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Tribological Properties of EN-GJL-150 grey Cast Iron Composites Produced Using Porous SiC and Al_2O_3 Inserts

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Abstract

The article presents the tribological properties of a newly developed cast iron–ceramic composite designed for modern braking systems, such as brake discs. The composite matrix consists of grey cast iron with flake graphite (EN-GJL-150), while the reinforcing phase comprises 10% SiC and 10% Al_2O_3 particles applied onto a porous structure. Tribological tests were performed using a pin-on-disc setup, and the results were compared with a standard friction material P50 094, representing PEX-type brake pads. The results indicate that reinforcing the matrix with ceramic particles significantly alters the tribological wear mechanism. Composites EN-GJL-150+SiC and EN-GJL-150+Al_2O_3 showed an almost fivefold reduction in mass loss compared to pure cast iron. In the tested pairings, wear of the friction material was also reduced, suggesting a synergistic improvement in the durability of the entire tribological system. The coefficient of friction for cast iron samples reinforced with SiC and Al_2O_3 ranged from $\mu = 0.20$–0.30, in contrast to the large variations ($\mu = 0.16$–0.46) observed in cast iron without reinforcing particles. In composites containing porous ceramic inserts, no characteristic running-in period to reach stable friction values was observed. The obtained results of reduced wear of friction components and lower scatter of the coefficient of friction for grey cast iron-based composites are promising. However, further studies are required, mainly for a comprehensive evaluation of other functional properties, including the selection of friction pad material and reduction of environmental dust from wear products, as required by the new European Union directives (e.g., EURO 7 standards).

Keywords: EN-GJL-150 cast iron, SiC and Al_2O_3 reinforcing particles, Tribological properties, Coefficient of friction

1. Introduction

One of the main components in terms of user safety and the technical level of a vehicle is the braking system. Its purpose is to reduce vehicle speed or bring it to a stop in the shortest possible time, regardless of road surface conditions or weather. The operation of the braking system essentially involves converting the vehicle's kinetic energy into thermal energy. The development of brakes for motor vehicles is continuously aimed at improving efficiency, reliability, and the stability of the braking vehicle.

The literature includes studies on the search for new materials for brake discs, but most often these are composites based on, for example, spheroidal cast iron [1, 2] or aluminium [3, 4]. The use of these materials stems from their good functional properties. For example, EN-GJS-600/700 spheroidal cast iron has approximately 2.5 times higher resistance to abrasive wear than grey cast iron. However, castings made from spheroidal cast iron are 30–50% more expensive to produce than grey cast iron. This is due to the complexity of the casting process and the use of cleaner, and therefore more expensive, charge materials (lower sulphur and phosphorus content).

Another significant factor is the need for additional metallurgical treatments (spheroidization, modification, heat treatment) using specialized equipment. In mass production, these are very important factors that work against the competitiveness of spheroidal castings. For this reason, alternative and cheaper materials are being sought for modern automotive designs. One such material is grey cast iron, whose properties can be improved using various matrix reinforcement methods. Moreover, grey cast iron castings meet basic quality requirements, which explains their wide application in many key industrial sectors, such as transportation and energy [5, 6]. This is because grey cast iron has many advantages, including the ability to produce castings with complex shapes, ease of machining, and the capacity to absorb high vibrations [7-9]. However, grey cast iron also has disadvantages, particularly its high brittleness, which makes it unable to withstand cyclic mechanical loads. The poor mechanical properties of grey cast iron can be improved by the addition of various elements [10-12] and by heat treatment [13]. Alloying elements added to cast iron, mainly Si, Mn, Cr, Ni, Mg, S, Cu, and Mo, are intended to enhance mechanical properties such as hardness, strength, ductility, impact toughness, and corrosion resistance [14, 15].

Recently, it has been noted that phenomena occurring during cast iron solidification indicate the potential for combining an iron matrix with advanced technical ceramics. The possibility of producing iron-based multiphase materials is one of the more interesting challenges in modern materials engineering. The mutual interaction between liquid iron and ceramic particles, such as aluminum oxide (Al_2O_3) or silicon carbide (SiC), leads to the combination of the advantageous physicochemical properties of cast iron and ceramics. This mainly concerns low wettability, small differences in thermal expansion and thermal conductivity, and high vibration damping. It is also beneficial that nuclei form on the surface of the ceramic, thereby strengthening the bonding of the integrated phases of the composite. In the context of broadly understood casting technology, the term ”composite” refers to the production of metal matrix composites (MMCs), where reinforcement, e.g., in the form of particles or fibers, is distributed throughout the metal matrix to achieve optimal material properties [16]. One of these properties is wear resistance, which is considered the key parameter of the practical significance of cast iron in industry [17, 18], especially in transportation [7]. Numerous studies [19] show that the durability and reliability of machines and equipment are primarily determined by the wear resistance of friction components, their lubrication, and the energy required to overcome friction. The surface layers of moving components of machines and equipment [20, 21], as well as cast iron-based multiphase composites [19], play a significant role in achieving this objective.

