Mechanical and Metallographic Characterization of GGV30 Vermicular Cast Iron applied in Road and Railway Vehicles

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Abstract: This study focuses on the mechanical characterization of GGV30 vermicular cast iron. GGV30 has gained increasing recognition in the automotive and railway industries, particularly for its use in critical components, like brake discs and clutch parts. Given the demanding nature of these applications, a thorough understanding of the material's mechanical properties and their variations under different operating conditions is essential to ensuring reliability and performance. A comprehensive review of various testing methods is provided, to analyze the mechanical behaviors of GGV30. These methods assess key parameters such as strength, durability and hardness, which are crucial for evaluating suitability, for automotive applications. By conducting these investigations, this study lays the foundation for future machining tests, offering valuable data from the workpiece perspective. This approach enhances the testing process, by identifying critical factors, reducing redundant experiments and optimizing the overall assessment of the material's performance.

Keywords: vermicular cast iron; microstructure investigation; tensile testing; Charpy test; automotive industry; railway industry

1 Introduction

During the first decade of the 21st Century in the automotive and railway vehicle industry, there was the aim to replace the sliding part material in the cars because of the reliability issues of the widely used GG25 grey cast iron (DIN 1691 [1], DIN 1561 [2]) material, and the choice was the GGV30 vermicular cast iron (DIN 1691 [1], DIN 1561 [2]). The comparison of the microstructure of the two materials shows that in the case of the GG25 material, the graphite morphology shows a flake form, and in the case of the GGV30 vermicular cast iron, the graphite morphology is between the flake and spherical; however, the chemical structure is very similar to the GG25 grey cast iron. The GGV30 vermicular cast iron is very similar to the predecessor in case of wear resistance but has better mechanical properties compared to the GG25 grey cast irons. It has a improved impact on toughness, elongation, comprehensive strength etc. It is also less sensitive to changes in wall thickness, during production and to variations in cooling speed. These parameters make vermicular cast irons a better choice overall for producing sensitive parts, such as brake drums, brake discs, or clutch sliding parts [3-5].

Vermicular cast iron, particularly grade GGV30, has been extensively studied for its mechanical and metallographic properties, making it a critical material for road and railway vehicle components. Also known as Compacted Graphite Iron (CGI), this material combines the advantages of ductile and gray cast iron, offering a balanced set of properties ideal for high-performance industrial applications. Its mechanical behavior is closely tied to its microstructure, which differs significantly from gray or ductile iron. The vermicular graphite morphology, for example, provides higher ultimate tensile and yield strength than gray iron while remaining below the values seen in ductile iron [6]. This balance makes GGV30 particularly effective in automotive and railway systems, where components are subjected to substantial mechanical stresses over time. Additionally, CGI exhibits superior wear resistance and thermal fatigue resistance compared to other cast irons [7]. The unique graphite structure also enhances damping capacity and machinability – key factors for parts exposed to dynamic loads and harsh operating conditions [8]. GGV30's thermal conductivity further supports its use in heat-sensitive applications, e.g., brake components, where efficient heat dissipation is crucial [9].

Metallographic analysis of vermicular cast iron reveals a microstructure dominated by graphite nodules with a distinctive "worm-like" shape. Unlike flaky graphite, this morphology reduces the risk of crack propagation, thereby improving ductility and toughness [10]. The resulting network of graphite enhances the material's strength-to-weight ratio, making it suitable for lightweight yet durable components [11]. Advanced techniques, such as X-ray tomography and electron microscopy, have provided more profound insights into the 3D distribution of graphite, clarifying how the microstructure influences mechanical and thermal properties [12].

Alloying elements play a crucial role in tailoring the properties of GGV30. Studies indicate that vanadium or titanium additions can refine the microstructure, thereby increasing hardness and tensile strength [13]. Post-casting treatments, such as laser strengthening and austempering, have also been explored to enhance wear resistance and fatigue performance [14]. However, production conditions must be carefully controlled, as cooling rates and thermal treatments significantly impact the final microstructure and mechanical behavior [15]. Historically, CGI has been challenging to manufacture due to its sensitivity to process parameters, requiring precise alloying and cooling to achieve optimal properties [15].

