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Effect of test conditions on wear properties of steel-matrix composites

Wpływ warunków testu na właściwości tribologiczne kompozytów o osnowie stalowej

Abstract
The friction coefficient and wear behavior of 316L austenitic stainless steel and 316L steel + 8vol% TiB_2 + 1vol% B composites were investigated within a temperature range of 20°C to 800°C. The materials were prepared by the powder metallurgy method. The wear behavior was studied by using a ball-on-disc wear tester at room temperature. The surface before and after wear tests was analyzed using scanning electron microscopy (SEM). The results indicated that the friction coefficient and wear resistance of stel-8TiB_2-1B composites depend on the wear test conditions.

Keywords: ball-on-disc method, friction coefficient, wear rate, composite

Streszczenie
W pracy określono współczynnik tarcia i odporność na zużycie dla stali austenitycznej 316L i kompozytów o osnowie stalowej zawierających 8% obj. TiB_2 i 1% obj. B. Materiały do badań wytworzono z wykorzystaniem metody metalurgii proszków. Badania właściwości tribologicznych przeprowadzono, stosując metodę ball-on-disk w zakresie temperatury 20–800°C. Badania mikrostrukturalne przed testami i po testach ścierania przeprowadzono przy zastosowaniu skaningowej mikroskopii elektronowej (SEM). Wyniki wykazały, że współczynnik tarcia i odporność na zużycie zależą od warunków testów ścierania (temperatury).

Słowa kluczowe: metoda ball-on-disk, wspólczynnik tarcia, szybkość ścierania, kompozyt

1. Introduction

Tribological wear is a kind of surface deterioration caused by a friction mechanism. This is a process of damage and material removal from the friction surface. Due to interaction of both processes, a change of the mass, microstructure, and physical properties of the wearing elements occurs. Abrasive wear dominates when a sample is subjected to dry friction, which is directly connected to the bulk properties of a material. The abrasive

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wear is solely a mechanical process of material deterioration [1, 2]. The wear resistance is strongly dependent on the working conditions (experimental conditions) and type of the tribological couple. The morphology, volume fraction of the hardening phases, and the kind and distribution of the phases along with their properties have an effect on the wear of composite materials. On the other hand, the experimental parameters influencing the characteristics of composite wear include the applied fiction force, rotational speed, displacement, temperature, and material of the counter sample [3–7].

According to research [8–10], incorporation of a ceramic phase to a steel matrix can result in improved wear resistance. Ashok and Karabi [10] indicated that the TiC and (Ti,W)C-reinforced composites show better dry sliding wear resistance than that of an unreinforced austenitic steel matrix. The abrasive wear resistance of a (Ti,W)C-reinforced composite is higher than that of a TiC-reinforced composite. Sulima *et al.* [11] showed that the friction coefficient of steel composites decreases with an increasing content of TiB_2. The best tribological properties were obtained for austenitic stainless steel reinforced with 20 vol% TiB_2 particles. Tjong and Lau [12, 13] studied the properties of composites reinforced with various volume fractions of TiB_2 particles. They indicated that the addition of TiB_2 particles was very effective in improving the wear resistance and ductility of austenitic stainless steel.

The aim of this research was to study the wear resistance of unreinforced steel and steel + 8vol% TiB_2 + 1vol% B composites at a temperature range of 25°C to 800°C. The tribological properties were studied using the ball-on-disc method. In the work, 316L austenitic stainless steel matrix composites containing 8 vol% TiB_2 and 1 vol% boron were marked as steel + 8TiB_2 + 1B.

2. Methods

The raw materials used in this research were 316L austenitic stainless steel and 316L steel matrix composites containing 8 vol% TiB_2 and 1 vol% boron. The materials were sintered using the high pressure/high temperature (HP/HT) method. The sintering process was carried out at a pressure of 5.0 ± 0.2 GPa and a temperature of 1300°C for 60 seconds. Details of the sintering technology applied in the case of the tested composites are described in the literature [14]. The densities of the composites were determined by the Archimedes method. The uncertainty of the measurements was no more than 0.02 g/cm^3. Young's modulus was measured based on the velocity of the ultrasonic waves' transition through the sample using the ultrasonic flaw detector Panametrics Epoch III. The accuracy of the calculated Young's modulus could be estimated to be 2%. Vickers microhardness measurements using a load of 2.94 N were carried out with an FM-7 microhardness tester.