Regardless of the production technology of wear-resistant materials, new studies are justified by the pursuit of improving the efficiency of tribological systems while complying with rigorous environmental standards. Modern brake systems therefore require components capable of absorbing and rapidly dissipating large amounts of kinetic energy while maintaining structural integrity. At the same time, it should be noted that non-exhaust emissions, such as tire wear particles and brake wear dust, will soon be subject to mandatory limits. The implementation of particulate matter (PM) emission limits imposed by the European Parliament under Euro 7 [22] requires a radical redesign of brake systems. This environmental condition, which relates to the mass of airborne particles generated by friction, requires the use of materials with improved wear resistance. Thus, future design considerations for brake disc materials depend not only on braking performance (i.e., reducing stopping distances) but also on minimizing non-exhaust particulate emissions.

2. Scope and aim of investigations

The aim of this study was to determine the effect of SiC or Al_2O_3 particles in a composites based on EN-GJL-150 cast iron on selected tribological properties and to compare the results with cast iron without the reinforcing phase. The study investigated three friction pairs in which the test specimens were:

1. composite: EN-GJL-150 grey cast iron reinforced with SiC,
2. composite: EN-GJL-150 grey cast iron reinforced with Al_2O_3,
3. EN-GJL-150 grey cast iron without ceramic particles.

The counterbody was the P50 094 friction material, representing a typical brake pad.

To achieve this objective, the scope of the study included:

- the development of a concept for melting and casting an EN-GJL-150 grey cast iron composite with ceramic particles (SiC or Al_2O_3),
- investigation of tribological properties, including cast iron specimen mass loss (Δm_GJL), counterbody mass loss (Δm_P), and the coefficient of friction (μ),
- macro- and microstructural analysis.

3. Research materials and methodology

3.1. Tribological testing methodology

Commercial EN-GJL-150 cast iron, used for casting brake discs and brake drums, was selected for the study. Casting was carried out at 1430-1450°C into a 300×300 mm sand mould, with a mould cavity of 150×100×20 mm. A porous insert was placed in the central of the mould box characterized by a pore density of 10 ppi. The ceramic foam insert was made by coating polyurethane foam with a SiC and Al_2O_3-based particle (separately and in combination). To bond the ceramic particles into a uniform porous structure, the entire assembly was fired at 1000°C.

The choice of SiC and Al_2O_3 is based on their very high hardness (2200–2800 HV) and thermal conductivity (320–490 $W \cdot (m \cdot K)^{-1}$ for SiC). However, the main reason for selecting these particles as reinforcement is their chemical activity with cast iron.

The reactivity of SiC at casting temperatures (approximately 1430–1450 °C) promotes wetting by the cast iron, since the contact angle of SiC decreases below 90° at temperatures up to about 1600 °C, where SiC diffusion into cast iron becomes very intense. In addition, silicon is a strongly graphitizing element, which increases the thermodynamic activity of carbon in the liquid solution and reduces its solubility. This leads to local supersaturation of the melt with carbon, which, being unable to remain in solution, precipitates as numerous small graphite nuclei that remain active for a long time after introduction into the melt.

On the other hand, the advantage of Al_2O_3 is its high mechanical and thermal stability. Once incorporated into the composite, it serves as an architectural, stable structural skeleton for the porous insert, resistant to geometrical changes during solidification.

The insert was intended to produce a cast iron - ceramic particle composite. The particle content (10 wt.% SiC or 10 wt.% Al_2O_3) was selected based on industrial practice [23] and previous studies [24]. A reinforcing phase content above 10 % causes only minor changes in tribological properties and is therefore not economically justified.

Specimens with a diameter of 45 mm, a thickness of 5 mm, and a working surface roughness Ra of 1.8 µm were cut from the cast iron castings. The counterbodies were made of commercial P50 094 friction material. This is PEX brake pad material, compliant with OEM standards and ECE-R90 homologation. Brembo P 50 094 brake pads belong to the Premium Prime line and feature Low-Metallic friction material. The chemical composition depends on the type (organic, ceramic, or metallic) and typically contains a mixture of friction materials (aluminium), fillers and binders (synthetic resins), and metal filings (copper and bronze) to improve thermal conductivity, performance at high temperatures, and overall durability and efficiency. Brake pads were cut and turned into pins of 5 mm diameter and 20 mm height. The pad material, with OE parameters, was developed to provide a stable, equivalent coefficient of friction to standard brakes. Tribological tests were conducted at room temperature under dry friction conditions. To ensure repeatable friction conditions and eliminate the influence of random surface factors, the counter-sample was reconditioned each time. The process involved cleaning the counter-sample surface, degreasing it with spirit, and drying it to ambient temperature.

