ORIGINAL STUDY

EFFECT OF ARGON FLOW RATE DURING AIR PLASMA SPRAYING ON THE STRUCTURE AND PROPERTIES OF NICRFEBSIC COATINGS

Dastan Buiktenov[1], Nurkhat Bimakhan[1]*, Nurmakhambet Raisov[1]

[1]Research Center "Surface Engineering and Tribology", Sarsen Amanzholov East Kazakhstan University,
Ust-Kamenogorsk, Kazakhstan
**Corresponding author:* Nurhat130820@gmail.com

Abstract. *In this work, self-fluxing metal-ceramic coatings based on the NiCrFeBSiC system were obtained by air plasma spraying, and their structural, mechanical, and tribological properties were investigated.. The effect of argon flow rate (1600 and 1800 L/h) during coating formation was consideredIt was found that an increase in argon flow rate leads to an approximately twofold increase in coating thickness and a twofold decrease in porosity. According to the microhardness measurement results, the microhardness was 1015.8 ± 81.5 HV, while the elastic modulus was 203.9 ± 5.4 GPa. Tribological tests were carried out using the ball-on-disk configurationAt an argon flow rate of 1800 L/h, the friction coefficient showed a lower value (≈0.107), indicating improved wear resistance of the coatings. Scratch test results showed a high level of adhesion between the coatings and the substrate. Although the critical load values (Lc) were similar for both regimes, the coatings obtained at 1800 L/h exhibited a more gradual and stable failure behavior.*

Keywords: air plasma spraying, self-fluxing metal-ceramic coatings, wear resistance, hardness, friction, adhesion.

1. Introduction

In modern industry, the performance and durability of components used in mechanical engineering and agriculture directly depend on the structure and properties of their surface layers [1]. During operation, components are exposed to friction, high temperature, and corrosion, which lead to rapid wear and failure [2]. This, in turn, leads to increased production costs [3]. Therefore, surface treatment of machine components with protective functional coatings to increase their service life is one of the important areas of modern scientific and technical research [4-6].

Among protective coatings, nickel-based self-fluxing alloys, particularly NiCrFeBSiC system alloys, are distinguished by their high efficiency. Due to the presence of boron and silicon in their composition, these alloys have a relatively low melting temperature and can form a dense, defect-free phase structure during remelting [7]. Nickel-based coatings are characterized by high adhesion to the metallic substrate, as well as high wear and corrosion resistance. These properties make them suitable for effective use under severe operating conditions [5].

Currently, one of the most widely used and effective methods for producing such coatings is air plasma spraying (APS). This method is based on using a high-temperature plasma jet to fully or partially melt the powder material and spray it onto the treated surface at high velocity. As a result, dense and multiphase coating layers are formed [8]. The microstructure of the obtained coatings is usually a complex system consisting of boron and silicon compounds dispersed in a nickel-based matrix. The main advantages of air plasma spraying include a wide range of processable materials, precise control of coating thickness and structure, and high production efficiency [9]. At the same time, the mechanical, tribological, and corrosion properties of the coatings depend on spraying parameters such as temperature, gas flow rate, and spraying distance, as well as powder particle size and subsequent heat treatment conditions [10].

Received 6 May 2026; revised 20 May 2026; accepted 18 June 2026.

DOI: https://doi.org/10.66310/FGFL9624

Recent studies show that plasma spraying of nickel-based self-fluxing coatings improves microstructural uniformity, reduces porosity, and enhances mechanical properties [11]. In addition, subsequent heat treatment or remelting processes increase the coating density and significantly improve its service performance. However, the effect of plasma gas flow rate, particularly argon flow rate, as one of the key technological parameters in the air plasma spraying process, on the structure and properties of coatings has not been sufficiently studied. In the literature, data on the effect of this parameter on coating thickness, porosity, and phase composition are limited and ambiguous, for example, in [12], the deposition of self-fluxing nickel-based coatings on cast iron components was investigated, and heat treatment was shown to increase their wear resistance by 1.5–2 times. However, the systematic effect of plasma spraying parameters, including gas flow rate, has not been sufficiently considered.

