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Analysis of The Influence of Alloying on the Performance Properties of Cast Iron Grades 280Cr29Ni and 330Cr17 with the Purpose of Increasing their Quality

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Abstract. The hardness and microstructure of the High chromium cast irons (HCCIs) grades 280Cr29Ni and 330Cr17, which are predominantly utilized in the production of components for mining and metallurgical equipment subject to wear conditions, have been thoroughly investigated. A thermodynamic analysis of multicomponent Fe-2.6C-Cr-alloying elements (a.e.), was conducted to investigate the crystallization processes of alloys, the development of their metallic matrix structure, and the formation and transformation of carbide phases. Based on the analysis, the optimal quantity and ratio of alloying elements (Cr, Mn, Si, and Ti) in the Fe-2.6C-Cr-a.e., system required for the formation of a metallic matrix and carbide phases that maximize the hardness of the alloy were determined. State diagrams were constructed for ternary, quaternary, and multicomponent systems, including Fe-C-Cr, Fe-C-Ni, Fe-C-Mn, Fe-C-V, Fe-C-Mo, Fe-C-Co, Fe-C-Cr-Ni, Fe-C-Cr-Mn, and Fe-C-Cr-Mn. These diagrams, along with their isothermal (at 200 °C) and polythermal sections, enriched the theory of phase diagrams, which form the foundation of HCCIs. The analysis covered a range of chromium concentrations (16-34%), nickel (0.4-3%), manganese (0.4-2%), carbon (2.4-4%), silicon (0.3-2%), titanium (0.4-5%), molybdenum (0.2-3%), and vanadium (0.01-2%). Phase equilibrium points were determined, encompassing an alloyed solid solution based on iron, multicomponent carbides, and a mixture of phases consisting of a solid solution of iron and carbides. An economical grade of HCCIs has been developed with the following composition: carbon 3.2-3.4%, manganese 0.4-0.6%, chromium 16-18%, silicon 0.4-0.6%, nickel 0.4-0.6%, molybdenum up to 0.4-0.5%, with the balance being iron.

Key words: high chromium cast iron, thermodynamic analysis, matrix, multicomponent systems, microhardness, hardness, microstructure, structure, alloying elements, phase diagrams, phase equilibrium, carbide phase.

Introduction

High chromium cast irons (HCCIs) represent a distinct class of materials characterized by an ongoing process of research and development, driven by continuous updates to their chemical compositions and structural configurations, which directly influence their operational properties. This dynamic nature underscores their unique position in materials science, where systematic investigations into alloy formulations, microstructural modifications, and corresponding performance enhancements are pivotal. Thus, the evolution of HCCIs remains a scientifically driven endeavor, perpetually refining and adapting to meet diverse industrial demands and technological advancements. [1-4]. In the realm of materials science, the evolution of HCCIs exemplifies a progressive trend marked by escalating production volumes and an expanding array of applications. This growth underscores a critical imperative within sectors such as mining and metallurgy: to enhance the economic efficiency of components crafted from HCCIs through advancements that amplify their operational performance and elevate mechanical properties. This imperative drives ongoing research and innovation aimed at refining the alloy compositions, optimizing manufacturing processes, and augmenting the structural integrity of HCCIs components. As a result, the scientific pursuit focuses on achieving superior durability, enhanced wear resistance, and heightened mechanical reliability, thereby meeting the burgeoning demands of industrial applications with improved efficacy and longevity. [5-8].

