

A Comparison of TiC Wetting Angles with Low Carbon Steel by Contact and Noncontact Methods

Andrey Anikeev

Zlatoust Branch, South Ural State University (National Research University), Zlatoust, Russia
anikeevan@susu.ru

Ilya Chumanov

Zlatoust Branch, South Ural State University (National Research University), Zlatoust, Russia
chumanoviv@susu.ru

Abdrakhman Naizabekov

Rudny Industrial University, Rudny, Kazakhstan
naizabekov57@mail.ru

Sergey Lezhnev

Rudny Industrial University, Rudny, Kazakhstan
sergey_legnev@mail.ru

Evgeniy Panin

Karaganda Industrial University, Temirtau, Kazakhstan
ye.panin@ttu.edu.kz (corresponding author)

Received: 9 May 2025 | Revised: 28 May 2025 and 9 June 2025 | Accepted: 15 June 2025

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: <https://doi.org/10.48084/etasr.12025>

ABSTRACT

This study investigates the kinetics of the high-temperature interaction between titanium carbide (TiC) and a low-carbon melt in an argon atmosphere, as well as the microstructure of the resulting substrate surface. A key feature of this work is the comparative analysis of two experimental techniques, contact and noncontact, to study the interaction between reinforcing particles and metal. This methodological approach highlights significant discrepancies in the results obtained by each technique, which is critical to optimizing processes in the fabrication of gradient materials, where reliable metal bonding is essential. The analysis showed that, under contact conditions, iron droplets enriched with titanium and carbon formed across the plate surface. In contrast, under noncontact conditions, droplet formation was minimal, and the metal was entirely absorbed into the substrate.

Keywords-kinetics of high-temperature interaction; contact and non-contact heating; wetting angle; titanium carbide

I. INTRODUCTION

The development and application of advanced materials are critical across diverse industrial sectors. Among the most promising is the design of metallic materials with property gradients, which enable the localization of specific mechanical and physical properties in regions subjected to high operational loads. Such materials exhibit a continuous variation in physical and mechanical characteristics, combining, for example, high strength and stiffness on one side with ductility or toughness on the other. This approach expands the design possibilities for

complex structures with spatially optimized performance. Gradient metallic materials can be fabricated using methods such as surfacing, laser processing, and plasma treatments [1-5]. However, these techniques are typically limited to surface modification and have drawbacks, including high thermal and residual stresses from localized heating and rapid cooling (leading to cracking), shallow penetration depths in laser methods, reduced layer density in plasma processes, and the formation of distinct phase interfaces that may weaken structural integrity. A more effective strategy to produce

property gradients involves reinforcing the metal matrix with dispersed particles [6-12] in the targeted regions, gradually decreasing their concentration across the remaining volume. Various reinforcement approaches have been explored for steel to achieve this effect. Notable methods include the following:

- Powder introduction during casting: In the casting of medium-carbon steel ingots into fireclay molds, a modification involved injecting a $\text{SiO}_2\text{-C}$ powder mixture into the molten steel stream through a dosing mechanism. This modification resulted in a significant refinement of the macrostructure, eliminating large dendritic formations and promoting the formation of a homogeneous grain structure. Mechanical properties improved substantially: tensile strength increased by 18%, ductility increased by 37-50%, and both crack resistance and toughness increased by a factor of 1.5-2 [13].
- Reinforcement during continuous casting: Experiments involving the introduction of Y_2O_3 , TiN, and TiCN, produced via plasma-chemical synthesis and Self-propagating High-temperature Synthesis (SHS), into the mold during continuous casting have shown that the maximum particle concentration in the billet did not exceed 0.005-0.007%. In contrast, introducing modifiers at the ladle stage achieved higher concentrations (0.015-0.025%), which led to notable improvements: billet density increased by 48-82 kg/m^3 , defect rates decreased by 40-56%, and shell thickness increased by 25.8-26.9%. Mechanical properties also improved, with yield strength increasing by 7.2% and elongation by 8.4% [14-17]. However, uniform particle distribution remains unattainable due to sedimentation and solidification phenomena inherent in the process.
- Centrifugal electroslag casting with modifiers: In this method, 0.3-0.5% TiCN was added in the form of pressed tablets during electroslag remelting combined with centrifugal casting. This approach suppressed transcrystallization, refined dendritic structures, and produced a ferritic-martensitic matrix with compact carbides. Reported mechanical properties of the resulting material are comparable to those of forged billets [18, 19].