Before the wear tests, the surfaces of the investigated materials were prepared in accordance with international standards [15]. The samples for the wear tests were prepared by standard methods of grinding (using SiC foil) and polishing up to 0.4 μm (using diamond suspension). All of the specimen surfaces were cleaned with alcohol and dried. The surface roughness of the specimens was under 0.2 μm (R_a).

The tribological properties of the materials were investigated on a UMT-2MT tribometer (CETR, USA). Tribological tests were carried out using the ball-on-disc method. The experimental procedure followed ISO 20808:2004(E) [15, 16]. The friction coefficients (μ) and specific wear rate ($W_{V(disc)}$) were determined. In the case of the ball-on-disc method, the sliding contact is established by pushing a ball on a rotating disc specimen under a constant load (Fig. 1). The friction force was continuously measured during the test using the extensometer. Table 1 presents the applied wear test conditions.

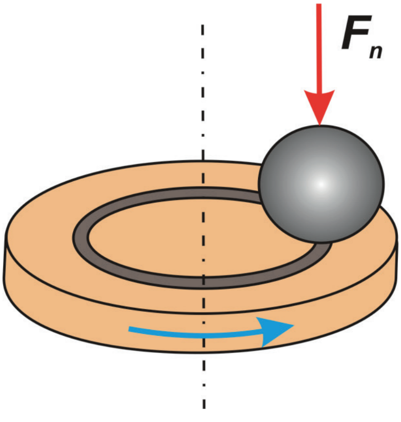

Fig. 1. Scheme of ball-on-disc method

Table 1. Wear test conditions of ball-on-disc method

Wear test conditions	
wear test temperature, *T*	20, 200, 400, 600, 800°C
material of ball	Al_2O_3
diameter of ball, *d*	3.175 mm
load, F_n	4 N
friction track diameter, *r*	4.0 mm
sliding speed, *v*	0.1 m/s
sliding distance, *L*	200 m
test duration	2000 s

The friction coefficient was calculated from the following equation:

$$\mu = \frac{F_f}{F_n L} \tag{1}$$

where:

F_f – measured friction force [N],
F_n – applied normal force [N],
L – sliding distance [m].

After the wear tests, the cross-sectional profile of the wear track was measured at four places at intervals of 90° using a contact stylus profilometer. The accuracy of the measurement was in a vertical axis of 0.01 μm and a horizontal axis of 0.1 μm. The cross-sectional area of the wear track was calculated using a specially designed PC program. Next, the wear volume of the disc specimen was calculated from Equation (2):

$$V_{disc} = \frac{\Pi}{2} R\left(S_1 + S_2 + S_3 + S_4\right) \tag{2}$$

where:

R – radius of wear track [mm],
S_1 to S_4 – cross-sectional areas at four places on the wear track circle [m^2].

Specific wear rate according to wear volume was calculated by means of Equation (3):

$$W_{V(disc)} = \frac{V_{disc}}{F_n L} \tag{3}$$

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].

The microstructure of the worn surface was observed using a scanning electron microscope (SEM) JEOL JSM 6610LV.

3. Results

Table 2 shows the physical properties of the sintered steel and steel + $8TiB_2$ + 1B composites. The results showed that, in all of the examined materials, a very high degree of compaction was achieved in a very short time of sintering (60 seconds). A high density (99%) of the theoretical value was obtained for the sintered composites and unreinforced steel.

The porosity was at a level of 0.012–0.021%. The obtained results (Tab. 1) clearly show an improvement in Young's modulus as a result of the reinforcing TiB_2 phase and boron addition introduced to the steel matrix. The microhardness of the unreinforced steel and steel + $8TiB_2$ + 1B composites is 225 and 436 HV0.3, respectively. Summarizing, the addition of 8% TiB_2 and 1% B significantly improves the microhardness.

