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COMPOSITES THEORY AND PRACTICE

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EFFECT OF ABRASION PARAMETERS ON TRIBOLOGICAL PROPERTIES OF CAST A339/SiC/10p COMPOSITE

The paper presents the results of tribological tests conducted on an A339/SiC/10p composite reinforced with SiC particles. The test method used in the research was the ball-on-disc method combined with variable abrasion test parameters. Different materials were used for the counter-specimen (steel, Al_2O_3, SiC), variable load (5 and 10N) and sliding speed (0.1 and 0.5 m/s). It was found that the use of a counter-specimen made from a material of higher hardness significantly reduced the friction coefficient and the specific wear rate of the tested A339/SiC/10p composite. On the other hand, in all the friction pairs, an increase in the load while maintaining the same test conditions caused a decrease in the friction coefficient value and an increase in the specific wear rate. Additionally, in the Al_2O_3 counter-specimens, an abnormal decrease in the friction coefficient was observed with an increasing load, but it had no impact on the results of the specific wear rate.

Keywords: **aluminium matrix composites, tribological behaviour, ball-on-disc method**

WPŁYW PARAMETRÓW ŚCIERANIA NA WŁAŚCIWOŚCI TRIBOLOGICZNE ODLEWANYCH KOMPOZYTÓW A339/SiC/10p

Przedstawiono wyniki badań właściwości tribologicznych kompozytów A339/SiC/10p. Testy metodą ball-on-disc przeprowadzono, stosując zmienne parametry, takie jak: różne przeciwpróbki (stalowa, Al_2O_3, SiC), obciążenie (5, 10 N) oraz prędkość ścierania (0,1 i 0,5 m/s). Badania wykazały, że zastosowanie przeciwpróbki z materiału o wyższej twardości wpływa na zmniejszenie współczynnika tarcia oraz wskaźnika zużycia badanego kompozytu A339/SiC/10p. Dla wszystkich badanych układów zaobserwowano, że wzrost obciążenia przy zachowaniu tych samych pozostałych warunków testu powoduje obniżenie wartości współczynnika tarcia oraz wzrost wskaźnika zużycia. W przypadku przeciwpróbki z Al_2O_3 obserwowano nietypową zależność. Wraz ze wzrostem obciążenia zanotowano jedynie nieznaczny spadek współczynnika tarcia, co nie miało bezpośredniego przełożenia na wartości wskaźnika zużycia.

Słowa kluczowe: **kompozyty aluminiowe, własności tribologiczne, metoda ball-on disc**

INTRODUCTION

The development of modern industry and new challenges faced by engineers calls for the use of new and increasingly better materials. Composite materials, developed for nearly the last fifty years, perfectly fit into this trend. However, it very often turns out that the developed solutions are not fully able to meet the high and specific demands, especially as regards the aerospace, defence and automotive industries. That is why there have been so many attempts to develop new methods for the fabrication of composites [1-7], and for their modification or recycling [8-13].

The group of materials that is undergoing development is the family of composites whose matrix is based on aluminium alloys reinforced with ceramic particles. They are increasingly used as a replacement for Al-Si and Al-Cu alloys which have been used so far [14]. Compared to conventional aluminium alloys, composites offer improved properties including, among others, a relatively high specific strength, corrosion resistance, and high resistance to abrasive wear [15]. Composite materials are increasingly used for heavily loaded constructions and those with high performance characteristics. Parts of internal combustion engines, disc brakes, cylinder liners and other similar solutions used in many well-known cars can serve as good examples here [16].

One of the main advantages of composite materials based on aluminium alloys is, in addition to high specific strength, their excellent resistance to abrasion. Numerous publications dealing with the problems of the frictional wear of aluminium-based composites usually overlook the role of the counter-specimen material, its hardness or surface condition - all discussed in terms of the specific operating conditions. So far, the effect of the manufacturing method and its parameters on the resulting tribological properties has never been examined in great detail [17-20], although - as claimed by the technical literature - these factors are extremely important and exert an essential, though not always obvious impact on the frictional wear of the tested material [21-24]. Thus, attempts to modify the existing materials to improve their abrasive resistance require creating an appropriate reference base every time. This should allow us to assess the impact of the conducted research works on well-known trends or dependences related to the type of material used for counter-specimens or their hardness.

The paper presents the results of tribological tests conducted on an A339/SiC/10p composite reinforced with SiC particles. The test method used in the research was the ball-on-disc method combined with variable abrasion test parameters (different materials used for the counter-specimen, variable load and rotational speed). The research is expected to help in creating a reference base for further studies related to the modification of selected composite materials by the methods of plastic forming to improve the resistance to frictional wear under dedicated operating conditions.

