Experimental Evaluation of the Tribological Behavior and Mechanical Properties of Cast Iron and Carbon–Ceramic Brake Discs

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Abstract. The practical part of the article focuses on the experimental comparison of brake discs made from two different materials – grey cast iron and a carbon-ceramic composite. Samples were extracted from the examined discs by water-jet cutting and subsequently subjected to a series of laboratory tests. Within the experiment, a spectral analysis of the chemical composition of the cast-iron samples was performed, along with microhardness measurements using the Vickers method on a QATM device, and tribological tests using the Ball-on-Disc method on the UMT TriboLab universal mechanical tester. Measurements were carried out under various loads in order to determine the coefficient of friction and volumetric wear of the materials. The obtained results revealed significant differences between the tested materials in terms of hardness, friction coefficient behavior, and wear resistance. Carbon-ceramic discs exhibited higher hardness and lower wear, whereas cast-iron discs showed variable friction characteristics depending on the applied load. The results provide a sound basis for an objective evaluation of the suitability of each material for different types of operational loading.

Keywords: brake; resistance; temperature; wear; tribology; friction; load.

INTRODUCTION

Brake discs represent highly loaded structural components that are exposed to extreme mechanical, thermal, and tribological conditions during operation. During braking, the kinetic energy of the vehicle is converted into heat, while the contact surfaces of the disc must withstand high contact pressures, steep temperature gradients, and repeated cyclic loading. For this reason, the material of the brake disc is subject to exceptionally demanding requirements in terms of strength, hardness, thermal stability, wear resistance, and heat dissipation.

In modern applications, advanced composite-based materials are increasingly employed, particularly carbon–ceramic materials of the C/SiC type. These materials combine low density with high hardness, excellent thermal resistance, and stability of mechanical properties even at temperatures exceeding 1,000 °C. At the same time, they exhibit specific tribological behavior and a brittle fracture character, which places increased demands on their material analysis and post-service condition assessment [1, 2].

From the perspective of operational safety, not only the proper structural design of the disc is crucial, but also a thorough evaluation of its material properties, microstructure, and changes induced by long-term thermal and

mechanical loading. Wear, formation of microcracks, local overheating, or changes in the structure of the carbon phase can significantly affect the functionality and service life of the disc. Therefore, it is essential to apply experimental methods that enable a comprehensive assessment of the material, including non-destructive and spectroscopic analyses [4].

Spectroscopic material analysis methods make it possible to identify elemental composition, evaluate the distribution of individual phases, and monitor potential degradation processes in the surface layer. When combined with hardness measurements, microscopic surface evaluation, and tribological testing, they provide a comprehensive picture of the material condition after operational loading. This approach is particularly important for composite materials, where the interaction between carbon reinforcement and the ceramic matrix fundamentally influences the resulting properties [3, 5].

The aim of this article is therefore to analyze the brake disc material in terms of its structure, chemical composition, and mechanical properties, with an emphasis on the application of spectroscopic and microscopic methods. Attention is focused on the experimental verification of the suitability of selected analytical procedures for the evaluation of carbon–ceramic composites and on the identification of potential changes caused by operational loading. The research results contribute to a better understanding of material degradation mechanisms and to the optimization of procedures for assessing the service life of brake discs [7, 8, 9].

MATERIALS

Within the experimental research, two types of materials used for the production of brake discs were analyzed: a carbon–ceramic composite of the C/SiC type and a conventional cast iron material based on grey cast iron with flake graphite. The objective was to compare their material, mechanical, and tribological properties with respect to the requirements imposed on highly loaded friction components [13].

The first investigated material was a carbon–ceramic brake disc manufactured from a C/SiC composite (carbon fiber reinforced silicon carbide). The material consists of carbon fibers forming the reinforcing phase and a ceramic matrix based on silicon carbide (SiC), which provides high hardness, thermal stability, and wear resistance. The structure may also contain residual free carbon or silicon formed during the infiltration manufacturing process.

The examined disc was obtained from real service conditions and exhibited signs of long-term thermal and mechanical loading. Surface discoloration caused by thermal cycling, local irregularities of the friction surface, and fine microcracks typical of brittle ceramic materials were identified [14].