Table 2. Properties of steel and composite sintered by HP-HT method

Sintered materials	Sintering conditions		Apparent density ρ_0 [g/cm^3]	$\frac{\rho_0}{\rho_{teor}}$ [%]	Porosity [%]	Young's modulus *E* [GPa]	$\frac{E}{E_{teor}}$ [%]	Microhardness HV0.3
	temperature [°C]	pressure [GPa]						
unreinforced steel	1300	5	7.88 ± 0.03	99	0.012	191 ± 3	92	225
steel + $8TiB_2$ + + 1B			7.51 ± 0.03	99	0.021	228 ± 3	7	436

Figures 2 and 3 show the microstructure of the steel + $8TiB_2$ + 1B composite sintered by HP-HT. Microstructural observations revealed a uniform distribution of the reinforcing TiB_2 phase in the steel matrix. Analysis of the chemical composition (WDS) in the microregions of the sintered composites revealed the presence of precipitates containing nickel. Additionally, in the steel + TiB_2 + 1B composites, the presence of characteristic boron-rich areas of sizes about 5–30 µm was observed.

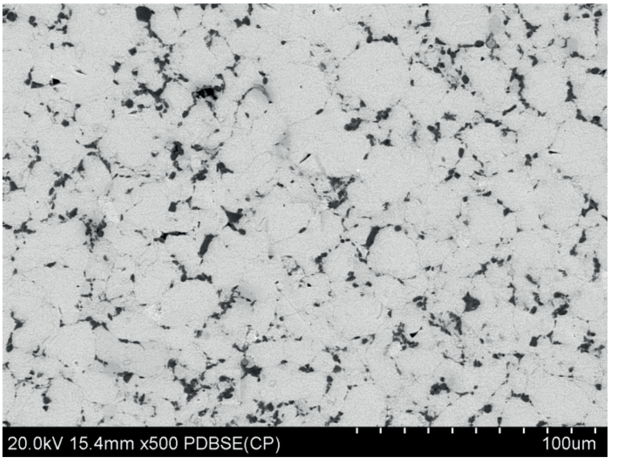

Fig. 2. Microstructure (SEM) of steel-$8TiB_2$-1B composite (HP-HT method, 1300°C / 5 GPa)