Despite the improvements achieved by these methods, a common limitation is the lack of precise control over the spatial distribution of reinforcing particles, which reduces the reproducibility and predictability of material properties. To address this, several Finite Element Modeling (FEM) approaches have been used to predict the particle distribution within a workpiece. A review of current numerical methods, using tools such as ProCAST [20, 21], PHYSICA [22, 23], Ansys Fluent [24, 25], DEM-based models [26, 27], and custom research codes [28, 29], shows that most rely on a key simplification: the assumption that reinforcing particles (e.g., carbides or oxides) do not chemically interact with the melt. This significantly limits the accuracy of predictions, particularly at steel casting temperatures above 1550 °C, where particle dissolution and chemical reactions become critical. For example, simulations of the carbide distribution in high-speed steels [26] and metal matrix composites [27] typically consider

only mechanical segregation under centrifugal forces, neglecting particle dissolution, agglomeration, or phase transformations. Similarly, crystallization models for gradient materials [25] often overlook the influence of reinforcing particles on solidification kinetics. However, at elevated temperatures, interactions between particles and the solidification front can significantly affect the final microstructure. Studying such interactions remains challenging due to the opacity of molten metals and the difficulty of maintaining controlled thermal conditions.

To overcome these issues, visualization techniques have been developed to observe interaction kinetics on the microscale. The lying drop method (contact heating) is commonly used to study wetting and dissolution kinetics. A more advanced technique is the capillary method (noncontact heating), which avoids thermal conduction artifacts. Both methods involve exposing a substrate, typically a compacted pellet, to a droplet of a liquid metal of known composition at controlled temperatures, with the wetting angle as the primary metric. Detailed implementations of these methods have been reported [30-33], including measurements of the wetting angle of titanium carbide in various steels and atmospheres [34-37].

This study presents an experiment employing both contact and noncontact heating techniques on a single titanium carbide substrate in an argon atmosphere. The resulting microstructural transformations are analyzed to evaluate the nature and extent of high-temperature interactions.

II. MATERIALS AND METHODS

A practical investigation was conducted into the wetting angle of titanium carbide (TiC). The investigation used an experimental installation that was developed and manufactured by scientists from South Ural State University to conduct a series of high-temperature experiments to study wetting kinetics (Figure 1). The laboratory experiment was carried out using two different methods to study the kinetics of the high-temperature interaction of reinforcing particles and metal, namely contact and non-contact heating.

For the experiment, commercial TiC with dimensions of 1-10 μm was selected as the substrate material. The pressing conditions involved a temperature of 180°C and a pressure of 300 MPa. The substrate was not polished. Low carbon steel with the following chemical composition was selected as the wetting material: C: 0.2-0.3%, Mn: 0.9%; Si: 0.21%, and Fe: base. The sample for contact heating was characterized by a cubic shape and underwent a mechanical cleaning process before the experiment, in addition to being wiped with isopropyl alcohol. To implement a noncontact heating method, the same steel was crushed and loaded into a special dosing device in the form of an inert material dropper (Al_2O_3).

The primary focus was on the initial 1-30 s of interaction, as in authentic casting processes that involve the formation of gradient materials by centrifugal casting [38, 39], the interaction time of the introduced carbides with the liquid metal is constrained. Consequently, this specific period was selected for the study of the high-temperature interaction of TiC with a low-carbon melt. In the experiment conducted to study the wetting angle of TiC with a low-carbon melt in an argon

atmosphere, a steel sample in the form of a cube was placed on a substrate using the contact heating technique. Subsequently, this substrate was installed in the heater area (zone of maximum heating) of the experimental installation. Subsequently, the working area of the installation was sealed with a water-cooled dome, and a protective atmosphere was established within by initially creating a vacuum of 10^{-2} atm and subsequently filling it with argon of 99.996% purity at a pressure of 850-900 mbar. Then, the titanium carbide substrate was heated in conjunction with the metal sample for three hours at a temperature of 1590°C at a rate of 530°C/h , ensuring uniform heating of the reacting materials and the avoidance of thermal shocks. Upon reaching the melting point of the steel sample, a drop of liquid metal forms on the substrate (sample No. 1). It was observed that the melting of sample No. 1 began at a temperature of 1460°C (Figure 2a), complete melting occurred after 10 s, and a drop of metal formed (Figure 2b). The measured wetting edge angle was 46° , and in the following 15 s, a uniform absorption of metal was observed in the substrate material.

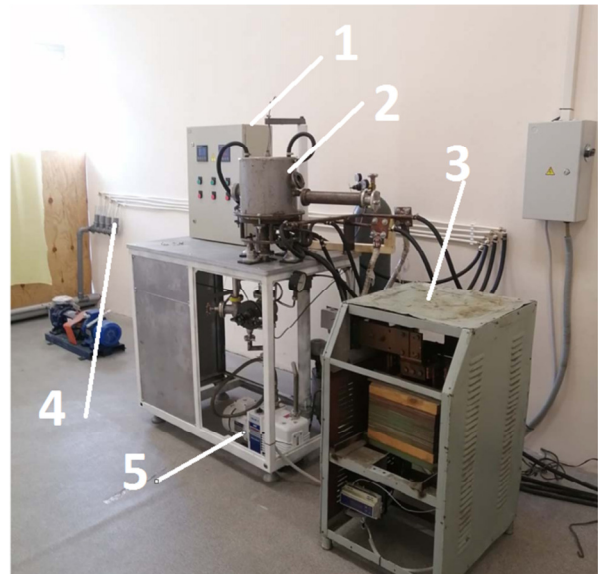


Fig. 1. Installation for high-temperature experiments on the study of wetting kinetics: 1 - electric cabinet, 2 - high-temperature chamber with an observation window, 3 - transformer, 4 - visual monitoring of cooling circuits, 5 - vacuum pump.

