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ACTA METALLURGICA SLOVACA

2026, VOL. 32, NO. 3, 181-184

SCICELL

RESEARCH PAPER

Effect of FeSi, FeB and FeSiB Ferroalloy Modifiers on the Microstructure and Mechanical Properties of High-Strength Cast Iron

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Received: 30.06.2026
Accepted: 27.07.2026

ABSTRACT

This study investigates the effect of ferrosilicon (FeSi), ferroboron (FeB), and complex ferrosilicoboron (FeSiB) modifiers on the microstructure and mechanical properties of high-strength cast iron produced by laboratory induction melting. Experimental melts (20-30 kg) were conducted in a medium-frequency induction furnace at 1450-1500 °C; the molten metal was poured into clay-sand molds at 1400-1450 °C. Mechanical properties were evaluated in accordance with ASTM E8/E8M (Standard Test Methods for Tension Testing of Metallic Materials), and microstructural analysis was performed by optical microscopy at magnifications of ×100-×500. The application of FeSiB at 0.3 wt.% of the melt yielded the highest tensile strength of 392 MPa - a 46% improvement over the unmodified control (268 MPa) - and the highest ductility (δ = 2.1%), demonstrating a clear synergistic effect of the combined silicon-boron system. Modification with FeB substantially increased hardness (236 HB) through formation of dispersed boron-containing carbide phases, while FeSi produced moderate improvements in both strength and graphite morphology. The results show that complex FeSiB modifiers are the most effective for simultaneously optimizing strength, hardness, and ductility in high-strength cast iron.

Keywords: High-strength cast iron, boron, modification, ferrosilicoboron, ferroboron, microstructure, mechanical properties, induction melting.

INTRODUCTION

High-strength cast iron is widely used in mechanical engineering, metallurgy, and the transportation industry due to its combination of high strength, good casting properties, and relatively low production cost [1-3]. The performance characteristics of cast iron are largely determined by its microstructure, the shape of graphite inclusions, and the condition of the metallic matrix [3,5].

Melt modification using ferroalloy inoculants is among the most practical and industrially proven methods for controlling cast iron microstructure [4,5]. Ferrosilicon (FeSi) is the most widely used inoculant; it promotes graphitization, refines graphite flakes, and stabilizes the pearlitic matrix [5,8]. At the same time, boron-containing ferroalloys have attracted growing research attention due to boron's high chemical activity and its pronounced influence on nucleation and crystallization kinetics [1,6,7].

Boron segregates preferentially at austenite grain boundaries and acts as a potent nucleation agent, increasing the number of crystallization centers and promoting the formation of dispersed carbide and graphite phases [6,7]. Small additions of boron (typically 0,002-0,05 wt.% in the final composition) can refine the metallic matrix and enhance strength, though excessive boron content may lead to the formation of coarse Fe_2B carbides that reduce ductility [6,9]. Previous studies have shown that ferroboron (FeB) additions consistently increase hardness and tensile strength in grey and ductile cast irons, but at the cost of some reduction in elongation [6, 9].

Complex ferrosilicoboron (FeSiB) modifiers that simultaneously incorporate silicon and boron offer particular promise. The silicon component stabilizes graphitization and moderates boron's carbide-forming tendency, while boron refines the matrix and increases the number of nucleation sites. This combined action is expected to yield a synergistic improvement in the overall property profile [7, 10]. However, systematic comparative data on the relative effectiveness of FeSi, FeB, and FeSiB under identical melting and casting conditions remain limited in the published literature [10-16].

The aim of this work is to comparatively investigate the effect of FeSi, FeB, and FeSiB ferroalloy modifiers on the microstructure and mechanical properties tensile strength, hardness, and elongation - of high-strength cast iron produced by laboratory induction melting.

MATERIAL AND METHODS

BASE MATERIAL AND MODIFIERS

A hypoeutectic cast iron with elevated carbon and silicon contents was selected as the base alloy. The chemical composition was controlled within narrow limits to ensure comparability across experimental series. The nominal composition of the base cast iron is given in **Table 1**.