TEST MATERIALS AND METHODS

Tests were carried out on an aluminium alloy-based composite of the trade name A339/SiC/10p reinforced with SiC particles. The chemical composition of this material was as follows (wt.%): 10% Si, 0.3% Fe, 2.8% Cu, 0.8% Mg, 1% Ni, 0.2% Ti, 0.003% other elements, the rest Al. The average size of the reinforcing particles was 15 μm according to the manufacturer's specification of this alloy.

Microstructural examinations were conducted using an OLYMPUS GX51 optical microscope with optical instrumentation, a JEOL JSM 6610 LV scanning electron microscope with software and detectors (an upper detector (SEI) and backscattering electron detector (BEI)), and Oxford energy dispersive spectrometer (EDS) with microprobe and AZtec Software. The procedure of preparing the surface for observations consisted in mechanical grinding with abrasive 180-grit to 2000-grit sandpaper. After grinding with the sandpaper of a gradually changing grit, the samples were subjected to washing. The ground samples were polished with Struers 9, 3 and 0.25 μm diamond pastes. The examinations were made on samples in an unetched condition.

The distribution of the reinforcing particles of the SiC phase was determined using the new theory of the representative volume element (RVE) [25-27].

Additionally, to determine whether the composite has or does not have anisotropic characteristics, microhardness was measured and compression tests were performed in three perpendicular directions. The microhardness tests were conducted with an Innovatest Vickers 4303 hardness tester under a load of 100 g. The mechanical properties of the composite were determined in the compression test conducted on an Instron TT-DM machine equipped with an electronic measuring circuit. The tests were performed on cylindrical samples with an *h/d* ratio of 1.5, cut out from the base material. The tests were performed at 293 K with an initial strain rate equal to 10^{-4} s^{-1}.

Tribological tests were carried out using an ELB-01 ball-on-disc tribotester made by ELBIT, Poland. The tests were carried out without lubricant according to the ISO 20808:2004(E) standard [28]. In the ball-on-disc method, the sliding contact is done by pushing a ball on a rotating disc under a constant load (Fig. 1).

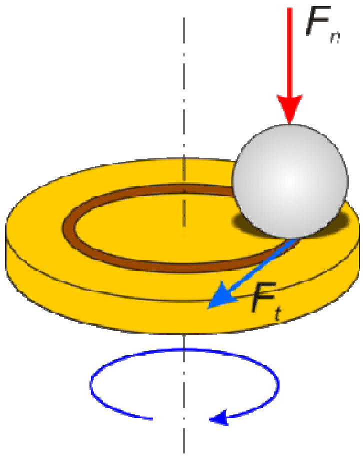

Fig. 1. Diagram of ball-on-disc wear test system [29]

Rys. 1. Schemat badania ścieralności metodą ball-on-disc [29]

The loading mechanism applied controlled load F_n to the ball holder. The friction force was measured continuously during the test with an extensometer. For each test a new ball was used. The specimens were washed in high purity acetone and dried. After mounting the ball and the specimen, both materials were washed in ethyl alcohol and then dried. The wear behaviour test was conducted under the following conditions:

- balls 3.175 mm in diameter made of Al_2O_3, SiC and steel
- friction track diameter: 5 mm
- sliding speed: 0.1 and 0.5 m/s
- total sliding distance: 200 m
- test duration: 2000 s
- load applied: 5 and 10 N
- room temperature.

The friction coefficient (μ) is calculated as the ratio of the friction force (F_n) and applied normal load (F_t). Following the wear test, the specific wear rate was calculated. For the wear track on the disc specimen, the cross-sectional profile of the wear track at four places at intervals of 90° using a contact stylus profilometer was measured with an accuracy of measurement in the vertical axis of 0.01 μm, in the horizontal axis of 0.1 μm. The specific wear rate according to wear volume was calculated by means of equation:

$$W_{V(disc)} = \frac{V_{disc}}{F_n \cdot L}$$

where:
$W_{V(disc)}$ - specific wear rate of disc [mm^3/Nm]
V_{disc} - wear volume of disc specimen [mm^3]
F_n - applied load [N]
L - sliding distance [m].

RESULTS AND DISCUSSION

The results of studies of the microstructure of the composite are presented in Figure 2. Microstructural examinations revealed the presence of dark coloured SiC particles and two additional components which appeared in the microstructure as a light grey silicon eutectic and darker FeAlSi phase assuming the form of the characteristic "Chinese script" [30]. The performed image analysis of the microstructure has shown that the size of the particles used as reinforcement was consistent with the manufacturer's data. A histogram of the particle size distribution in the tested area is presented in Figure 3.