Therefore, the main objective of this work is to comprehensively investigate the effect of argon flow rate on the structure, mechanical properties, and tribological performance of NiCrFeBSiC coatings obtained by air plasma spraying, and to determine the optimal spraying parameters.

2. Materials and methods

In this study, Chinese-manufactured self-fluxing nickel powder based on the NiCrFeBSiC system was used as the coating materia. The powder particles were mainly spherical, with an average size of approximately 150 μm, which ensured good flowability and uniform feeding during spraying.

Carbon structural steel grade 45, widely used in mechanical engineering, was used as the substrate material for coating deposition; its chemical composition is presented in Table 1, and the material is characterized by a combination of high strength and ductility. Samples were prepared from a steel rod with a diameter of 50 mm and fabricated in the form of discs with a thickness of 5 mm.

Table 1. Chemical composition of grade 45 steel.

C	Si	Mn	Ni	S	P	Cr	Cu
0.42 - 0.5	0.17 - 0.37	0.5 - 0.8	<0.3	<0.04	<0.035	<0.25	<0.3

Before coating deposition, the sample surfaces were specially prepared: first, they were ground using abrasive papers with different grit sizes (120–600), followed by sandblasting with electrocorundum particles of approximately 40 μm to improve adhesion. After treatment, the surfaces were cleaned with compressed air and then washed in an ethanol solution in an ultrasonic bath for 10 min at a frequency of 40 kHz and a temperature not exceeding 35 °C, which ensured the complete removal of grease and other contaminants.

The coatings were deposited by air plasma spraying using an SX-60 system. The following technological parameters were used during spraying: arc current of 550 A, hydrogen flow rate of 150 L/h, argon flow rates of 1600 and 1800 L/h, spraying distance of 120 mm, and powder feed rate of 5 g/min. During the study, two different regimes with argon flow rates of 1600 and 1800 L/h were comparatively investigated.

The microstructural characterization of the as-deposited coatings was performed by scanning electron microscopy (SEM) in backscattered electron (BSE) mode, providing enhanced phase contrast. The elemental composition and spatial distribution of constituent elements were analyzed using energy-dispersive spectroscopy (EDS). These complementary techniques enabled a comprehensive evaluation of coating porosity, particle melting state, and microstructural homogeneity.

The mechanical properties of the coatings were evaluated by instrumented microindentation using a Fischerscope HM2000S system. During testing, a load of 1000 mN was progressively applied to the sample surface over 20 s using a diamond pyramidal indenter. The loading process was conducted under strictly controlled conditions, allowing continuous recording of the material's mechanical response throughout the loading cycle. The primary measured parameters were hardness (HV) and elastic modulus (E). Additionally, the load–indentation depth relationship was recorded and analyzed during the experiments.

The tribological properties were evaluated using a TRB^3 tribometer under lubricated conditions in a ball-on-disk configuration (Fig. 1). A 100Cr6 steel ball with a diameter of 3 mm was used as the counterbody. The tests were conducted at a sliding radius of 2 mm, a sliding speed of 5 cm/s, a normal load of 10 N, and a total sliding distance of 200 m. As a result, the evolution of the coefficient of friction (CoF) was determined.

