The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 38, Pages 283-288

IConTES 2025: International Conference on Technology, Engineering and Science

Investigation of the Possibility of Introducing Dispersed Boron Carbide Particles into the Melt of Austenitic Steel 12X18H10T During Centrifugal Casting

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Abstract: The principal way to improve the mechanical and operational properties of steel is to adjust its chemical composition or to grind the metal structure. An alternative to the use of expensive alloying elements to improve the mechanical and operational properties of steel can be the dispersed hardening of steel with hard refractory fine particles of carbides, oxides, nitrides. This work, which was carried out within the framework of grant № AP23485709, funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, is devoted to the study of the possibility of introducing dispersed boron carbide particles into the melt of austenitic steel 12X18H10T during centrifugal casting. At the first stage of the research, the interaction of dispersed particles of boron carbide and steel was simulated using the FactSage software package. The simulation showed that boron carbide particles will interact with the metal melt of austenitic steel 12X18H10T, which can lead to their complete dissociation. At the next stage of crystallization, the formation of carbide phases based on titanium carbide with a HCC structure, as well as a carbide phase based on chromium carbide with the formula $M_{23}C$, will begin, starting at a temperature of 1250°C. When the temperature decreases to 1050°C, the separation of boride phases based on chromium begins in the system under consideration. The experiments and metallographic analysis carried out at the second stage of the research confirmed the results of thermodynamic modeling. The introduced boron carbide particles completely dissociate when interacting with a metal melt. The carbon contained in the composition of boron carbide and in the composition of the initial melt contributes to the formation of carbide and carbon-nitride phases based on titanium.

Keywords: Centrifugal casting, Boron carbide, Thermodynamic modeling, Microstructure, Microhardness

Introduction

Austenitic steels 08-12X18H10T are used everywhere in various fields of industry due to their versatility (it combines corrosion-resistant properties, heat resistance, good machinability, etc.), as well as a large amount of research devoted to it. Austenitic class steels have a FCC lattice, which provides a sufficient level of mechanical properties, however, in terms of resistance to various kinds of influences (for example, weldability, corrosion resistance), steels of this class lose to ferritic class steels (BCC lattice) (Salama et.al., 2019; Shlyamnev et.al., 2008; Devine, 1996). For this reason, there has been a recent trend in the world to use austenitic-ferritic grade steels to ensure better corrosion resistance and higher mechanical properties (Li et.al., 2015; Bagwe, 2014; Efimushkin et.al., 2022). Such "duplex" steels produced by smelting have a huge disadvantage in the form of difficult machinability and low ability to plastic deformation. Another technology for connecting austenitic and ferritic steels is to weld one steel onto another. A significant disadvantage of technology is the need to weld the sublayer onto the hardening steel in order to avoid the formation of brittle interlayers in the fusion zone with the base metal.

In this study, another method is proposed for obtaining various chemical and structural states of steel without a pronounced phase boundary and with an acceptable level of workability. This is achieved by introducing boron carbide into the melt during centrifugal casting, which ensures its controlled distribution over the cross-section of the resulting blanks. The introduced particles serve as crystallization centers, grind the metal grain, and implement the mechanism of dispersed hardening (Chumanov et.al., 2022; Korostelev et.al., 2011). Small boron additives in steel cause significant grain grinding, increased heat resistance as a result of hardening of grain boundaries with borides, increased hardness and wear resistance, hot ductility of ingots, improved weldability of heat-resistant austenitic steels (Liu et.al., 2024; Herring, 2018). At the same time, the resulting billet does not have a pronounced separation of the interface of the layers, which causes the absence of internal stresses (Watanabe et.al., 2009). Thus, the purpose of this article is the thermodynamic modeling of the interaction of boron carbide with austenitic steel 12X18N10T, to verify the fundamental possibility of introducing dispersed boron carbide particles into the melt during centrifugal casting, and to study its effect on the microstructure of the obtained blanks.

Method

To simulate the interaction of dispersed boron carbide particles and steel, the FactSage software package version 7.0 was used. During thermodynamic modeling, both traditional methods of equilibrium thermodynamics based on the CALPHAD approach (Figure 1) and the model of nonequilibrium crystallization of melts (Sheil-Gulliver model) were used, which allows a more accurate description of the process of real metal crystallization. and oxide melts (Figure 2), rather than using the equilibrium crystallization model. During the simulation, the crystallization of metal with carbide additives was investigated. In the calculation, the interaction of substances was assumed at a ratio of 1/100 (the interaction of 1% boron carbide B_4C with 99% of the melt was modeled). The initial composition of the metal for modeling was as follows: 69.25% Fe, 18 % Cr, 10% Ni, 1.5% Mn, 0.5% Si, 0.1 % C.