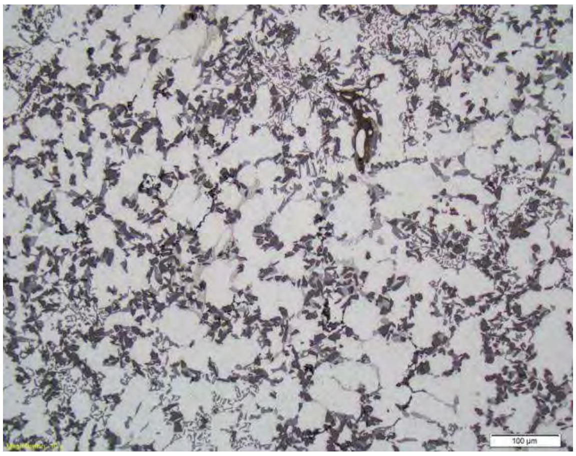

Fig. 2. Microstructure of aluminium-based A339/SiC/10p composite in initial condition

Rys. 2. Obraz mikrostruktury kompozytu A339/SiC/10p w stanie wyjściowym

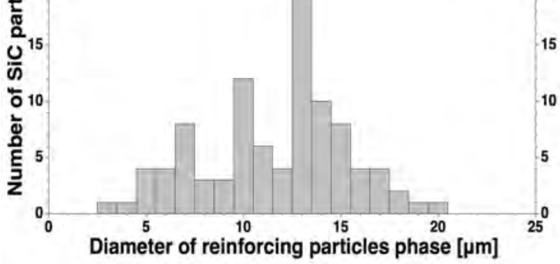

Fig. 3. Distribution of diameters of maximum particles of reinforcing SiC phase in A339/SiC/10p composite

Rys. 3. Rozkład średnic maksymalnych cząstek wzmacniających SiC w kompozycie A339/SiC/10p

One of the most important factors shaping the tribological properties of composite materials is the volume fraction of the reinforcement and its distribution. Particularly in the case of ex-situ composites fabricated by casting methods, segregation of the reinforcement or other disorders in the particle size distribution can occur, and they will have a direct impact on the measured values. To determine the concentration of the reinforcing SiC phase particles in the composite, calculations were performed using the available microstructure images. Tests were carried out in different areas of the base material containing from 10 to 5000 particles. The results of the calculations are described in Figure 4a. It was observed that the degree of concentration of the reinforcing phase particles depended on the size of the examined area and was stable at the level of 10% specified by the manufacturer in areas with more than 800 particles. Below this value, areas with increased or decreased concentration of SiC particles were detected. Stabilisation of the reinforcement concentration in the range of 50÷100 particles was also observed. At the same time, the anisotropy coefficient was determined for the examined areas, applying for this purpose the new RVE theory based on a monodispersive model. The results of the analysis are shown in Figure 4b.

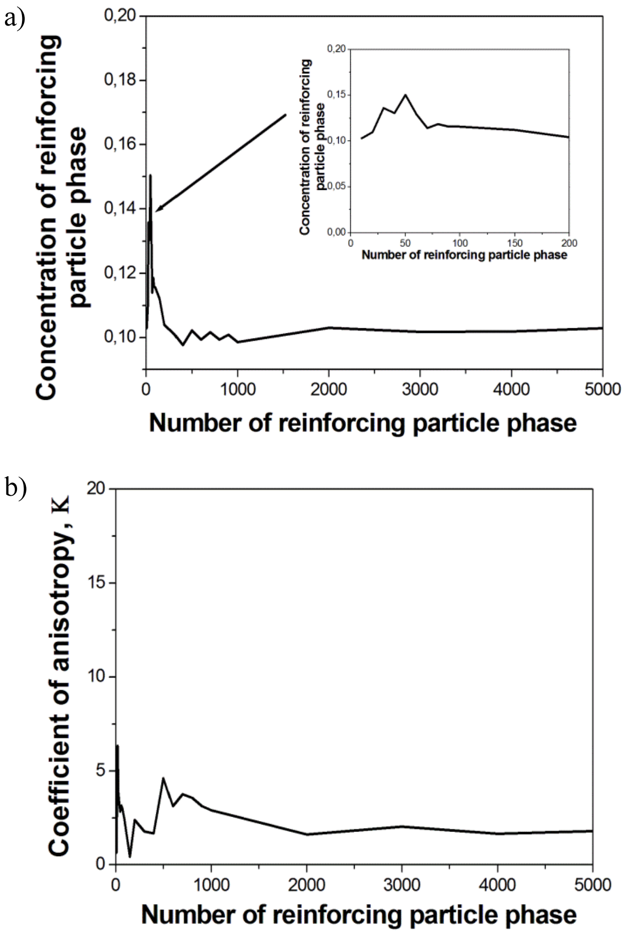

Fig. 4. Distribution of reinforcing SiC phase in A339/SiC/10p composite: a) concentration, b) anisotropy coefficient

Rys. 4. Dystrybucja fazy wzmacniającej SiC w kompozycie A339/SiC/10p: a) koncentracja, b) współczynnik anizotropii

In the examined material, stabilization of the anisotropy coefficient value at a similar level of concentration was observed to take place only in the areas containing approximately 1000 particles or more. The anisotropy coefficient value at a level of about 3 has indicated that the distribution of the reinforcement was not isotropic.