GGV30 is widely used in road and railway vehicle components, including brake discs, cylinder heads, and engine blocks. Its stability under thermal cycling is especially valuable, as these parts frequently endure thermal shock and mechanical fatigue [16]. For instance, GGV30's graphite structure improves heat distribution in brake discs, reducing thermal cracking risks and enhancing braking reliability [16].

Despite its advantages, further research is necessary to optimize the performance of GGV30. Investigating alloy compositions, cooling rates, and treatment methods could yield even more resilient variants for specific automotive and rail applications [17]. Machine learning and data analytics can also help predict material behavior from microstructural data, aiding in design and production decisions [18]. Additionally, as sustainability becomes a priority, research into recycling CGI and its property retention will be essential [19]. Understanding the interplay between alloying elements, graphite morphology, and mechanical properties could extend the lifespan of GGV30 components, reinforcing its role in modern engineering.

In this paper, the main properties of the GGV30 vermicular cast iron are presented to demonstrate its impact stress resistance under various thermal conditions and to provide an overview of its tensile stress stability. The parts machined from this material are crucial in the perspective of safety in the automotive industry, and they must be operational in very different weather conditions, ranging from very low temperatures to very high ones, due to factors such as friction, for example, during emergency braking. There is also a significant advantage of this material compared to its predecessors: it is possible to produce lighter parts from this material due to its better resistance to changes in wall thickness. However, there is a relevant disadvantage: vermicular cast irons have much higher ferrite content compared to grey cast irons, and this parameter limits the cutting tool materials that can be used during the machining processes. For example, during the machining of grey cast irons like GG25, it is possible to apply CBN (Cubic-Boron-Nitride) materials with very high cutting speeds (between 1200 m/min and 2000 m/min), but in GGV30 is impossible due to the relatively high ferrite content (between 40-80%). This significantly reduces the efficiency of machining GGV30 materials compared to GG25. The main aim of this paper is to identify the main properties of the GGV30 vermicular cast iron to be able to increase the productivity of the machining processes during the following experiments and tests and to reduce the overall production cost of these workpieces [20-22].

The aim of the experiments – presented in the current paper – is to investigate the mechanical and structural properties of the increasingly widespread GGV30 vermicular cast iron. The mechanical tests include a comprehensive analysis of parameters such as tensile strength, hardness, and impact toughness. These tests were conducted under various conditions, with some performed only at room temperature, while others were carried out at sub-zero temperatures and an elevated temperature of 200°C. This approach enables a deeper understanding of how temperature variations impact the material's performance in real-world applications.

The structure of the paper is as follows: Section 2 deals with materials and methods, and Section 3 presents the results and discussions; hence, Section 4 summarizes the main findings.

2 Materials and Methods

The goal during the development of the entire testing system was to establish an exact and reproducible method. To achieve this, adhering to the relevant standards while preparing the test specimens and throughout the examinations was imperative. The measurements carried out based on these standards provided highly reproducible results, enabling precise and well-founded conclusions.

2.1 Materials

The specimens for the various investigations and tests were machined out from two raw, not pre-machined clutch discs from the same casting batch (Fig. 1) in the machining laboratory of the Széchenyi István University using various metal cutting methods and machine tools like a bandsaw, milling machine or universal lathe. The preparation of the machining process began by removing the material's surface (Fig. 2) to create markings for cutting (Fig. 3).

Figure 1
Raw material for the tests

Figure 2
Pre-machined material for marking

Figure 3
Marked disc before cutting

It is visible in Fig. 3 that during the marking process, it was not possible to have all the specimens marked in the same direction on the workpiece, but because of the material properties, it is not important because, in the cast iron materials, there is not possible to identify any fiber direction. After the marking, the specimens were cut out with a precision bandsaw. The cut dimensions were at least 1 mm larger in every direction to allow for milling the specimens to the exact size and meet the dimensional requirements after the milling process.

In the case of the Charpy specimens, after the cross-section and the length were prepared, it was necessary to prepare a U-shaped notch according to the ISO 148-1:2016 standard [23] (Fig. 4). It was machined by a special rounded disc mill with a bottom radius of 1 mm (Fig. 5). In the case of tensile stress specimens, after the milling process, it was necessary to use the lathe to prepare the round cross-sectioned specimens (Fig. 6).