Wear tests were conducted using a T-01M pin-on-disc tribological tester, which is used to investigate friction and wear of structural materials (Institute for Sustainable Technologies, Radom, Poland).

The tribological test parameters were as follows:

- sliding radius, r = 14 mm,
- friction distance s = 5000 m (corresponding to 100 braking cycles of a 2000 kg vehicle in urban traffic),
- unit pressure p_1 = 1 MP,
- sliding speed v = 0.5 $m \cdot s^{-1}$ under friction and wear conditions, corresponding to braking of a vehicle from the minimum permitted speed in a city centre, i.e. 30 $km \cdot h^{-1}$.

The mass loss of the brake disc material specimen (Δm_GJL) and the mass loss of the friction material pin (Δm_P) were determined using an HM-300 laboratory balance with an accuracy of 0.1 mg. The specimens were stored in a room with constant temperature and humidity. During the tests, friction forces were measured and recorded using strain-gauge force transducers connected to a Spider 8 strain-gauge bridge, with a root mean square (RMS) measurement error of up to 3%.

Wear tests were conducted under conditions simulating driving a passenger car in city traffic at the lowest permissible speed of 30 $km \cdot h^{-1}$. The assumed speed corresponds to the wear friction conditions in the tribological tests of 0.5 $m \cdot s^{-1}$. The friction distance corresponds to 100 braking cycles of a 2000 kg vehicle in city traffic. Constant dry friction conditions were assumed. Each time, the friction system is considered as unrun-in (brand new).

3.2. Microstructure research methodology

Light microscopy (LM) microstructural examinations were performed using an Olympus GX71MeF2 light microscope (Olympus Global EMC Ltd., Tipton, UK). Ten micrographs were taken, from which selected images are representative of the microstructure of the investigated cast iron with ceramic particles.

SEM/EDS studies were performed using scanning electron microscopy with a Tescan Mira scanning microscope (Tescan Brno, Brno, Czech Republic). The studies were performed on polished and nital-etched and Stead's reagent-etched microsections. The schematic diagram and the location of specimen extraction are shown in Figure 1.

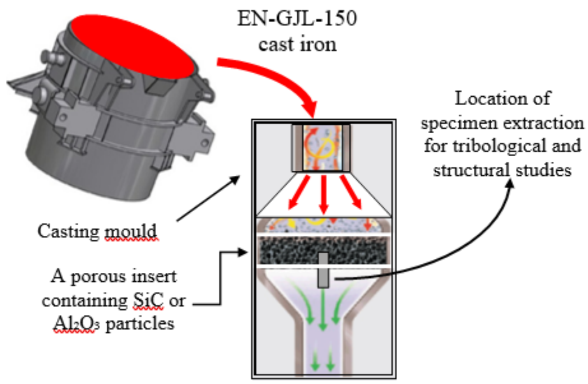


Fig. 1. Schematic of the experimental plan and the specimen extraction method

Tribological test stand is shown in Figure 2.

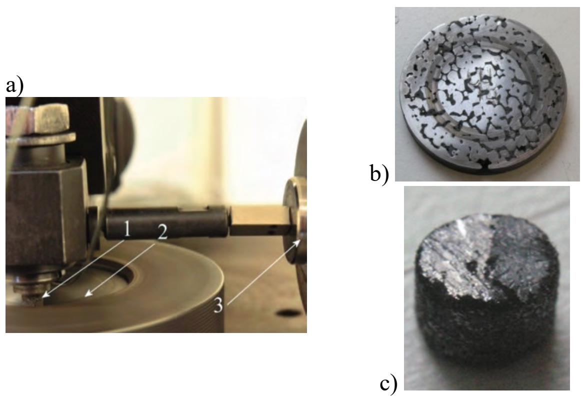


Fig. 2. Experimental setup: (a) T-01M tribological tester; (b) GJL-150+SiC specimen (1); (c) counterbody made of friction material (2); (3) strain-gauge transducer for measuring friction force

4. Test Results

4.1. Tribological Test Results

The chemical composition of the cast iron is presented in Table 1. The tribological test results for EN-GJL-150, EN-GJL-150+SiC and EN-GJL-150+Al_2O_3 composites are presented in Tables 2 - 4. The presented results represent the average values from five repetitions, after excluding the two extreme values.

