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RESEARCH

Tribotechnical Characteristics of Iron–Cast Iron–Glass Powder Composite Material

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A B S T R A C T

The aim of this study was to evaluate the microstructure and tribological properties of an iron–cast iron–glass (Fe–CI–Glass) composite produced by conventional powder metallurgy and to determine its optimum composition. The composite was fabricated from SLM-12 iron powder, gray cast iron powder, and C88 vacuum glass powder by mixing, compaction, and sintering. The component proportions were varied according to the experimental design. The effects of oxidation, compaction pressure, and glass content on the microstructure and tribological behavior were investigated. Oxidation at 200 °C for 1 h produced a more homogeneous microstructure and stronger bonding between the metallic and glass phases. Tribological tests conducted under a load of 4 MPa and a sliding speed of 1 m/s showed low friction and wear. Graphite in the gray cast iron acted as a solid lubricant, while the glass phase partially filled pores and improved structural homogeneity. Fuzzy Logic and Fuzzy C-Means modeling identified the optimum composition as 52 wt.% Fe, 42 wt.% gray cast iron, and 6 wt.% glass. The results indicate that the investigated composite may be suitable for antifriction applications under the studied conditions.

1. INTRODUCTION

In modern engineering and industrial applications, there is a growing demand for structural materials that combine high mechanical strength, wear resistance, and long-term structural stability. Components such as sliding bearings, friction nodes, filter elements, and various machine parts operating under severe tribological conditions are subjected to high contact stresses, temperature fluctuations, and intensive wear. Under such conditions, traditional monolithic materials often fail to provide the required performance characteristics. Consequently, the development of composite materials with high tribological stability is considered one of the most relevant scientific and technological directions [1,2].

Iron-based powder composite materials are widely utilized due to their low cost, sufficient mechanical strength, and compatibility with classical powder metallurgy technologies. The addition of cast iron and glass components to the iron matrix allows for the purposeful adjustment of the material's microstructure and tribological properties. Specifically, graphite inclusions originating from the cast iron phase function as a solid lubricant during sliding, contributing to a reduction in the coefficient of friction and adhesive wear. The glass phase, in turn, enhances structural homogeneity by partially filling pores and improving interfacial bonding [3-6].

Powder metallurgy technology enables the production of Fe–CI–Glass type composites with controlled porosity and microstructure. Technological parameters such as compaction pressure, sintering temperature, and oxidation regime significantly influence the final mechanical and tribological properties of the composites [7-10]. In particular, controlled pre-sintering oxidation of metal powders can strengthen the interaction between metal and glass phases, leading to improved tribological performance. However, excessive increases in oxidation and sintering parameters may result in structural brittleness and the formation of undesirable oxide phases [11–13].

Analysis of the literature indicates that extensive research has been conducted on iron-based tribological composites and metal–glass systems. However, the combined effect of composition, oxidation regime, and technological parameters on the tribological behavior of ternary Fe–CI–Glass systems has not been sufficiently investigated. Existing studies predominantly focus on the influence of individual components, while limited attention has been paid to the optimization of multiphase structures and the modeling of non-linear relationships between parameters [14].

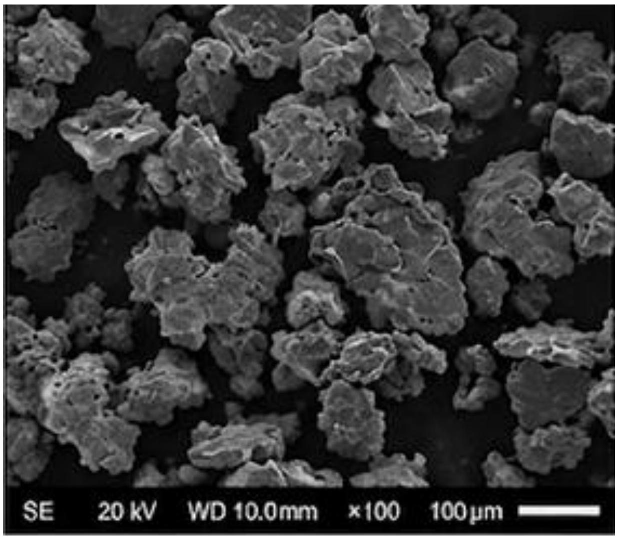
In this regard, the present work focuses on an Fe–CI–Glass multicomponent powder composite, its structural and tribological characterization, and the application of Fuzzy Logic and Fuzzy C-Means approaches for compositional optimization.

The proposed methodology provides a framework for investigating complex non-linear relationships between material composition, technological processing parameters, and tribological properties [15].

The objective of the research was the fabrication of an Fe–CI–Glass powder composite material with high wear resistance and structural stability, and the investigation of its tribological behavior. The effects of the oxidation regime, compaction pressure, and sintering parameters on the composite's microstructure, coefficient of friction, and wear intensity were experimentally evaluated. The obtained results provide valuable data for the optimization of iron-based antifriction composites and their utilization in tribological applications.

2. MATERIALS AND METHODS

SLM-12 iron powder, gray cast iron powder, and C88 vacuum glass powder were used as the main raw materials for preparing the investigated Fe–cast iron–glass antifriction powder composite. SLM-12 iron powder served as the main metallic matrix component and was selected because of its high compressibility and favorable diffusion characteristics. The particle size of the powder was predominantly within the range of 50–160 μm (Fig. 1 a, b, c, d and Table 1).



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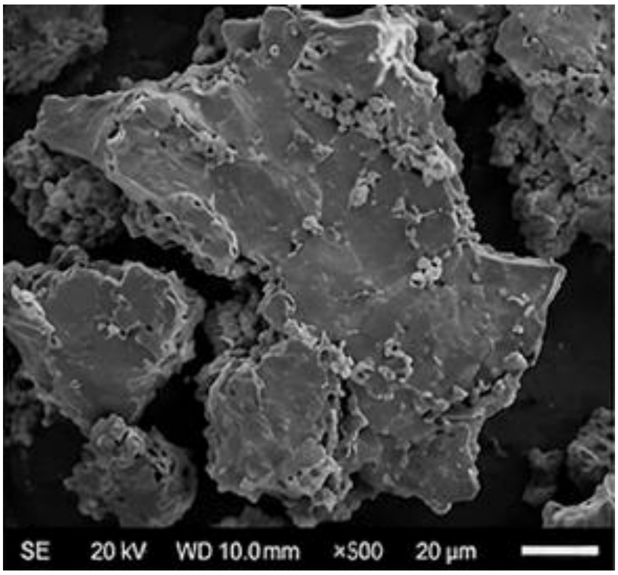

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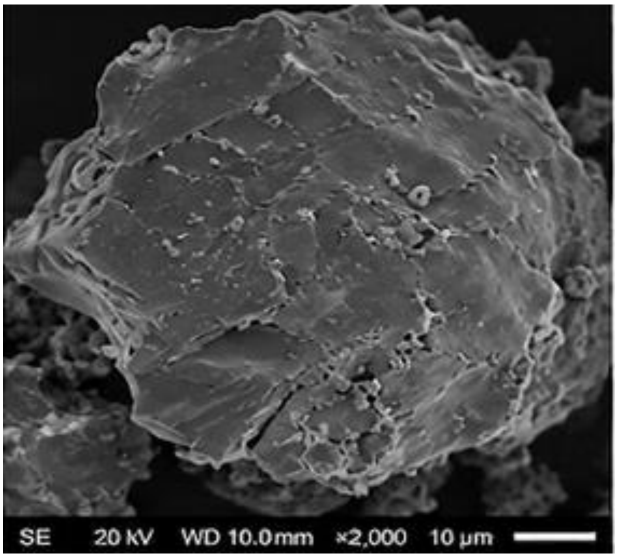