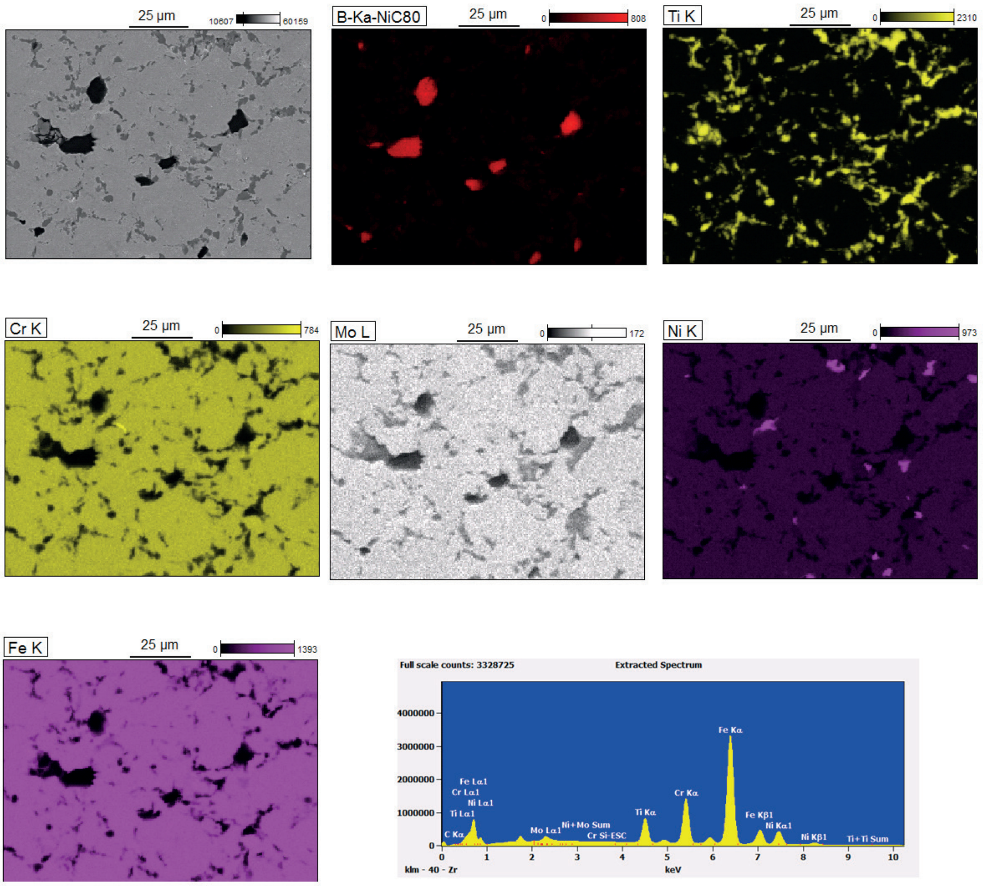

Fig. 3. Microstructure (SEM) of steel-8TiB$_2$-1B composite and element distribution maps by WDS analysis for titanium, boron, chromium, iron, nickel, and molybdenum

Figures 4 and 5 show the results of the tribological tests, which were carried out by the ball-on-disc method. These shows that the friction coefficient and specific wear rate depend on the wear test temperature. An analysis of the results (Tab. 3) indicates that the application of wear test temperatures of 200°C and 400°C did not affect the change of the coefficient of friction (0.64–0.65 for the unreinforced steel and 0.52–0.53 for the composite) as related to the values obtained at room temperature (0.65 for the unreinforced steel and 0.54 for the composite). Raising the temperature to 600°C and 800°C resulted in a significant deterioration in the wear resistance of the materials tested. The highest values of the friction coefficient have materials that were tested at a temperature of 800°C. The coefficient of friction determined at 800°C is 0.75 and 0.63 for the unreinforced steel and steel-8TiB$_2$-1B composite, respectively.