Table 1.
Chemical composition of EN-GJL-150 cast iron

Element content, wt.%					
C	Si	Mn	P	S	Fe
3.2-3.5	1.8-2.3	0.6-0.8	<0.2	<0.15	93-94

Table 2.
Tribological test results – specimen mass loss Δm_GJL

Specimen designation	Measurement No. 1	2	3	4	5	Δm_GJL (max-min), mg
GJL-150	6.8	19.6	15.6	9.8	21.7	14.9
GJL+SiC	4.0	2.2	3.5	3.8	1.6	2.4
GJL+Al_2O_3	4.0	3.2	2.3	3.5	3.6	1.7
	Mean value, mg			Standard Deviation SD		
GJL-150	14.7			5.66		
GJL+SiC	3.0			0.94		
GJL+Al_2O_3	3.3			0.57		

Table 3.
Tribological test results – counterbody mass loss Δm_P

Specimen designation	Measurement No. 1	2	3	4	5	Δm_P (max-min), mg
GJL	3.0	5.7	8.2	9.9	12.7	9.7
GJL+SiC	2.8	2.4	3.3	3.2	2.3	1.0
GJL+Al_2O_3	5.0	4.4	4.6	4.8	4.2	0.8
	Mean value, mg			Standard Deviation SD		
GJL	7.9			3.34		
GJL+SiC	2.8			0.40		
GJL+Al_2O_3	4.6			0.28		

Table 4.
Tribological test results – friction coefficient

Specimen designation	Measurement No. 1	2	3	4	5
GJL	0.16-0.32	0.26-0.42	0.24-0.40	0.18-0.34	0.22-0.46
GJL+SiC	0.20-0.26	0.20-0.26	0.22-0.30	0.24-0.28	0.22-0.26
GJL+Al_2O_3	0.24-0.26	0.21-0.23	0.24-0.28	0.22-0.24	0.23-0.25

The average values of the friction coefficient change along with error bars are presented in Figure 3.
Representative microstructures of GJL-150 cast iron, GJL-150+SiC, and GJL-150+Al_2O_3 composites are shown in Figure 4.

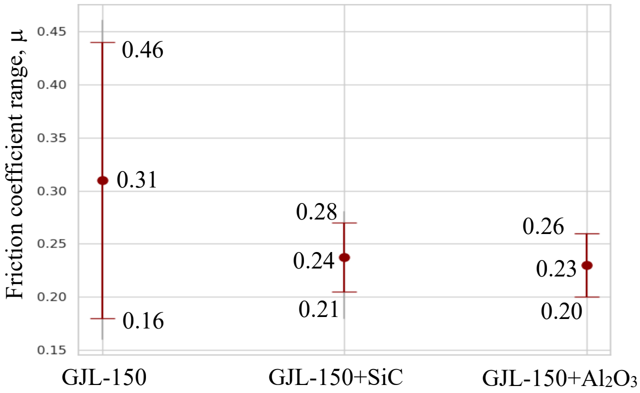


Fig. 3. Change in friction coefficient depending on the material used

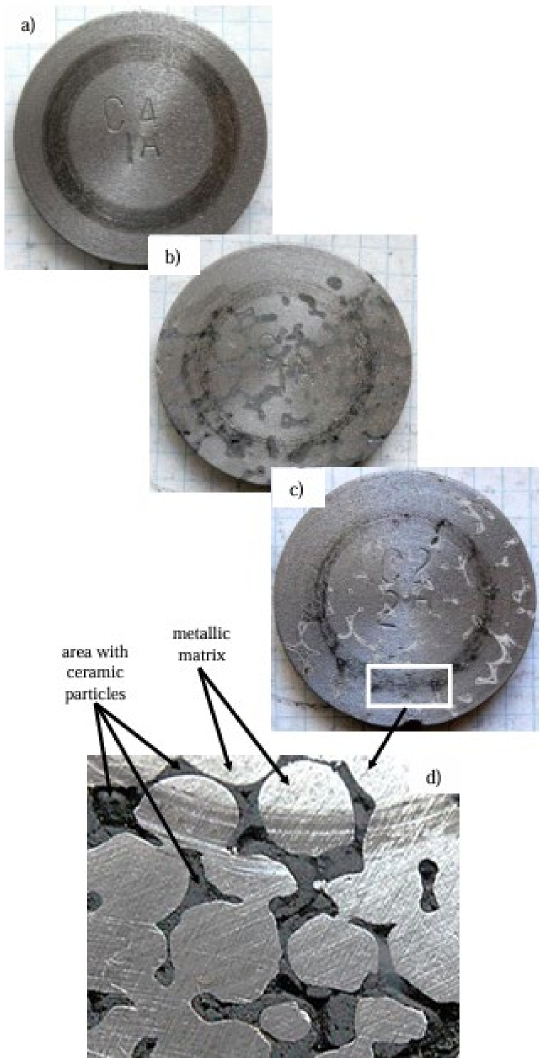


Fig. 4. Macrostructure of the specimens: a) EN-GJL-150 cast iron; b) EN-GJL-150+SiC composite; c) EN-GJL-150+Al_2O_3;

d) fragment of the sample after tribological tests at 200 times magnification

Example plots of the friction coefficient (μ) as a function of sliding distance (S) for the specimen - counterbody pairs are shown in Figure 5.