At the Navoi Machine-Building Plant in Uzbekistan, the utilization of HCCIs grade 280Cr29Ni is integral to the fabrication of components designed to endure challenging operational environments characterized by abrasive wear and impact loads. These specific cast iron alloys are selected based on their tailored properties to withstand the combined effects of abrasion and impact, reflecting a strategic approach in material selection for industrial applications. This strategic deployment underscores the plant's commitment to optimizing component longevity and reliability under demanding working conditions, aligning with stringent performance criteria essential for enhancing operational efficiency and sustaining productivity in critical sectors such as machine-building and heavy industry. The primary focus of investigation revolves around the essential quality parameters of hardness and wear resistance in HCCIs alloy 280Cr29Ni and 330Cr17. Despite exhibiting similar high levels of hardness, these alloys demonstrate varied service lives when subjected to identical operating conditions [9-13]. This discrepancy, likely attributed to differences in their chemical compositions, underscores the pivotal role of alloy structure in influencing durability and performance. The central aim of this study is to elucidate the underlying factors contributing to this observed variability, thereby providing insights into optimizing the structural integrity of these alloys for enhanced longevity and reliability in practical applications. Furthermore, in the context of alloy preparation practices, there is a pressing imperative to minimize the degree of alloying in these HCCIs. Previous research has explored the profound impact of alloying elements on the structural characteristics and functional properties of HCCIs. This ongoing scientific inquiry aims to refine alloy formulations with the goal of achieving optimal performance efficiencies while reducing alloying costs and enhancing manufacturing feasibility. Thus, the study not only seeks to unravel the structural basis for performance disparities but also strives to advance practical methodologies for alloy optimization in industrial settings [14-18]. Currently, the establishment of definitive compositional guidelines to achieve an optimal structure that guarantees maximum hardness in HCCIs remains elusive. This unresolved challenge underscores the relevance and significance of the present study and its formulated objectives. Specifically, within the foundry operations of the Navoi Machine-Building Plant, the production volume exceeds 200 tons per month of castings made from HCCIs. The critical need to enhance understanding of alloy composition's impact on structural properties is paramount, aiming to unlock methodologies that can reliably optimize alloy formulations. By addressing this gap in knowledge, the study endeavors to pioneer insights into refining casting practices, thereby bolstering the plant's capability to consistently deliver components with superior hardness and enhanced performance characteristics. Consequently, the research not only aims to advance scientific understanding but also holds practical implications for optimizing industrial processes and maximizing the utility of HCCIs in demanding operational environments. The operational demands placed on machinery functioning in abrasive and waterjet environments are progressively intensifying each year. Consequently, there is a corresponding escalation in the standards for materials used in the fabrication of cast components for such machines and mechanisms [19-23]. This ongoing evolution highlights the unresolved challenge surrounding the selection of optimal materials for manufacturing cast parts essential to various industrial equipment. These components include centrifugal crushers, wheels, covers, and housings of dredges, sand, and slurry pumps, impellers of flotation machines, and various parts utilized in concentrating factories, grinding ball mills, and shot blasting machines.

The criticality of material selection is underscored by the need to meet stringent performance criteria in these aggressive operational settings. The quest for suitable materials is driven by the imperative to enhance durability, extend service life, and elevate operational efficiency of machinery subjected to abrasive wear and high-pressure waterjet environments. Addressing this multifaceted challenge involves advancing scientific understanding of material properties, refining alloy compositions, and developing robust manufacturing techniques. By doing so, the aim is to deliver cast components that not only withstand harsh operating conditions but also contribute to optimizing performance and reliability across diverse industrial applications. Thus, the ongoing pursuit of material innovation remains pivotal in meeting the evolving demands of modern industrial sectors.

To achieve the main goal of this study, the following tasks are delineated:

- based on an analysis of the chemical composition, structure and properties of the alloys used, simplify their composition and increase mechanical and performance properties;
- simplification of the chemical composition of three-, four- and multicomponent phase diagrams by analyzing the phase composition, equilibrium and their structure during crystallization;
- by analyzing the chemical composition, structure and properties of model alloys, simplifying the chemical composition of practically used malleable white cast irons and improving their mechanical and performance properties.

1. Methods and materials

Wear-resistant white cast irons 280Cr29Ni and 330Cr17 were chosen as the material under study, the chemical composition of which is given in Table 1.

Table 1. Compositions of the studied cast irons

Cast iron grade	Content of chemical elements,% by weight						
	C	Si	Cr	Mo	Ni	P	S
280Cr29Ni	2,55	≤ 1,5	28,0	-	0,6	≤ 0,01	≤ 0,01
330Cr17	3,40	0,6	16,5	0,5	0,6	≤ 0,01	≤ 0,01

Cast irons according to table 1 are used for castings of mining and processing equipment operating under conditions of intense abrasive wear, namely: feeding disks, substrates, plates for crushers, etc.

