The niobium effect on the structure and properties of cast iron ChH16

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This study investigates the effect of a 1 % niobium addition on the microstructure and properties of high-chromium cast iron ChH16. Thermodynamic modeling using the ThermoCalc software and the TCFE13 database demonstrated that niobium promotes NbC carbide formation, with its precipitation occurring most actively in the 1000–600 °C range. The experimental results confirm that niobium refines the cementite structure, increasing hardness and wear resistance without significantly reducing bending strength. Comparative analysis of ChH16 alloyed with 1 % Nb and ChH32 indicates that the experimental alloy offers improved wear performance while maintaining mechanical integrity. Microstructural analysis using scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) revealed that NbC carbides are distributed uniformly throughout the matrix. This contributes to enhanced wear resistance due to their high hardness and stability. Hardness and wear tests confirmed an increase in wear resistance comparable to that of ChH32, while the bending strength remained unchanged, making the material suitable for applications involving abrasive and impact loads. Additionally, the formation of niobium carbides facilitates chromium retention in the matrix, suggesting improved heat resistance. These findings suggest that ChH16 with 1 % Nb is a promising material for mining and metallurgical equipment components subjected to severe wear conditions and high temperatures.
Key words: high-chromium cast iron, niobium alloying, wear resistance, hardness, toughness, microstructure.
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Introduction

Present-day requirements for materials used in mining and metallurgical equipment are primarily driven by the need for increased wear resistance and hardness, as a significant portion of this equipment operates under conditions of abrasive wear, often accompanied by impact loads (e.g., conveyor couplings, sliding shoes, chains, etc.). In this regard, materials used for manufacturing such components must combine high hardness, wear resistance, and adequate toughness [1, 2].

In addition to the properties of the metal matrix, the performance characteristics of high-chromium cast irons are significantly influenced by factors such as the size, shape, nature, and distribution of carbides [3, 4].

High-chromium cast irons with a chromium content of 11–14 % represent a well-balanced material that offers a combination of good hardness, wear resistance, and moderate plasticity. Within this range, chromium promotes the formation of M7C3 carbides, which enhance hardness and resistance to abrasive wear, making the alloy suitable for moderate operating conditions [5].

When the chromium content exceeds 20 %, large primary carbides are formed in the alloy, which negatively affects its overall performance. On the one hand, the hardness and wear resistance of the alloy increase; on the other hand, toughness decreases, limiting the applications of cast irons with chromium content above 20 %. These alloys are unsuitable for components that experience both abrasive and impact loads simultaneously.

Niobium alloying has attracted considerable research interest due to its strong carbide-forming ability. Niobium carbides exhibit high hardness and a favorable morphology, contributing to increased wear resistance, hardness, and heat resistance of the alloy [5, 6].

The objective of this study is to determine the effect of niobium on the microstructure and properties of the ChH16 alloy.

Methods and materials

At the first stage of the study, computer modeling of phase transitions in the ChH16 alloy with the addition of 1 % Nb was conducted. This initial niobium content was selected based on literature analysis and considerations regarding the feasibility of carbide phase formation. The ThermoCalc software and the TCFE13 database, which includes data on 435 [7, 8, 9] phases and accounts for oxygen-nitrogen conditions to assess the stability of alloy components, were used for the modeling. The TCFE13 database was chosen due to its high accuracy in predicting phase compositions of steels and iron-based alloys across various temperatures and alloying element concentrations. The analysis covered a temperature range from 500 to 1600 °C to provide a comprehensive understanding of phase transformations.

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At the second stage of the study, ChH16 cast iron was melted in a UIP-25 induction furnace equipped with a modernized cooling system. The melting process was carried out in an alumina crucible to prevent additional carburization. During smelting, ferroalloy FNb60 was introduced into the melt to achieve a final niobium content of 1 %. The chemical composition of the test samples was analyzed using a Niton spectrometer and a Spas-05 spectrometer. The microstructure was examined using a TESCAN Vega scanning electron microscope (SEM) equipped with an energy-dispersive spectroscopy (EDS) attachment.

Hardness was measured using a Brinell hardness tester at no fewer than five points.

Wear resistance was evaluated based on the relative change in sample mass after abrasive wear testing. The wear test lasted 10 hours, with a tungsten carbide ball used as the counter-body.