Samples were extracted from the disc by water-jet cutting in order to minimize thermal influence on the microstructure. Subsequently, they were ground and polished for microscopic and spectral analysis. The material was characterized in terms of microstructure and hardness. The prepared samples are shown in (Fig. 1). In (Fig.2), a detail of the sample from the carbon–ceramic brake disc prepared for mounting in the measuring device is shown.

Figure 1. Samples for measurements

Figure 2. Carbon–ceramic sample

The second investigated material was a disc made of grey cast iron with flake graphite, representing a traditional material used in brake disc manufacturing. This material is characterized by a pearlitic–ferritic matrix with uniformly

distributed graphite flakes. Graphite acts as a natural solid lubricant, contributing to stabilization of the coefficient of friction and reduction of seizure risk.

The investigated cast iron disc was also obtained from service and exhibited typical signs of wear surface grooving, localized thermal marks, and partial microstructural changes in the surface layer. Compared to the carbon–ceramic material, cast iron has higher density, lower hardness, and significantly higher toughness, which affects its behavior under thermal cycling and mechanical loading.

Samples from the cast iron disc were prepared using the same technological procedure as for the composite material to ensure comparability of results. The material was subjected to microscopic analysis, hardness measurement, and spectral analysis aimed at identifying the main alloying elements (primarily Fe, C, Si, Mn, and other trace elements). The prepared samples are shown in (Fig. 1).

METHODS

To fulfill the objectives of the article and to objectively assess the mechanical properties and wear resistance of the brake discs, several analytical and experimental methods were employed.

In the initial phase of the research, spectral analysis was performed using a dedicated analytical device. The aim of this method was to determine the chemical composition of the investigated materials.

Subsequently, tribological measurements were carried out using a BRUKER UMT TriboLab device. Three measurements were performed on each prepared sample. For these three measurements on a single sample, the applied load remained constant, while the ball track radius was varied (10, 15, and 20 mm). After completing three measurements on one sample, testing continued on another sample with a different applied load, again varying the ball track radius in the same manner as for the first sample. The same procedure was applied to the third sample. The applied normal loads were 5N, 10N, and 15N. The Ball-on-Disc method was used for all tribological tests [11, 12].

Another method employed was hardness measurement using a QATM QNESS 250 CS evo device, performed according to the Vickers method. Hardness testing was conducted to evaluate the mechanical properties of the investigated materials.

By combining visual diagnostics and tribological testing, it was possible to comprehensively assess the wear resistance of the individual materials. More detailed surface analysis was carried out using a confocal microscope (OLYMPUS LEXT OLS 5100), which subsequently enabled calculation of the removed micro-volumes of material during the experiment.

RESULTS

Spectral analysis was performed on samples taken from the cast iron brake disc, as it was not possible to conduct spectral analysis of the carbon–ceramic sample using the given device. A total of ten measurements were carried out on the instrument and subsequently averaged to obtain a single mean value. The percentage composition of chemical elements in the cast iron brake disc samples is presented in (Tab. 1).

Table 1. Result of the spectral analysis of the cast iron sample

Chem. element	**C**	**Si**	**Mn**	**P**	**S**	**Cu**	**W**	**Sn**	**B**	**Fe**
Content [%]	2.71	0.59	0.37	0.01	0.11	0.16	0.62	0.04	0.01	94.40

The initial hardness measurements were carried out on a sample taken from the cast iron brake disc (Tab. 2). The surface of the examined specimen observed under the microscope is shown in Fig. 3. A total of five Vickers hardness measurements were performed using a load of HV1. Based on the arithmetic mean of the five values, the average hardness of the material was determined to be 318 HV1.

(Fig.4) shows the indentation marks formed after the measurements were performed. This procedure enabled reliable evaluation of the material hardness and simultaneously provided visual verification of the indentation geometry and the surface response of the investigated cast iron sample.