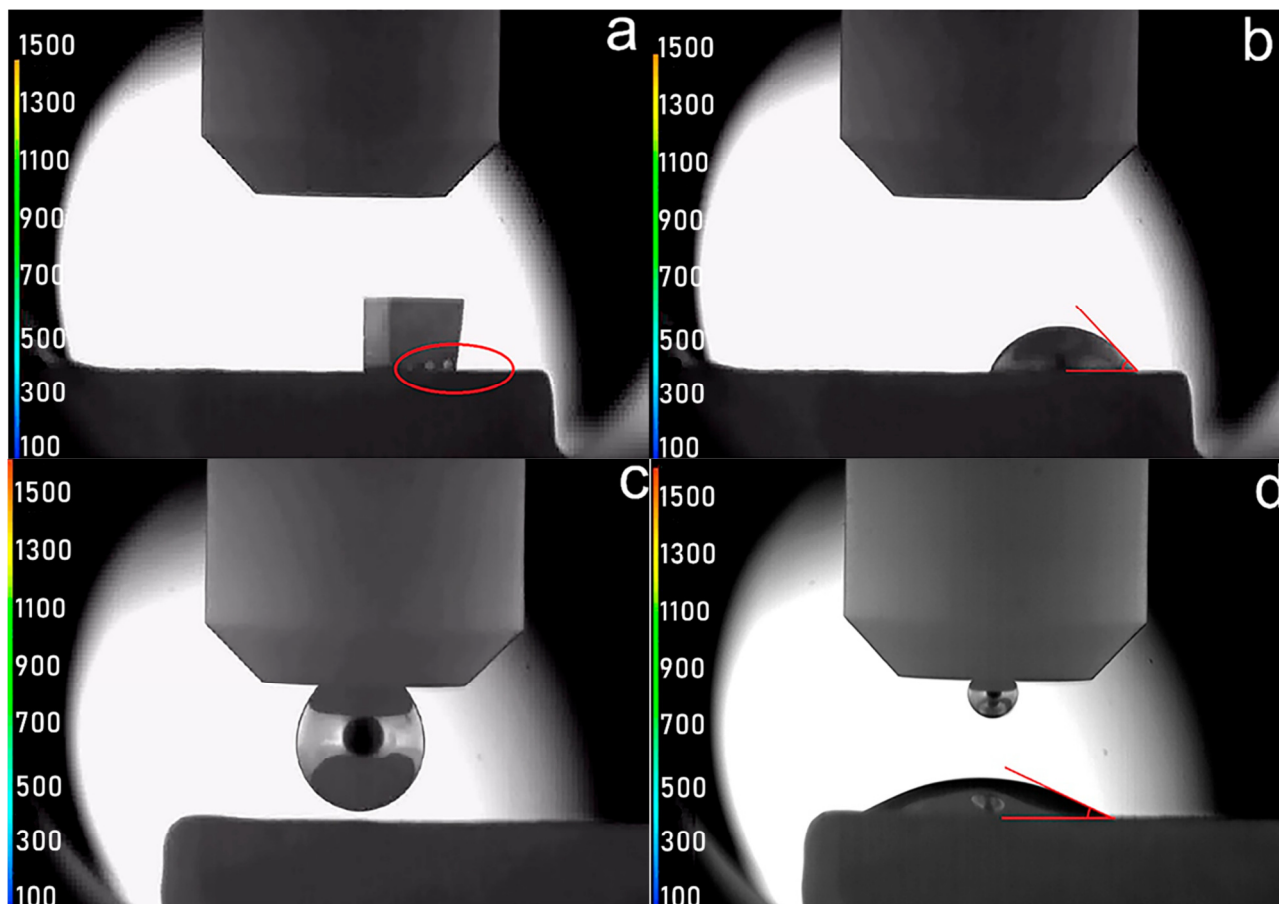


Fig. 2. High-temperature interaction of low-carbon steel with a TiC substrate in an argon atmosphere: (a) Onset of melting for the steel sample using the contact heating method at 1460°C , (b) formation of a molten metal droplet on the TiC surface via contact method at 1485°C , (c) onset of melting using the non-contact method at 1590°C , (d) Formation of a molten droplet applied via the dropper in the non-contact setup, showing improved wetting and symmetry.

Following the complete absorption of the metal from sample No. 1 into the substrate material, an experiment was carried out to study the wetting angle of TiC with a low-carbon melt in an argon atmosphere using a non-contact heating technique (i.e., the metal did not come into contact with the substrate during melting). To this end, a drop of molten metal was applied to the exposed area of the previously used TiC substrate from a specialized dosing device (dropper) located within the high-temperature chamber of the experimental apparatus (the temperature in the chamber was 1590°C) (sample No. 2, Figure 2c). Upon impact, the contact angle of the wetting was measured, revealing an initial edge angle of 24° (Figure 2d). The experiment further demonstrated that a drop of low-carbon metal pressed onto the substrate was absorbed within 6 s. Furthermore, the experiment demonstrated that both droplets (Figures 2 b and d) exhibited a symmetric shape, without discernible inclusions or irregularities in the geometry of the droplet surface.