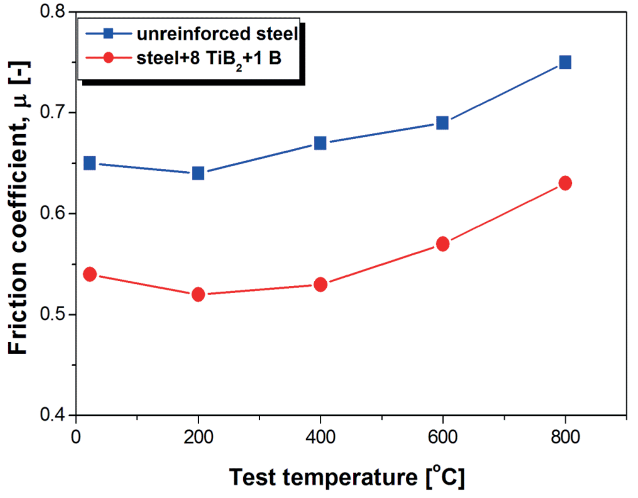

Fig. 4. Effect of the test temperature on the friction coefficient

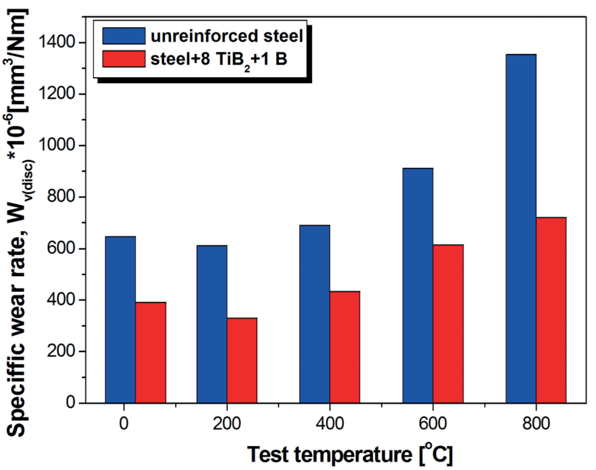

Fig. 5. Effect of test temperature on specific wear rate

The examinations show that the additions of TiB_2 and boron result in an improvement in the wear resistance of steel matrix. The friction coefficients for the steel-8TiB_2-1B composite are smaller as compared to the results for the unreinforced steel. This is mainly the effect of the high hardness of TiB_2 ceramics (reaching 3400 HV [17]). The TiB_2 particles protect the steel-matrix during the process of friction, reducing its rate of wear. These results are consistent with the studies of Tjong and Lau [12, 13], which examined the wear properties of composites with different volume fractions of TiB_2. The authors showed that the wear resistance of a steel matrix increases with an increase in TiB_2 content.

Table 3. Tribological properties of steel and steel + 8TiB$_2$ + 1B composites

Materials	Temperature T [°C]	Friction coefficient, [μ]	Standard deviation of μ	Specific wear rate, $W_{v(disc)}$·10^{-6} [mm^3/Nm]	Uncertainty of specific wear rate $\Delta W_{s(disc)}$ [%]
unreinforced steel	23	0.65	0.06	648.25	4.9
	200	0.64	0.04	612.23	5.1
	400	0.65	0.04	689.68	6.5
	600	0.7	0.05	912.14	7.0
	800	0.75	0.05	1354.93	7.0
steel + 8TiB$_2$ + 1B	23	0.54	0.05	391.60	5.7
	200	0.52	0.04	331.45	5.2
	400	0.53	0.05	434.61	5.6
	600	0.59	0.04	615.21	9.8
	800	0.63	0.05	720.85	5.9

Similar correlations were observed in the specific wear rate of the tested materials (Fig. 4). The specific wear rate increased with increasing wear test temperatures for the sintered steel and composite. According to the results, the specific wear rate for the steel-8TiB$_2$-1B composite was within a range of $391 \cdot 10^{-6}$ to $720 \cdot 10^{-6}$ mm^3/N for wear test temperatures of 20°C and 800°C, respectively. For a comparison with the unreinforced steel, the specific wear rate was within a range of $648 \cdot 10^{-6}$ to $1355 \cdot 10^{-6}$ mm^3/N for wear test temperatures of 20°C and 800°C, respectively. Additionally, the results indicate that the unreinforced steel exhibits higher values of the specific wear rate. The addition of 8% TiB_2 and 1% boron to the steel matrix was effective in reducing the specific wear rate of the composites.

Based on the conducted studies, it is to state that steel-8TiB$_2$-1B composites are characterized by good wear resistance at temperatures up to 400°C. At higher temperatures, the wear resistance of the material decreases. The process can be explained by oxidations and the formation of brittle oxides at the surface at higher test temperatures (600°C and 800°C), which may cause a quicker wear on the composite surface, a larger mass loss, and a worsening of the abrasive properties of the studied material. The studied composites may be applied in friction conditions up to a temperature of 400°C without any significant influence on the tribological properties of these materials.

After the tribological tests, the traces of wear formed at various temperatures were observed with the scanning electron microscope; examples of these are presented in Figures 6 and 7.