Table 1 Chemical composition of the base cast iron

C	Si	Mn	P	S	Fe
3,4-3,6	2,2-2,6	0,3-0,5	≤0,05	≤0,02	The rest

Three ferroalloy modifiers were used in this study:
- ferrosilicon FeSi (≈ 75 wt.% Si), introduced at 0,3 wt.% of the melt mass;
- ferroboron FeB (17-20 wt.% B), introduced at 0,3 wt.% of the melt mass;
- ferrosilicoboron FeSiB (≈ 50 wt.% Si, ≈ 2 wt.% B), introduced at 0,3 wt.% of the melt mass.

Based on the certified chemical composition of the ferroalloy modifiers and the addition rate of 0.3 wt.% of the melt, the nominal silicon and boron additions introduced into each experimental series were calculated. The calculated values are presented in **Table 2**. Since post-modification chemical analysis of the modified melts was not performed, these values represent calculated nominal additions rather than experimentally measured final chemical compositions.

Table 2 Calculated nominal silicon and boron additions introduced by ferroalloy modifiers

Exp. series	Modifier	Modifier addition (wt.%)	Calculated Si addition (wt.%)	Calculated B addition (wt.%)
S0	None	0	0	0
S1	FeSi(≈75 wt.% Si)	0,3	0,225	-
S2	FeB (17-20 wt.% B)	0,3	-	0.051-0.060
S3	FeSiB (≈50 wt.% Si, ≈2 wt.% B)	0,3	0,150	0,006

MELTING PROCEDURE AND SAMPLE PRODUCTION

Experimental melts were carried out in a laboratory medium-frequency induction furnace equipped with a graphite crucible. Each melt consisted of a 20–30 kg charge of pig iron, steel scrap, and the appropriate ferroalloy additions. The melt temperature was monitored continuously with an optical pyrometer and held at 1450-1500 °C throughout the melting stage.

After complete dissolution of the metallic charge, the melt surface was deslagged and the chemical composition was adjusted. Modifiers were introduced by the in-ladle plunge method immediately prior to pouring, at a melt temperature of approximately 1460°C, to minimize modifier oxidation losses and ensure uniform distribution.

Casting molds were prepared from a clay-sand mixture comprising quartz sand, bentonite clay (8-10 wt.%), and water (3-4 wt.%), which provided the required mold strength and thermal stability. Molten metal was poured into the molds at 1400-1450 °C. Following complete solidification and cooling to room temperature, castings were removed from the molds, cleaned of residual molding mixture, and machined to produce standard cylindrical test specimens (diameter 20-30 mm, gauge length 120-150 mm).

The four experimental series were: (S0) unmodified control; (S1) FeSi-modified; (S2) FeB-modified; and (S3) FeSiB-modified. Key melting and sample production parameters are summarized in **Table 3**, including furnace type, melting temperature, modifier addition conditions, pouring temperature, mold material, and specimen geometry.

Table 3 Parameters of experimental melting and sample production

Parameter	Value
Furnace type	Medium-frequency induction furnace (graphite crucible)
Melt mass	20-30 kg
Melting temperature	1450-1500°C
Modifier addition temperature	1460°C (in-ladle plunge)
Modifier addition rate	0.3 wt.% of melt mass
Pouring temperature	1400-1450°C
Mold material	Clay-sand (quartz sand + bentonite water)
Sample geometry	Cylindrical: ø 20-30 mm, length 120-150 mm

MECHANICAL TESTING

The mechanical properties of the obtained samples were determined using a universal Instron testing machine.

Tensile tests were conducted at room temperature in accordance with the requirements of the international ASTM E8/E8M standards. The loading rate was maintained constant throughout the entire experiment.

During the tests, the following parameters were determined:

- tensile strength (σ_β);
- relative elongation (δ);
- fracture behavior of the samples.