Some pieces that fell off during cutting were retained for microstructure checking and hardness testing. From these pieces, one was embedded in phenolic resin under high pressure at room temperature and prepared for checking by the polishing method. To be more precise, microstructure checking and hardness testing were done on the same specimen (Fig. 7).

Figure 4
Charpy specimen with U shape notch

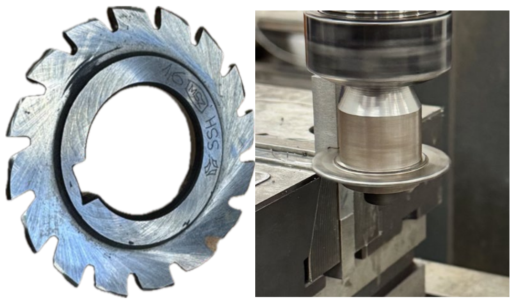

Figure 5
Special disc mill and the machining process

Figure 6
Special disc mill and the machining process

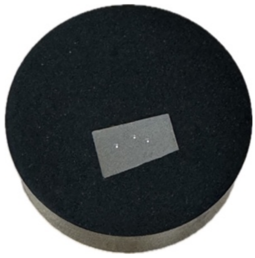

Figure 7
Special disc mill and the machining process

2.1 Methods

After the specimens had been prepared, the following tests were performed in the laboratory.

Charpy impact test on –20°C, +20°C, +200°C according to the ISO 148-1:2016 standard [23]. During the test, 3 specimens were placed in a VÖTSCH climatic chamber to reduce the temperature to –20°C (Fig. 8), and 3 specimens were placed in a Binder climatic chamber to increase the temperature to 200°C (Fig. 8). While these specimens achieved the desired temperature the 3 remaining specimens were tested on room temperature on the mechanical Charpy testing device.

Figure 8
Vötsch and Binder climatic chambers for exact tempering of the specimens

After the three specimens reached the desired temperature for the "cold test", they were removed one by one and immediately placed into the Charpy testing device to prevent further temperature increase, and the test was performed. The "hot test" with the other 3 specimens did the same process. In all 9 cases, the results were documented from the Charpy testing device and recorded in an Excel file for further analysis.

Tensile strength test on 20°C according to the ISO 6892-1:2019 standard [24]. The 3 prepared specimens were tested on an INSTRON 5582 100 kN Universal Testing Machine (UTM) equipped with a non-contact video extensometer. The specimens were clamped prismatically. Before the tests, all specimens were marked with a white permanent marker to provide reference points for the non-contact video extensometer. During the tests, the results were taken from the data of the non-contact video extensometer and saved in an Excel file, for further analysis.

Microstructural investigation of the raw surface, according to the ISO 945-1:2019 standard [25], reveals the graphite structure in the investigated material. It was an additional test to check the exact spreading of the graphite in the material under investigation. The investigation was conducted using a ZEISS Discovery V20 Stereo microscope and documented with pictures directly from the system at two different magnifications.

Microstructural investigation after Nital etching, according to the ISO 643:2019 standard [26], is a process that enables the identification of grain size and spread in austenitic and ferritic materials within the investigated material. In this case, the investigated components were the ferrite content and ferrite grain size because of their influence on machinability with CBN cutting tools. To perform this investigation, the specimens must be etched in a 5% Nital solution, which contains 5% nitric acid and 95% ethanol or methanol. After the etching, the test was performed on the same ZEISS Discovery V20 stereo microscope, and pictures were taken with different magnifications to investigate the ferrite content and spreading in the material.

Brinell Hardness test, according to ISO 6506-1:2014 standard [27], is a mechanical testing process. In this case, the method used was the HBW 2.5/62.5/10 method. During the test, a 2.5 mm diameter tungsten carbide ball is pressed into the surface with a 62.5 kgf (612.9 N) force for 10 s, and the hardness value is calculated from these values and the diameter of the marking left on the surface using Eq. (1).

$$HBW = \frac{0.102 \cdot 2 \cdot F}{\pi \cdot D\left(D - \sqrt{D^2 - d^2}\right)} \tag{1}$$

where:

HBW is the Brinell-hardness value in HB

F is the force in N unit

D is the diameter of the ball in mm unit

d is the diameter of the marking on the surface in mm unit

The tests were performed on the KB Prüftechnik KB 750 universal hardness tester device, which is capable of evaluating the tests in automated mode to ensure consistency and avoid human errors. During this process, three tests were made on the same surface prepared for the microstructure investigation.