The thermodynamic state diagrams of the Fe-2.6C-Cr-Ni, Fe-2.6C-Cr-Mn, Fe-2.6C-Cr-Si and Fe-2.6C-Cr-Ti systems for four components were calculated using Thermo-Calc program [24-26].

To reveal the structure, the samples were etched with a reagent of the following composition: 15 ml of nitric acid, 15 ml of hydrochloric acid and 15 ml of glycerol. Etching time is 10 seconds, at a reagent temperature of 60˚C.

Microsections were prepared on a NERIS grinding and polishing machine.

To measure hardness according to HRCe, a TK-2M hardness meter was used, and to measure hardness according to HV_{50}, a PMT-3M hardness meter was used.

The chemical composition of the castings was determined by the emission spectral method using a Spectro-Lab –M device.

The structures of the alloys were studied on a TESCAN VEGA4 SEM scanning electron microscope at different magnifications.

2. Results and discussion

The hardness of the samples was determined on the surface and in the core, at least at 5 points with three duplicates. The average test results are given in table. 2.

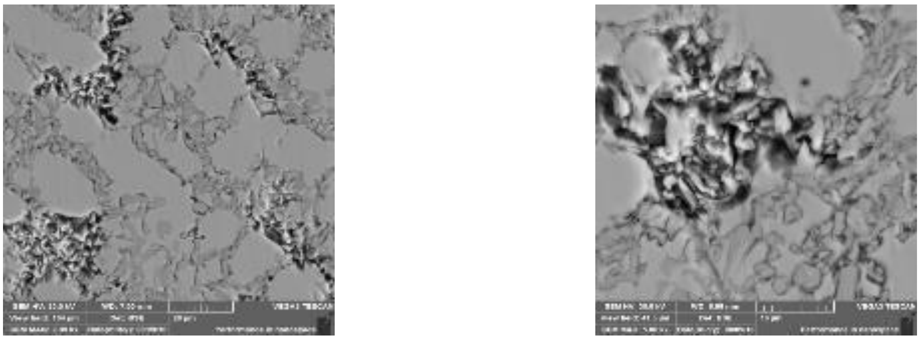
Table 2. Hardness of prototypes

Cast iron grade	330Cr17	280Cr29Ni
Surface hardness in cast state HRC	57-62	46-47
Hardness in the core in the cast state HRC	47-48	40-41

Based on the data presented in the table, it is evident that the HCCIs of the 280Cr29Ni grade exhibits a lower hardness compared to the 330Cr17 grade. This observation suggests that, in scenarios where abrasive wear is the sole mode of degradation without the presence of concurrent shock loads, the 280Cr29Ni HCCIs is likely to have a reduced service life. Furthermore, it is important to highlight that the 280Cr29Ni alloy is 1.5 times more expensive than the 330Cr17 alloy, primarily due to its alloying with costly nickel. Consequently, the use of the 280Cr29Ni alloy is economically unjustifiable for components subjected exclusively to abrasive wear conditions.

The microstructure of HCCIs 280Cr29Ni and 330Cr17 was meticulously examined under magnifications of 500, 1000, 2000, and 5000 times. This detailed analysis allowed for an in-depth investigation of the microstructural features, providing critical insights into the phase distributions, grain boundaries, and the morphology of the carbides and matrix. Such high-resolution studies are essential for understanding the intrinsic material properties and their implications on the mechanical performance and wear resistance of these alloys.

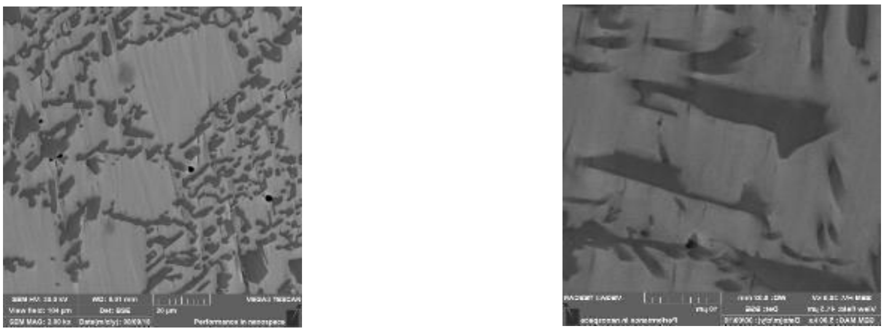
Figure 1 illustrates the microstructure of the white cast iron alloy 280Cr29Ni. The matrix of this alloy is composed predominantly of pearlite and austenite. Within this matrix, the structure features carbides of types M_3C and, to a lesser extent, M_7C_3. The carbide phase is characterized by an average size ranging from 15 to 20 microns. This microstructural configuration is crucial for understanding the alloy's mechanical properties, wear resistance, and overall performance in various applications.