Additionally, hardness measurements were performed using the Brinell hardness method (HB). To improve the reliability of the results, at least three samples from each series were tested, and the average values were then calculated..

The reported values represent the average of at least three tested specimens for each experimental series; however, detailed statistical analyses (e.g., standard deviation and significance testing) were not performed.

METALLOGRAPHIC INVESTIGATIONS

For microstructure analysis, the samples were subjected to standard metallographic preparation, including:

- cutting;
- grinding;
- polishing;
- chemical etching.

Etching was carried out using a 4% nitric acid solution in ethyl alcohol (nital).

The microstructure investigation was performed using an optical microscope at magnifications of ×100, ×200, and ×500.

Attention was paid to:

- the shape of graphite inclusions;
- the dispersion of the pearlitic matrix;
- the distribution of carbide phases;
- the structural uniformity.

RESULTS AND DISCUSSION

During the melting process, it was established that the use of boron-containing modifiers has a significant effect on the crystallization process of cast iron. Melts containing FeSiB were characterized by a more stable solidification process and the formation of a dense structure without pronounced shrinkage defects.

The obtained cast samples had a smooth surface, a minimal number of casting defects, and satisfactory structural quality.

The results of mechanical tests are presented in **Table 4**.

Table 4 Mechanical properties of modified cast iron

Sample	Modifier	Hardness HB	σ_β, МПа	δ, %
S0	Unmodified	182	268	1,1
S1	FeSi	201	312	1,6
S2	FeB	236	368	1,2
S3	FeSiB	228	392	2,1

The results showed satisfactory reproducibility, with deviations between individual tests of 5-7%. The obtained results showed that the application of boron-containing modifiers significantly improves the mechanical properties of cast iron. The highest tensile strength was obtained with FeSiB, reaching 392 MPa, which is 46% higher than that of the control sample.

The application of FeB led to a significant increase in hardness (236 HB), which may be associated with the formation of boron-containing hard phases during solidification. However, a slight reduction in ductility (δ = 1.2%) was also observed.

The complex FeSiB modifier provided the most effective combination of strength, hardness, and ductility. The effects of the ferroalloy modifiers on tensile strength and hardness are summarized in **Fig. 1** and **Fig. 2**.