The results of the tests on the changes in the mechanical properties examined on selected mutually perpendicular directions are shown in Figure 5. Regardless of the direction in which the samples were cut for the compression test, similar results were obtained. In all three cases, the mechanical deformation characteristics practically coincide, showing only minor deviations. Additionally, the composite microhardness was measured to confirm the isotropic character of the mechanical properties in small areas. The test results are given in Table 1. The obtained hardness values are not substantially different, confirming the lack of anisotropy of the mechanical properties despite the confirmed anisotropic distribution of the reinforcement. The obtained results of the mechanical tests allowed unrestrained preparation of specimens for tribological studies without the need to take into account any preferred direction or to conduct additional tests in different directions.

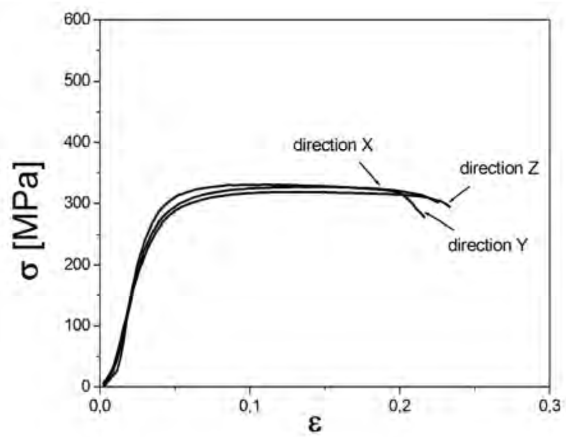

Fig. 5. True compressive stress versus true compressive strain at room temperature calculated for three perpendicular directions in A339/SiC/10p composite

Rys. 5. Charakterystyki mechaniczne odkształcania kompozytu w temperaturze pokojowej dla trzech prostopadłych kierunków

TABLE 1. **Results of hardness measurements ($HV_{0.1}$) obtained for A339/SiC/10p composite**

TABELA 1. **Wartości liczby twardości ($HV_{0.1}$) dla kompozytu A339/SiC/10p**

	Direction X	Direction Y	Direction Z	Mean
Average $HV_{0.1}$	123.2	118.3	122.7	121.4
Standard deviation	18.5	20.3	19.6	

The results of the tribological tests carried out by the ball-on disc method are presented in Figure 6 in the form of graphs showing changes in the friction coefficient as a function of the time of wear. The results were obtained for two different loads, i.e. 5 N (Fig. 6a) and 10 N (Fig. 6b), using three different friction pairs.

Regardless of the applied load, the occurrence of a visible range of lapping was observed in none of the friction pairs, confirming the statements made in some publications. The nature of changes in the friction coefficient observed for each pair was similar and was characterized by an increase in its value in the initial period of the test. It was observed, however, that after a short time of about several tens of seconds, for both variants of load, the friction coefficient decreased until the moment of its stabilisation at a constant level. An exception to this rule was the test variant involving a counter-specimen made of Al_2O_3 and a load of 10 N. In this case, the friction coefficient rose after a decline.