3 Results and Discussions

After every test and investigation, all the saved data had to be evaluated to get a comprehensive picture of the investigated material.

After the Charpy test, the results were evaluated in Excel (Table 1), and the impact of the cold and hot environment was identified to get the thermal stability of the GGV 30 vermicular cast iron.

Table 1
Charpy test results at different temperatures (SD is Standard Deviation, RSD is Relative SD)

Specimen	Results [J] at +20 °C	Results [J] at –20 °C	Results [J] at +200 °C
1	6		
2	5		
3	5		
4		4	
5		4	
6		4	
7			6
8			6
9			6
Average	5.33	4.00	6.00
SD	0.58	0.00	0.00
RSD	10.88%	0.00%	0.00%

According to the results, it is evident that the temperature difference affects only one Joule in the results compared to the room temperature. However, since the room temperature value is only 5 Joules, this difference represents a ±20% change in the investigated material. In the case of higher notch impact energy values, this 20% difference would be significant; however, because the room temperature value serves as the basis is low, the impact of the temperature change can be disregarded concerning the notch impact energy change [28].

During the tensile strength test, all data were saved from the video extensometer in digital form, allowing for evaluation in Excel to view the results in a single table and diagram (Table 2, Fig. 9).

Table 2
Result of tensile strength test (SD means standard deviation, RSD means Relative SD)

Specimen	Yield [MPa]	Strength [MPa]	A	$F_{max.}$	d_0
Specimen 1	353	458.50	3.73	23.05	8
Specimen 2	305	332.77	0.72	23.05	8

Specimen 2	314	435.50	4.33	23.05	8
Average	324	408.92	2.93	23.50	8
SD	25.51	66.95	1.93	-	-
RSD	7.87%	16.37%	65.90%	-	-

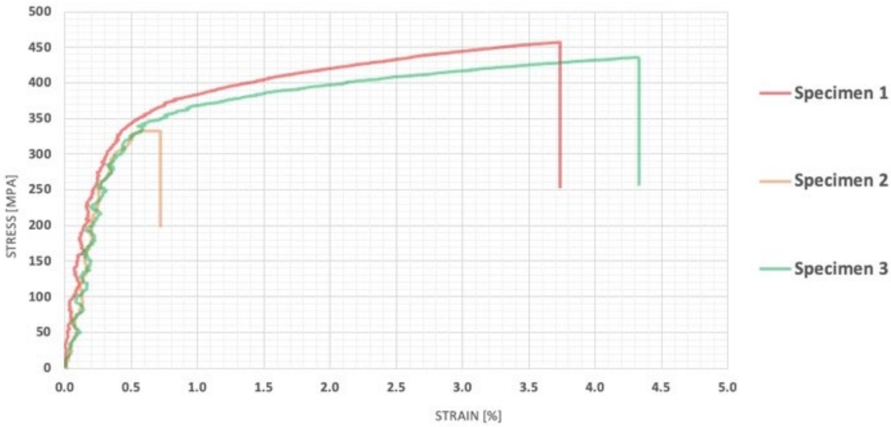

Figure 9
Result of tensile strength test

In the evaluation process, it was necessary to consider mistakes or false data during the tests because the second specimen showed a much smaller tensile strength result than the other two. There is a possibility that the specimen had some internal defects or uneven spreading of the ferrite and the graphite, and that was the reason for having more than 25% less tensile strength; however, the yield strength is only 8.5% below the average of the two other specimens. Both specimens breaking at a higher tensile stress were within the standard range for GGV 30, from both tensile strength and yield strength perspectives. However, the specimen breaking at a lower tensile stress was outside the standard range in terms of tensile strength but within the range from a yield strength perspective. This means there must have been a defect in the material [24].

During the microstructure investigation of the raw surface, pictures taken with the ZEISS Discovery V20 stereo microscope revealed a clear image of the two types of graphite forms (Fig. 10).

In the two pictures, the small black dots represent the distribution of compacted graphite, while the short black lines indicate the presence of flake-type graphite. Based on the graphite distribution seen in the two pictures, it can be concluded that the examined material is vermicular cast iron.