Table 2. Hardness measurements of the cast iron sample

Measurement No.	**HV 1**

1	331
2	305
3	322
4	306
5	326
Arithmetic mean	**318**

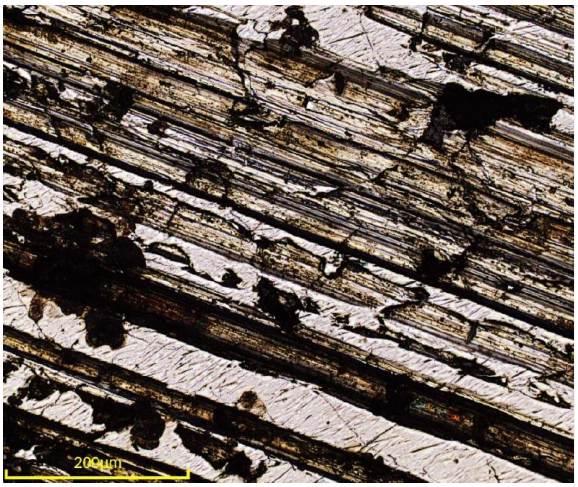

Figure 3. Surface of the cast iron sample under the microscope

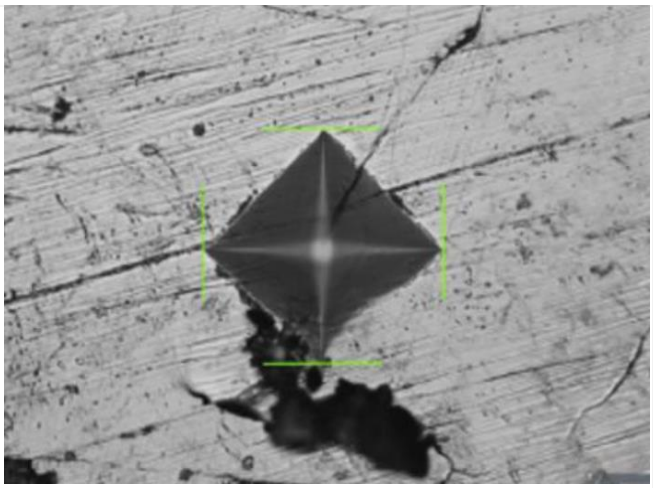

Figure 4. Hardness measurement on a sample from the cast iron brake disc

Additional hardness measurements were performed on the carbon–ceramic sample. Since this is a composite material, the measurements on a single specimen were divided into two groups. The microstructure of the sample was clearly visible under the microscope, which allowed distinction between carbon grains and silicon grains. The surface structure of the carbon–ceramic sample is shown in (Fig. 5), where both silicon and carbon grains can be observed. Furthermore, wear in the form of a crack propagating across the entire sample is visible. Such cracks were present throughout the carbon–ceramic brake disc and are indicative of long-term service and significant wear. This type of brake disc tends to develop cracks during wear, a behavior that is not typical for conventional cast iron brake discs.

The first hardness measurements on the carbon–ceramic sample were carried out on carbon grains. Again, five measurements were performed. As these areas are considerably more brittle, a lower load of HV0.2 was applied to prevent surface cracking. After completing the five measurements, the values were averaged, resulting in a hardness of 626 HV0.2 for the carbon grains of the carbon–ceramic samples (Tab. 3).

The final hardness measurements were conducted on the same carbon–ceramic sample, this time focusing on silicon grains (white phase) as shown in (Fig. 6). Since these regions were significantly harder, the measurements were performed under a load of HV1. After five measurements on the silicon grains, the arithmetic mean indicated that the hardness in these locations reached 2,728 HV1 (Tab. 4).

Table 3. Hardness of the carbon grain

Measurement No.	HV 0,2
1	631
2	625
3	619
4	626
5	629
Arithmetic mean	**626**

Table 4. Hardness of the silicon grain

Measurement No.	HV 1
1	2,678
2	2,885
3	2,653
4	2,672
5	2,752
Arithmetic mean	**2,728**