(a) (b)

Fig. 1. Structural HCCIs brand 280Cr29Ni: a) x2000, b) x5000

Figure 2 depicts the microstructure of the HCCI grade 330Cr17. The matrix is primarily composed of austenite. The carbide phase within this matrix is represented by two distinct types of carbides: M_7C_3 and $M_{23}C_6$. The average size of these carbide particles ranges between 8 and 13 microns. This detailed structural composition is pivotal for comprehending the material's mechanical attributes and its suitability for various industrial applications, particularly those requiring enhanced wear resistance.



(a) (b)

Fig. 2. Structural HCCIs brand 330Cr17: a) x2000, b) x5000

A comprehensive comparison of the structural characteristics, specifically the nature of the matrix and the carbide phase, alongside the varying dispersion of the carbide phase, elucidates the differences in hardness observed in the studied alloys. The distinct composition and distribution of the matrix - whether it is predominantly pearlite, austenite, or a combination thereof - along with the specific types and average sizes of carbides such as M_3C, M_7C_3, and $M_{23}C_6$, play critical roles in defining the hardness of each alloy. These microstructural variations are fundamental in understanding the mechanical performance and wear resistance of the 280Cr29Ni and 330Cr17 HCCIs.

To elucidate the influence of various alloying elements on the processes of structure formation and the development of the carbide phase, a thermodynamic analysis was conducted utilizing the Thermo-Calc software. This advanced computational tool enables a detailed examination of the phase equilibria and transformations occurring within the alloy system, providing valuable insights into how different alloying elements contribute to the microstructural evolution and the stabilization of specific carbide phases. Such analysis is instrumental in optimizing the alloy design for improved mechanical properties and performance.

An isothermal section of the phase diagram for the four-component system Fe-2.6C-Cr-Ni at a temperature of 200 °C was constructed. This phase diagram elucidates the phase equilibria and stability regions for the various phases within this alloy system at the specified temperature. At 200 °C, multiple phases are observed to form, including distinct carbide phases and metallic matrices. The detailed depiction of these phases within the Fe-2.6C-Cr-Ni system provides critical insights into the microstructural evolution and phase transformations that occur during the alloying process, contributing to a deeper understanding of the material properties and their potential industrial applications. At a nickel content of 1.2% and chromium content of 16%, the alloy's microstructure includes free graphite, ferritic and austenitic structures, and M_3C_2 carbide phases. When the chromium content is increased to 16-25% and the nickel content exceeds 1.1%, the microstructure of the alloy fully develops into austenite and ferrite, with the formation of carbide phases M_3C_2 and M_7C_3 also becoming apparent. These compositional adjustments significantly influence the phase composition and distribution within the alloy, thereby affecting its overall mechanical properties and performance characteristics. It is important to note that when the chromium content reaches 26%, the metallic matrix of the alloy comprises both austenite and ferrite, while the carbide phase is exclusively represented by M_7C_3 carbides. This specific compositional threshold marks a significant shift in the microstructural configuration, influencing the alloy's mechanical properties and behavior under various operating conditions. The exclusive presence of M_7C_3 carbides at this chromium level highlights the critical role of chromium in stabilizing particular carbide phases and modifying the alloy's overall performance.

When the chromium content in the alloy exceeds 16% and the nickel content is increased to 1%, the microstructure predominantly exhibits a ferritic phase, with fully formed M_7C_3 type carbides (Fig. 3).