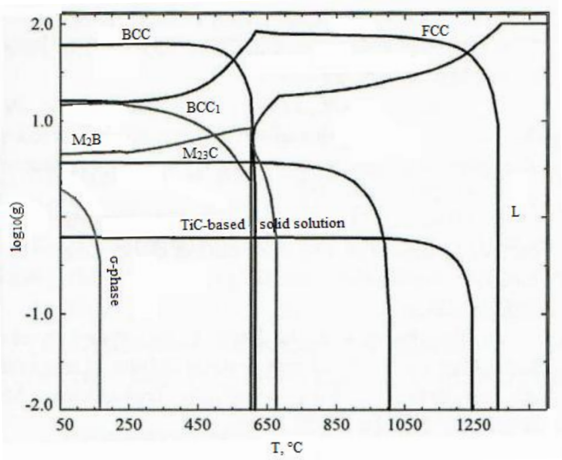


Figure 1. Simulation results of equilibrium phase compositions of metal with boron carbide addition depending on temperature

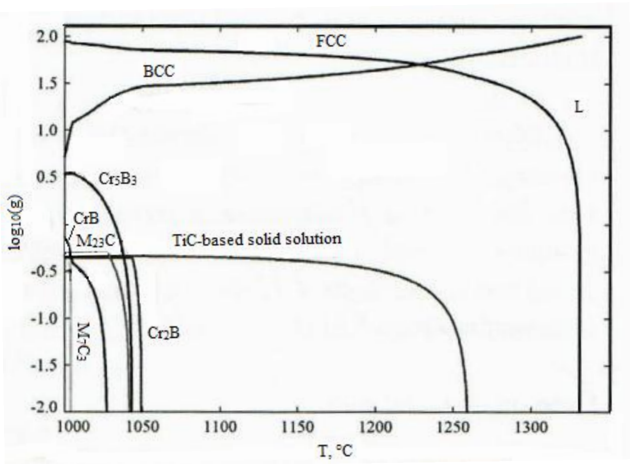


Figure 2. Diagram of nonequilibrium crystallization of a metal with boron carbide (Sheil-Gulliver model)

Based on the simulation results, it can be concluded that the crystallization of a metallic melt will be accompanied by the expected formation of metallic phases with BCC and FCC crystal lattices. In this case, boron carbides will interact with the metal melt, which can lead to their complete dissociation. At the next stage of crystallization, regardless of the degree of dissolution of boron carbide, the formation of carbide phases based on titanium carbide with a FCC structure, as well as a carbide phase based on chromium carbide with the formula $M_{23}C$, will begin, starting at a temperature of 1250°C. When the temperature drops to 1050°C, chromium-based boride phases are released in the system under consideration.

Under long-term operation conditions at temperatures no higher than 200°C, the structural components of a dispersed-hardened metal can undergo the following transformations: the transformation of most of the metal with a FCC structure into a solid solution with a BCC structure, as well as the appearance of a second chromium-based BCC phase and a σ-phase. This can reduce the mechanical properties of the metal, which must be taken into account during operation. At the same time, the stability of the carbide and boride phases is obviously not in danger.

Metal melting was carried out in an induction furnace with a main lining by remelting rolled steel 12X18H10T. The slag was made from lime, and the slag was deoxygenated with aluminum powder. During the smelting process, titanium alloying was performed 5 minutes before casting, aluminum deoxidation 2 minutes before casting, and niobium immediately before release to stabilize the structure. The casting temperature from the furnace to the intermediate ladle was 1680°C, from the ladle to the rotating mill of the centrifugal casting machine 1650°C. The rotation speed of the mill was 800 rpm, boron carbide B_4C particles with a dispersion of 1...2 microns were fed to the metal jet during the entire casting time. As a result of the experiment, three cylindrical blanks were obtained: No. 1 – without additives (standard), No. 2 – with 0.25% boron carbide from the mass of the billet; No. 3 – with 0.40% boron carbide from the mass of the billet. The dimensions of the workpieces are: outer diameter 180 mm, inner diameter 165 mm, wall thickness 15 mm, length 210 mm. The blanks had satisfactory external surface quality, with no visible defects. The inner surface of the workpieces has shrinkage phenomena typical of this casting method.