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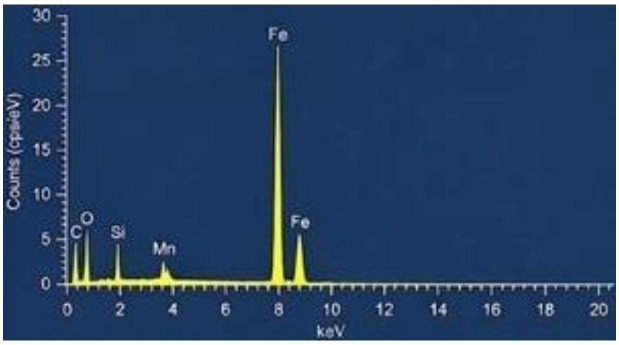

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Fig. 1. SEM micrographs: (a) low-magnification image showing the general morphology and particle size distribution, (b) medium magnification revealing irregular and angular particle geometry, (c) high-magnification image showing rough surface topography with adhered fine particles, (d) EDS spectrum.

Table 1. Elemental composition in weight percent (Wt.%) and atomic percent (At.%).

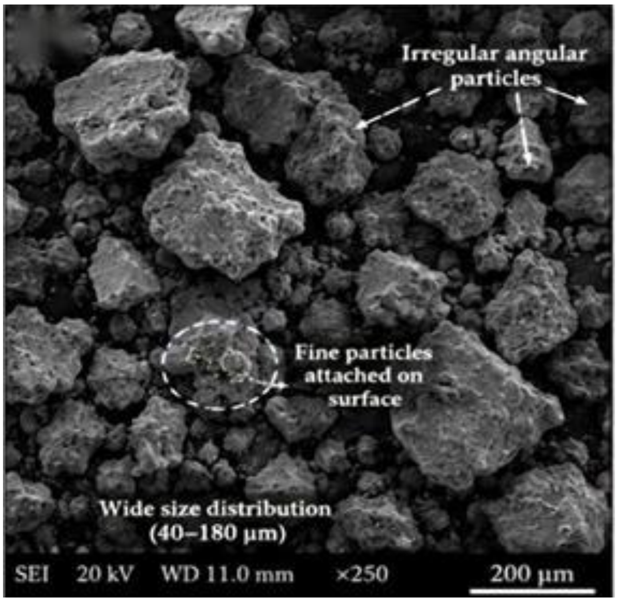
Element	Wt. %	At. %
Fe	95.1	94.3
O	2.8	4.0
Si	1.1	1.0
Mn	0.7	0.5
C	0.3	0.2
Total	**100.0**	**100.0**

Fe is the dominant element, while minor amounts of O, Si, Mn and C are also detected.

SEM observations indicated that the SLM-12 powder particles primarily exhibited a homogeneous structure, with thin oxide layers observed on the surface. These oxide layers played a crucial role in the formation of the metal–glass interfacial bonding during the subsequent steam-thermal oxidation process.

The chemical composition of the gray cast iron powder, used as a reinforcing and antifriction phase, was within the following ranges: C: 3.1–3.9 wt.%, Si: 1.7–3.0 wt.%, Mn: 0.85–1.05 wt.%, P: 0.04–0.09 wt.%, and S: 0.045–0.095 wt.%.

The main function of the cast iron powder was to reduce the coefficient of friction and wear intensity due to the presence of graphite inclusions. The particle size of the cast iron was predominantly in the range of 100–160 µm (Fig. 2 a, b, c, d and Table 2).



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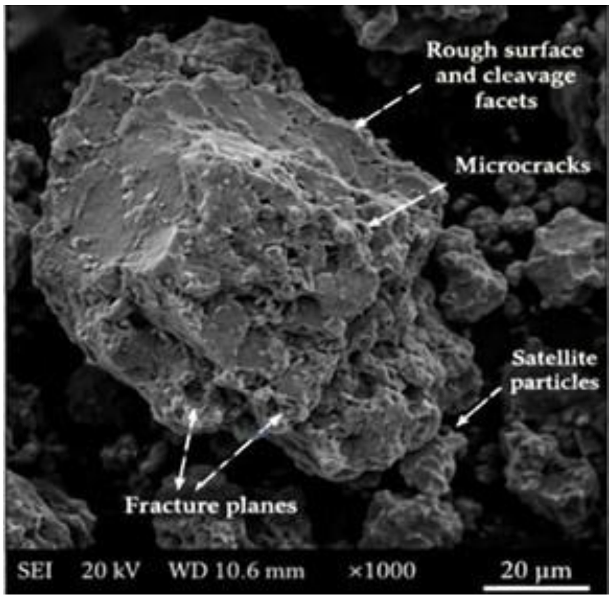

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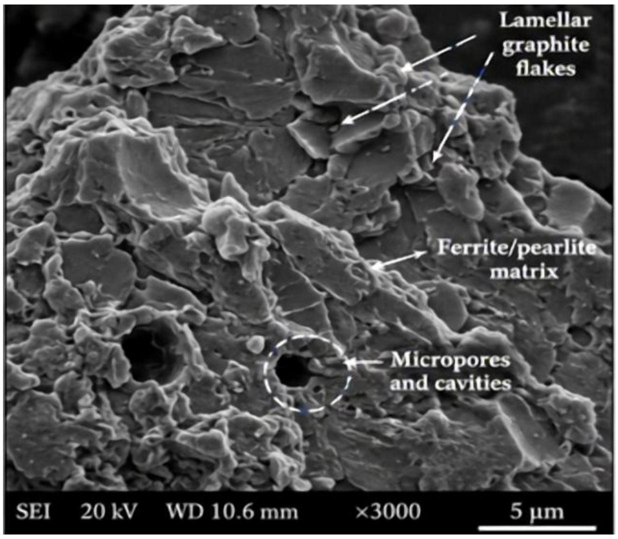

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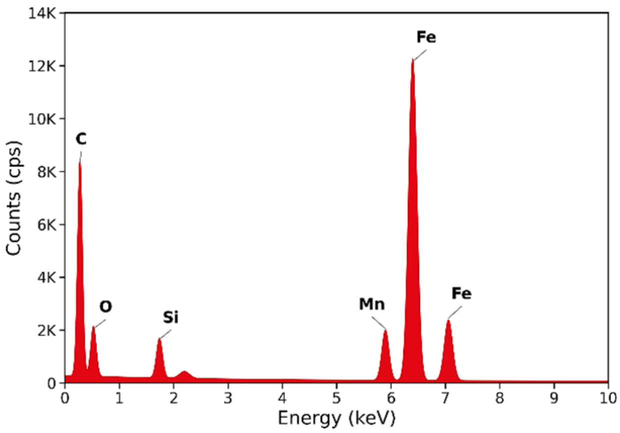


(d)

Fig. 2. Original SEM micrographs and EDS spectrum of the SC-20 (СЧ-20) cast iron powder characterized in the present study: a) low-magnification image (×250), b) medium-magnification image (×1000), c) high-magnification image (×3000), d) EDS spectrum.

Table 2. Elemental composition of SC-20 cast iron powder by EDS.