III. RESULTS AND DISCUSSION

Optical and Scanning Electron Microscopy (SEM) images revealed distinct differences between the surfaces subjected to contact and non-contact heating (Figure 3). In the contact heating case, metallic droplets rich in iron, titanium, and carbon were clearly observed on the surface. In contrast, the noncontact method resulted in minimal surface residue, with most of the metal absorbed into the substrate. Elemental analysis (EDS) revealed the following (Figure 4):

- Contact heating: Iron-rich droplets contained significant amounts of titanium and carbon, suggesting localized alloying at the interface.
- Non-contact heating: A more uniform diffusion of iron into the substrate was observed, without pronounced droplet formation. Oxygen content was detected in all spectra, reaching up to 2.5%. This is likely due to brief exposure to air before electron microscopy. Future experiments should minimize this delay or use in-situ analysis to avoid surface oxidation artifacts.

The initial wetting angles differed substantially between methods:

- Contact method: 46°, with absorption over 15 s.
- Noncontact method: 24°, with full absorption in just 6 s.

Although only one sample per method was evaluated, these observations suggest that the noncontact technique leads to more effective wetting and faster interaction, likely due to improved thermal distribution and reduced surface contamination. For robust conclusions, future work should include multiple trials to evaluate statistical variation in wetting angles.

These results underscore the importance of heating technique selection. Noncontact heating minimizes surface artifacts and promotes better carbide-matrix integration, which is critical for gradient material casting applications.

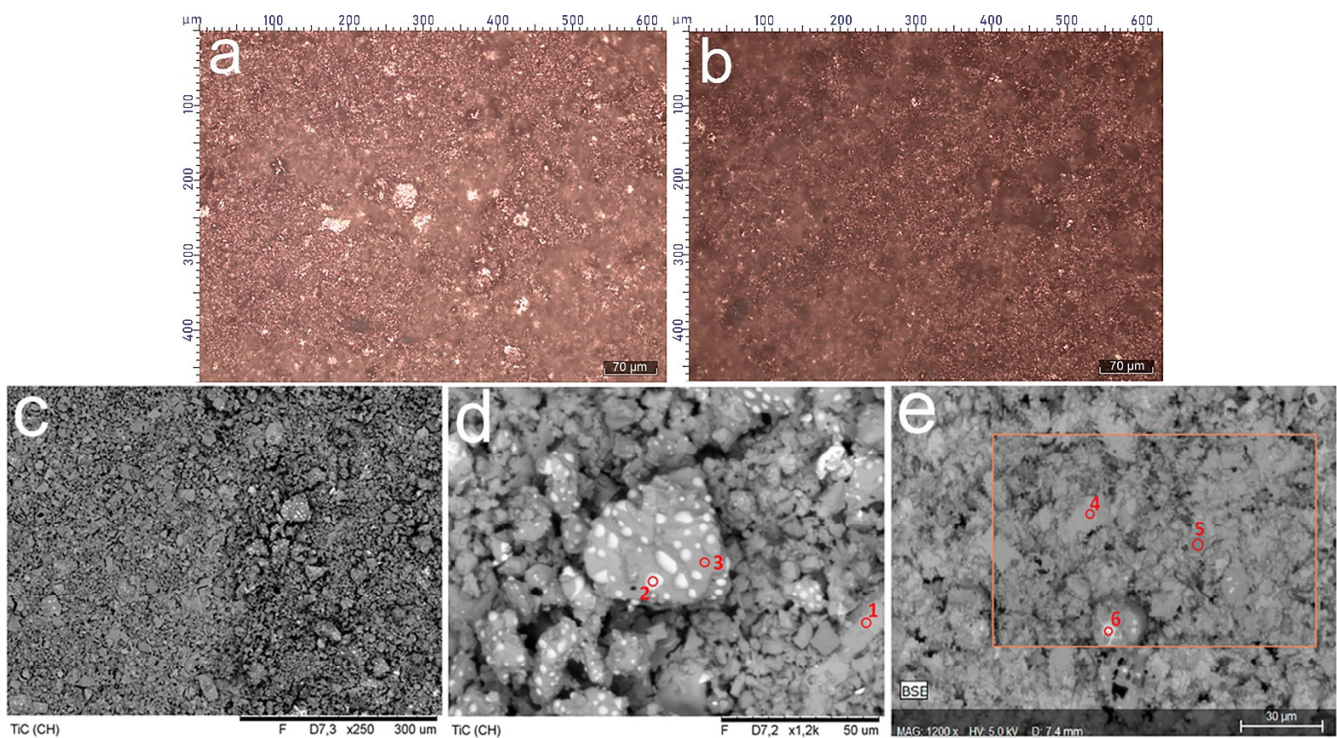


Fig. 3. Surface morphology and microstructural analysis of the TiC substrate after interaction with molten steel: (a) Optical image showing the contact heating absorption zone (sample No. 1), with visible metallic deposits, (b) optical image of the non-contact heating zone (sample No. 2), showing a cleaner surface and less surface residue, (c) SEM image showing the transition region between absorption zones of sample No. 1 (right) and sample No. 2 (left), (d) SEM region analyzed by EDS in the contact heating area, highlighting Fe-Ti-C rich zones, (e) EDS scan site in the non-contact area, showing more uniform elemental distribution.