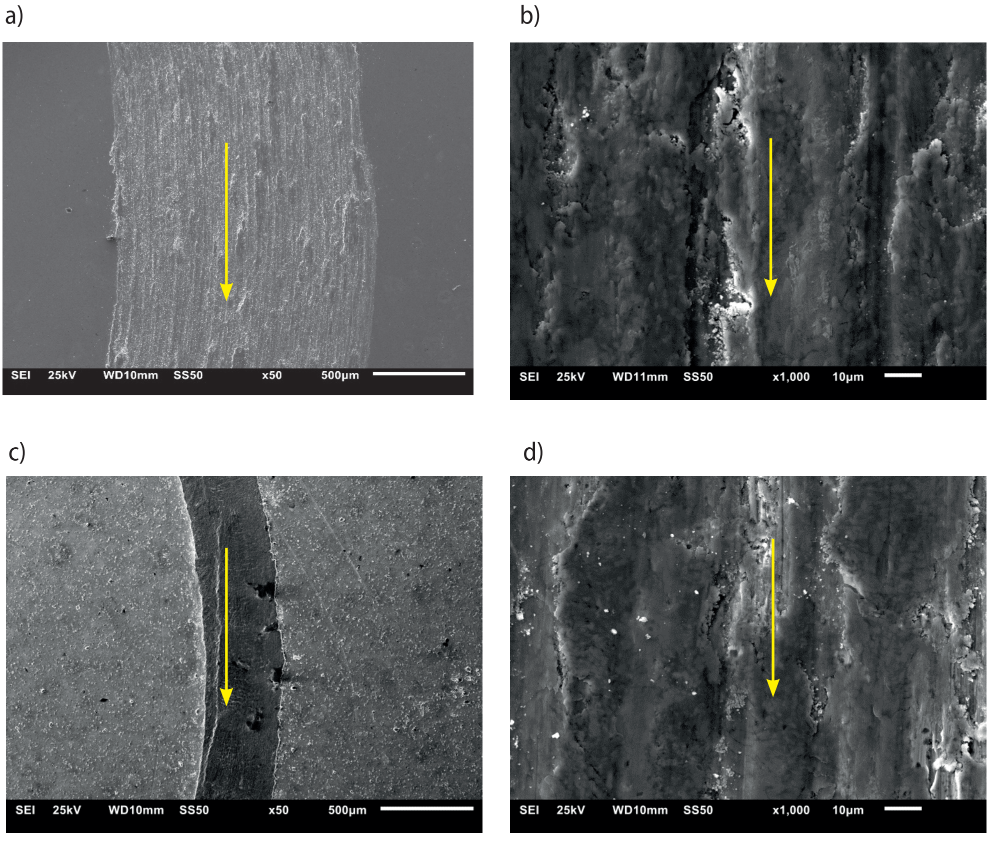

Fig. 6. Selected micrograph (SEM) of worn surface of composites: a, b) unreinforced steel; c, d) steel + 8TiB$_2$ + 1B (wear test temperature of 20°C)

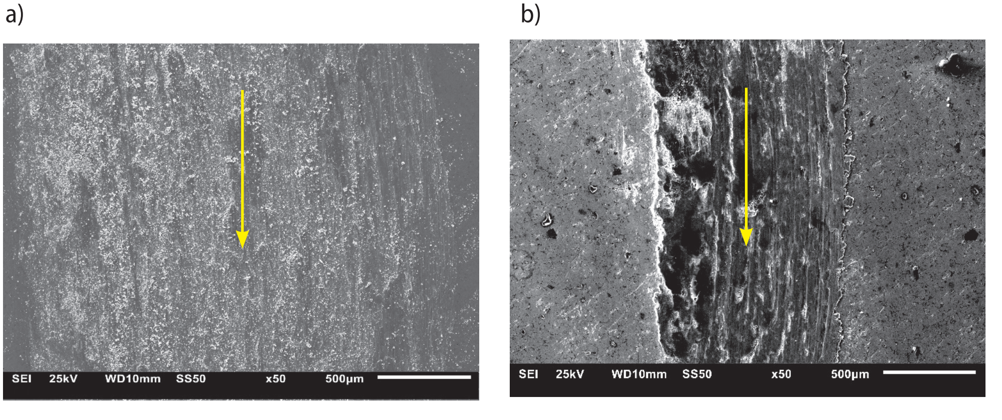

Fig. 7. Selected micrograph (SEM) of worn surface of composites: a) unreinforced steel; b) steel + + 8TiB$_2$ + 1B (wear test temperature of 800°C)

Comparing the wear traces for all of the studied materials, characteristic features of abrasive wear were observed at the surface, such as scratches and, grooves aligned in parallel to the direction of the ball's movement (yellow arrows in the images). It was noted that, due to the friction process, the permanent deformation of the sintered materials was limited to the place of wear together with where its abrasion occurred. The microstructure observations showed that the width of wear in the case of steel without reinforcement is greater as compared to those for the steel + $8TiB_2$ + 1B composites. These results confirm, that Al_2O_3 ball is more likely to wear a the surface of the reinforcement-free steel by removing larger volume of material. The particles of TiB_2 protect a the matrix made of an austenite steel against wear while limiting the removal of material.