Elemental composition (wt.%)		**Elemental composition (at.%)**	
Element	wt.%	Element	at.%
Fe	92.80	Fe	86.40
C	3.05	C	9.90
Si	2.10	Si	1.90
Mn	0.72	Mn	0.70
O	0.95	O	1.00
P	0.20	P	0.06
S	0.18	S	0.04
Total	**100.00**	**Total**	**100.00**

C88 vacuum glass powder was used as a binder and structural stabilizing component. The glass powder exhibited a silicate-based amorphous structure and enhanced interparticle bonding by intensifying liquid-phase sintering during the heating process.

The glass particle size was selected within the range of 50–200 μm.

The proportions of iron, cast iron, and glass powders were varied according to the experimental design, with the investigated compositions presented in Tables 4 and 5.

This composition range was selected to achieve high compressibility, optimal porosity, favorable mechanical strength, and superior tribological performance. The powders were selected to ensure good pressability and sinterability, improve structural homogeneity, and enhance the tribological properties of the resulting composite material. The chemical composition and particle size distribution of the powders were chosen in accordance with standard requirements for antifriction powder composite materials. Before mixing, the powders were dried and sieved to obtain a homogeneous particle size distribution. Subsequently, the components were blended in predetermined ratios to produce composite powder mixtures suitable for the pressing and sintering processes (Fig. 3).

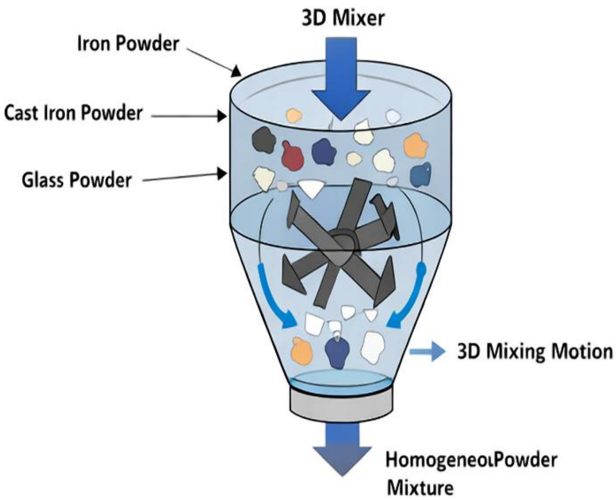


Fig. 3. Schematic of the 3D powder mixer [1,16].

The fabrication of composite samples was carried out based on conventional powder metallurgy technology. This technology encompasses the stages of powder mixing, compaction, oxidation treatment, and sintering. The powder mixtures were thoroughly homogenized in a mechanical mixer to ensure uniform distribution of the metal and glass phases. Twelve experimental replicates were prepared. The powder mixtures were compacted using a hydraulic press in a rigid steel die with a floating die system at compaction pressures of 400, 800, and 1000 MPa.

The pressing process ensured sufficient contact between the powder particles and formed the green density necessary for the subsequent sintering stage. Cylindrical specimens were prepared for the evaluation of mechanical and tribological properties. Following the compaction stage, a portion of the specimens underwent controlled steam-thermal oxidation treatment. This treatment was performed to ensure the formation of a thin oxide layer on the surface of the metal particles, thereby improving the adhesion between the metal matrix and the glass phase during sintering. The effects of these parameters on the structural and tribological properties of the composite materials were studied by varying the oxidation temperature and duration.

The sintering process was carried out in a high-temperature furnace under a controlled atmosphere. The specimens were heated to the required sintering temperature and held at that temperature for a specific period to ensure the formation of strong bonds between the powder particles.

All technological operations involving pressing, sintering, and steam-thermal oxidation were conducted using modern laboratory and industrial equipment from Koyo–Lindberg (USA) and Mannesmann "Elino" (Germany). Microstructural investigations of the prepared composite materials were conducted using modern metallographic and electron microscopy techniques. Metallographic analyses were performed using a NEOPHOT-21 metallographic microscope (Germany) to examine the general microstructure, phase distribution, and porosity levels of the sintered composites. Detailed structural studies were carried out using a Tescan Vega 3 scanning electron microscope (SEM).

This microscope was used to examine interfacial bonding between the metallic and glass phases, phase morphology, and the distribution of graphite inclusions originating from the cast iron powder. The scale of the micrographic structures was 50 μm. Dilatometric studies were conducted to examine the kinetics of the sintering process and the dimensional changes of the powder composites under thermal influence. These studies were performed using a DIL402-2 (NETZSCH) high-temperature dilatometer. Dilatometric measurements allowed for the determination of dimensional changes in the specimens as a function of temperature and time, providing critical data regarding densification mechanisms and phase transformations occurring during sintering.

The mechanical and tribological properties of the prepared composite materials were evaluated based on standard methodologies accepted in the field of powder metallurgy [17]. The primary parameters investigated included microhardness, wear intensity, coefficient of friction, and structural stability of the material. Tribological tests were conducted under dry friction conditions to determine the coefficient of friction and wear intensity of the composite materials. The tests modeled the operating conditions characteristic of sliding bearings and bushings [18]. Following the tests, the wear surfaces were analyzed using optical and electron microscopy techniques to identify the dominant wear mechanisms. This analysis facilitated the evaluation of the influence of composition and technological parameters on the tribological properties. In addition to experimental research, theoretical and numerical methods were employed to analyze the relationships between the material composition, technological parameters, and the properties obtained in the experiments [19]. The theoretical modeling was based on established principles of the mechanics of composite powder materials and deformation theory [17,20].

To describe the relationship between the composition of the composite material and its properties, a data-driven modeling approach based on the Fuzzy C-Means (FCM) clustering method was employed [21,22]. Experimental data obtained from tribological and mechanical testing were analyzed using the FCM clustering technique to identify data groups with similar characteristics. Based on the clustering results, a system of IF–THEN fuzzy rules was established to describe the relationships between the following parameters:

- the compositional makeup of the Fe–CI–Glass powder mixture;
- technological processing parameters (compaction pressure, oxidation conditions, sintering temperature);
- the mechanical and tribological properties of the composite material.

Fuzzy logic modeling enabled the prediction of optimal technological parameters and material composition for the developed composite system [23].

3. RESULTS AND DISCUSSION

This study investigates an iron–cast iron–glass antifriction powder composite, evaluates its tribological properties, and models composition–property relationships using a fuzzy logic approach. The conducted research demonstrated that Fe–CI–Glass powder composite materials can be fabricated with favorable wear resistance, adequate mechanical strength, and stable tribological characteristics. The structural formation behavior of the composite was investigated, and a fuzzy logic-based optimization methodology was proposed.

The selection of the optimal composition for the “iron–cast iron–glass” composite material was substantiated through both theoretical and experimental methods [24]. During the theoretical justification of the charge composition, “If–Then” type fuzzy logic rules were established to describe the interrelationships between the component composition of the material and its mechanical and physical properties. The primary reason for employing fuzzy mathematical logic is the existence of complex non-linear relationships between the composition, technological parameters, and tribological properties within the investigated Fe–CI–Glass composite system. Classic analytical and regression methods are insufficient for the precise description of such systems due to uncertainty, parameter overlap, and multi-parameter interactions. Fuzzy logic modeling allows for the inclusion of uncertain and partially overlapping relationships within the experimental data into a unified predictive framework. Furthermore, the Fuzzy C-Means clustering approach was deemed suitable for selecting the optimal composition and processing parameters of the composite, as it facilitates the identification of hidden correlations between the composition and the mechanical/tribological properties. These rules were derived based on the analysis of experimental data by applying the Fuzzy C-Means (FCM) clustering method [24]. The FCM clustering method was used to partition the dataset in an n-dimensional space into a specified number of fuzzy clusters, (c). The main objective of this method is to find an objective function that minimizes the weighted sum of the distances between data elements and cluster centers. During this process, the degree of membership of each data element to a specific cluster was determined. The membership degree takes values within the range of 0 to 1, indicating the extent to which an element belongs to the respective cluster.