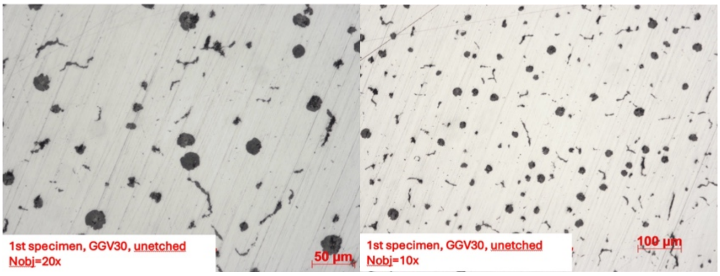

Figure 10
Graphite forms on microscopic pictures on raw surface

In the microstructure investigation on the etched surface, the exceptionally high ferrite content is visible as a bright part (Fig. 11). According to the standard for GGV 30 materials [1] [2] [25] [26], the ferrite content must be between 40-80%. In the case of the specimens, the tolerance level was near the upper level during the investigation. Because of this high level of ferrite content, there would be a high risk of tool wear if this workpiece was machined with CBN inserts because of the chemical reaction between the ferrite and the CBN material at higher temperatures [29-35].

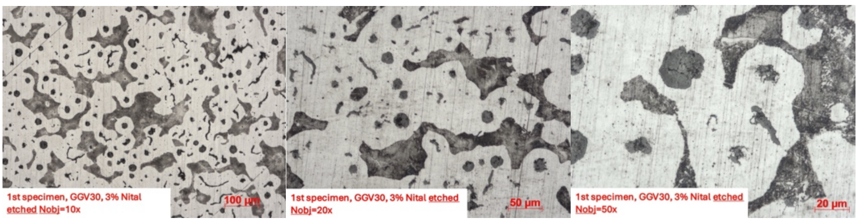

Figure 11
Graphite forms on microscopic pictures on raw surface

The results of the Brinell hardness test method were calculated automatically by the KB Prüftechnik KB 750 device and recorded in an Excel file for evaluation (Table 3).

Table 3
Values of the three Brinell hardness tests (SD means standard deviation, RSD means relative standard deviation)

No. of the test	HBW 2.5/62.5/10 values
1	166
2	167
3	167
Average	167 (166.667)
SD	0.577
RSD	0.350%

According to the standard [1] [2] [13], all the 3 measured values and the average value are below the defined tolerance of the GGV 30 material. The HBW value is between 170 and 230. The main reason for this low value is the very high content of ferrite, which is the softest microstructural component. In the microscopic pictures, it was visible that the specimen material contained a very high amount of ferrite.

Conclusions

The GGV30 vermicular cast iron investigation provided valuable insights into its mechanical properties, thermal stability and microstructural characteristics. The results obtained from Charpy impact tests, tensile strength measurements, microstructural investigations, and Brinell hardness testing confirm that GGV30 exhibits a balanced combination of strength, toughness, and wear resistance, making it a suitable material for automotive applications, particularly for components such as brake discs and clutch parts. However, some limitations in its machinability were observed, due to its high ferrite content.

Impact of temperature on mechanical properties

The Charpy impact test results demonstrated that temperature variations influence the material's notch impact energy, but the absolute energy values remain relatively low. The maximum deviation observed was ±20%, which may not be highly significant in the context of such a brittle material. This suggests that GGV30 maintains its impact resistance across a wide range of operational temperatures, making it reliable under extreme weather conditions and during high-friction events, such as emergency braking.

Tensile strength and structural integrity

The tensile strength tests revealed some variation in the results, with one specimen exhibiting significantly lower tensile strength. This outlier suggests the presence of internal defects or an uneven distribution of ferrite and graphite, which could impact the consistency of mechanical performance. Nevertheless, most samples met the required tensile and yield strength standards [10] for GGV30, reinforcing its suitability for high-stress applications.

Microstructural analysis and machinability challenges

The microstructure analysis confirmed that the material exhibits the expected graphite morphology for vermicular cast iron, characterized by a mixture of compacted and flake-type graphite formations. However, Nital etching revealed a high ferrite content, estimated to be near the upper tolerance limit (40-80%) specified in the standard [11] [12].

This high ferrite content adversely affects machinability, increasing tool wear when using CBN (Cubic Boron Nitride) cutting tools at high temperatures. While GG25 grey cast iron allows for high-speed machining with CBN (1200-2000 m/min), the presence of ferrite in GGV30 makes such machining methods impractical.