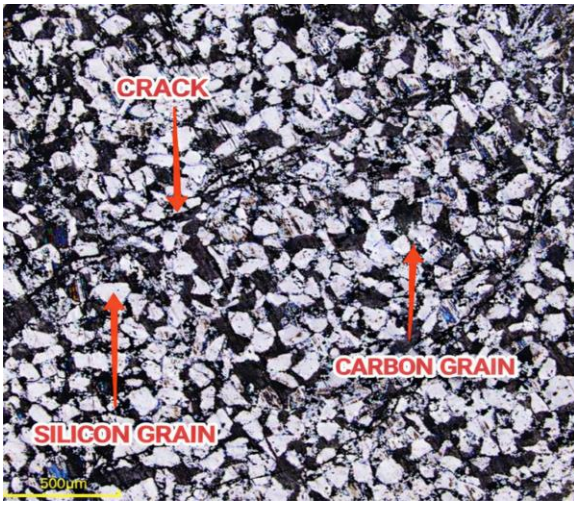

Figure 5. Surface structure of the carbon–ceramic sample

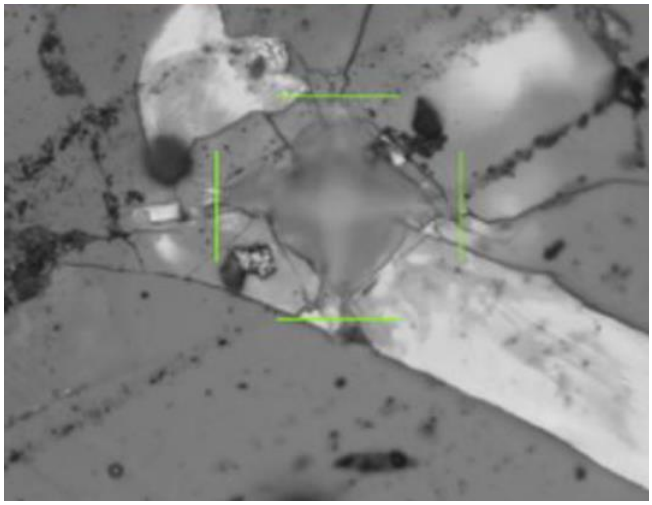

Figure 6. Silicon grain – white trace

The next step involved the tribological evaluation of the samples. (Fig.7) compares the measurements performed under different loads and identical ball track radii on three samples taken from carbon–ceramic brake discs.

The COF results of the carbon–ceramic brake disc indicate that the coefficient of friction slightly decreases with increasing load. This behavior is influenced by temperature, which rises as the applied load increases and directly contributes to the reduction in COF.

An important observation in monitoring the coefficient of friction of the carbon–ceramic samples is that, after a short running-in period (separated by the red line), all measurements reach stable COF values. This means that the coefficient of friction achieves a steady-state condition and remains nearly constant thereafter. It can therefore be concluded that the average COF value, with respect to the given rotational speed, is approximately 0.55.

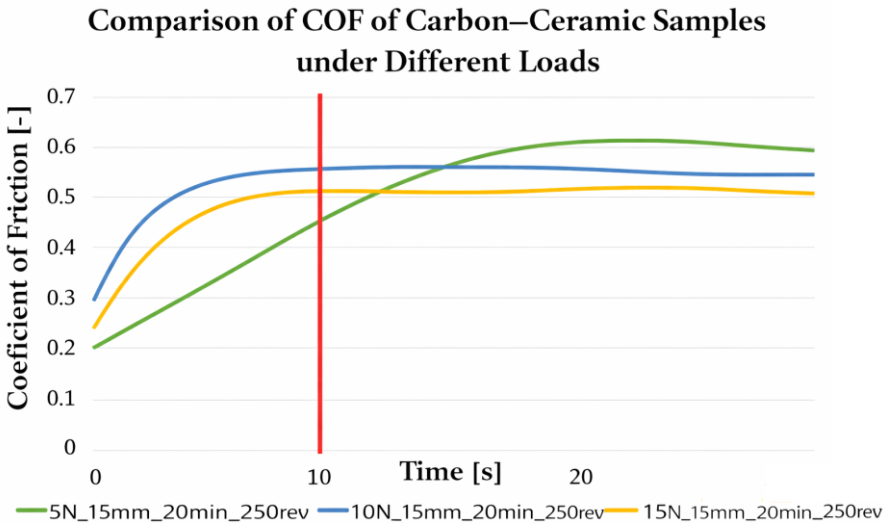

Figure 7. Comparison of the COF of Carbon–Ceramic Samples

(Fig.8) compares the measurements performed under different loads and identical ball track radii on three samples taken from cast iron brake discs. The red line again represents the running-in phase of the measurement.