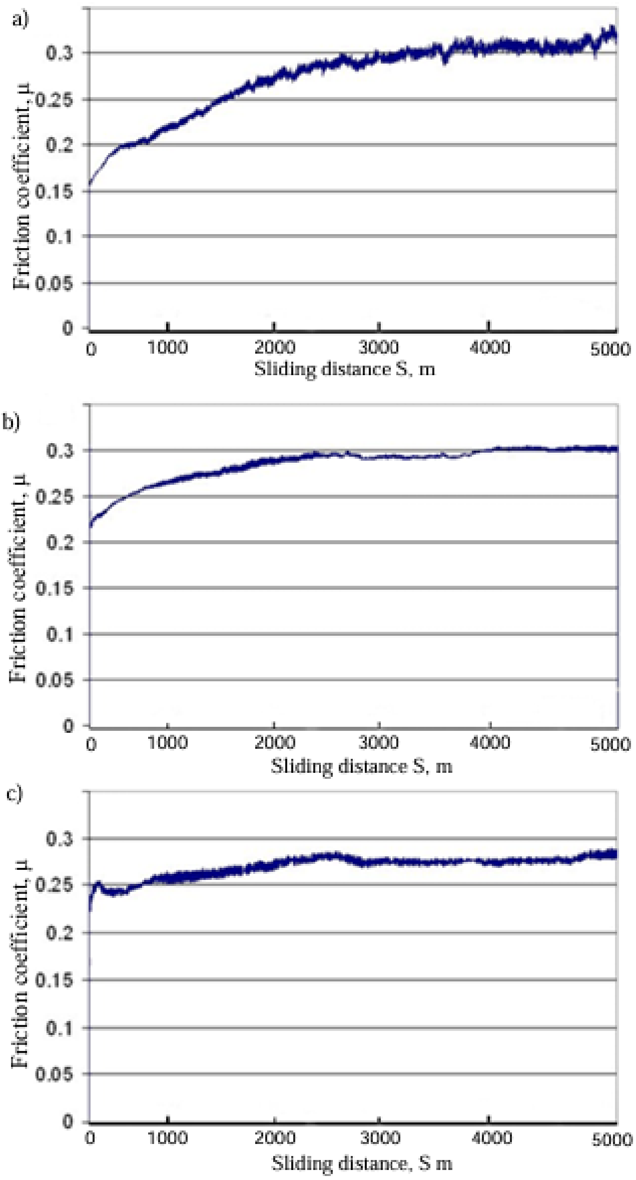
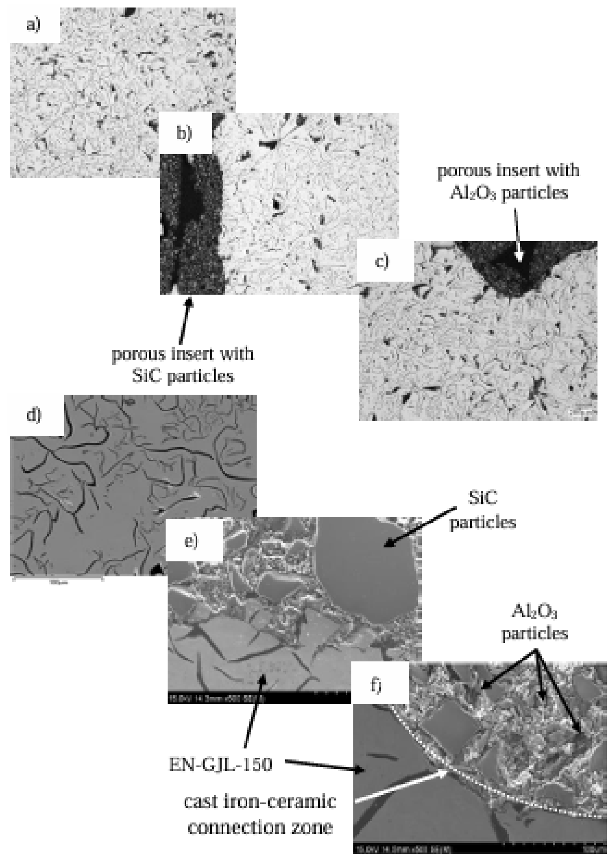


Fig. 5. Friction coefficient as a function of sliding distance for the pairs: (a) EN-GJL-150 cast iron; (b) EN-GJL-150+SiC; (c) EN-GJL-150+Al_2O_3 – counterbody: P50 094 friction material

4.2. Microstructure Test Results

Representative microstructures of EN-GJL-150 cast iron and GJL-150+SiC and GJL-150+Al_2O_3 composites are shown in Figure 6.