Consequently, optimizing cutting tool materials and machining parameters will be crucial for enhancing manufacturing efficiency and lowering production costs.

Brinell hardness evaluation

The Brinell hardness test (HBW 2.5/62.5/10) results revealed that all measured values were below the standard tolerance range (170-230 HBW) for GGV30 [13]. This low hardness correlates with the high ferrite content, confirming that ferrite is the softest microstructural component in the material. While this property enhances ductility, it also contributes to reduced wear resistance, compared to grey cast iron.

Final remarks

This study highlights both the advantages and challenges of GGV30 vermicular cast iron. While the material offers improved mechanical strength, impact resistance, and thermal stability, its high ferrite content presents machining difficulties that must be addressed. Future research should focus on optimizing machining processes, exploring alternative tool materials, and refining casting methods to enhance the material's performance and cost-effectiveness in industrial applications.

Future research possibilities

Future research will aim to address the mechanical and metallographic characterization of GGV30 vermicular cast iron applied in road and railway vehicles by focusing, e.g., on AI-driven design and data analysis optimization [36-38], fuzzy logic [39-41], or traditional statistical [42-44]. Sophisticated finite element simulation and modeling methodologies can be applied for supplementary investigations [45-48]. The aspects and trends of cognitive mobility and sustainability, must be considered in detailed examinations [49-51] that encompass the aspects of automotive and railway vehicles, transportation and engineering.

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References

[1] DIN 1691:1985-06 Grey cast iron - Grades (original German title: "Gusseisen mit Lamellengraphit - Sorten"), withdrawn in 2011

[2] DIN EN 1561:2011-10 Founding - Grey cast irons (original German title: "Gießereiwesen - Gusseisen mit Lamellengraphit")

[3] M. X. Zhang, J. C. Pang, L. J. Meng, S. X. Li, Q. Y. Liu, A. L. Jiang, Z. F. Zhang. Study on thermal fatigue behaviors of two kinds of vermicular graphite cast irons. Materials Science and Engineering: A, Vol. 814, 2021, 141212

[4] H. K. D. H. Bhadeshia, R. W. K. Honeycombe. Iron and its interstitial solutions. Steels, 2024, pp. 1-22

[5] L. Holappa. Iron and Steelmaking – Introduction. Treatise on Process Metallurgy, 2024, pp. 3-5

[6] Q. Liu, A. Jiang, J. Wang, D. Shi. Influence factors for the determination of vermicular graphite ratio in cast iron measured by ultrasonic method. Materials Transactions, Vol. 59(7), 2018, pp. 1186-1191

[7] C. Wang, H. Zhou, P. Lin, N. Sun, Q. Guo, P. Zhang et al. The thermal fatigue resistance of vermicular cast iron coupling with h13 steel units by cast-in process. Materials & Design (1980-2015), Vol. 31(7), 2010, pp. 3442-3448

[8] H. Hasırcı, K. Karacif, B. Karatay. Effects of vermiculariser, inoculant and copper addition on microstructure and corrosion properties of vermicular graphite cast iron. Politeknik Dergisi, Vol. 25(3), 2022, pp. 1113-1121

[9] F. Sun, K. Cai, X. Li, M. Pang. Research on laser cladding co-based alloy on the surface of vermicular graphite cast iron. Coatings, Vol. 11(10), 2021, 1241

[10] P. Lin, Z. Zhang, S. Kong, H. Zhou, X. Tong, L. Ren. Mechanical properties of composite coating on cast iron by laser. Surface Engineering, Vol. 34(4), 2018, pp. 289-295

[11] M. Górny, M. Kawalec. Role of titanium in thin wall vermicular graphite iron castings production. Archives of Foundry Engineering, Vol. 13(2), 2013, pp. 25-28

[12] Y. Liu, J. Xing, Y. Li, S. Wang, D. Tao. Tomographical study of the effect of graphite on properties of cast iron. Steel Research International, Vol. 89(8), 2018

[13] M. Górny, M. Kawalec. Effects of titanium addition on microstructure and mechanical properties of thin-walled compacted graphite iron castings. Journal of Materials Engineering and Performance, Vol. 22(5), 2012, pp. 1519-1524