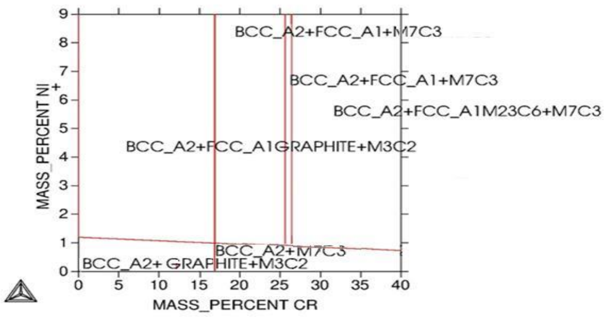


Fig. 3. Phase diagram of Fe-2.6C-Cr-Ni, T-200 ^{0}C

This compositional adjustment is crucial as it enhances the formation and stabilization of M_7C_3 carbides, significantly influencing the alloy's mechanical properties and wear resistance. The presence of these well-defined carbides within a ferritic matrix underscores the impact of chromium and nickel in determining the alloy's structural characteristics and overall performane. When the chromium content in the alloy exceeds 16% and the nickel content is increased to 1%, a microstructure characterized by a ferritic matrix and fully developed M_7C_3 type carbides is observed. This composition facilitates the stable formation of M_7C_3 carbides within the ferritic structure, influencing the alloy's mechanical properties, particularly its hardness and wear resistance. Upon further increasing the chromium content to 26% and maintaining the nickel content at 1%, the alloy's microstructure transitions to include both ferritic and austenitic phases. Additionally, this composition promotes the formation of carbides of both M_7C_3 and $M_{23}C_6$ types within the alloy's structure. This dual-phase microstructural configuration, comprising both ferrite and austenite along with distinct carbide phases, enhances the alloy's mechanical strength, corrosion resistance, and suitability for applications requiring robust performance under demanding conditions [27].

In the analysis of the Fe-2.6C-Cr-Mn system, alloys containing chromium levels up to 45% and manganese levels up to 9% exhibit a fully developed matrix structure. This structure encompasses phases such as ferrite and austenite, accompanied by the formation of carbide phases including M_3C_2, M_7C_3, and $M_{23}C_6$. These carbides play a critical role in determining the alloy's mechanical properties, including hardness and wear resistance. However, as the manganese content surpasses 9%, a notable transformation occurs in the alloy's microstructure. Specifically, the presence of free graphite becomes evident alongside the metallic phases. This change is indicative of manganese's influence in promoting graphite formation, altering the alloy's characteristics and potentially impacting its suitability for specific applications where graphite presence may affect performance parameters such as strength and machinability.

At manganese contents ranging from 3-4%, the alloy exhibits a fully developed ferritic structure accompanied by the formation of carbide phases M_7C_3 and $M_{23}C_6$. This composition supports the stable presence of both carbide types within the ferritic matrix, influencing the alloy's mechanical properties, particularly its hardness and wear resistance (Fig. 4).

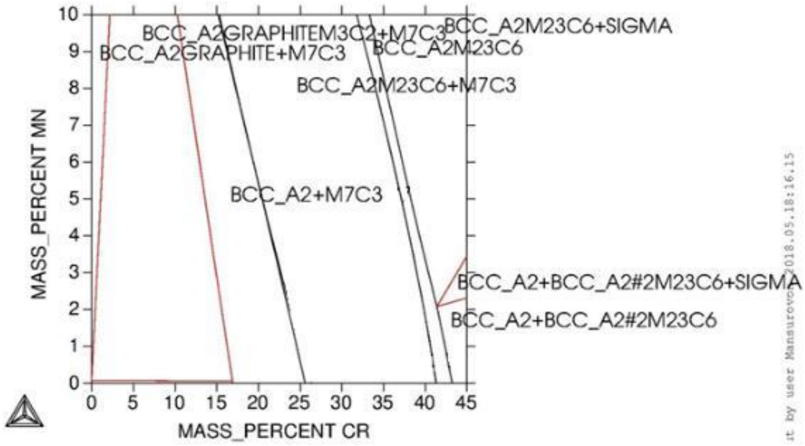


Fig. 4. Phase diagram of Fe-2.6C-Cr-Mn, T-200 ^{0}C

In contrast, at lower manganese contents of 0.7-0.8% and chromium levels spanning 16-45%, the alloy's microstructure predominantly consists of a ferritic matrix. Despite the reduced manganese content, the formation of M_7C_3 carbides is observed. This suggests that chromium plays a crucial role in facilitating the formation and stability of M_7C_3 carbides even in the absence of higher manganese levels. Such microstructural configurations are pivotal in determining the alloy’s suitability for applications requiring specific mechanical and wear-resistant properties.