By minimizing the objective function, the data set was divided into clusters, and a center was identified for each cluster. Here, the Euclidean distance was used to determine the distance between cluster elements and cluster centers, while the parameter m determined the level of fuzziness of the clusters. A large volume of experimental data was utilized to establish the relationship between the material composition and its properties. The structure of this data is presented in Table 3.

Table 3. Structure of experimental data.

Experiment	Composition, (%)					Properties		
#	Iron, y_1	...	Cast iron, y_2	...	Glass, y_n	Property 1, z_1	...	Property m, z_m,
1	y_{11}	...	y_{12}	...	y_{1n}	z_{11}	....	z_{1m}
.								
.								
.								
S	y_{s1}	...	y_{s2}	...	y_{sn}	z_{sl}	...	z_{sm}

The experimental data were characterized by a certain degree of uncertainty. Therefore, this uncertainty was taken into account when constructing the model describing the relationship between the material composition and its properties.

Based on the data provided in Table 3, the Fuzzy C-Means (FCM) clustering method was utilized to establish "If–Then" type fuzzy rules. Each cluster was projected onto the coordinate axes of the multidimensional space and expressed in the following general rule format:

IF y_1 is A_{j1} AND ... AND y_n is A_{jn},
THEN z_1 is B_{j1} AND ... AND z_m is B_{jm},
(j = 1, ..., c).

Here A_{j1}, ..., A_{jn} and B_{j1}, ..., B_{jm} are fuzzy sets characterizing the quantities of the material components and its properties, respectively, while c represents the number of formulated rules. Such an approach may be useful for analyzing material properties and supporting the design of similar composite materials. A portion of the experimental data used to model the relationship between the composition of the "iron–cast iron–glass" composite material and its mechanical properties is presented in Table 4. In this model, the input variables are the components of the charge—the amounts of iron, cast iron, and glass powders. The output variables are the indicators characterizing the mechanical properties of the composite material: tensile strength, flexural strength, hardness, impact toughness, and relative density.

Table 4. Fragment of experimental data for the "iron–cast iron–glass" system.

Composition			Properties				
1 (Iron, wt.%)	y_2 (Cast iron, wt.%)	y_3 (Glass, wt.%)	z_1 (σ_b, MPa)	z_2 (σ_f, MPa)	z_3 (HB)	z_4 (KC, kJ/m^2)	z_5 (θ, %)
91	3	6	259	212	57	11	48
19	75	6	142	51	134	12	23
			.				
			.				
			.				
44	50	6	335	357	115	48	91
34	50	16	261	160	54	20	79

As a result of applying the Fuzzy C-Means (FCM) clustering method, the experimental data were partitioned into five clusters, and the following fuzzy rules were derived:

1. If the iron content is high, the cast iron content is below average, and the glass content is at an average level, then the material's strength, hardness, and relative density attain high values.
2. If the iron content is very high, the cast iron content is very low, and the glass content is at an average level, then the mechanical properties are predominantly at average and low levels.
3. If the iron content is very low, the cast iron content is high, and the glass content is at an average level, then while the hardness of the material remains high, other properties attain low values.
4. If the contents of all components are close to average levels, the mechanical properties of the material develop at high or average levels.
5. If the iron content is low, the cast iron content is above average, and the glass content is high, the mechanical properties of the material are primarily at average and low levels.

The fuzzy partition (standard) used during the formulation of the rules is illustrated in Fig. 4.

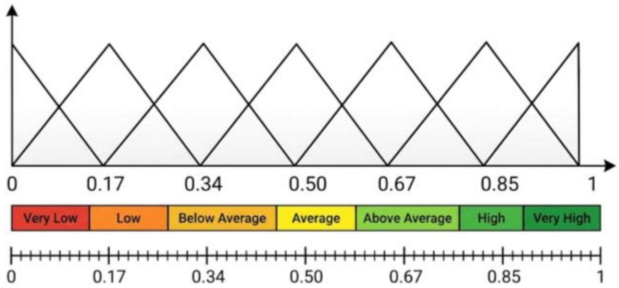


Fig. 4. Fuzzy partition.

To calculate the material composition based on the specified characteristics, the Mamdani fuzzy logic inference algorithm [25] was applied. This algorithm is briefly presented below.

According to the Mamdani fuzzy logic inference algorithm, the value of the model's output variable for the given values of the input variables y is calculated as follows:

1. Membership function values $\mu_{A_{ji}}$ are computed for the fuzzy terms $A_{j1}, \dots, A_{jn}$ of the input variables
2. The activation degrees (or firing levels) of the rules are determined:

$$w_j = \min\left(\mu_{A_{j1}}(x_1), \mu_{A_{j2}}(x_2), \dots, \mu_{A_{jn}}(x_n)\right),$$

where min - represents the logical minimum operator.

3. The "clipped" membership functions for the B_{jl} output terms are calculated:

$$\mu'_{B_{jl}}(y) = w_j \cdot \mu_{B_{jl}}(y).$$

4. Based on the operation of the union of fuzzy sets, the aggregated fuzzy set for the output variable and its membership function are determined:

$$\mu_B(y) = \max\left(\mu'_{B_1}(y), \mu'_{B_2}(y), \ldots, \mu'_{B_m}(y)\right),$$

where, max represents the logical maximum operator.

5. The precise (crisp) value of the output variable is calculated by performing defuzzification using the centroid (center of gravity) method:

$$y^* = \frac{\int_{y_{\min}}^{y_{\max}} y \cdot \mu_B(y)\, dy}{\int_{y_{\min}}^{y_{\max}} \mu_B\,(y)\, dy},$$

where $y_{\min}$ and $y_{\max}$ are the lower and upper bounds of the universe of discourse for the variable y, respectively, and $\int$ denotes the integral sign.

A graphical representation of these rules was constructed within the MATLAB software environment, providing a visual interpretation of the fuzzy partition (Fig. 5.). To calculate the material composition corresponding to the specified mechanical properties, a Mamdani-type fuzzy logic inference algorithm was employed [25-27].

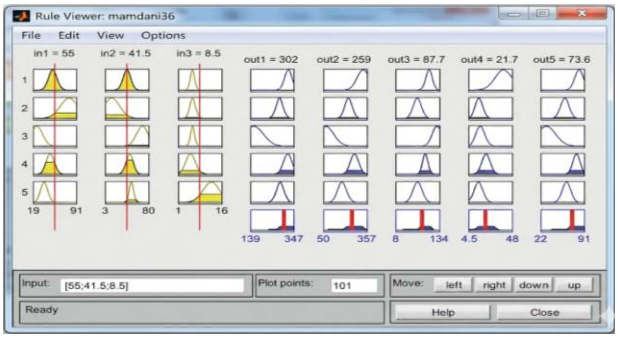


Fig. 5. Graphical representation of the fuzzy rules.

According to this algorithm:

1. The values of the membership functions for the fuzzy terms of the input variables were determined.
2. The activation degrees (firing strengths) of the rules were calculated using the minimum (min) operator.
3. The membership functions of the output terms were clipped.
4. The consequences of the rules were aggregated using the maximum (max) operator to formulate the final fuzzy set.
5. The precise value of the output variable was determined by performing defuzzification using the centroid (center of gravity) method.