In this case, the COF results differ from those obtained for the carbon–ceramic brake disc samples. First, the COF values in all measurements exhibit a slightly increasing trend over time. Compared to the coefficient of friction values of the carbon–ceramic samples, the COF values of the cast iron samples are approximately half, around 0.25. In practical terms, this indicates lower frictional resistance during braking and consequently a lower braking effect.

With increasing load, it can be concluded that the coefficient of friction also increases. Although the highest COF value was achieved at a load of 10N, it should be noted that at a load of 15N, the COF values overlap with those measured at 10N in certain intervals.

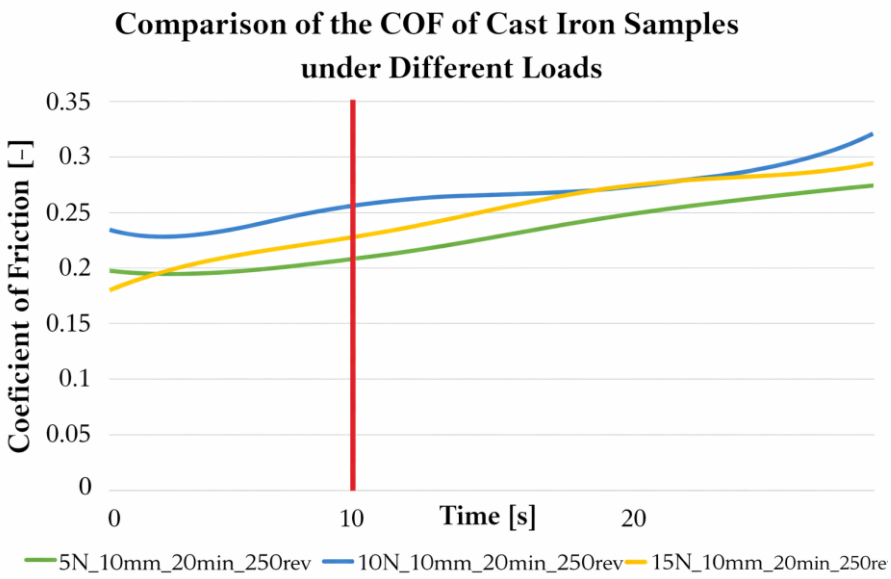

Figure 8. Comparison of the COF of Cast Iron Samples

After the measurements performed on the UMT TriboLab device, the wear volume of the investigated samples was calculated based on the resulting wear tracks.

In (Fig.9), the upper part shows the wear track and its width formed by the ball during testing on the carbon–ceramic sample at a load of 10N and a ball track radius of 10 mm. The measured width of the wear track is 395.299 µm. The lower part of the figure illustrates the measured area corresponding to the surface affected by the ball action.

(Fig.10) presents the same type of evaluation for the cast iron sample, also tested at a load of 10N and a ball track radius of 10 mm. In this case, the width of the resulting wear track is slightly larger, reaching 492.836 µm.

It should be noted that both the wear track widths and the measured areas varied for each individual measurement.