Results and discussion

The phase diagram (**Fig. 1*a***) of Fe–Cr alloys with the addition of 1 % niobium demonstrates that at temperatures above 1300 °C, the liquid phase predominates, transitioning into the austenite (γ) phase as the temperature decreases, confirming the alloy's suitability for casting. In the temperature range of 900–1300 °C, this confirms the presence of M_7C_3 carbides in the initial ChH16 alloy structure, prior to Nb addition. At temperatures below 900 °C, ferrite additionally appears.

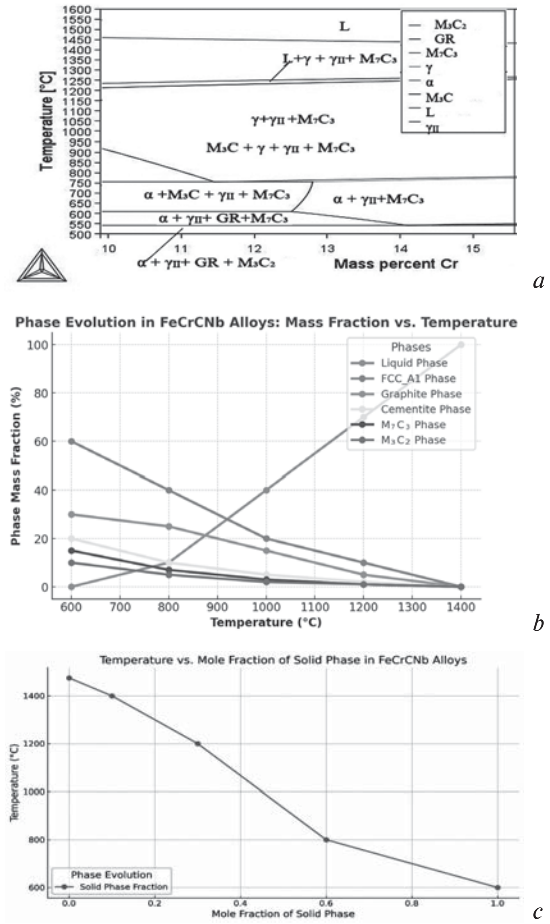

Fig. 1. Equilibrium phase diagram of the C–Fe–Cr–Nb system: *a* – General view of the phase diagram; *b* – Variation in phase content as a function of temperature; *c* – Effect of temperature on the molar fraction of the solid phase

The graph of phase mass fractions (Fig. 1*b*) shows that the mass fraction of the γ-phase reaches its maximum between 1000 and 1200 °C, coinciding with active carbide phase formation. As the temperature drops below 900 °C, the mass fraction of the ferrite (α) phase increases, while alloying elements dissolve and carbide inclusions stabilize.

The dependence of the solid-phase mole fraction on temperature (Fig. 1*c*) indicates a gradual increase in the solid fraction during cooling, with complete stabilization occurring at temperatures below 700 °C. The addition of 1 % niobium enhances the stability of carbide phases over a wide temperature range, which is expected to improve the hardness and wear resistance of the alloy.

The thermodynamic analysis of the C–Fe–Cr–Nb system revealed the intensive formation of stable NbC carbide, along with the formation of Me_3C, Me_7C_3, and Me_3C_2 carbides. The primary matrix is a solid solution of the FCC type, which in this case can be interpreted as alloyed austenite. The formation of the NbC carbide phase begins just below the liquidus, with the process being most intense in the temperature range of 1000–600 °C.

The second stage of the study involved experimental investigations. Experimental melts of the ChH16 alloy with the addition of 1 wt.% Nb were carried out. The chemical composition of the samples is presented in **Table 1**. ChH16 and ChH32 cast irons were used as reference samples for comparison.

The conclusion regarding the intensive formation of NbC is based on the phase fraction trends (Fig. 1*b* and 1*c*), where NbC appears and remains stable over a wide temperature range (1000–600 °C). Additionally, EDS analysis (**Table 2**) shows 84 % niobium content for the sample No. 3, which confirms the dominant formation of NbC carbides in the structure.

After complete cooling, the samples were prepared for further analysis. **Fig. 2** presents the microstructures of the samples.

The analysis revealed that while the structures of the initial and alloyed samples share common features, a detailed examination uncovers significant differences. In its initial state, the ChH16 alloy, as well as ChH32, exhibits a typical microstructure for this material, consisting of ledeburite, pearlite colonies, and cementite lamellae. At low magnification, this structure appears almost identical to that of the sample containing 1 wt.% niobium (Fig. 2*a*). However, at higher magnification, notable changes become apparent (Fig. 2*b*).