The microstructure of the cast samples was studied using optical microscopy on a microscope "C.Zeiss ObserverD1m", equipped with a software package "Thixomet.PRO ". The structure was studied on both etched and non-etched samples. The microstructure was detected using a reagent of the following composition: 40 % HCl, 30% HNO_3, 30% H_2O. The chemical composition of the obtained materials was studied using an MCA II emission spectrometer. The microhardness of the samples was studied using a stationary hardness tester using the Vickers method. The load used is 4.9 N, the holding time is 60 seconds. The ratio of microhardness to macrohardness, set by Rockwell C, is 0.01. The measurement was carried out in 10 iterations with an interval of 200 microns from the inner edge to the outer edge of each sample.

Results and Discussion

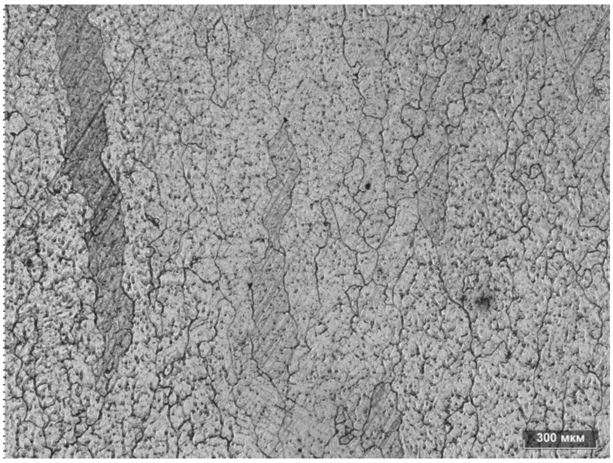
The results of the chemical composition study are presented in Table 1. According to the data provided, it can be concluded that when boron carbide is introduced into steel, the boron concentration can increase to values of 0.003-0.004 wt. %, and the carbon concentration is also increasing.

Table 1. Chemical composition of experimental castings, wt. %

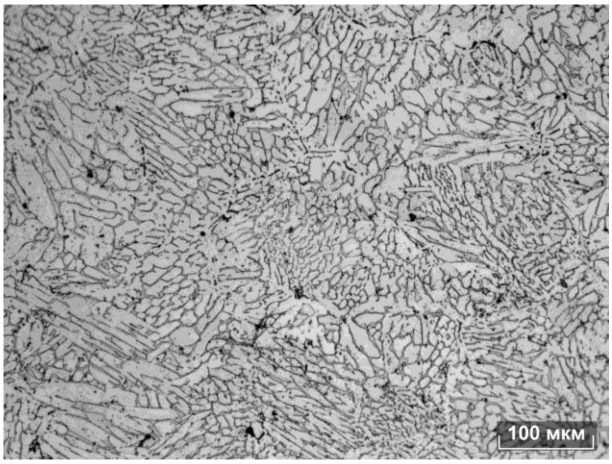
Sample	C	Si	Mn	S	P	Cr	Ni	Cu	W	Ti	B	Al
1	0.082	0.52	0.92	0.007	0.012	17.26	9.55	0.21	0.02	0.78	0.001	0.12
2	0.091	0.55	0.82	0.005	0.013	17.50	9.68	0.17	0.02	0.75	0.003	0.09
3	0.095	0.59	0.96	0.005	0.010	17.45	9.69	0.21	0.02	0.72	0.004	0.10

The results of the microstructure study (Figure 3) showed that the microstructure of all samples is represented by austenitic grains and carbide particles located along the grain boundaries (primary carbides) and in the grain body (secondary carbide precipitates). The ferrite content in sample No. 1 is 4.5%. In sample No. 2, compared with sample No. 1, sulfide inclusions have both a compact shape and a dotted shape along the grain boundaries, point oxides are located along the grain boundaries, and titanium nitrides are in the grain body (Fig. 3b). The austenitic grain size corresponds to 9 points according to GOST 5639, and the proportion of the ferritic phase is 19-21%. The metal of sample No. 3 contains the same inclusions as in sample No. 2, but they all have a more compact shape (Fig. 3c). The austenitic grain size corresponds to 10 points according to GOST 5639, and the proportion of the ferritic phase is 12-15%.