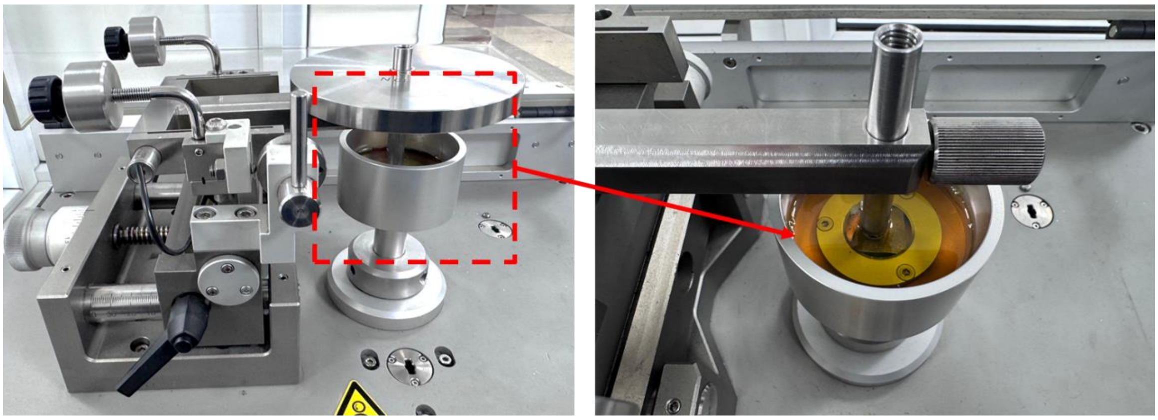


Fig.1. General view of the TRB3 tribometer for conducting tribological tests.

The adhesive strength of the coatings was evaluated by scratch testing using an RST300 instrument. During the test, a load of up to 100 N was applied to a diamond indenter, which was translated across the sample surface at a constant speed of 6 mm/min over a scratch length of 6 mm. Throughout the test, the failure behavior at the coating–substrate interface was continuously monitored. Critical loads corresponding to different stages of coating failure were determined, including the initiation of microcracks, crack propagation, and complete delamination of the coating layer. In addition, the friction force, indenter penetration depth, and acoustic emission signals were continuously recorded, enabling a comprehensive assessment of the mechanical stability of the coatings.

3. Results and discussion

Scanning electron microscopy (SEM) results demonstrated that the argon flow rate during air plasma spraying significantly affected the microstructure of the coatings (Fig. 2 and Fig. 3). At an argon flow rate of 1600 L/h, structural heterogeneity was observed in the cross-section of the obtained coating (Fig. 2). SEM images clearly reveal a considerable number of pores and incompletely melted particles. The average coating thickness was approximately 181 μm, while the porosity level was about 2%. The structure shows clearly visible interparticle boundaries, indicating relatively weak bonding between the particles. Most of the pores have a rounded shape and are mainly located between partially unmelted powder particles. In addition, microcracks and intergranular gaps were observed. These features indicate insufficient thermal input during spraying and a low degree of particle melting. According to the energy-dispersive spectroscopy (EDS) results, the main elements (Ni, Cr, Fe, B, Si, and C) were relatively uniformly distributed throughout the coating volume. Nickel predominates as the matrix phase, while chromium is uniformly distributed and contributes to the protective properties of the coating. Silicon and boron were observed to be concentrated in separate phases. The detection of oxygen indicates the occurrence of oxidation processes on the coating surface and in the pore regions.

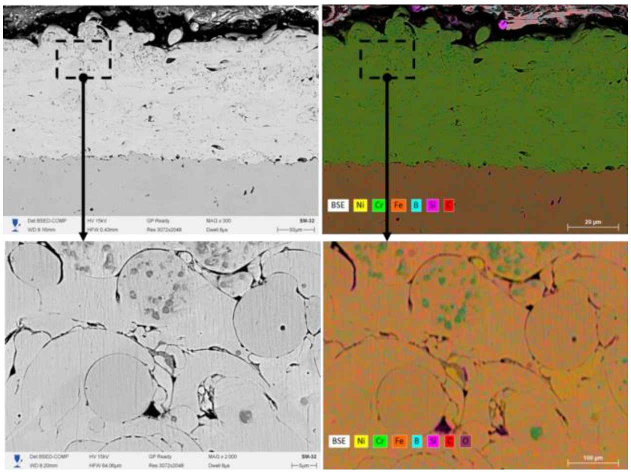


Fig. 2. Structure of the NiCrFeBSiC coating obtained by air plasma spraying at an argon flow rate of 1600 L/h.