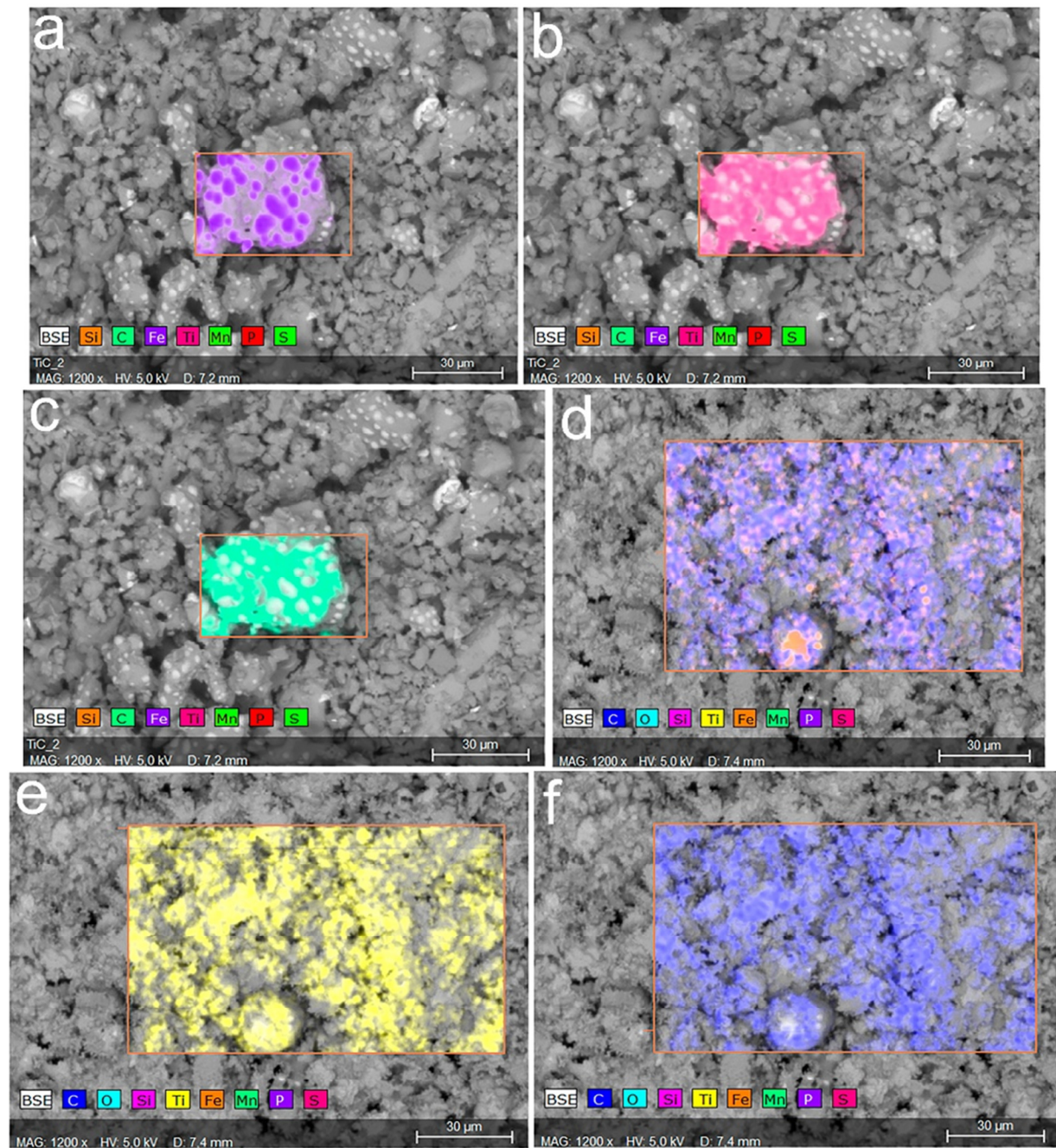


Fig. 4. Maps of element distributions by samples: a – Fe with contact heating; b – Ti with contact heating; c – C with contact heating; d – C and Fe with noncontact heating; e – Fe with noncontact heating; f - C with noncontact heating.