High manganese content in white cast iron promotes the formation of graphite within the alloy’s structure. This phenomenon occurs due to manganese’s tendency to favor graphite precipitation over carbide formation. Consequently, the microstructure of the alloy is characterized by the presence of ferrite, graphite, and brittle carbide phases of the M_3C_2 type. This combination of phases contributes to reduced mechanical properties, as the presence of graphite and brittle carbides diminishes the alloy’s strength and toughness. Therefore, manganese’s influence in promoting graphite formation and impeding carbide development significantly impacts the alloy's suitability for applications requiring high mechanical performance and wear resistance.

Based on the thermodynamic state diagram of white cast iron 280Cr29Ni of the Fe-2.6C-Cr-Mn system, it was determined that the optimal amount of manganese is 0.4-0.6%, and the optimal amount of chromium is at least 16.5%.

Thermodynamic analysis of the Fe-2.6C-Cr-Si system indicates that at silicon concentrations exceeding 4.5%, the alloy structure comprises ferrite along with free graphite. Silicon's presence promotes the formation of free graphite, which can impact the alloy's mechanical properties due to graphite's tendency to act as a stress concentration site, potentially reducing strength and ductility.

In contrast, when the chromium content exceeds 25-26%, a transformation occurs where free graphite transitions into a bound form within the alloy structure. This transformation suggests that chromium plays a crucial role in stabilizing graphite in a manner that mitigates its detrimental effects on mechanical properties. Bound graphite typically exhibits a more distributed and interconnected structure, which can enhance the alloy's mechanical strength and mitigate potential weaknesses associated with free graphite.

These thermodynamic insights are essential for understanding how variations in silicon and chromium content influence the microstructural evolution and mechanical behavior of Fe-2.6C-Cr-Si alloys, guiding their application in different industrial contexts where specific mechanical properties are required (Fig. 5).

In the phase diagram of the Fe-2.6C-Cr-Si system, the presence of silicon and chromium influences the formation of various phases, including carbides such as M_3C_2, M_7C_3, and $M_{23}C_6$. Additionally, chromium silicide (Cr_3Si) forms under certain silicon and chromium concentrations. Chromium silicide is undesirable in this context due to its brittle nature, which can adversely affect the alloy's mechanical properties, particularly its toughness and ductility. The formation of chromium silicide alongside carbide phases underscores the complex interplay between alloying elements and phase stability within the Fe-2.6C-Cr-Si system.

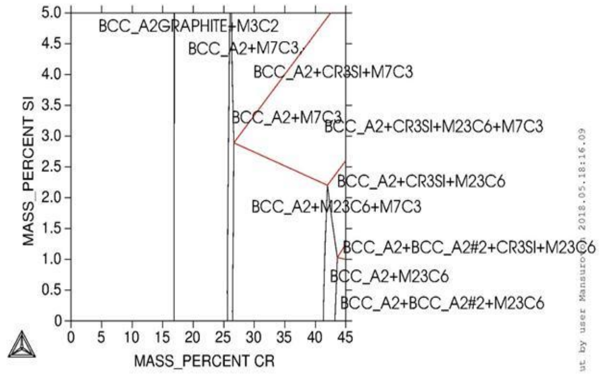


Fig. 5. Phase diagram of Fe-2.6C-Cr-Si, T-200 ⁰C

Understanding these phase relationships is crucial for optimizing alloy compositions to minimize the formation of brittle phases like chromium silicide, thereby enhancing the alloy's suitability for applications requiring superior mechanical performance and durability.