The cementite lamellae growing through pearlite colonies become finer and acquire a more rounded shape. In Fig. 2*b* (*right*), it is clearly visible that the cross-section of the lamellae along the (001) plane has a smaller area and a more rounded shape compared to the corresponding phase in the initial sample (Fig. 2*b*, *left*). It is possible that these are not purely cementite needles but instead another carbide phase,

Table 1. Chemical analysis of the samples

Sample No.	Sample characteristic	Element content, %								
		C	Cr	Mn	Si	Nb	S	P	Ti	Fe
1	ChH16	1.6–2.4	13–19	to 1.0	1.5–2.2	–	to 0.05	to 0.1	–	Rest
2	ChH32	1.6–3.2	30–34	1.0	1.5–2.5	–	0.08	0.1	0.1–0.3	Rest
3	ChH16+1 % Nb	2.3	13.4	0.6	1.93	1.0	0.05	0.07	–	Rest

Table 2. Micro-X-Ray Spectral (MXS) Analysis Results

	C–K	O–K	Si–K	Cr–K	Mn–K	Fe–K	Nb–K
Sample 1 pt1	6.4	0.0	0.1	13.2	1.5	78.8	0.0
Sample 2 pt2	6.5	0.0	0.09	2.1	1.7	78.8	0.8
Sample 2 pt3	9.4	0.0	0.1	1.85	1.9	68.53	84.8

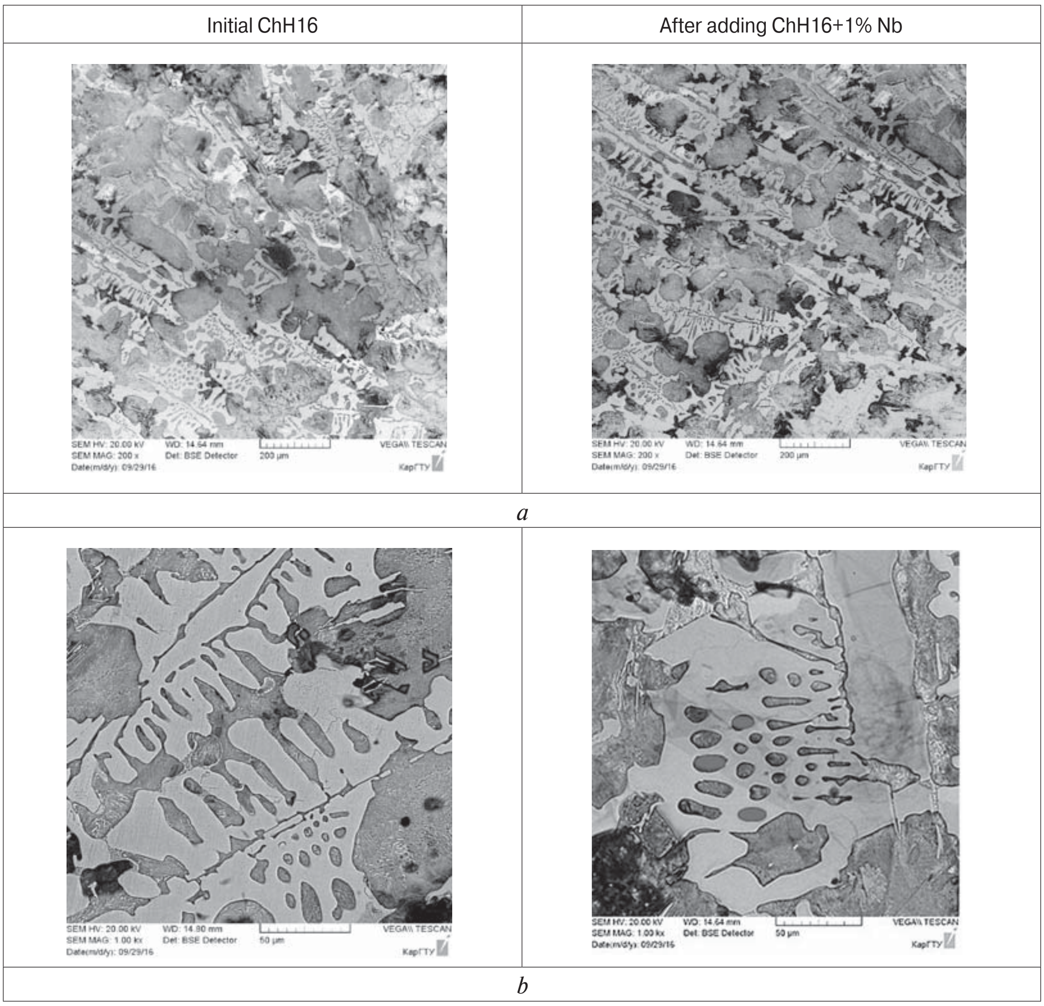

Fig. 2. Microstructures of the initial and experimental samples

such as NbC. To investigate this hypothesis, a micro-X-ray spectral (MXS) analysis [10–12] of these structural regions was conducted.