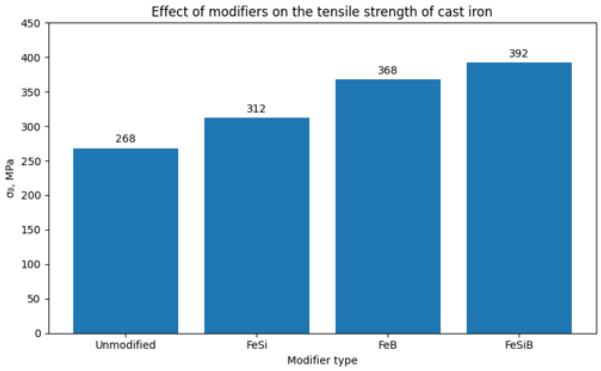


Fig. 1 Effect of modifiers on the tensile strength of cast iron

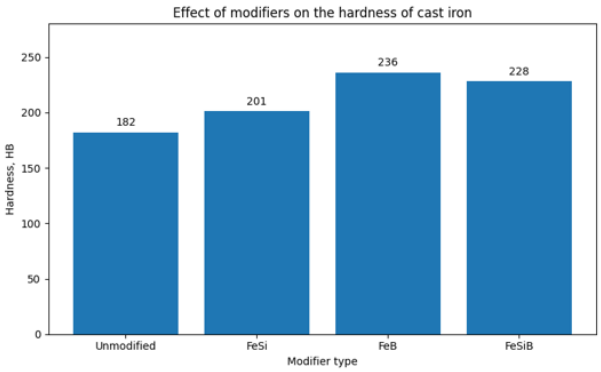


Fig. 2 Effect of modifiers on the hardness of cast iron

As shown, FeSiB produced the highest tensile strength (392 MPa), whereas FeB resulted in the highest hardness (236 HB), confirming the different strengthening mechanisms of the modifiers investigated.
The experimental results obtained are in good agreement with the literature data, according to which boron-containing modifiers contribute to structural refinement and an increase in the strength properties of high-strength cast iron.
The combined use of silicon and boron provides a synergistic effect associated with the stabilization of graphitization and an increase in the number of crystallization centers.
Representative optical micrographs of the control and modified samples are presented in **Figs. 3-6**. The micrographs demonstrate the effects of FeSi, FeB, and FeSiB modifiers on graphite morphology and matrix refinement, consistent with the observed changes in mechanical properties.

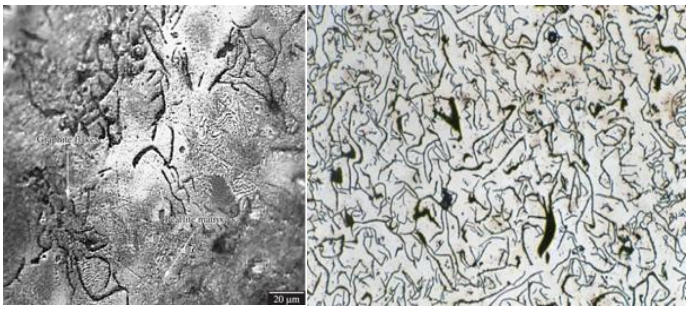


Fig. 3 Microstructure of the unmodified control sample (×500)

The control samples had a microstructure consisting of coarse, unevenly distributed flake graphite and a relatively coarse-grained pearlitic matrix. Such a structure increases stress concentration and limits the mechanical properties.

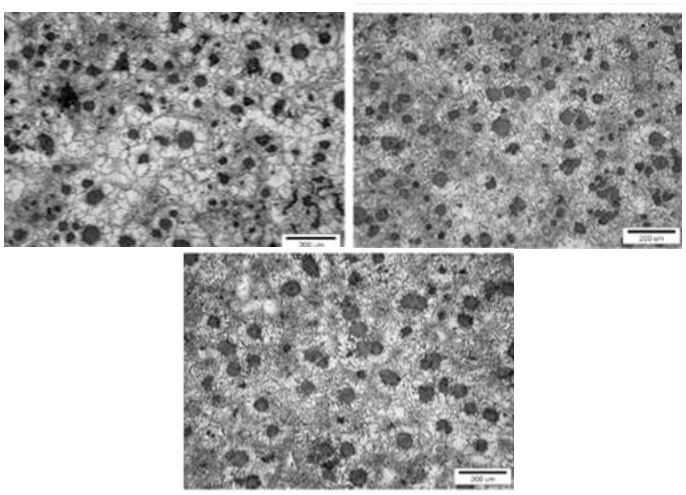


Fig. 4 Microstructure of the sample after FeSi modification (scale bar = 200 μm)

The FeSi-modified sample exhibits a relatively uniform distribution of graphite particles within the metallic matrix. Compared with the unmodified sample, the microstructure appears more homogeneous and refined. The observed structural features are consistent with the improvement in mechanical properties obtained after modification.
The FeB-modified sample exhibits a refined microstructure and a relatively uniform distribution of graphite particles within the metallic matrix. The increased hardness of the FeB series may be associated with the formation of hard boron-containing structural constituents during solidification.