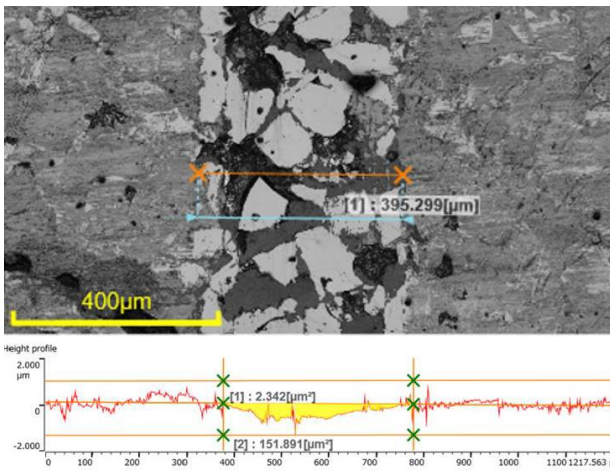

Figure 9. Wear track on the carbon–ceramic sample

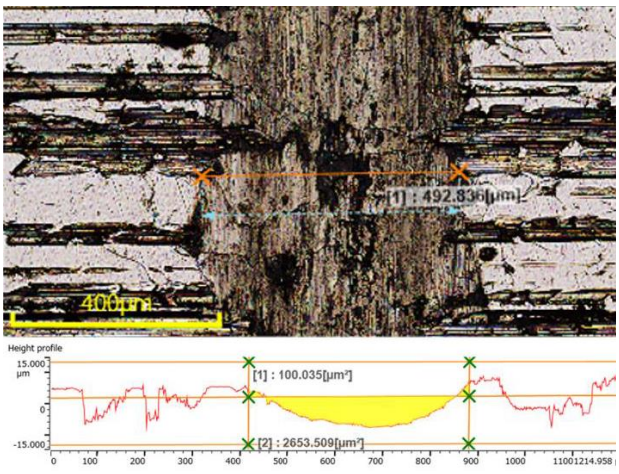

Figure 10. Wear track on the cast iron sample

To calculate the wear volume for the individual samples, it was first necessary to perform three additional measurements for each test conducted on the UMT TriboLab device. These additional measurements allowed three

different locations to be evaluated at each track radius and under each applied load, enabling determination of the cross-sectional areas formed by the ball on the sample surface. The measured values were subsequently averaged into a single representative value, which was used in the calculation.

The calculation procedure consisted of determining the circumference of a circle, into which the corresponding ball track radius for the given measurement was substituted. This circumference was then multiplied by the averaged cross-sectional area value. The final result was converted into mm^3 to obtain the wear volume.

From the graph (Fig. 11), it can be observed that increasing the ball track radius leads to an increase in wear volume at the same applied load. This increase in wear at constant load is caused by higher circumferential speed associated with larger track radii. The graph also clearly shows that higher wear volumes are achieved with increasing load at identical ball track radii. After averaging all measurements, the mean wear volume of the carbon–ceramic samples was determined to be 0.0178 mm^3.

For the cast iron samples, the graph (Fig. 12) indicates that the wear volume results exhibit a similar trend to those of the carbon–ceramic samples. However, the average wear volume of the cast iron samples, calculated from all measurements, reached 0.3335 mm^3. This demonstrates that, compared to the carbon–ceramic samples, the wear volume of the cast iron samples is significantly higher.