Thus, the optimal amount of silicon in white cast iron is no more than 1%, which ensures good casting properties. The thermodynamic state diagram of the four-component Fe-2.6C-Cr-Ti alloy at 200 ^{0}C consists of several phases. Chromium content up to 16% and titanium up to 10% leads to the formation of a ferritic-austenitic structure, as well as the presence of free graphite. The carbide phase is represented by M_3C_2 type carbide.

When the chromium content falls within the range of 16-26% in the Fe-2.6C-Cr-Si system, the alloy structure does not exhibit free graphite. Instead, the carbide phase is characterized by the presence of two types of carbides: M_3C_2 and M_7C_3. (Fig. 6).

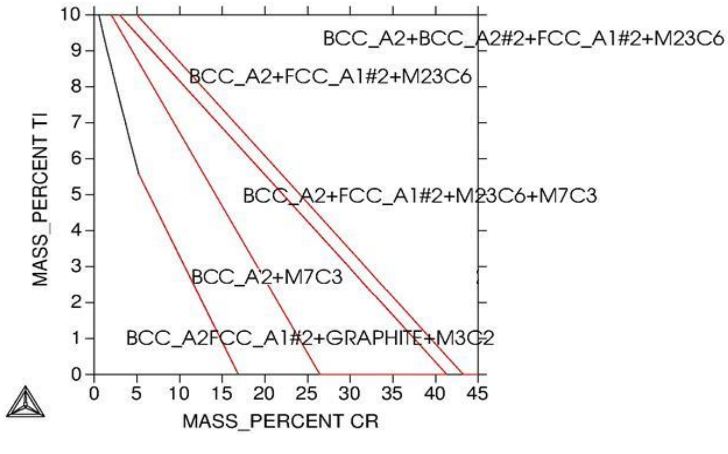


Fig. 6. Phase diagram of Fe-2.6C-Cr-Ti, T-200 ⁰C

This compositional range supports the stable formation of these carbide phases, which play crucial roles in enhancing the alloy's hardness, wear resistance, and overall mechanical properties. The absence of free graphite is significant as it helps maintain the alloy's structural integrity and mitigates potential weaknesses associated with graphite formation, thereby optimizing its performance in demanding industrial applications. When the chromium content in the alloy is 26-42%, the structure of the alloy is represented by a ferritic-austenitic matrix, the carbide phase is represented by M_7C3 and $M_{23}C_6$. Only when the chromium content in the alloy is more than 42%, only one type of carbides is present in the alloy structure - $M_{23}C_6$.

Conclusions

The hardness and microstructure of high-chromium cast irons (HCCIs) grades 280Cr29Ni and 330Cr17, which are commonly used in wear-resistant components for mining and metallurgical equipment, have been thoroughly studied. The investigation showed that the alloy's performance is closely linked to its metallic matrix structure and the formation of carbide phases, which are influenced by the specific alloying elements used.

A comprehensive thermodynamic analysis of the multicomponent Fe-2.6C-Cr-alloying elements system was performed to understand crystallization processes. The analysis identified the optimal ratio of alloying elements such as Cr, Mn, Si, and Ti, which are critical for the development of a metallic matrix and carbide phases that enhance the hardness of the alloy.

Ternary, quaternary, and multicomponent phase diagrams, including systems like Fe-C-Cr, Fe-C-Ni, Fe-C-Mn, and Fe-C-Cr-Ni, were developed. The resulting iso- and polythermal sections (at 200 °C) enriched the theoretical understanding of phase equilibria in high-chromium cast irons. These phase diagrams are essential for guiding the design of cast irons with tailored properties.

The research determined that the composition of 3.2-3.4% carbon, 0.4-0.6% manganese, 16-18% chromium, 0.4-0.6% silicon, 0.4-0.6% nickel, and 0.4-0.5% molybdenum (with the remainder being iron) represents an economical and high-performing grade of HCCIs. This optimized alloy composition not only improved the mechanical properties but also resulted in significant cost savings in the alloying process, particularly in reducing the consumption of ferrochrome, nickel, and other elements.

The optimized chemical composition and the use of advanced casting and heat treatment processes led to an extension of component life by at least 20% and a reduction in production costs by 30%, making the alloy highly suitable for industrial applications requiring enhanced wear resistance.

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