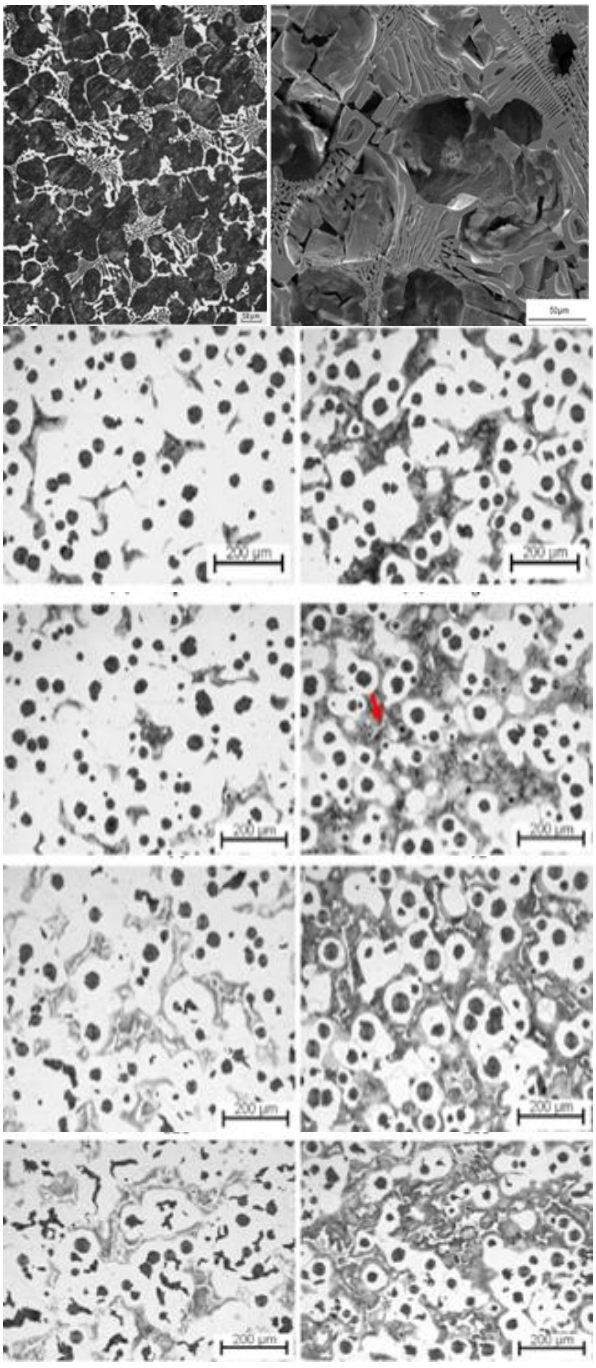


Fig. 5 Microstructure of the sample after FeB modification (×500)

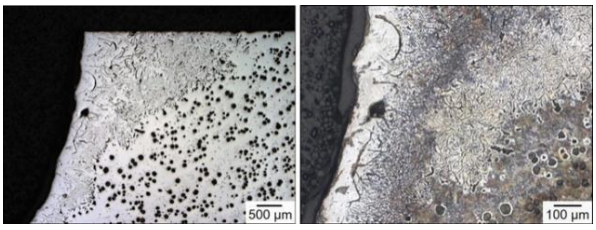


Fig. 6 Microstructure of the sample after FeSiB modification (×500)

Samples treated with ferrosilicoboron (FeSiB) exhibit the most homogeneous microstructure among the investigated series. A relatively uniform distribution of graphite particles within the metallic matrix can be observed. The observed structural features are consistent with the improved combination of strength, hardness, and ductility obtained after FeSiB modification.

DISCUSSION

The experimental results demonstrate that the type of modifier has a decisive influence on both the phase composition and the resulting mechanical properties of high-strength cast iron. The observed trends can be interpreted in terms of the known metallurgical mechanisms of silicon and boron.

Silicon is a strong graphitizer: it lowers the activity of carbon in the melt, promotes the precipitation of stable graphite over metastable iron carbide (Fe_3C), and increases the number of graphite nuclei [5,8]. This explains the finer graphite distribution observed in S1 relative to S0, which is consistent with the moderate improvement in strength and elongation.