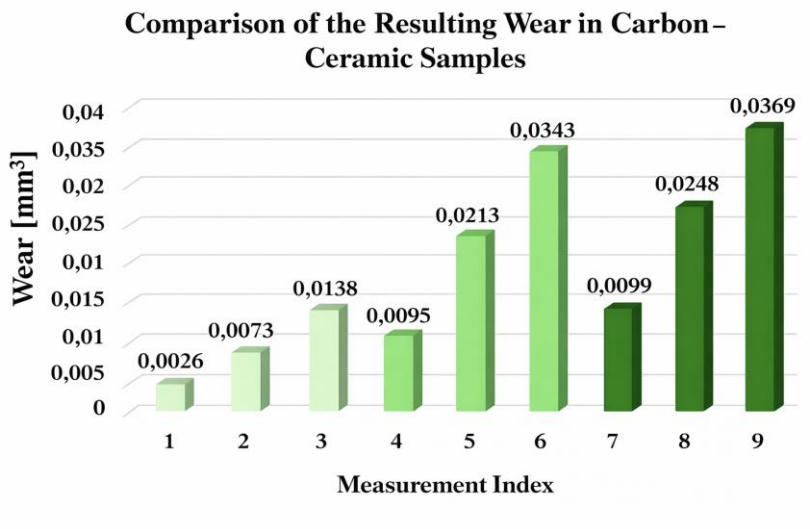

Figure 11. Measured Wear of Carbon–Ceramic Samples

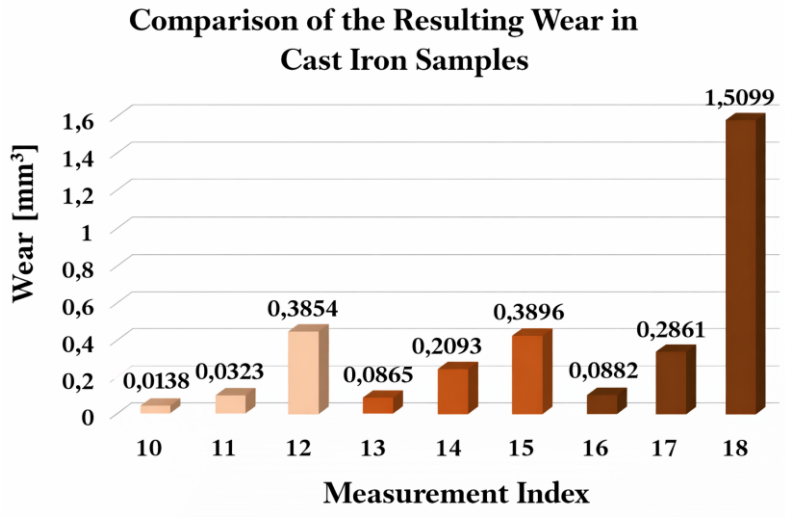

Figure 12. Measured Wear of Cast Iron Samples

DISCUSSION OF RESULTS

The results of this study clearly demonstrate significant differences between carbon–ceramic (C/SiC) composites and conventional grey cast iron, primarily arising from their distinct microstructural characteristics. Grey cast iron with flake graphite exhibits a relatively homogeneous structure with a pearlitic matrix, which is reflected in its measured hardness (318 HV1), consistent with values reported in the literature. This type of microstructure provides good toughness and vibration damping capacity but limits wear resistance.

In contrast, the C/SiC composite is characterized by a highly heterogeneous structure with pronounced differences in phase hardness. The extremely high hardness of SiC grains (2,728 HV1), combined with the softer carbon phase (626 HV0.2), results in a material with excellent wear resistance. This hardness contrast supports load-bearing mechanisms where hard SiC particles carry the majority of the load, while the carbon phase contributes to friction stabilization and partial lubrication effects.

Tribological testing confirmed that C/SiC composites achieve a higher and more stable coefficient of friction (approximately 0.55) compared to grey cast iron (approximately 0.25). The stability of the friction coefficient after the running-in period is particularly important for applications requiring consistent braking performance. The slight decrease in COF with increasing load in C/SiC materials can be attributed to thermal effects and changes in surface interaction mechanisms, which aligns with findings reported in international studies. Conversely, grey cast iron exhibited lower COF values with a slight increasing trend under higher load, indicating lower frictional performance and, consequently, reduced braking efficiency.

The most pronounced difference was observed in wear behavior. The C/SiC composite showed an order-of-magnitude lower wear volume (0.0178 mm^3) compared to grey cast iron (0.3335 mm^3). This confirms the dominant role of the SiC phase in resisting both abrasive and adhesive wear. However, microscopic analysis revealed the presence of cracks in the composite, indicating its brittle nature. This is a well-known limitation of ceramic-based materials, particularly under cyclic thermal and mechanical loading, where crack initiation and propagation may occur.

Grey cast iron, in contrast, demonstrated higher resistance to brittle fracture due to the presence of graphite, but at the expense of significantly higher wear. From a practical standpoint, this represents a trade-off between wear resistance and mechanical tolerance.

CONCLUSIONS

Based on the experimental results, it can be concluded that carbon–ceramic C/SiC composites offer significantly superior performance in terms of hardness, tribological properties, and wear resistance compared to conventional grey cast iron. Their high and stable coefficient of friction, combined with minimal wear, makes them highly suitable for high-performance braking systems subjected to severe thermal and mechanical loads.

On the other hand, grey cast iron remains a viable material for standard automotive applications due to its lower cost, good toughness, and reduced susceptibility to brittle failure. However, its disadvantages include higher wear and lower braking efficiency compared to C/SiC composites.

This study highlights the importance of a comprehensive material evaluation approach, combining mechanical, tribological, and microstructural analyses. Furthermore, it points to the need for future research focused on reducing the brittleness of carbon–ceramic composites, which could further expand their applicability in practical engineering applications.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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