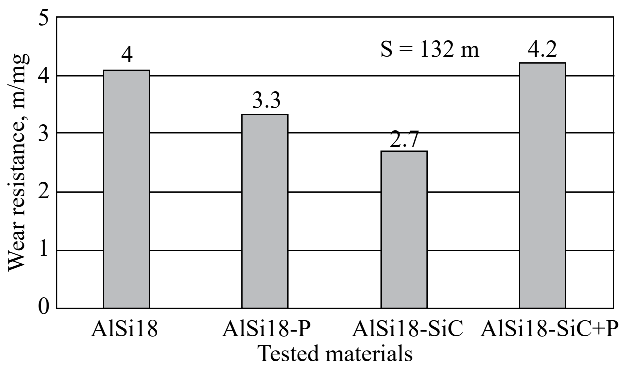

Fig. 19. Wear resistance diagram of a hypereutectic aluminum-silicon alloy AlSi18 modified by a nanomodifier – silicon carbide (SiC) for a friction path S=132

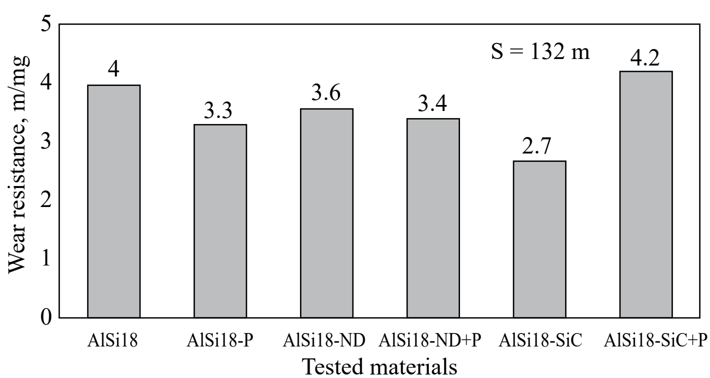

Fig. 20. Wear resistance diagram of all tested hypereutectic AlSi18 aluminum-silicon alloys modified by nanomodifiers SiC and ND for a friction path S = 132 m

CONCLUSION

The abrasive wear resistance for a certain number of cycles of the hypereutectic aluminum-silicon alloy AlSi18 with unmodified primary silicon crystals and highly refined silicon crystals in the eutectic composition is the lowest. The non-refined and irregularly shaped silicon crystals located in the hardened eutectic matrix do not have a positive effect on the wear resistance (modified by a SiC nanomodifier).

The hypereutectic aluminum-silicon alloy AlSi18 in which the primary silicon crystals have been modified, and the silicon crystals in the eutectic composition have been heavily refined, has a low abrasive wear resistance for a certain number of cycles. The modified silicon crystals located in the strengthened eutectic matrix also do not have a positive effect on the wear resistance (modified by a ND nanomodifier and a combination of a standard modifier P and a nanomodifier ND).

The highest wear resistance of the hypereutectic aluminum-silicon alloy AlSi18 to abrasive wear for a certain number of cycles has been recorded when the primary silicon crystals are highly refined, the silicon crystals in the eutectic composition are modified to a size at which the matrix is hardened but does not lose plasticity, i.e., does not get too brittle (modified by a combination of a standard modifier P and a nanomodifier SiC).

The results, obtained from the experiments, conducted to investigate the abrasive wear resistance of the hypereutectic aluminum-silicon alloy AlSi18 over a certain number of cycles show low abrasive wear resistance and are a prerequisite for new studies on the alloy wear resistance in a tribological friction system with boundary lubrication.

ACKNOWLEDGEMENT

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 June 2020