At an argon flow rate of 1800 L/h, a significant improvement in the coating microstructure was observed (Fig. 3). The coating thickness was approximately 250 µm, which was about 40% higher compared with the coating obtained at 1600 L/h. SEM images show that the coating structure is dense, uniform, and composed of well-melted particles. A significant decrease in porosity was observed in the cross-section. Higher-magnification images reveal the formation of a fine-grained and compact microstructure. Although some pores remain, they are smaller in size and are uniformly distributed throughout the coating. Energy-dispersive spectroscopy (EDS) results showed a uniform distribution of elements (Ni, Cr, Fe, and Si) throughout the coating volume. The interface between the coating and the substrate was clearly observed, while no distinct transition layer was detected. A relatively high oxygen content was detected in the surface regions of the coating, which may be associated with high-temperature interaction with the atmospheric environment during plasma spraying. The obtained results indicate that increasing the argon flow rate enhances the degree of particle melting and improves the coating density and structural homogeneity.

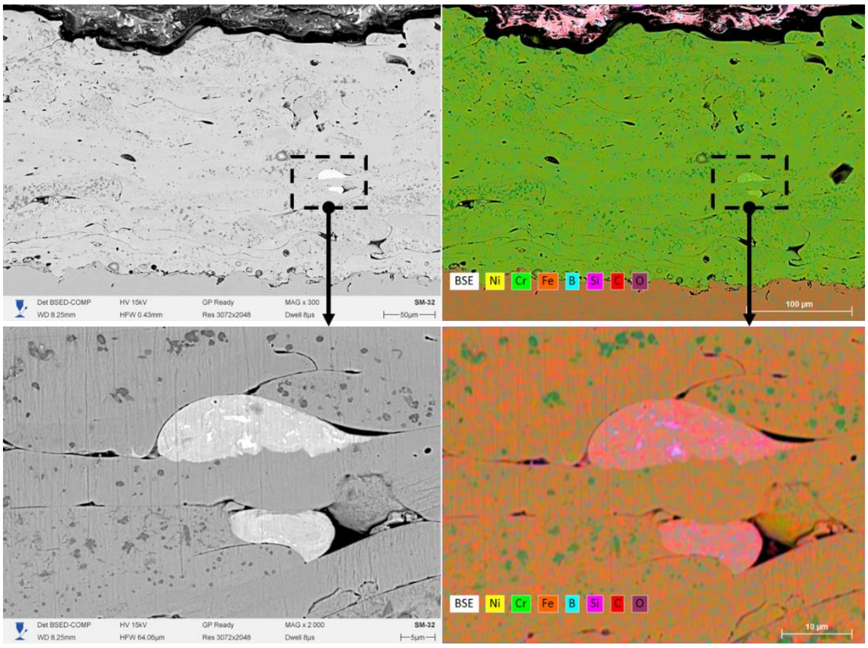
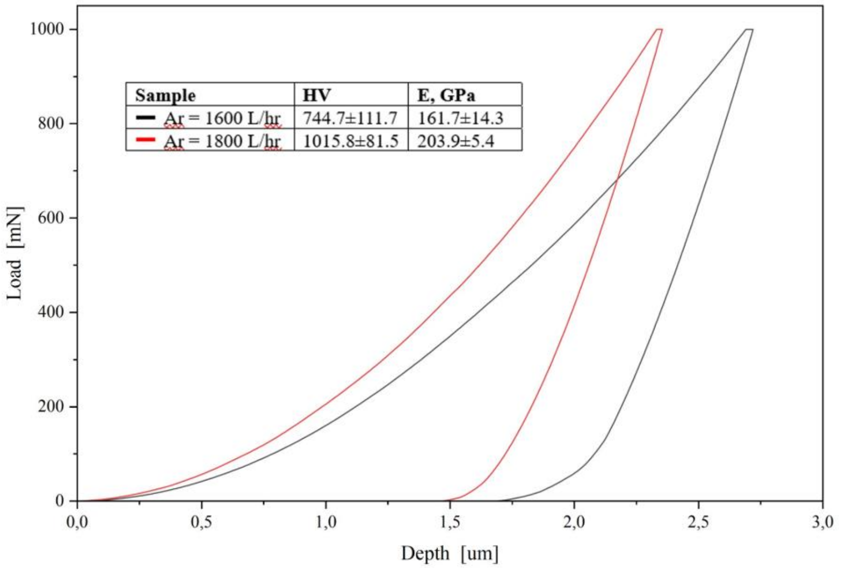