4. Conclusions

The wear behavior of the unreinforced steel and steel + $8TiB_2$ + 1B composites was studied using the ball-on-disc method. The results show that the tribological properties depend on the wear test temperature. The highest values of the friction and specific wear coefficients were found in materials that were tested at a temperature of 800°C.

The addition of 8% TiB_2 and 1% boron to the steel matrix was effective in reducing the friction coefficient and specific wear rate of the composites.

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References

[1] Hebda M., Wachal A.: Trybologia. Wydawnictwo Naukowo-Techniczne, Warszawa 1980

[2] Płaza S., Margielewski L., Celichowski G.: Wstęp do tribologii i tribochemia. Wydawnictwo Uniwersytetu Łódzkiego, Łódź 2005

[3] Vardavoulias M., Jouanny-Tresy C., Jeandin M.: Sliding-wear behaviour of ceramic particle-reinforced high-speed steel obtained by powder metallurgy. Wear, 165, 2 (1993), 141–149

[4] Akhtar F.: Microstructure evolution and wear properties of in situ synthesized TiB_2 and TiC reinforced steel matrix composites. Journal of Alloys and Compounds, 459 (2008), 491–497

[5] Velasco F., Gordo E., Isabel R., Ruiz-Navas E.M., Bautista A., Torralba J.M.: Mechanical and wear behaviour of high-speed steels reinforced with TiCN particles. International Journal of Refractory Metals & Hard Materials, 19 (2001), 319–323

[6] Niranjan K., Lakshminarayanan P.R.: Dry sliding wear behaviour of in situ Al-TiB_2 composites. Materials and Design, 4 (2013), 167–173

[7] Darabara M., Papadimitriou G.D., Bourithis L.: Tribological evaluation of Fe-B-TiB_2 metal matrix composites. Surface and Coatings Technology, 202, 2 (2007), 246–253

[8] Zhang Z., Chen Y., Zhang Y., Gao K., Zuo L., Qi Y.: Tribology characteristics of ex-situ and in-situ tungsten carbide particles reinforced iron matrix composites produced by spark plasma sintering. Journal of Alloys and Compounds, 704 (2017), 260–268

[9] Pagounis E., Lindroos V.K., Talvitie M.: Influence of reinforcement volume fraction and size on the microstructure and abrasion wear resistance of hot Isostatic pressed white iron matrix composites. Metallurgical and Materials Transactions A, 27, 12 (1996), 4171–4181

[10] Ashok K.S., Karabi D.: The abrasive wear resistance of TiC and (Ti,W)C-reinforced Fe-17Mn austenitic steel matrix composites. Tribology International, 43 (2010), 944–950

[11] Sulima I., Jaworska L., Wyżga P., Perek-Nowak M.: The influence of reinforcing particles on mechanical and tribological properties and microstructure of the steel-TiB_2 composites. Journal of Achievements in Materials and Manufacturing Engineering, 48, 1 (2011), 52–57

[12] Tjong S.C., Lau K.C.: Sliding wear of stainless steel matrix composite reinforced with TiB_2 particles. Materials Letters, 4, 4 (1999), 153–158

[13] Tjong S.C., Lau K.C.: Abrasion resistance of stainless-steel composites reinforced with hard TiB_2 particles. Composites Science and Technology, 60, 8 (2000), 1141–1146

[14] Sulima I., Figiel P., Kurtyka P.: Austenitic stainless steel-TiB_2 composities obtained by HP-HT method. Composities. Theory and Practice, 4 (2012), 245–250

[15] ISO 20808:2004 – Fine ceramics (advanced ceramics, advanced technical ceramics) – Determination of friction and wear characteristics of monolithic ceramics by ball-on-disc method

[16] Meozzi M.: Special use of the ball on disc standard test. Tribology International, 39, 6 (2006), 496–505

[17] Shackelford J.F., Alexander W.: CRC Materials Science and Engineering Handbook, Third Edition, CRC Press, 2001