As seen from Table 2, the composition of the pt1 spectrum corresponds to the $(Fe, Cr, Mn)_3C$ phase. In the pt2 spectrum, in addition to the main elements, niobium was detected. This suggests that niobium may be incorporated into a more complex carbide of the $(Fe,Cr,Mn,Nb)_3C$ type, which may correspond to Me_3C_7 carbides. The chemical composition of this phase indicates partial redistribution of chromium between the matrix and the carbide, which may contribute to enhanced oxidation resistance. In the pt3 spectrum, the niobium content reaches 84 %, which almost certainly confirms the formation of NbC carbide.

These structural changes directly influence the properties of the alloy. Niobium carbides are characterized by high hardness and wear resistance, which will undoubtedly enhance the hardness and strength of the material. However, according to thermodynamic analysis, the alloy matrix remains a solid solution of the FCC type (alloyed austenite), which should not lead to a significant change in the overall toughness of the alloy.

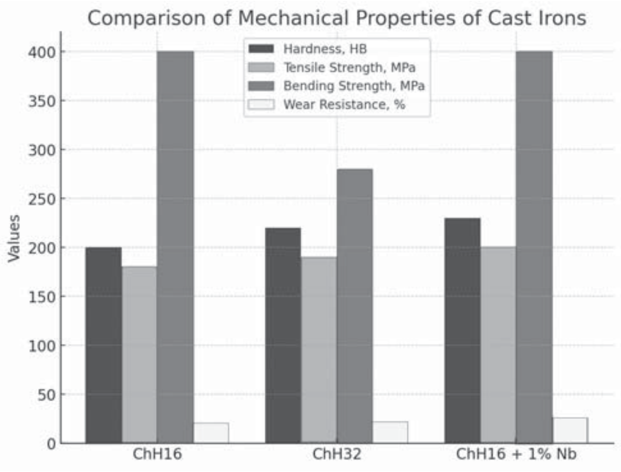

Fig. 3. Comparative diagram of properties

To verify this assumption, hardness, wear resistance, tensile strength, and bending strength tests were conducted. ChH16 and ChH32 cast irons were used as reference samples for comparison. The results of these studies are presented in **Fig. 3**.

The diagram shows that the properties of ChH16 and ChH32 cast irons are comparable in terms of hardness, tensile strength, and wear resistance. A significant difference (approximately 30 %) is observed in bending strength values, indicating lower plasticity and toughness reserve in ChH32 cast iron.

ChH32 cast iron is primarily used for manufacturing parts that operate under abrasive wear conditions without impact loads but at elevated temperatures and in oxidizing environments. The heat resistance of ChH32 is attributed to the presence of chromium and titanium in amounts ranging from 0.1 % to 0.3 %.

After the addition of 1 % Nb to ChH16 cast iron (pilot sample), its wear resistance increased and became comparable to that of ChH32. At the same time, its bending strength remained virtually unchanged, exceeding the corresponding value for ChH32 by nearly 30 %. Additionally, the presence of niobium carbides suggests that the experimental sample may possess some degree of heat resistance. This is because niobium carbide formation facilitates the transition of most chromium into the matrix due to the resulting carbon deficiency.

Conclusion

Based on the carried out studies, the following conclusions can be made. The addition of 1 wt.% niobium to ChH16 cast iron resulted in a hardness increase from 380 to 445 HB and an approximate 28 % reduction in wear loss, while maintaining the original bending strength of around 360 MPa. The presence of hard and stable NbC carbides in the structure was confirmed by EDS analysis, which explains the improved wear behavior. These combined factors confirm the effectiveness of niobium as a performance-enhancing element. It should be noted that the improved high-temperature performance is only hypothesized based on structural changes and chromium redistribution. Further oxidation and scaling resistance tests are required to confirm this assumption.

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