Fig. 3. Structure of the NiCrFeBSiC coating obtained by air plasma spraying at an argon flow rate of 1800 L/h.

Fig. 4 presents the microhardness and elastic modulus results of the coatings obtained by air plasma spraying. The graph illustrates the dependence of indenter penetration depth on the applied load. According to the curves in the graph, the red line corresponds to the 1800 L/h regime, while the black line represents the 1600 L/h regime. When the argon flow rate was increased to 1800 L/h, a decrease in the indenter penetration depth was observed under the same applied load. This indicates an increase in the hardness and elastic modulus of the coating. At an argon flow rate of 1600 L/h, the coating microhardness was 744.7 ± 111.7 HV, while the elastic modulus was 161.7 ± 14.3 GPa. At the 1800 L/h regime, these values increased to 1015.8 ± 81.5 HV and 203.9 ± 5.4 GPa, respectively. The obtained results indicate that increasing the argon flow rate significantly improves the mechanical properties of the coatings. This may be attributed to more complete and uniform particle melting, the formation of a denser structure, and reduced porosity.



Sample	HV	E, GPa
▬ Ar = 1600 L/hr	744.7±111.7	161.7±14.3
🟥 Ar = 1800 L/hr	1015.8±81.5	203.9±5.4

Fig. 4. Load–indenter penetration depth dependence curve.

Fig. 5 shows the results of tribological testing of NiCrFeBSiC coatings obtained by air plasma spraying. The tests were carried out under lubricated conditions using a ball-on-disk configuration. The figure shows that the coefficient of friction for both coatings remained relatively stable throughout the test. At an argon flow rate of 1800 L/h, the coefficient of friction of the coating represented by the red line stabilized at approximately 0.107, showing a lower value compared with the coating obtained at 1600 L/h, represented by the black line. The decrease in the coefficient of friction with increasing argon flow rate may be attributed to the improved coating structure, namely reduced porosity, better particle melting, and increased microhardness.

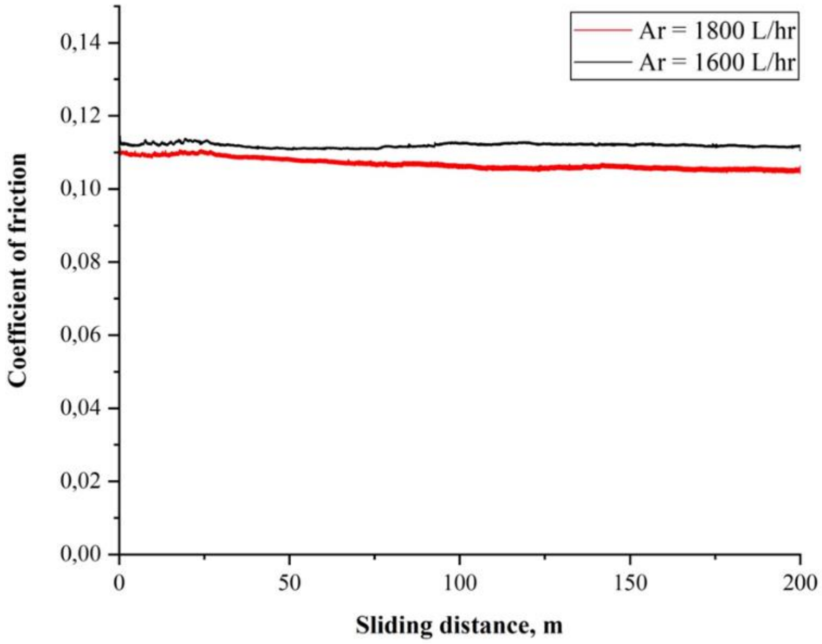


Fig. 5. Dependence of the coefficient of friction on sliding distance for NiCrFeBSiC coatings obtained at argon flow rates of 1600 and 1800 L/h.