[14] O. Akinribide, O. Ogundare, O. Oluwafemi, K. Ebisike, A. Nageri, S. Akinwamide et al. A review on heat treatment of cast iron: phase evolution and mechanical characterization. Materials, Vol. 15(20), 2022, 7109

[15] K. Laneri, P. Bruna, D. Crespo. Microstructural characterisation and kinetics modelling of vermicular cast irons. Materials Science and Technology, Vol. 24(10), 2008, pp. 1214-1221

[16] C. Lim, B. Goo. Development of compacted vermicular graphite cast iron for railway brake discs. Metals and Materials International, Vol. 17(2), 2011, pp. 199-205

[17] C. Fragassa, M. Babič, C. Bergmann, G. Minak. Predicting the tensile behaviour of cast alloys by a pattern recognition analysis on experimental data. Metals, Vol. 9(5), 2019, 557

[18] G. Gumienny, B. Kacprzyk, B. Mrzygłód, K. Regulski. Data-driven model selection for compacted graphite iron microstructure prediction. Coatings, Vol. 12(11), 2022, 1676

[19] M. Abouelela. An overview on thin wall cast iron castings and its applications in automotive industry. International Journal of Materials Technology and Innovation, 3(1), 2023, pp. 57-69

[20] I. Milosan. The Manufacturing of a Special Wear-resistant Cast Iron Used in Automotive Industry. Procedia Social and Behavioral Sciences, Vol. 109, 2014, pp. 610-613

[21] I. G. Akande, O. S. Isaac Fayomi, P. N. Okore. Investigation of the microstructure, corrosion resistance and hardness of bone particle reinforced cast iron for engine blocks application in automotive and marine industries. Hybrid Advances, Vol. 2, 2023, 100022

[22] Q. Guo, Y. Zhong, T. Dong, P. Gao, Y. Guo, J. Li. Effects of vermicular graphite rate on the oxidation resistance and mechanical properties of vermicular graphite iron. Journal of Alloys and Compounds, Vol. 765, 2018, pp. 213-220

[23] ISO 148-1:2016 Metallic materials - Charpy pendulum impact test - Part 1: Test method

[24] ISO 6892-1:2019 Metallic materials - Tensile testing - Part 1: Method of test at room temperature

[25] ISO 945-1:2019 Microstructure of cast irons - Part 1: Graphite classification by visual analysis

[26] ISO 643:2019 Steels - Micrographic determination of the apparent grain size

[27] ISO 6506-1:2014 Metallic materials - Brinell hardness test - Part 1: Test method

[28] Z. J. Ma, D. Tao, Z. Yang, Y. C. Guo, J. P. Li, M. X. Liang, L. T. Li Yeung. The effect of vermicularity on the thermal conductivity of vermicular graphite cast iron. Materials & Design, Vol. 93, 2016, pp. 418-422

[29] S. E. Bilim, M. Rafighi, S. Dengiz. Machinability of GG25 gray cast iron using carbide inserts. Materials Today: Proceedings, 2023

[30] K. M. Kumar, K. Arun, N. Sathishkumar, M. Pathri Narayanan, E. Raviraj. Experimental investigation on the machinability of nodular ductile iron with cubic boron nitride and tungsten carbide inserts. Materials Today: Proceedings, Vol. 39, 2021, pp. 1386-1389

[31] M. H. Faisal, A. Mohana Krishnan, S. Prabagaran, R. Venkatesh, D. Satish Kumar, J. Christysudha, A. H. Seikh, A. Iqbal, E. Ramaraj. Optimization and prediction of CBN tool life sustainability during AA1100 CNC turning by response surface methodology. Heliyon, Vol. 9(8), 2023, e18807

[32] K. Velraja, V. Srinivasan. Performance and analysis of sputtered CBN inserts in machining. Materials Today: Proceedings, 2023

[33] Y. Lin, S. He, D. Lai, J. Wei, Q. Ji, J. Huang, M. Pan. Wear mechanism and tool life prediction of high-strength vermicular graphite cast iron tools for high-efficiency cutting. Wear, Vol. 454-455, 2020, 203319

[34] F. Schultheiss, V. Bushlya, F. Lenrick, D. Johansson, S. Kristiansson, J. E. Ståhl. Tool Wear Mechanisms of pcBN tooling during High-Speed Machining of Gray Cast Iron. Procedia CIRP, Vol. 77, 2018, pp. 606-609