TABLE I. COMPOSITIONS OF SPECTRA FROM THE AREAS OF METAL-SUBSTRATE CONTACT (%)

Area	Point	Ti	C	O	Fe	Mn
Contact heating	1	75.75	21.34	2.06	1.08	0.77
	2	6.32	5.58	2.20	85.03	0.86
	3	69.45	21.59	1.48	7.01	0
Noncontact heating	4	76.50	22.11	0.92	0.46	0
	5	76.74	19.01	2.51	1.75	0
	6	40.71	13.68	1.47	43.26	0.88

IV. CONCLUSION

This study investigates the kinetics of the high-temperature interaction of TiC with low-carbon melt in an argon atmosphere and analyzes the microstructure of the substrate surface after this interaction. Despite existing studies, one of the remaining problems is the lack of accurate data on high-temperature interaction due to the different research techniques.

Two methods of wettability investigation were used: contact and noncontact heating. The main experimental steps included the preparation of TiC wafers, high-temperature testing at 1590°C in an argon atmosphere, and subsequent surface analysis by scanning electron and optical microscopy. The results showed that the initial wetting angle for the non-contact method was 24°, while for the contact method was 46°. This difference is attributed to the presence of interaction products between the substrate and the melt during contact heating, as well as the difference in measurement temperatures. In addition, the rate of metal absorption into the substrate in the noncontact method was 1.6 times higher, which confirms the influence of temperature on the kinetics of the process.

Comparison with literature data [34, 36] shows that the obtained values of wetting angles are consistent with the results of other studies, where the dependence of wettability on the gas phase composition and temperature is also noted. However, the uniqueness of this work lies in the simultaneous application of two methods, which allowed us to reveal significant differences in the melting behavior and microstructure of the substrate. For example, at contact heating on the substrate surface, iron droplets with increased content of titanium and carbon were observed, whereas, at the noncontact method, such formations were practically absent.

The practical importance of this study lies in the possibility of optimizing technological processes for the production of gradient materials. For example, an argon atmosphere can improve the interaction, and regulating the casting temperature and reducing the interaction time can reduce the rate of dissolution of carbides. In addition, the proposed method of noncontact heating can be useful for studying the interaction of other refractory compounds with metal melts of different compositions.