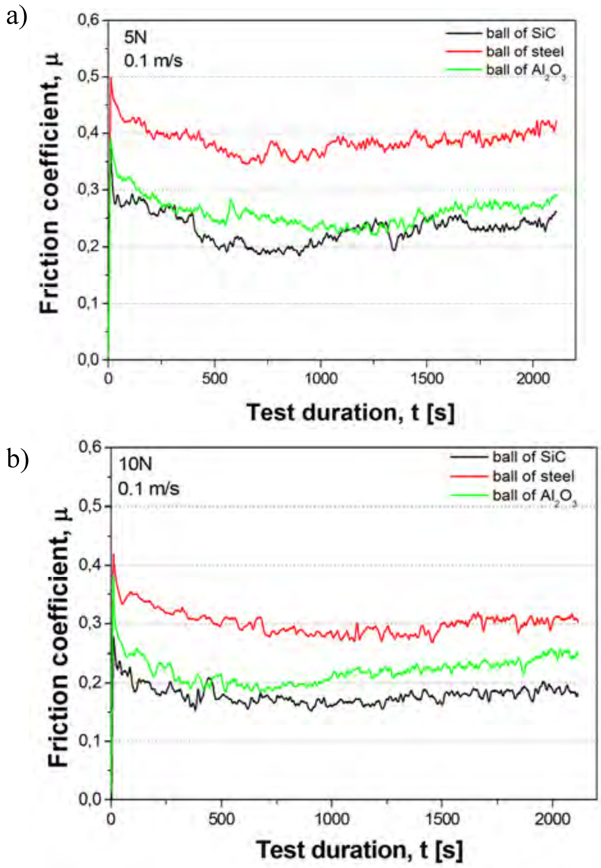

Fig. 6. Typical friction coefficient curves plotted for composite tested under load of: a) 5 N and b) 10 N at sliding speed of 0.1 m/s

Rys. 6. Współczynnik tarcia dla kompozytu badanego pod obciążeniem a) 5 N, b) 10 N z prędkością ścierania 0.1 m/s

The graphs in Figures 7a and 7b show the quantitative differences in the friction coefficient and specific wear rate obtained for the examined friction pairs. It has been proven that the highest values of the friction coefficient, i.e. 0.39 and 0.30 for the load of 5 and 10 N, respectively, and of the specific wear rate were obtained in the friction pair composed of the A339/SiC/10p composite and steel counter-specimen. Differences between the friction pair with the highest friction coefficient and the composite-SiC pair were observed to reach about 40%. This tendency was maintained irrespective of the applied load. The situation was quite opposite when the results obtained for the counter-specimens of steel and Al_2O_3 were compared. For these variants, the difference in the friction coefficient recorded for the 5 N load was about 35%, while with the load raised to 10 N, it decreased to about 5%. This trend was not confirmed by the values of the specific wear rate obtained for the tested pairs. In all the examined cases, the values of the specific wear rate calculated for the composite-steel pair amounted to approximately 40 to 60%, regardless of the applied load. It was noted, however, that the highest values of the specific wear rate were always obtained for the steel counter-specimen, and the lowest for the SiC counter-specimen. In contrast, the differences obtained for the examined ceramic counter-specimens were negligible.

An image of the composite surface microstructure after the abrasion test using a soft steel counter-specimen is shown in Figure 8a. The dominant mechanism is abrasive wear of the samples, accompanied by the occurrence of numerous parallel grooves on the friction surface, consistent with the counter-specimen movement. Additionally, grinding of the base material was observed on the periphery of the wear track as shown in Figure 8b.

a)

b)

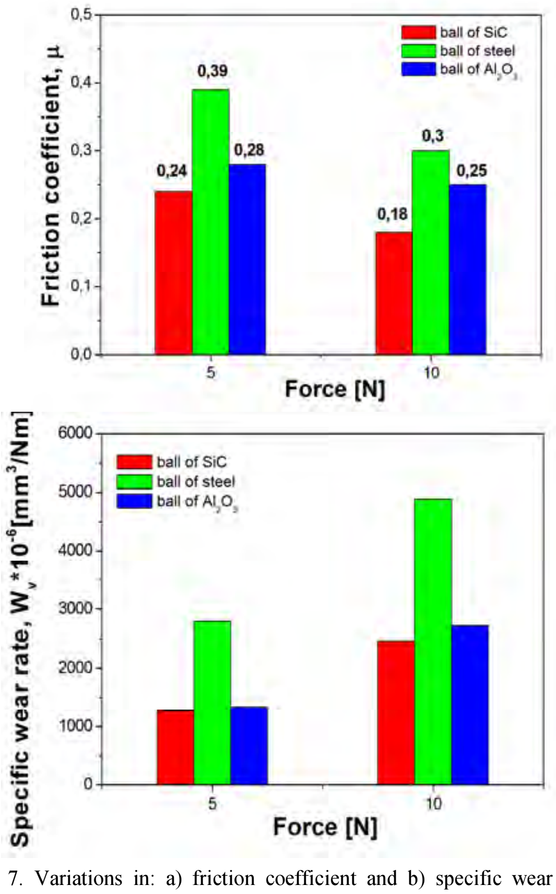

Fig. 7. Variations in: a) friction coefficient and b) specific wear rate observed for composite tested under load of 5 and 10 N at sliding speed of 0.1 m/s

Rys. 7. Zestawienie: a) współczynnika tarcia oraz b) wskaźnika zużycia dla kompozytu badanego pod obciążeniem 5 i 10 N z prędkością ścierania 0,1 m/s

a)

b)