To identify the intermetallic phases detected during cast iron microstructure analysis, EDS microstructure tests were performed. The results of these tests for the EN-GJL-150+Al_2O_3 composite are shown in Figure 7. The EN-GJL-150+SiC composite had a very similar phase composition.



g)

Graphite type*	A 75%	E 15%	B 10%
Graphite morphology	Flake		
Size*	3	4	5
Matrix type	100% Pearlite		

* - based on the standard PN-EN ISO 945-1 Microstructure of cast iron - Part 1 Classification of graphite precipitations based on visual analysis.

Fig. 6. Microstructures of the tested cast irons: a, d) EN-GJL-150; b, e) EN-GJL-150+SiC; c, f) EN-GJL-150+Al_2O_3; a-c) LM; d-f) SEM images; g) quantitative analysis of microstructure

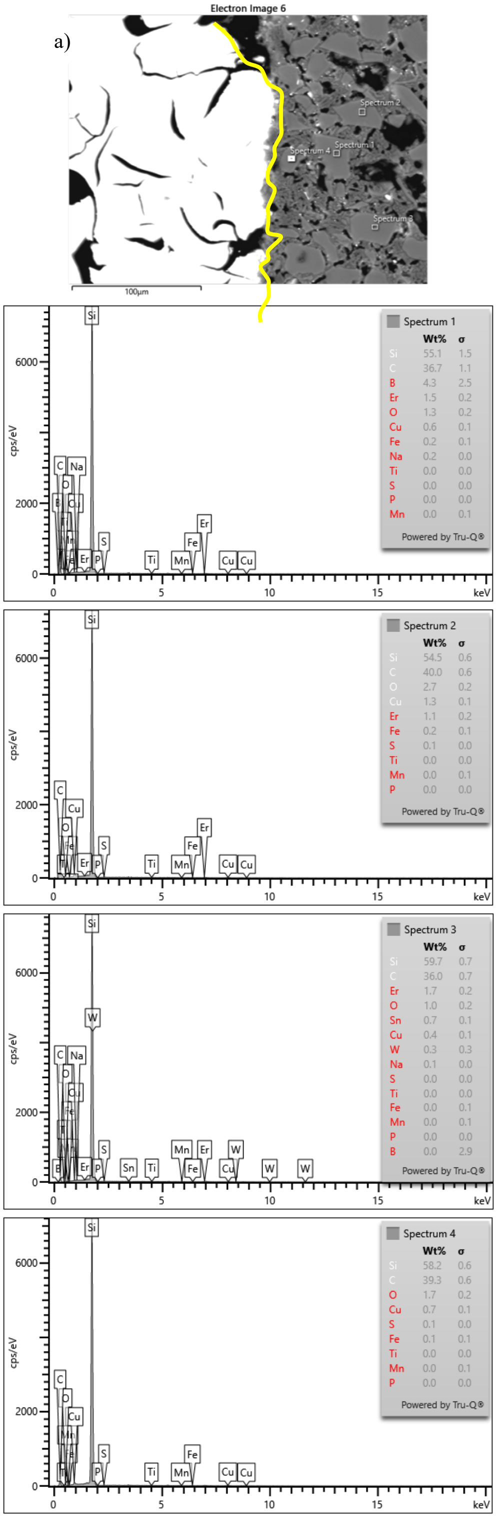


Fig. 7. EDS microstructure (a) and EDS analysis results at points 1; 2; 3; 4 of the EN-GJL-150+Al_2O_3 composite

5. Discussion of results

A key advantage of grey cast iron is its cost-effectiveness resulting from low manufacturing costs. In addition to numerous advantages (good machinability, vibration damping, and good sliding properties), this cast iron exhibits relatively low strength, which can be improved, among others, by the introduction of alloying additions. This can be achieved in various ways [6-9]; however, an innovative approach to strengthening the iron matrix is the introduction of discrete ceramic particles, such as SiC or Al_2O_3, as applied in the present study.

Such a combination of the matrix and the reinforcing phase allows for increased resistance to abrasive wear and improved heat dissipation, while maintaining production costs at a level comparable to traditional cast iron melting and modification processes.