Significant differences were observed in the adhesion strength test results of the NiCrFeBSiC coatings (Fig. 6). For the coating obtained at an argon flow rate of 1600 L/h, the critical loads were Lc1 = 32.44 N, Lc2 = 68.43 N, and Lc3 = 99.16 N. These values characterize the coating failure stages: initiation of microcracks, crack propagation and partial delamination, followed by complete failure. Within the scratch length range of

2–5 mm, sharp changes in the coefficient of friction, friction force, penetration depth, and acoustic emission signal were observed, indicating the onset of coating degradation. The scratch track morphology confirms the presence of localized failure and delamination regions, with pronounced loss of coating integrity observed particularly at the final stage of the test. For the coating obtained at an argon flow rate of 1800 L/h, similar critical load values were recorded: Lc1 = 33.57 N, Lc2 = 67.75 N, and Lc3 = 99.61 N. However, the failure behavior was more stable and uniform. The uniform distribution of defects along the scratch track and the absence of pronounced delamination zones indicate improved adhesion between the coating and the substrate. Scratch test results demonstrate that the argon flow rate directly affects the adhesion behavior of the coatings. Although the absolute values of the critical loads were similar for both regimes, the coating obtained at 1800 L/h exhibited a more uniform and stable failure behavior. This can be explained by the increase in the thermal energy of the plasma jet at a higher argon flow rate: the particles melt more completely, the splats bond more tightly with the substrate, and the cohesive strength increases. As a result, the mechanical load applied to the coating surface is distributed more uniformly, reducing the probability of local stress concentration.

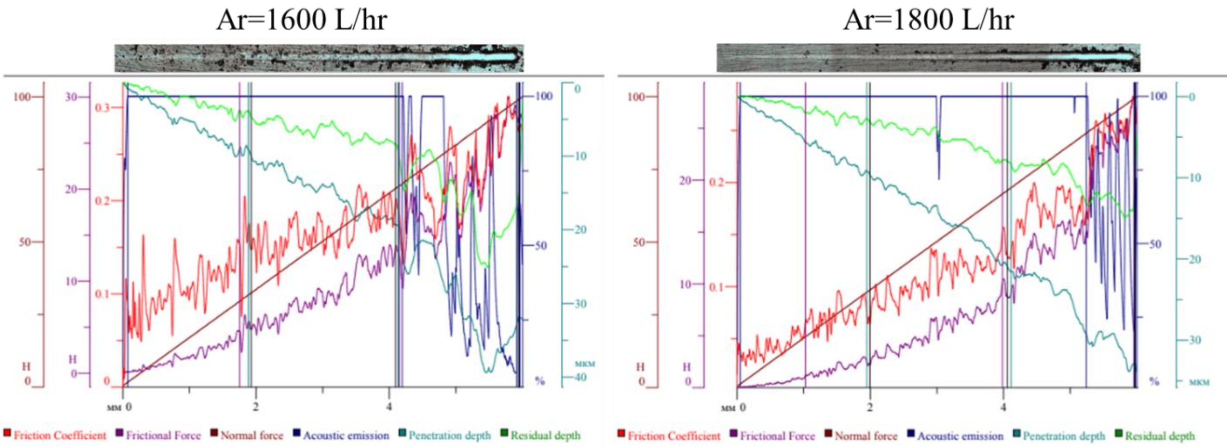


Fig. 6. Adhesion strength test results of NiCrFeBSiC coatings.