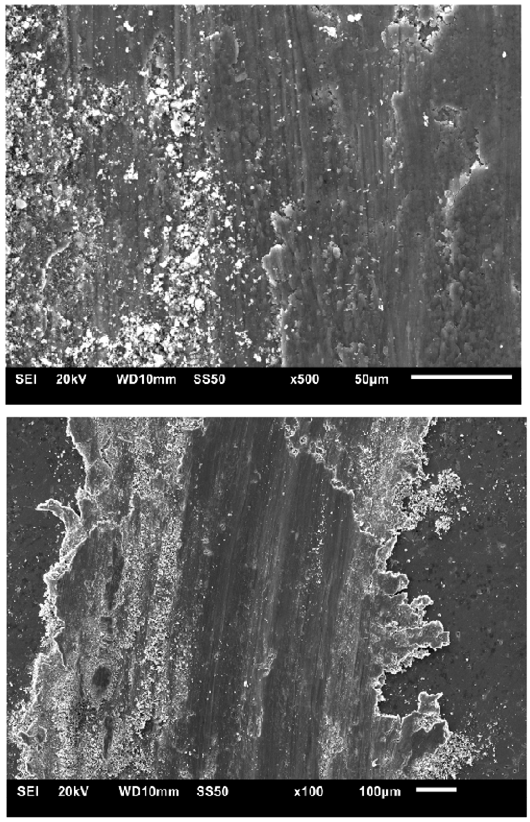

Fig. 8. SEM micrograph of wear track left on composite surface by steel ball

Rys. 8. Obrazy mikrostruktury śladu wytarcia otrzymane przy badaniu z kulką stalową

In hard counter-specimens, the wear rate was reduced. The contribution of abrasion to the overall wear rate was less pronounced, and the specimen surfaces were much smoother, though the effect of grinding the base material continued on the periphery of the wear track. Under these conditions, the friction surface of the specimens showed patch losses occurring as a result of the delamination-type wear (Fig. 9a, b).

In summary, it can be concluded that the use of a counter-specimen made from a material of higher hardness significantly reduces the friction coefficient and the specific wear rate of the tested A339/SiC/10p composite. On the other hand, in all the friction pairs, an increase in the load while maintaining the same test conditions caused a decrease in the value of the friction coefficient and an increase in the specific wear rate.

Further comparative studies of the impact of process parameters on the tribological properties have been carried out only for the two hardest friction pairs (composite-Al_2O_3 and composite-SiC). The influence of changes in the sliding speed and load on the friction coefficient and wear rate of the composites was examined. Figure 10 shows changes in the friction coefficient as a function of test time, applying two loads of 5 and 10 N and sliding speeds of 0.1 m/s (Fig. 10) and 0.5 m/s (Fig. 10b). It was observed that for the lower sliding speed, the friction coefficients are very similar regardless of the applied load and counter-specimen type. The coefficient values are in the range of about

0.17 to 0.27. The smallest differences in the friction coefficients were obtained for the composite-Al_2O_3 friction pair. In this case, a time interval was reported in which the obtained values were almost at the same level. Increasing the sliding speed increased the scatter of the friction coefficient values, depending on the type of friction pair used.

a) b)

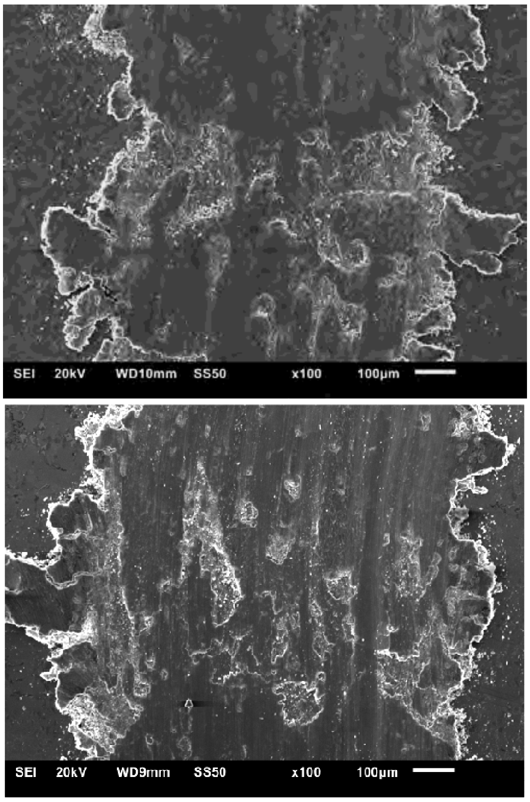

Fig. 9. SEM micrograph of wear track left on composite surface by a) Al_2O_3 and b) SiC ball