Taking into account the following required mechanical properties for the "iron–cast iron–glass" composite material:

- Tensile strength: σ_b = 302 MPa
- Flexural strength: σ_f = 259 MPa
- Hardness: 88 HB
- Impact toughness: KC = 22 kJ/m^2
- Relative density: θ = 73.6 %

Calculations performed based on the fuzzy logic model demonstrated that these properties are achieved with the following composition:

- Iron powder: 52 wt.%
- Cast iron powder: 42 wt.%
- Glass powder: 6 wt.%

During the experimental justification for selecting the charge composition, the optimization of its constituents was carried out using mathematical design of experiments (DOE) methods. In the optimization process, the quantitative ratio of cast iron and glass, as well as the particle size distribution (granulometric composition) of the iron, cast iron, and glass powders, were taken into account. Compaction of the powder mixture was performed in the form of specially prepared test specimens (55×10×10 mm).

The pressing was conducted under a cold compaction pressure of 1000 MPa, followed by a sintering process at a temperature of 1150 °C in an endogas atmosphere for a duration of 5.4 ks [27,28]. The results presented in Table 5 indicate that specimens with a higher content of cast iron (particle sizes of 100–160 μm) and containing 2–6 wt.% vacuum glass (particle sizes of 50–200 μm) exhibit superior strength characteristics.

Table 5. Charge component contents, particle size distribution of cast iron, and mechanical properties of the composition.

Particle content, wt.%		**Particle size distribution, µm**		**Mechanical properties after heat treatment**					
Cast iron	Glass	Cast iron	Glass	ρ, g/cm^3	Porosity, %	σb, MPa	σu, MPa	KC, kJ/m^2	HB
10	6	-160+100	-200+50	6,40	14,6	134	289	285	72
30	6	-160+100	-200+50	6,20	15,4	227	392	241	95
50	6	-160+100	-200+50	6,40	9,3	298	335	281	107
70	6	-160+100	-200+50	6,0	16,0	98	180	92	109
50	2	-160+100	-200+50	6,35	14,4	249	310	119	102
50	10	-160+100	-200+50	6,3	10,1	200	330	199	110
50	6	-630+400	-200+50	5,6	20,5	234	281	127	105
50	6	-400+200	-200+50	5,7	19,5	261	301	193	109
50	6	-100+50	-200+50	5,6	20,3	136	172	192	101
50	6	-160+100	-200+50	6,0	14,0	210	329	187	106
50	6	-160+100	-160+100	6,0	14,6	200	368	160	103
50	6	-160+100	-100+50	6,0	14,6	190	337	204	105

Tribological properties (coefficient of friction and wear rate) were determined under dry friction conditions using a CSM Instruments Linear Tribometer according to a block-on-disk configuration. The disk was fabricated from Grade 45 steel with a post-quenching hardness of HRC 50, while the block was made from the investigated material. The input parameters used for predicting the coefficient of friction and wear rate included:

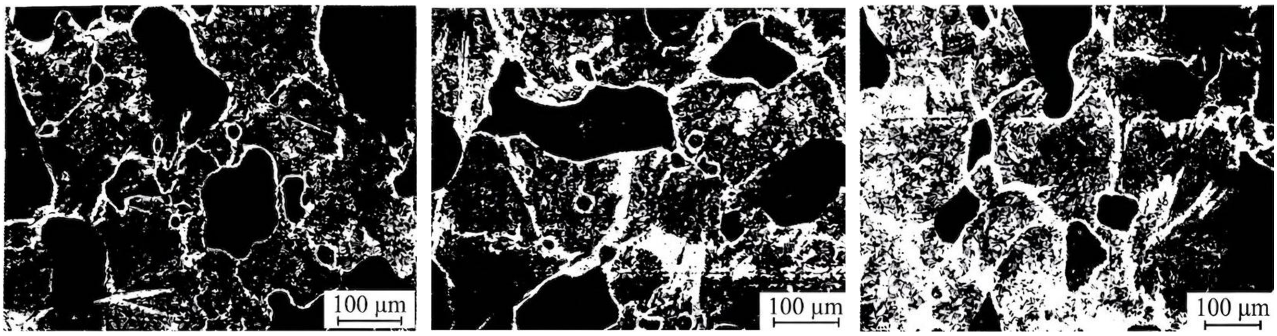
- iron powder content (wt.%);
- cast iron powder content (wt.%);
- glass powder content (wt.%);
- compaction pressure;
- oxidation temperature;
- oxidation duration;
- sintering temperature;
- particle size distribution (PSD) of the powders.

During friction testing, the test specimen was loaded with a constant load at a selected pressure of 4.0 MPa, and the sliding speed was 1.0 m/s. The charge was compacted via cold pressing under a pressure of 1000 MPa and subsequently subjected to a sintering process at 1150 °C in an endothermic gas atmosphere. Since the poor compressibility of the charge is primarily attributed to the brittleness of the cast iron and glass powders, very high cold compaction pressures were applied [29,30].

The influence of oxidation temperature and duration on the tribological properties of the oxidized composite material was studied under dry friction conditions with load of 4 MPa. The green compacts were consolidated in a standard die under a pressure of 1000 MPa.

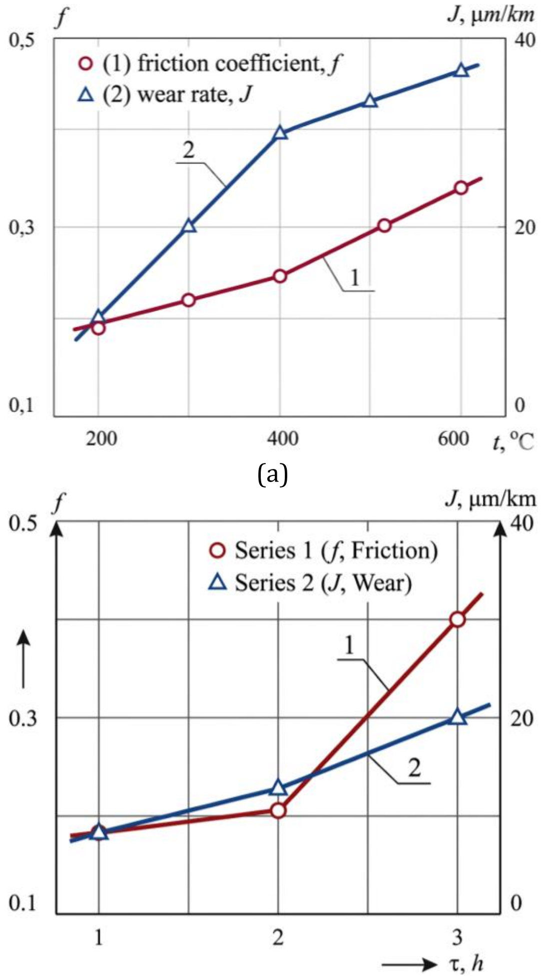
Increasing the oxidation temperature and duration resulted in significant changes in the microstructure of the composite material. Specifically, high-temperature and prolonged oxidation led to the formation of large oxide clusters on the surface of the iron and cast iron particles, while a portion of the pores became filled with metal oxides. These changes caused the weakening of interparticle metallic bonds and the disruption of the material's matrix integrity. Consequently, both the mechanical strength and antifriction properties of the composites deteriorated (Fig. 6 a, b and c).