Boron is a potent surface-active element with a strong tendency to segregate to solidification interfaces, where it substantially raises the nucleation rate of the metallic matrix [6,7]. Even small boron additions (≈ 0.003 wt.% in the final composition in this study) produced a pronounced matrix refinement and increased the density of pearlite colonies. However, boron's high affinity for carbon may facilitate the formation of boron-containing carbide phases during solidification [9]. Although no direct phase identification was performed in the present study, the increased hardness (236 HB) and reduced ductility observed in the FeB series suggest the possible presence of such hard structural constituents.

In the FeSiB system, the simultaneous presence of silicon and boron creates a synergistic mechanism: silicon stabilizes graphitization and moderates boron's carbide-promoting tendency by competing for carbon activity, while boron refines the matrix and multiplies nucleation sites. The result is a more homogeneous and refined microstructure with fine, well-distributed graphite, providing an improved balance of strength, hardness, and ductility [7, 10]. The 46% improvement in tensile strength achieved by FeSiB in this study is in quantitative agreement with data reported by Kurnakov and Taran [6], who obtained strength improvements of 40-50% with analogous FeSiB additions in ductile cast iron.

The superior performance of the FeSiB modifier compared with FeSi and FeB individually indicates that the improvement cannot be explained by the independent action of silicon or boron alone. Rather, the combined addition promotes a more balanced evolution of the microstructure, in which silicon enhances graphite nucleation and growth while boron contributes to matrix refinement without causing excessive embrittlement. Similar synergistic effects have been reported by Stefanescu [7], Riposan and Chisamera [8], and Tian et al. [12], who emphasized that combined silicon-boron modification improves both graphite morphology and the uniformity of the metallic matrix. The present results are consistent with these findings and further demonstrate that FeSiB provides a more favorable combination of strength, hardness, and ductility than the individual FeSi and FeB modifiers under identical experimental conditions.

The slight inter-specimen scatter in mechanical properties (≤ 5-7%) is attributable to local compositional and thermal heterogeneity inherent in sand-cast structures and is consistent with the expected variability for laboratory-scale castings [3].

A limitation of the present study is that the modifier addition rate was fixed at a single level (0.3 wt.%). Future work should systematically vary the FeSiB addition from 0.1 to 0.6 wt.% to determine the optimal concentration window, and should also investigate the effect of post-casting heat treatment (annealing, normalising) on the resulting microstructure and properties. Industrial-scale verification of the laboratory results is also recommended before implementation in production practice.

CONCLUSION

In this study, laboratory technology for producing high-strength cast iron with FeSi, FeB, and FeSiB ferroalloy modifiers was developed and evaluated. The following principal conclusions are drawn:

1. All three modifiers improved the mechanical properties of cast iron relative to the unmodified control (σb = 268 MPa, HB = 182, δ = 1.1%).
2. FeSi modification improved graphite morphology and increased tensile strength by 16% (312 MPa) and elongation to 1.6%, primarily through enhanced graphitization.
3. FeB modification produced the highest hardness (236 HB, +30%) and a 37% strength improvement (368 MPa), which may be associated with the formation of hard boron-containing structural constituents, at a slight cost to ductility (δ = 1.2%).
4. FeSiB complex modification achieved the optimal combination of properties: σb = 392 MPa (+46%), HB = 228, and δ = 2.1% - the highest elongation among all modified series. The synergistic silicon–boron interaction promoted microstructural refinement and improved the balance between strength, hardness, and ductility.
5. The results confirm the industrial potential of complex FeSiB modifiers for the production of wear-resistant, high-strength cast components for the metallurgical and mechanical engineering sectors. Future work should optimise modifier concentration and investigate post-casting heat treatment effects.

Funding: «This research is funded by the Committee of Industry of the Ministry of Industry and Construction of the Republic of Kazakhstan under program-targeted funding for scientific research for 2024-2026, BR23991563: «Creation of Innovative Resourch-Saving Technologies for Mining and Integrated Processing of Mineral and Technogenic Raw Materials.»

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