Rys. 9. Obrazy mikrostruktury śladu wytarcia otrzymane przy badaniu z kulką: a) Al_2O_3 oraz b) SiC

The greatest effect of the applied sliding speed was found in the composite-Al_2O_3 friction pair, where the differences in the values obtained for the loads of 5 and 10 N could reach even 0.2. Such an impact of load at a higher sliding speed was not found in the composite-SiC friction pair. Figure 11 shows the effect of load on the specific wear rate for both friction pairs at the two sliding speeds of 0.1 m/s (Fig. 11) and 0.5 m/s (Fig. 11b). It was observed that for the sliding speed of 0.1 m/s, the load impact on the specific wear rate was similar for both friction pairs and the resulting difference between the values of the specific wear rate for the SiC and Al_2O_3 counter-specimens did not exceed 10%. In contrast, for the tests carried out at higher sliding speeds and the load of 5 and 10 N, the differences between the specific wear rate values were much higher. For the SiC and Al_2O_3 counter-specimens, they amounted to 60 and 40% for the loads of 5 and 10 N, respectively. It was also observed that with a load increasing from 5 to 10 N, the wear rate for the composite-SiC pair increased by approximately 50%, while for the composite-Al_2O_3 pair it rose up to 70%.

a) b)

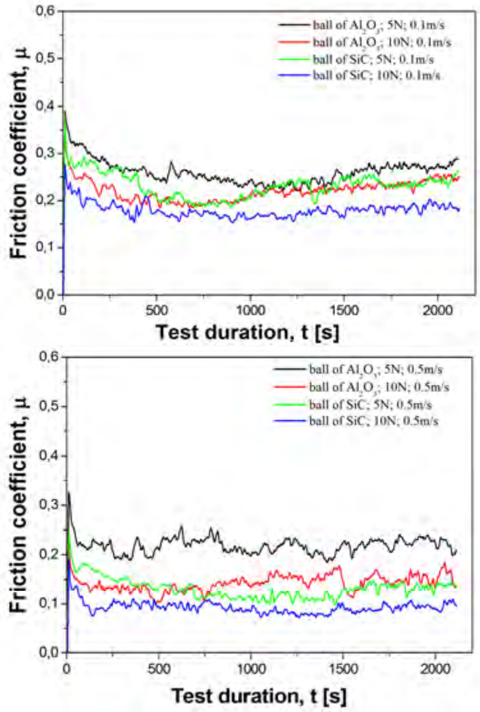

Fig. 10. Typical friction coefficient curves of composite tested at sliding speed of: a) 0.1 m/s and b) 0.5 m/s under load of 5 and 10 N

Rys. 10. Współczynnik tarcia dla kompozytu badanego pod obciążeniem 5 oraz 10 N z prędkością ścierania: a) 0,1m/s oraz b) 0,5 m/s

a) b)

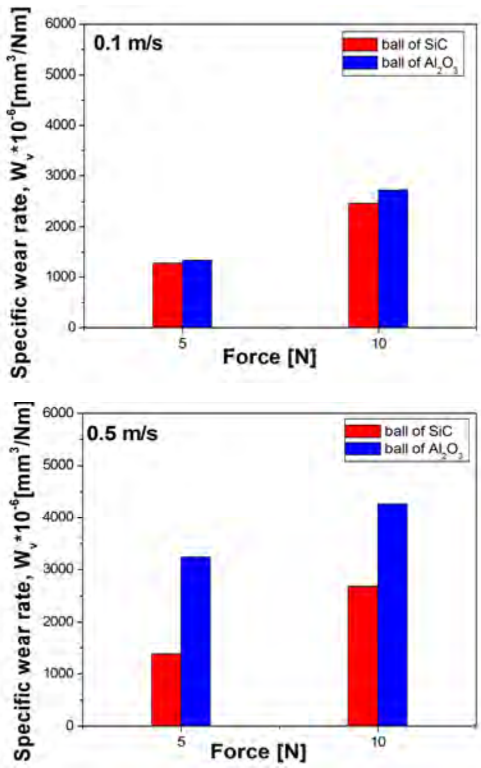

Fig. 11. Variations in specific wear rate of composite tested at sliding speed of: a) 0.1 m/s and b) 0.5 m/s

Rys. 11. Zestawienie wskaźnika zużycia dla kompozytu badanego z dwoma prędkościami ścierania: a) 0,1 m/s oraz b) 0,5 m/s

The comparative results of the effect of the applied sliding speed on the friction coefficient and the strain hardening rate are shown in Figure 12.