Tribological tests have shown that the oxidation regime directly influences the friction and wear processes. At a temperature of 200 °C, where the oxide layer has a limited thickness and is more uniformly distributed, a stable tribolayer with a protective effect formed on the material surface. As a result, the lowest values of the friction coefficient (f) and wear rate (J) were achieved (Fig. 7a). In particular, the lowest values of the friction coefficient and wear intensity were recorded after 1 hour of oxidation in air at 200 °C (Fig. 7b). Increasing the oxidation duration to 2 and 3 hours resulted in higher friction and wear values.



(a) (b) (c)

Fig. 6. Microstructure of the Fe–CI–Glass powder composite material oxidized at 200 °C: a), b), c) – oxidation duration of 1, 2, and 3 hours, respectively.



(b)

Fig. 7. Dependence of the coefficient of friction f (1) and wear intensity J (2) of compacted samples on oxidation temperature a) and oxidation duration b).

However, a further increase in the oxidation duration did not yield positive results (Fig. 7 b). The minimum f and J values obtained during a 1-hour isothermal holding at 200 °C indicate that deviating from the optimal oxidation regime causes an excessive increase in the amount of the oxide phase. In this case, hard and brittle oxide particles act as abrasive elements in the friction zone, disrupting the stability of the tribolayer and accelerating wear. The modeling of the wear process of the Fe–Cast Iron–Glass (Fe–CI–Glass) composite material and the analysis of the dominant wear mechanisms have shown that the tribological behavior of the material is closely related to its microstructural features. The wear rate depends significantly not only on external loading parameters but also on the phase composition, porosity level, degree of oxidation, and the distribution of the glass phase. The homogeneous microstructure and uniformly distributed oxide-glass phases formed under the optimal oxidation regime ensure the creation of a protective tribolayer during friction, thereby reducing wear. Conversely, large oxide clusters and non-uniform phase distribution resulting from excessive oxidation cause local stress concentrations, accelerate material destruction, and worsen tribological indicators. A fuzzy logic approach based on experimental results was utilized to model the wear process.

The following variables were accepted as input parameters in the model:

- iron powder content (Fe);
- cast iron powder content (CI);
- glass powder content ($Glass$);
- compaction pressure (P);
- oxidation temperature (T_{ox});
- oxidation duration (t_{ox});
- sintering temperature (T_s);
- particle size distribution (d).

The output variables were defined as:

- friction coefficient (f);
- wear intensity (J) was adopted.

The functional relationship between the variation in wear rate and the technological parameters was expressed in the following general form:

$$J = f(Fe, CI, Glass, P, T_{ox}, t_{ox}, T_s, d)$$

Due to the non-linear nature of the system, a Mamdani-type fuzzy inference algorithm was utilized instead of classical regression models. Based on the fuzzy model, the following was determined:

- An increase in the cast iron phase reduces the coefficient of friction by increasing the quantity of graphite inclusions.
- An optimal amount of the glass phase fills the pores, thereby reducing stress concentration at the contact area.
- Excessive oxidation leads to the formation of brittle oxide clusters on the surface, which accelerates wear intensity.

The physical mechanism of the wear process was evaluated based on SEM analysis and tribological observations. It was established that the primary wear mechanisms in Fe–CI–Glass composite materials are as follows:

- Adhesive wear: Localized micro-welding zones occurred between the metal surfaces during friction. However, graphite inclusions released from the cast iron phase formed a thin solid lubricant layer on the sliding surface, significantly reducing adhesive wear.
- Abrasive wear: Hard oxide particles present within the composite and partially crystallized glass phases exerted a micro-abrasive effect. Large oxide aggregates formed at high oxidation temperatures led to the development of scratches and micro-pitting on the surface.
- Oxidative wear: Secondary oxide layers were formed due to localized temperature increases in the contact zone during friction. Under optimal oxidation conditions, these layers played a protective role, reducing wear intensity. However, the spalling of thick and brittle oxide layers accelerated the wear process.
- Fatigue wear*:* The formation of micro-cracks in the subsurface zones was observed as a result of repeated contact loading. The propagation of these micro-cracks led to localized particle detachment (delamination). Fatigue wear was particularly more intensive in specimens with high porosity.

SEM micrograph analysis showed that in composites with optimal composition, the glass phase was uniformly distributed within the metal matrix and filled a portion of the pores. This resulted in a more homogeneous distribution of stresses across the contact area and retarded the wear process. The composition of the Fe–CI–Glass composite material and its tribological properties were predicted using the proposed Fuzzy Logic model and subsequently compared with experimentally obtained results. To evaluate the accuracy of the model, a quantitative comparison was conducted for the primary output parameters, namely the friction coefficient (f) and wear rate (J). The comparison between the experimentally measured values and the model-predicted results is summarized below in Table 6.

Table 6. Comparison of model predictions with experimental measurements.

Parameter	Experi-mental value	Fuzzy model prediction	Relative error, (%)
Friction coefficient, f	0.42	0.40	4.8
Wear rate, J ($\times 10^{-4}$ mm^3/N·m)	2.85	2.72	4.6
Tensile strength, σ_b (MPa)	302	295	2.3
Hardness, HB	88	86	2.3

The obtained results indicate that the Fuzzy Logic model demonstrates a high level of agreement with the experimental data, with the average relative error ranging between 2% and 5%. This confirms that the model is sufficiently reliable for predicting both tribological and mechanical properties of the investigated composite system. Furthermore, the optimal composition identified via Fuzzy C-Means clustering (approximately 52 wt.% Fe, 42 wt.% cast iron, and 6 wt.% glass) coincides with the experimentally determined composition that provides the lowest wear rate and stable frictional behavior.

This consistency confirms that the model is capable of correctly capturing the underlying structure–property relationships within the system.

Overall, the quantitative comparison demonstrates that the proposed Fuzzy Logic-based approach is an effective and reliable method for the optimization of the Fe–CI–Glass composite system under tribological conditions. Based on the conducted modeling and experimental results, the minimum wear intensity was achieved under the following conditions:

- Iron (*Fe*): approximately 52 wt.%
- Cast Iron: 42 wt.%
- Glass: 6 wt.%
- Oxidation temperature: 200 °C
- Oxidation duration: 1 hour
- Compaction pressure: 1000 MPa

Under these parameters, an optimal interfacial bond was formed between the metal matrix and the glass phase, a stable tribological layer was created on the friction surface, and consequently, minimum values for both the coefficient of friction and wear intensity were achieved.

Analysis of the SEM micrographs indicates that the cast iron and glass particles are relatively homogeneously and uniformly distributed within the iron matrix in the microstructure of the composite material (Fig. 8).