FUNDING

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

REFERENCES

- [1] V. P. Vijeesh, M. R. Ramesh, and A. D. Anoop, "Inconel 625 Coatings on AISI 304 Steel using Laser Cladding: Microstructure and Hardness," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11911–11916, Oct. 2023, <https://doi.org/10.48084/etasr.6297>.
- [2] B. Pace *et al.*, "Tuning Ta coating properties through chemical and plasma etching pre-treatment of NiTi wire substrates," *Surface and Coatings Technology*, vol. 418, Jul. 2021, Art. no. 127214, <https://doi.org/10.1016/j.surfcoat.2021.127214>.
- [3] R. Saeedi, R. Shoja Razavi, S. R. Bakhshi, M. Erfanmanesh, and A. Ahmadi Bani, "Optimization and characterization of laser cladding of NiCr and NiCr–TiC composite coatings on AISI 420 stainless steel," *Ceramics International*, vol. 47, no. 3, pp. 4097–4110, Feb. 2021, <https://doi.org/10.1016/j.ceramint.2020.09.284>.
- [4] I. Shishkovsky, N. Kakovkina, and V. Scherbakov, "Fabrication of heat-resisting nickel composite gradient structures with TiC nano additive during powder bed fusion process," *Procedia CIRP*, vol. 74, pp. 68–71, 2018, <https://doi.org/10.1016/j.procir.2018.08.032>.
- [5] S. Yang, N. Chen, W. Liu, M. Zhong, Z. Wang, and H. Kokawa, "Fabrication of nickel composite coatings reinforced with TiC particles by laser cladding," *Surface and Coatings Technology*, vol. 183, no. 2–3, pp. 254–260, May 2004, <https://doi.org/10.1016/j.surfcoat.2003.09.062>.
- [6] F. Qiu *et al.*, "Application of nanoparticles in cast steel: An overview," *China Foundry*, vol. 17, no. 2, pp. 111–126, Mar. 2020, <https://doi.org/10.1007/s41230-020-0037-z>.
- [7] S. Jiang *et al.*, "Ultrastrong steel via minimal lattice misfit and high-density nanoprecipitation," *Nature*, vol. 544, no. 7651, pp. 460–464, Apr. 2017, <https://doi.org/10.1038/nature22032>.
- [8] S. H. Kim *et al.*, "Heat treatment response of TiC-reinforced steel matrix composite," *Metals and Materials International*, vol. 22, no. 5, pp. 935–941, Sep. 2016, <https://doi.org/10.1007/s12540-016-6176-5>.
- [9] B. X. Dong *et al.*, "Design of TiC nanoparticles and their morphology manipulating mechanisms by stoichiometric ratios: Experiment and first-principle calculation," *Materials & Design*, vol. 181, Nov. 2019, Art. no. 107951, <https://doi.org/10.1016/j.matdes.2019.107951>.
- [10] X. Sun, J. Kang, and Q. Yong, "Revealing the difference of precipitation kinetics between TiC and VC in low-carbon tempered martensitic steels," *Journal of Materials Science*, vol. 55, no. 33, pp. 16018–16032, Nov. 2020, <https://doi.org/10.1007/s10853-020-05176-3>.
- [11] I. Kayabasi, G. Sur, H. Gokkaya, and Y. Sun, "Functionally Graded Material Production and Characterization using the Vertical Separator Molding Technique and the Powder Metallurgy Method," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8785–8790, Aug. 2022, <https://doi.org/10.48084/etasr.5025>.
- [12] C. Zhang *et al.*, "Additive manufacturing of functionally graded materials: A review," *Materials Science and Engineering: A*, vol. 764, Sep. 2019, Art. no. 138209, <https://doi.org/10.1016/j.msea.2019.138209>.
- [13] S. A. Guzenkov, D. N. Fedorov, D. V. Rutsikii, and S. B. Gamanyuk, "Increasing the structural strength of cast steel by powder modification," *Steel in Translation*, vol. 40, no. 3, pp. 294–297, Mar. 2010, <https://doi.org/10.3103/S096709121003023X>.
- [14] E. V. Protopopov, V. P. Komshukov, L. A. Ganzer, and D. B. Foigt, "Promising technologies for metal modification with nanopowder inoculators," *Chernaya Metallurgiya = Izvestiya. Ferrous Metallurgy*, vol. 6, pp. 39–43, Jun. 2011.
- [15] E. V. Protopopov, Yu. A. Seleznev, A. N. Cherepanov, D. V. Foigt, R. S. Aizatylov, and L. A. Ganzer, "Metal modification with nanopowder materials for the quality of slab continuous casting improvement," *Izvestiya Vissikh Uchebnykh Zavedenii. Chernaya Metallurgiya = Izvestiya. Ferrous Metallurgy*, vol. 56, no. 12, pp. 8–11, Mar. 2015, <https://doi.org/10.17073/0368-0797-2013-12-8-11>.
- [16] E. V. Protopopov, Yu. A. Seleznev, A. N. Cherepanov, D. V. Foigt, R. S. Aizatulloev, and L. A. Ganzer, "Nanopowder modification of metals to improve continuous-cast slab," *Steel in Translation*, vol. 43, no. 12, pp. 773–776, Dec. 2013, <https://doi.org/10.3103/S0967091213120139>.
- [17] E. V. Protopopov, Yu. A. Seleznev, A. N. Cherepanov, V. Ya. Chinokalov, D. V. Foigt, and L. A. Ganzer, "Modifying metal with nanopowder in a continuous bar-casting machine," *Steel in Translation*, vol. 43, no. 6, Jun. 2013, <https://doi.org/10.3103/S0967091213060168>.
- [18] S. N. Zhrebtsov, S. N. Mikhaillets, I. V. Zabegailo, and E. A. Rogachev, "Use of Centrifugal Electroslag Casting for Producing Cold-Resistant Steel Grade Ring Blanks of Flange Objects," *Chemical and Petroleum Engineering*, vol. 53, no. 5–6, pp. 347–352, Sep. 2017, <https://doi.org/10.1007/s10556-017-0346-2>.
- [19] S. N. Zhrebtsov and A. B. Korostelev, "Electroslag remelting of the metal wastes of nickel alloys," *Russian Metallurgy (Metally)*, vol. 2012, no. 6, Jun. 2012, <https://doi.org/10.1134/S0036029512060237>.
- [20] S. L. Lu, F. R. Xiao, S. J. Zhang, Y. W. Mao, and B. Liao, "Simulation study on the centrifugal casting wet-type cylinder liner based on ProCAST," *Applied Thermal Engineering*, vol. 73, no. 1, pp. 512–521, Dec. 2014, <https://doi.org/10.1016/j.applthermaleng.2014.07.073>.
- [21] S. Lu, F. Xiao, Z. Guo, L. Wang, H. Li, and B. Liao, "Numerical simulation of multilayered multiple metal cast rolls in compound casting process," *Applied Thermal Engineering*, vol. 93, pp. 518–528, Jan. 2016, <https://doi.org/10.1016/j.applthermaleng.2015.09.114>.
- [22] N. J. Humphreys *et al.*, "Modelling and validation: Casting of Al and TiAl alloys in gravity and centrifugal casting processes," *Applied Mathematical Modelling*, vol. 37, no. 14–15, pp. 7633–7643, Aug. 2013, <https://doi.org/10.1016/j.apm.2013.03.030>.