The present study focuses on the comparison of selected tribological properties - namely the mass loss of the cast iron specimen (Δm_GJL), the mass loss of the counterbody (Δm_P), and the friction coefficient (μ) - of the developed composite with those of EN-GJL-150 cast iron currently used for the production of brake discs and brake drums.

To verify the desired effect of SiC and Al_2O_3 particles on the strengthening of the pearlitic matrix in the developed composites, VH hardness tests were performed. VH measurements were performed in accordance with the PN-EN ISO 6507-1 standard using a Zwick Roell ZHF hardness tester (GmbH Co. Germany) on separately cast samples. The load was 30 kgf. The test results are presented in Figure 8.

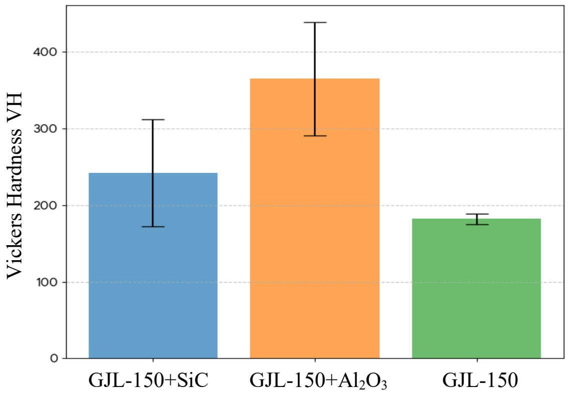


Fig. 8. HV hardness of the tested materials

The specimen represented a brake disc, while the counterbody represented a brake pad.

To determine the effect of porous inserts containing SiC or Al_2O_3 on the tribological properties of the cast iron matrix, comparative tests were carried out on the following three friction pairs:

- specimen: EN-GJL-150 cast iron – counterbody: P50 094 friction material,
- specimen: EN-GJL-150+10% SiC composite - counterbody: P50 094 friction material,
- specimen: EN-GJL-150+10% Al_2O_3 composite - counterbody: P50 094 friction material.

During the tribological tests, a slow increase in the friction coefficient (μ) as a function of sliding distance (S) was observed; however, for the GJL-150+Al_2O_3 specimens, this increase was the smallest (Fig. 5c). As is well known, a higher friction coefficient provides better adhesion and prevents skidding (e.g., in car tires, brake components, and similar applications). It should be noted that the machined specimens were not fully covered with a porous structure. The values of μ=0.3 and μ=0.4, required in the automotive industry [23], were achieved only during the wear of standard EN-GJL-150 cast iron (without ceramic particles).

The lowest wear of both the pin (2.8 mg/5000 m) and the disc (3.03 mg/5000 m) was obtained for specimens containing SiC particles. This is probably a result of the lower coefficient of friction (μ=0.20-0.30). Similar mass loss values and the smallest difference between the tested specimens were observed for porous inserts containing Al_2O_3 particles (3.3 mg/5000 m). However, it should be noted that the wear of the counterbody was higher than that of the tested specimen.

The results of the tribological tests indicate a significant difference in wear among the tested specimens. The reference EN-GJL-150 cast iron exhibited behaviour typical of oxidative - adhesive wear. The high variability in mass loss (from 6.8 mg to 21.7 mg) and fluctuations in the coefficient of friction (μ = 0.16 - 0.46) suggest periodic formation and delamination of oxide layers during the running-in process. When these layers crack, abrasive particles are formed, which significantly accelerate wear, as observed in the EN-GJL-150 cast iron specimen. These results are consistent with previous studies [8, 15, 19, 24].

In contrast, the GJL-150+SiC composite exhibited mild abrasive wear. The foam structure of the SiC insert appears to act as a barrier, preventing direct metal-to-metal contact and inhibiting adhesive wear. It should be emphasized that the precision of the measurement method is limited by the heterogeneity of the tested materials. This applies especially to the counterbody, which, due to its complex chemical composition, is macroscopically heterogeneous. Its components may cause excessive crumbling of the friction lining. It can therefore be concluded that tribological studies should be conducted for a specific type of brake pads used in motor vehicles. A mass comparison of brake disc castings made from the proposed composites was also performed. A brake disc of similar dimensions (diameter 350 mm) made of GJL-150 grey cast iron weighs approximately 5800 g, whereas a disc made of GJL-150+SiC or GJL-150+Al_2O_3 composites has a mass about 10% lower (5220 g).

It should be noted that the advantage of the developed composites is not an increase in the coefficient of friction. The small scatter of results is more significant (Fig. 3). This potential could be worth developing, as a small scatter of results is a benefit of the brakes in terms of efficiency and even wear. To fully demonstrate the advantages of composite cast iron-ceramic brake discs compared to pure cast iron discs, a dedicated brake pad material for the developed composites would need to be found.