The maximum values of contamination with non–metallic inclusions are relevant for all samples and according to OC - 1.5 points, C – 1 point, HT – 1 point. Nonmetallic inclusions are mainly represented by aluminum oxides, iron and manganese sulfides, and titanium and aluminum nitrides. In samples with boron carbide additive, the appearance of titanium carbonitrides Ti(C,N) located between the crystallites is observed (Figure 3d). Carbonitrides are not detected on the reference sample. According to the results of the microhardness study (Table 2), it can be noted that the microhardness of the reference sample (No. 1) is maximal at the outer edge and decreases as it moves towards the inner edge, which fully corresponds to the theory of crystallization of centrifugal cast blanks.



a)



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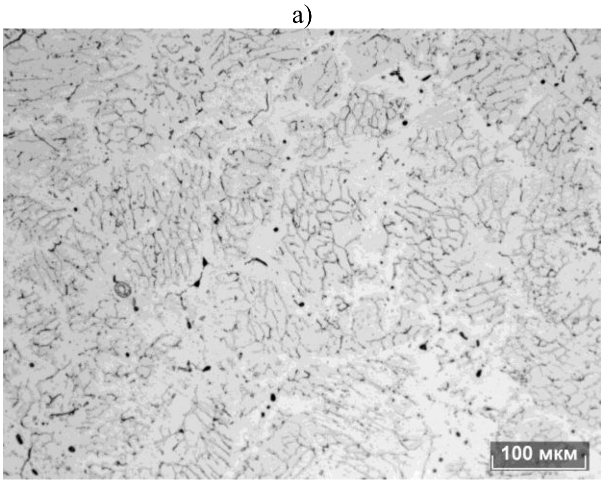
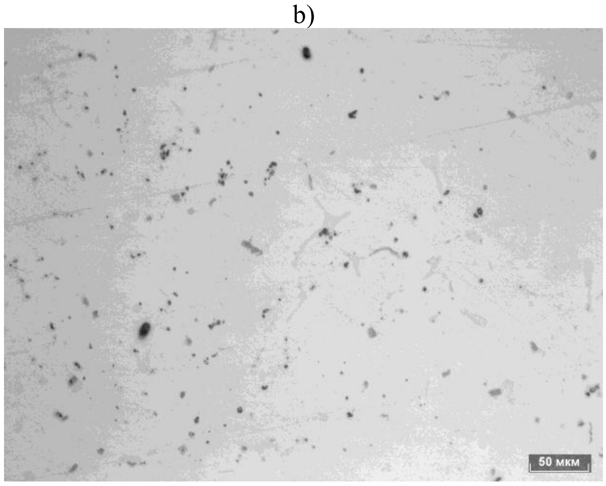


c)



d)

Figure 3. Microstructure of the studied samples: a – sample No. 1, ×65; b – sample No. 2, ×200; c – sample No. 3, ×200; d – general appearance of non-metallic inclusions in the samples, ×500

With the introduction of 0.25 wt. % B_4C (sample No. 2) microhardness increases, while the minimum value obtained for this parameter is higher than the maximum observed in the reference. With an increase in the concentration of B_4C to 1 wt. % microhardness does not increase proportionally, however, the smallest difference in microhardness values is observed over various cross-sections of the sample.

Table 2. Results of the microhardness study, HV

Sample	Place of measurement								
		Inner edge			Central part			Outer edge	
1	137.0	148.5	153.8	156.4	151.4	159.8	154.3	156.7	163.3	167.4
2	164.7	178.7	183.3	173.5	181.9	179.5	176.5	177.7	180.6	182.8
3	149.9	163.8	159.1	158.0	158.5	160.8	161.6	155.0	157.1	159.6

Conclusion

The experiments performed confirmed the results of thermodynamic modeling of the crystallization of a metallic melt by the formation of metallic phases with BCC and FCC lattices. The introduced boron carbide particles completely dissociate when interacting with the metal melt. The carbon contained in boron carbide and in the initial melt contributes to the formation of carbide and carbon-nitride phases based on titanium. The uneven microhardness over the cross-section of the resulting blanks is caused by different crystallization rates, which led to a nonequilibrium structure. The introduced boron carbide affects the proportion of the ferritic phase: as the amount of introduced carbide increases, the amount of ferrite increases. The data obtained can be used in ferrous metallurgy enterprises engaged in the production of materials with gradient properties obtained in a single product. With additional research and development of technology, the proposed method makes it possible to obtain a given ferrite/austenite ratio in certain areas (on the outer or inner surface) of a single workpiece without a clear interface between the layers.

Scientific Ethics Declaration

* The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

Funding

* This study was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP23485709).

Acknowledgements or Notes

* This article was presented as a poster presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Türkiye on November 12-15, 2025.

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To cite this article:

Naizabekov, A., Kuzmin, S., Chumanov, I., Anikeev, A., Sedukhin, V., Panin, E., & Marukov, A. (2025). Investigation of the possibility of introducing dispersed boron carbide particles into the melt of austenitic steel 12X18H10T during centrifugal casting. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 38,* 283-288.