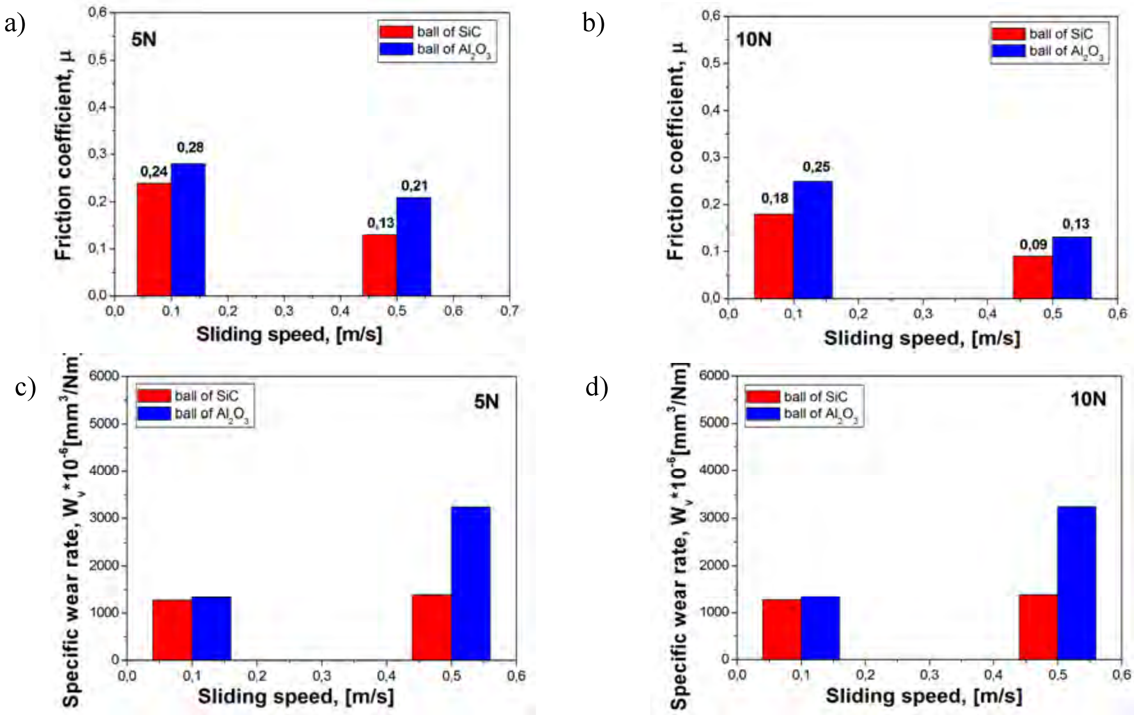

Fig. 12. Variations in: (a, b) friction coefficient and (c, d) specific wear rate of composite for two sliding speeds and (a, c) test load of 5 N and (b, d) test load of 10 N

Rys. 12. Zestawienie (a, b) współczynnika tarcia oraz (c, d) wskaźnika zużycia dla kompozytu badanego z dwoma prędkościami ścierania pod obciążeniem (a, c) 5 N i (b, d) 10 N

A distinct drop in the friction coefficient value with an increasing sliding speed was observed regardless of the applied load value (Fig. 12a, b). Moreover, it can be concluded that an increase in sliding speed had a substantial effect on the increase in the composite wear rate. For the sliding speed of 0.1 m/s with counter-specimens made from SiC and Al_2O_3, similar specific wear rate values were obtained for the loads of 5 and 10 N. On the other hand, in the case of the sliding speed of 0.5 m/s, significant differences appeared depending on the type of material used for the counter-specimen. In the composite-SiC pair, no substantial increase was observed with an increase in sliding speed, while in the composite-Al_2O_3 pair, the differences reached 60% and depended on the applied sliding speed.

CONCLUSIONS

The obtained results of the tribological tests carried out on the A339/SiC/10p composite have proved that the frictional wear and the wear process itself have a substantial impact on all the tested parameters. The impact of the counter-specimen material, load value and sliding speed on the specific wear rate and friction coefficient was studied. The obtained results allowed us to draw the following conclusions:

- The highest wear rate took place in the counter-specimens with the lowest hardness values (steel ball). This trend persisted regardless of the sliding speed and load. Therefore, the highest values of the composite friction coefficient were obtained for the steel counter-specimen and the lowest for the counter-specimen made from SiC.
- With an increasing load, the friction coefficient value decreased in the tested friction pairs, while the specific wear rate showed an increase.
- In the Al_2O_3 counter-specimens, an abnormal decrease in the friction coefficient was observed with an increasing load, but it had no impact on the specific wear rate results.
- In the SiC counter-specimens, changes in the sliding speed had practically no effect on the specific wear rate, contrary to the Al_2O_3 counter-specimens, where the specific wear rate increased by more than 100% (for 5 N loads).

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