The obtained tribological test results clearly confirm the beneficial effect of the applied ceramic reinforcement on the performance parameters of the brake disc. A fourfold reduction in wear products was observed for both the disc and the friction pad. In the SiC sample, higher wear of the brake pad than of the disc was observed. The obtained values of the coefficient of friction for the composite materials indicate that they do not meet current automotive industry requirements. However, it should be emphasized that there are currently no standards or regulations defining the coefficient of friction for grey cast iron–ceramic particle composites. This is a new material (still in the testing phase), which differs in its wear mechanism from standard EN-GJL-150 cast iron, making direct comparison difficult.

The results indicate the need for optimization of the friction pad material. One possible solution could be the use of composite discs paired with ceramic brake pads. The current situation, in which the brake disc contributes more significantly to pad wear, is unacceptable, primarily due to road safety concerns and environmental impact.

The results of the microstructural examination showed that traditional EN-GJL-150 cast iron is characterized by a homogeneous distribution of type A graphite (Fig. 6). The formation of porous structures did not cause any change in the homogeneity of the microstructure of the tested specimens.

Quantitative tests of the microstructure of the developed composites were performed in accordance with the PN-EN ISO 945-1 standard. Microstructure of cast iron - Part 1 Classification of graphite precipitations based on visual analysis (Fig. 6). The size of graphite flakes ranges from 3 to 5. There is no degeneration of graphite precipitates and no presence of cementite in the transition zone. Due to technical difficulties in digestion, quantitative measurements of eutectic cells were not performed. In the cast iron region, type A graphite precipitates are still present and are uniformly distributed within the iron matrix. However, it should be emphasized that studies on the influence of SiC and Al_2O_3 particles on changes in the morphology of EN-GJL-150 cast iron microstructural constituents should be continued and are currently at the stage of further experimental investigations.

The introduction of ceramic particles into cast iron significantly changes the crystallization conditions. This results in a combination of bulk crystallization phenomena (on endogenous inclusions) and surface crystallization (on exogenous reinforcement). This creates a unique microstructure of the transition zone – the phase boundary (Fig. 7a). Aluminum oxide, as a passive and stabilizing component, ensures the mechanical integrity of the porous structure (ceramic framework) at high temperatures. Silicon carbide, on the other hand, acts as the active (reactive) component.

The EDS test results confirm the presence of manganese and sulfur in the interfacial area, but this zone is not continuous along the entire length of the connection. Its thickness (from approx. 40 to 80 μm) depends on the diffusion zone of SiC grains. The positive effect on the change in the morphology of graphite flakes is due to the local supersaturation of the cast iron matrix with carbon and silicon according to the reaction:

$$SiC + Fe \rightarrow FeSi + C$$

which play a catalytic role in the graphite nucleation process.

Based on the presented studies, it can be concluded that the use of a porous composite structure based on SiC or Al_2O_3 with a grey cast iron matrix produced positive results in the form of reduced abrasive wear. However, at this stage of the research, it cannot be unequivocally stated whether the effectiveness of a disc–pad system made from such a composite will be higher than that of the traditional solution in which the disc is made of grey cast iron. To fully answer this question, further studies are necessary. It should also be noted that the presented concept of producing composites using a porous structure containing ceramic particles has significant research potential in the field of combining cast iron with ceramics. At this stage of the research, the material appears to meet functional performance requirements; however, further studies should be conducted to assess its influence on other material properties, such as strength, fatigue, heat dissipation, and thermal shocks, etc.

6. Conclusions

The results of the study allow the following conclusions to be drawn:

1. The use of EN-GJL-150+10% SiC and EN-GJL-150+10% Al_2O_3 composites reduces the wear of abrasive elements by approximately five times. It stabilizes the required friction coefficient over a shorter running-in distance than 100 m. This may have potential to improve braking performance under so-called "cold brake" conditions.
2. The use of porous structures containing SiC and Al_2O_3 ceramic particles as a reinforcing phase simplifies the brake disc manufacturing process, ensuring a homogeneous distribution of reinforcement without the need for additional mixing. This reduces production costs and stabilizes the tribological properties, as indicated by a smaller variation in the friction coefficient.
3. The narrow range of friction coefficient (0.20 - 0.30) ensures that the material maintains the required consistency during wear. This is one of the key criteria required by advanced stability control systems. The selection of a dedicated friction material may adjust the friction coefficient to an appropriate level, tailored to the specific application.
4. The presented tribological study is fundamental in nature and suggests further research on new composite materials for brake discs. However, further studies should examine the behaviour of the composites at higher temperatures and over extended braking distances. Additionally, the material should also undergo fatigue testing.

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