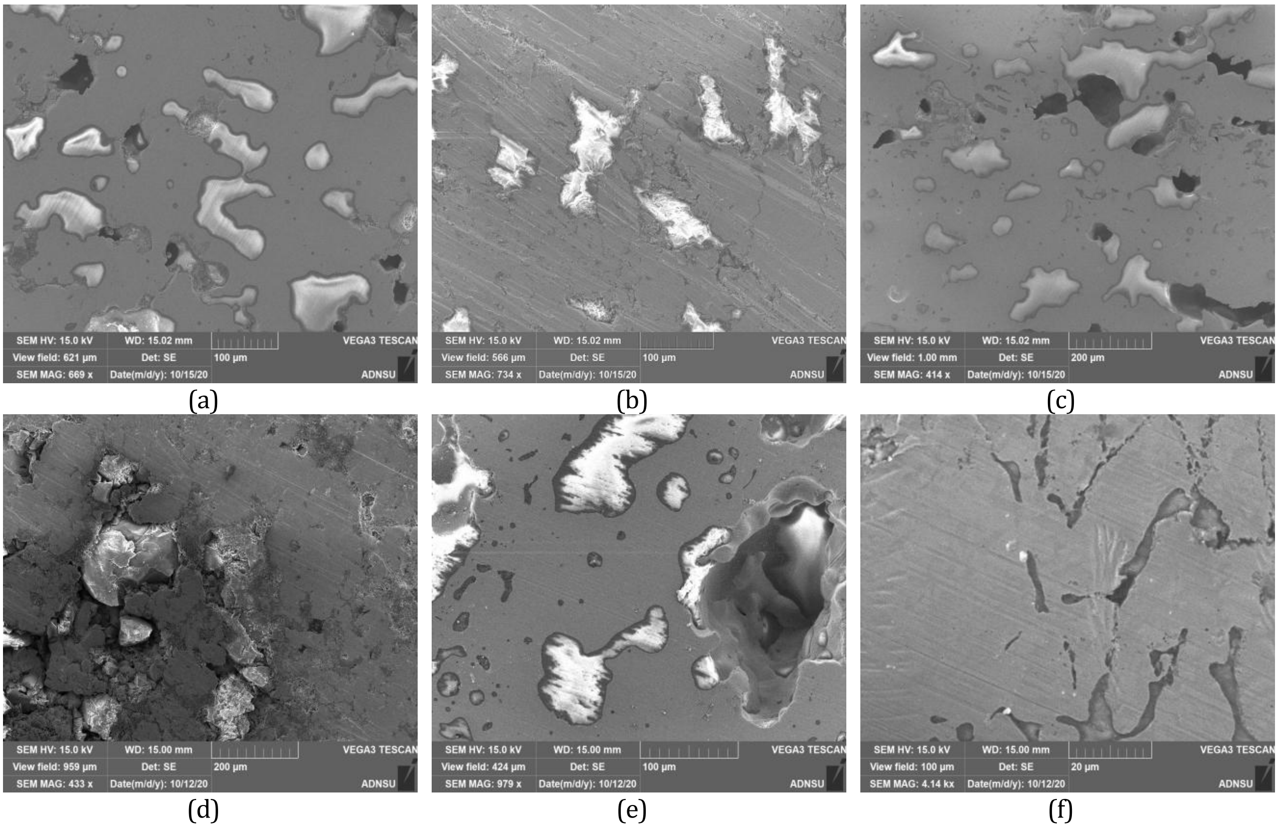


Fig. 8. Deformation of glass particles during sintering at compaction pressures of: (a, b) 400 MPa; (c, d) 800 MPa; and (e, f) 1000 MPa. The cast iron and glass contents were 30 and 6 wt.%, respectively, in (a, c, e), and 40 and 8 wt.%, respectively, in (b, d, f).

This confirms the high efficiency of the applied 3D powder mixing process and demonstrates that good dispersion between the components was achieved. No localized clustering of component particles or formation of large-scale agglomerations was observed in the micrographs, indicating that homogeneity was ensured during the technological preparation stage of the charge.

The uniform distribution of cast iron particles within the iron matrix plays a critical role in determining the mechanical and tribological properties of the composite material. Due to the graphite inclusions, these particles were able to create a self-regulating lubricating effect during friction, resulting in a reduction of the friction coefficient and a decrease in wear intensity. The graphite inclusions originating from the cast iron particles facilitated the formation of a solid lubricant film, thereby reducing adhesion and friction. The glass phase, in turn, strengthened the interfacial bonding and reduced localized stress concentrations. Conversely, excessive oxidation led to the formation of brittle oxide layers, which increased crack initiation and abrasive wear. At the same time, the distribution of the glass phase within the matrix facilitated the strengthening of interparticle bonds during the sintering process and contributed to the increased structural stability of the composite material.

4. CONCLUSIONS

The results of the experimental and theoretical studies demonstrate that it is possible to fabricate iron–cast iron–glass (Fe–CI–Glass) antifriction composite materials using classical powder metallurgy technologies. The investigated composites exhibited specific mechanical and tribological advantages, and a correlation between their structural characteristics and performance indicators was established. The investigated Fe–CI–Glass powder composite material demonstrated a low coefficient of friction, good wear resistance, and a stable microstructure under the studied condition.

Graphite inclusions originating from the cast iron phase acted as a solid lubricant during friction, reducing adhesive wear, while the glass phase partially filled the pores, improving interfacial bonding and structural homogeneity. The optimal oxidation regime strengthened the metal–glass adhesion and led to an enhancement of tribological properties. Furthermore, Fuzzy Logic-based modeling enabled the determination of optimal composition and technological parameters. The results obtained suggest that the Fe–CI–Glass composite may have potential for antifriction applications under tribological conditions similar to those investigated in this study.

The application of Fuzzy Logic and Fuzzy C-Means approaches allowed for the analysis of the complex non-linear dependencies existing between the material composition and its mechanical properties. Based on the modeling results, it was determined that a composition containing approximately 52 wt.% Fe, 42 wt.% cast iron, and 6 wt.% glass yielded optimal results within the studied parameters. Nevertheless, to expand the application scope of these results, further experimental verification is considered appropriate. Based on the mathematical design of experiments (DOE), it was determined that mechanical strength indicators were relatively higher in composites containing cast iron particles sized 100–160 μm and a 2–6 wt.% glass addition. This result was attributed to the formation of a more homogeneous structure within the metal matrix.

Tribological tests showed that the investigated composites exhibited stable tribological behavior under dry friction conditions (at a load of 4 MPa and a sliding speed of 1 m/s). However, for a more accurate assessment of wear mechanisms, additional research under various loads, speeds, and long-term operating conditions is required. It was established that the pre-sintering oxidation of metal powders influences the interfacial bonding and tribological properties. In particular, more favorable tribological performance was observed in specimens oxidized at a temperature of 200 °C for a duration of 1 hour. However, an excessive increase in oxidation parameters led to the formation of large oxide phase clusters, resulting in the weakening of certain mechanical properties of the material.

SEM analysis showed that the applied 3D mixing process resulted in a relatively homogeneous distribution of cast iron and glass particles within the iron matrix. No significant agglomeration was observed in the micrographs, which positively impacted structural stability. Nonetheless, a deeper investigation into the processes influencing microstructure formation requires further study. Increasing the compaction pressure had a specific effect on the deformation level of the glass phase and the densification of the composite. It was determined that increasing the pressure within the 400–1000 MPa range facilitates improved interfacial contact.

Overall, the conducted research indicates that Fe–CI–Glass composite materials can be considered promising for specific tribological applications. At the same time, to fully evaluate their industrial potential, additional experimental studies under dynamic loading, thermal cycling, and long-term wear conditions are deemed necessary.

REFERENCES

[1] R. M. German, *Powder Metallurgy and Particulate Materials Processing*. Princeton, NJ, USA: Metal Powder Industries Federation, 2005.

[2] B. Bhushan, *Introduction to Tribology*, 2nd ed. Hoboken, NJ, USA: Wiley, 2013, doi: 10.1002/9781118403259.

[3] P. J. Blau, *Friction Science and Technology: From Concepts to Applications*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2009.

[4] C. Suryanarayana, "Mechanical alloying and milling," *Prog. Mater. Sci.*, vol. 46, no. 1–2, pp. 1–184, 2001, doi: 10.1016/S0079-6425(99)00010-9.