- [23] N. J. Humphreys, D. McBride, T. N. Croft, D. M. Shevchenko, N. R. Green, and M. Cross, "Modeling of Centrifugal Casting Processes with Complex Geometries," in *CFD Modeling and Simulation in Materials Processing*, 1st ed., L. Nastac, L. Zhang, B. G. Thomas, A. Sabau, N. El-Kaddah, A. C. Powell, and H. Combeau, Eds. Wiley, 2012, pp. 187–196.
- [24] S. Sen, S. Reddy, B. K. Muralidhara, and P. G. Mukunda, "Study of Flow Behaviour in Vertical Centrifugal Casting," *Materials Today: Proceedings*, vol. 24, 2020, <https://doi.org/10.1016/j.matpr.2020.04.457>.
- [25] B. Balout and J. Litwin, "Mathematical Modeling of Particle Segregation During Centrifugal Casting of Metal Matrix Composites," *Journal of Materials Engineering and Performance*, vol. 21, no. 4, pp. 450–462, Apr. 2012, <https://doi.org/10.1007/s11665-011-9873-8>.
- [26] N. Song, Y. Luan, Y. Bai, Z. A. Xu, X. Kang, and D. Li, "Numerical Simulation of Solidification of Work Roll in Centrifugal Casting Process," *Journal of Materials Science & Technology*, vol. 28, no. 2, pp. 147–154, Feb. 2012, [https://doi.org/10.1016/S1005-0302\(12\)60035-8](https://doi.org/10.1016/S1005-0302(12)60035-8).
- [27] J. T. O. Florenciano, A. Ambrosi, D. Hotza, and S. Y. G. González, "Understanding centrifugal casting in the manufacture of functionally graded materials," *Journal of the European Ceramic Society*, vol. 42, no. 15, Dec. 2022, <https://doi.org/10.1016/j.jeurceramsoc.2022.08.042>.
- [28] J. Bohacek, A. Kharicha, A. Ludwig, and M. Wu, "Simulation of Horizontal Centrifugal Casting: Mold Filling and Solidification," *ISIJ International*, vol. 54, no. 2, pp. 266–274, 2014, <https://doi.org/10.2355/isijinternational.54.266>.
- [29] J. Yin, "Numerical modelling of centrifugal casting process," M.S. Thesis, KTH, Stockholm, Sweden, 2016.
- [30] N. Sobczak, R. Nowak, W. Radziwill, J. Budzioch, and A. Glenz, "Experimental complex for investigations of high temperature capillarity phenomena," *Materials Science and Engineering: A*, vol. 495, no. 1–2, pp. 43–49, Nov. 2008, <https://doi.org/10.1016/j.msea.2007.11.094>.
- [31] M. Malaki, A. Fadaei Tehrani, B. Niroumand, and M. Gupta, "Wettability in Metal Matrix Composites," *Metals*, vol. 11, no. 7, Jun. 2021, Art. no. 1034, <https://doi.org/10.3390/met11071034>.
- [32] C. Xuan, H. Shibata, Z. Zhao, P. G. Jönsson, and K. Nakajima, "Wettability of TiN by Liquid Iron and Steel," *ISIJ International*, vol. 55, no. 8, 2015, <https://doi.org/10.2355/isijinternational.ISIJINT-2014-819>.
- [33] W. Fu *et al.*, "Wetting and interfacial behavior of Sn–Ti alloys on zirconia," *Journal of Materials Science*, vol. 54, no. 1, pp. 812–822, Jan. 2019, <https://doi.org/10.1007/s10853-018-2829-8>.
- [34] Q. Zeng, B. Wang, and Z. Guo, "Recent advances in microfluidics by tuning wetting behaviors," *Materials Today Physics*, vol. 40, Jan. 2024, Art. no. 101324, <https://doi.org/10.1016/j.mtphys.2023.101324>.
- [35] D. V. Sergeev, A. N. Anikeev, and I. V. Chumanov, "A study of the products reaction titanium carbide and low-carbon tungsten-containing steel in the oxidative atmosphere," in *Physics, Technologies and Innovation (PTI-2018): Proceedings of the V International Young Researchers' Conference*, Ekaterinburg, Russia, 2018, Art. no. 020093, <https://doi.org/10.1063/1.5055166>.
- [36] M. Kiviö, L. Holappa, S. Louhenkilpi, M. Nakamoto, and T. Tanaka, "Studies on Interfacial Phenomena in Titanium Carbide/Liquid Steel Systems for Development of Functionally Graded Material," *Metallurgical and Materials Transactions B*, vol. 47, no. 4, pp. 2114–2122, Aug. 2016, <https://doi.org/10.1007/s11663-016-0658-1>.
- [37] Q. Lin and R. Sui, "Wetting of carbide ceramics (B₄C, SiC, TiC and ZrC) by molten Ni at 1753 K," *Journal of Alloys and Compounds*, vol. 649, Nov. 2015, <https://doi.org/10.1016/j.jallcom.2015.07.138>.
- [38] I. V. Chumanov, V. I. Chumanov, and A. N. Anikeev, "Preparation of precipitation-strengthened hollow billets for rotary dispersers," *Metallurgist*, vol. 55, no. 5–6, pp. 439–443, Sep. 2011, <https://doi.org/10.1007/s11015-011-9449-8>.
- [39] A. N. Anikeev, I. V. Chumanov, I. A. Alekseev, and V. V. Sedukhin, "Calculation of Cutting Conditions, Including the Estimation of the Machinability of Experimental Samples of Centrifugally Cast Precipitation-Hardened Metallic Materials," *Russian Metallurgy (Metally)*, vol. 2021, no. 12, pp. 1517–1523, Dec. 2021, <https://doi.org/10.1134/S003602952112003X>.