[35] M. X. Zhang, J. C. Pang, Y. Qiu, S. X. Li, M. Wang, Z. F. Zhang. Influence of microstructure on the thermo-mechanical fatigue behavior and life of vermicular graphite cast irons. Materials Science and Engineering: A, Vol. 771, 2020, 138617

[36] P. Ficzere. The Role of Artificial Intelligence in the Development of Rail Transport. Cognitive Sustainability, Vol. 2, 2023, 81

[37] I. A. Zamfirache, R. E. Precup, E. M. Petriu. Q-Learning, Policy Iteration and Actor-Critic Reinforcement Learning Combined with Metaheuristic Algorithms in Servo System Control. Facta Universitatis, Series: Mechanical Engineering, Vol. 21(4), 2023, pp. 615-630

[38] M. Nosonovsky, A. S. Aglikov. Triboinformatics: Machine Learning Methods for Frictional Instabilities. Facta Universitatis, Series: Mechanical Engineering, Vol. 22(3), 2024, pp. 423-433

[39] I. Taran, A. Karsybayeva, V. Naumov, K. Murzabekova, M. Chazhabayeva. Fuzzy-Logic Approach to Estimating the Fleet Efficiency of a Road Transport Company: A Case Study of Agricultural Products Deliveries in Kazakhstan. Sustainability, Vol. 15(5), 2023, 4179

[40] A. R. Mishra, P. Rani, F. Cavallaro, A. F. Alrasheedi. Assessment of sustainable wastewater treatment technologies using interval-valued intuitionistic fuzzy distance measure-based MAIRCA method. Facta Universitatis, Series: Mechanical Engineering, Vol. 21(3), 2023, pp. 359-386

[41] M. Radovanović, D. Božanić, D. Tešić, A. Puška, I. M. Hezam, C. Jana. Application of hybrid DIBR-FUCOM-LMAW-Bonferroni-grey-EDAS model in multicriteria decision-making. Facta Universitatis, Series: Mechanical Engineering, Vol. 21(3), 2023, pp. 387-403

[42] L. Ézsiás, R. Tompa, S. Fischer. Investigation of the possible correlations between specific characteristics of crushed stone aggregates. Spectrum of

Mechanical Engineering and Operational Research, Vol. 1(1), 2024, pp. 10-26

[43] S. Fischer, D. Harangozó, D. Németh, B. Kocsis, M. Sysyn, D. Kurhan, A. Brautigam. Investigation of heat-affected zones of thermite rail weldings. Facta Universitatis, Series: Mechanical Engineering, 2024, pp. 689-710

[44] S. Fischer. Investigation of the settlement behavior of ballasted railway tracks due to dynamic loading. Spectrum of Mechanical Engineering and Operational Research, Vol. 2(1), 2025, pp. 24-46

[45] A. T. J. Kuchak, D. Marinkovic, M. Zehn. Parametric investigation of a rail damper design based on a lab-scaled model. Journal of Vibration Engineering and Technologies, Vol. 9(1), 2021, pp. 51-60

[46] A. T. J. Kuchak, D. Marinkovic, M. Zehn. Finite element model updating – Case study of a rail damper. Structural Engineering and Mechanics, Vol. 73(1), 2020, pp. 27-35

[47] J. Dižo, J. Harušinec, M. Blatnický. Computation of modal properties of two types of freight wagon bogie frames using the finite element method. Manufacturing Technology, Vol. 18(2), 2018, pp. 208-214

[48] R. Melnik, S. Koziak, J. Seńko, J. Dižo, J. Caban. Evaluation of Dynamics of a Freight Wagon Model with Viscous Damping. Applied Sciences, Vol. 14(22), 2024, 10624

[49] M. Zöldy, P. Baranyi. The cognitive mobility concept. Infocommunications Journal, Vol. 15, 2023, pp. 35-40

[50] M. Zöldy, P. Baranyi, Á. Török. Trends in cognitive mobility in 2022. Acta Polytechnica Hungarica, Vol. 21(7), 2024, pp. 189-202

[51] M. Zöldy. Changes at mobility space use in the cognitive mobility era. Acta Technica Jaurinensis, Vol. 17(4), 2025, pp. 163-168