[5] L. Ertürk and B. Selçuk, "The effect of the borosintering process in iron-based materials on abrasive and sliding wear," *Rev. Metal.*, vol. 60, no. 1, 2024, doi: 10.3989/revmetalm.e254.1610.

[6] J. G. Tirado-González, J. Esguerra-Arce, and A. Esguerra-Arce, "3D printing iron/iron oxide composites by metal material extrusion," *JOM*, vol. 76, no. 4, pp. 1924–1936, 2024, doi: 10.1007/s11837-024-06371-2.

[7] M. R. Rezaei and A. Albooyeh, "Comparative analysis of tribological behavior in aluminum matrix composites incorporating metallic glass particles," *Tribol. Trans.*, vol. 67, no. 1, pp. 129–140, 2024, doi: 10.1080/10402004.2023.2297824.

[8] J. J. Liu, J. Lin, M. Kang, J. N. Ndumia, and F. Huang, "Microstructure and tribological properties of Fe-based composite coatings prepared by high-velocity arc spraying," *J. Therm. Spray Technol.*, vol. 31, no. 3, pp. 644–657, 2022, doi: 10.1007/s11666-022-01338-8.

[9] S. Wang, Y. Li, J. Wang, T. Luo, K. Zheng, Z. Zheng, J. Long, and Y. Lin, "Study on the microstructure and properties of iron-based composites locally reinforced by in-situ submicron TiC particles," *Mater. Chem. Phys.*, vol. 287, p. 126376, 2022, doi: 10.1016/j.matchemphys.2022.126376.

[10] P. Sarmah and K. Gupta, "Tribological analysis of innovative hybrid Al-SiC-ZrO_2 metal matrix composites fabricated using powder metallurgy route for automotive applications," *Adv. Eng. Lett.*, vol. 4, no. 4, pp. 187–197, 2025, doi: 10.46793/adeletters.2025.4.4.2.

[11] L. M. Anselmo, T. de Souza Lamim, M. Hromatka, J. D. Biasoli de Mello, A. N. Klein, G. Hammes, and C. Binder, "Influence of post-sintering sizing process on the tribological behaviour of self-lubricating iron-based composite," *Wear*, vols. 496–497, art. no. 204287, 2022, doi: 10.1016/j.wear.2022.204287.

[12] G. Liu, Y. Hui, J. Du, and H. Lan, "Friction and wear properties of particle-reinforced iron-based composites under continuous high temperature braking," *Powder Metall. Technol.*, vol. 41, no. 1, pp. 63–70, 2023, doi: 10.19591/j.cnki.cn11-1974/tf.2021030031.

[13] G. Zhang, Y. Yin, R. Li, B. Tong, and C. Liu, "Mechanical and tribological properties of Fe-based powder metallurgy materials with multi-layer porosity, " *Tribology*, vol. 39, no. 5, pp. 619–627, 2019, doi: 10.16078/j.tribology.2019040.

[14] B. P. Samal, R. K. Behera, A. Behera, B. Sarangi, S. K. Behera, K. Muduli, R. Rajan, and I. Panigrahi, "Fuzzy logic application on dry sliding wear behavior of matrix aluminum composite produced by powder metallurgy method," *Compos. Mech. Comput. Appl. Int. J.*, vol. 13, no. 1, pp. 49–62, 2022, doi: 10.1615/CompMechComputApplIntJ.2022039388.

[15] M. A. Ballem and M. O. Sari, "Effect of graphite content on the physical and mechanical properties of self-lubricating iron-based composites fabricated by powder metallurgy," *J. Technol. Res.*, pp. 684–702, 2025, doi: 10.26629/jtr.2025.64.

[16] J. D. Biasoli De Mello, C. Binder, G. Hammes, R. Binder, and A. N. Klein, "Tribological behaviour of sintered iron based self-lubricating composites," *Friction*, vol. 5, pp. 285–307, 2017, doi: 10.1007/s40544-017-0186-2.

[17] R. M. German, P. Suri, and S. Park, "Review: liquid phase sintering in powder metallurgy," *J. Mater. Sci.*, vol. 44, no. 1, pp. 1–39, 2009, doi: 10.1007/s10853-008-3008-0.

[18] T. G. Jabbarov, "The choice of powder charges and properties of the powder composite material iron–cast iron–glass," in *Proc. Fifth Int. Iron and Steel Symp. (IISS 2020)*, Karabük, Turkey, 2021, pp. 210–216.

[19] T. G. Jabbarov, O. A. Dyshin, M. B. Babanli, and I. I. Abbasov, "Numerical simulation of the sintering process of multicomponent composite materials based on iron and glass," *Funct. Mater.*, vol. 28, no. 1, pp. 158–169, 2021, doi: 10.15407/fm28.01.158.

[20] L. M. Erich, L. D. Winston, and D. Oropeza, "Metal powder atomization: A literature review and experimental comparison," *Powder Technol.*, vol. 482, art. no. 122630, 2026, doi: 10.1016/j.powtec.2026.122630.

[21] T. J. Ross, *Fuzzy Logic with Engineering Applications*, 4th ed. Chichester, UK: Wiley, 2016.

[22] J. C. Bezdek, *Pattern Recognition with Fuzzy Objective Function Algorithms*. New York, NY, USA: Springer, 2013, doi: 10.1007/978-1-4757-0450-1.

[23] R. A. Aliev and R. R. Aliev, *Soft Computing and Its Application*. London, UK: World Scientific, 2001.

[24] M. B. Babanli, *Fuzzy Logic-Based Material Selection and Synthesis*. Singapore: World Scientific, 2018, doi: 10.1142/11164.

[25] E. H. Mamdani and S. Assilian, "An experiment in linguistic synthesis with a fuzzy logic controller," *Int. J. Man-Mach. Stud.*, vol. 7, no. 1, pp. 1–13, 1975, doi: 10.1016/S0020-7373(75)80002-2.

[26] M. B. Babanli, "Synthesis of new materials by using fuzzy and big data concepts," Procedia Computer Science, vol. 120, pp. 104–111, 2017, doi: 10.1016/j.procs.2017.11.216.

[27] T. G. Jabbarov, "Synthesis of 'iron–cast iron–glass' obsolete powder composite materials using fuzzy logic," in *Proc. 10th Int. Conf. Theory and Application of Soft Computing with Words and Perception (ICSCCW 2019)*, Prague, Czech Republic, 2019, pp. 866–871. doi: 10.1007/978-3-030-35249-3_115.

[28] F. C. Robles Hernandez, J. M. Herrera Ramírez, and R. Mackay, "Powder metallurgy," in *Al-Si Alloys*. Cham, Switzerland: Springer, 2017, doi: 10.1007/978-3-319-58380-8_4.

[29] A. Mora, L. Chandía, N. Landero, C. Salvo, N. Araya, C. Aguilar, and G. O. Neves, "Low-temperature-sintered Fe-based self-lubricating composites reinforced with graphite and graphene oxide," *Lubricants*, vol. 14, no. 8, art. no. 283, 2026, doi: 10.3390/lubricants14080283.

[30] Yu. A. Getmanovsky, I. M. Maltsev, E. S. Belyaev, and S. S. Belyaeva, "Study of influence of silicon oxide on performance properties of metal-glass materials based on iron powder," *Chernye Metally*, no. 8, pp. 46–50, 2024, doi: 10.17580/chm.2024.08.05.

Nomenclature:

SLM-12	SLM-12 iron powder
SEM	Scanning Electron Microscopy
FCM	Fuzzy C-Means
DOE	Design of Experiments
EDS	Energy Dispersive X-ray Spectroscopy