4.Conclusion

As a result of the study, it was established that the structure, mechanical properties, and tribological performance of self-fluxing NiCrFeBSiC-based coatings obtained by air plasma spraying directly depend on the argon flow rate. It was shown that the coating obtained at an argon flow rate of 1600 L/h exhibited structural heterogeneity, higher porosity, and incompletely melted particles, which led to reduced coating density and strength. These factors, in turn, resulted in poorer adhesion properties and lower service performance of the coating. When the argon flow rate was increased to 1800 L/h, a significant improvement in the coating microstructure was observed. The coating became denser, porosity decreased, and the degree of particle melting increased. As a result, the microhardness (1015.8 ± 81.5 HV) and elastic modulus (203.9 ± 5.4 GPa) increased, leading to enhanced mechanical properties. Tribological tests showed that increasing the argon flow rate led to a decrease in the coefficient of friction from 0.112 to 0.107, confirming improved wear resistance of the coating. In addition, although the critical load values obtained from scratch testing were comparable for both regimes, the coating deposited at 1800 L/h exhibited a more uniform and stable failure behavior. Thus, using an argon flow rate of 1800 L/h improves the structural integrity, mechanical properties, and tribological performance of NiCrFeBSiC coatings. The obtained results indicate that this regime is effective for producing wear-resistant and reliable coatings under industrial conditions.

Funding

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. BR24992876).

Conflict of interest

The authors declare that they have no competing interests.

References

1 Bukaeva, A. Z., Bulekbaeva, G. Zh., Madiyarova, A. S., Chazhabayeva, M. M., & Bilashova, G. S. (2024). *Study of modern methods for applying protective coatings to the metal surfaces of machine parts*.*Yessenov University*, 133(4), 47–54. DOI: https://doi.org/10.52167/1609-1817-2024-133-4-47-54. [In RUS]

2 Bulekbaeva, G. Zh., Tabylov, A. O., Kozhabekova, P. A., Bukaeva, A. Z., & Suyeuova, N. B. (2024). *Comprehensive assurance of surface layer quality parameters of parts using an innovative method of combined finishing-strengthening treatment*. *L.N. Gumilyov Eurasian National University146*(1), 8–20. DOI: https://doi.org/10.32523/2616-7263-2024-146-1-8-20. [ENG]

3 Smagulova, N. K., Kurmangaliyeva, L. A., & Iskakova, T. K. (2024). Review of studies of corrosion of metals and alloys. *Engineering Journal of Satbayev University*, 146(2), 1–8. DOI: https://doi.org/10.51301/ejsu.2024.i2.01. [ENG]

4 Khabay, A. (2024). Research of modern technologies for application of wear-resistant coatings on machine parts. *Yessenov Science Journal*, 47(2). DOI: https://doi.org/10.56525/YJRK6370. [ENG]

5 Li, C.-J., Luo, X.-T., Dong, X.-Y., Zhang, L., & Li, C.-X. (2022). Recent research advances in plasma spraying of bulk-like dense metal coatings with metallurgically bonded lamellae. *Journal of Thermal Spray Technology*, 31(1–2), 5–27. DOI: https://doi.org/10.1007/s11666-022-01327-x [ENG]

6 Buitkenov, D., Raisov, N., Alimbekuly, T., & Alibekova, B. (2025). Study of the tribological properties of self-fluxing nickel-based coatings obtained by gas-flame spraying. *Crystals*, 15, 862. DOI: https://doi.org/10.3390/cryst15100862. [ENG]

7 Skulev, H., Malinov, S., Sha, W., & Basheer, P. A. M. (2005). Microstructural and mechanical properties of nickel-base plasma sprayed coatings on steel and cast iron substrates. *Surface and Coatings Technology*. DOI: https://doi.org/10.1016/j.surfcoat.2005.01.039. [ENG]

8 Sytnykov, P. (2023). Structural-phase state and properties of sprayed plasma coatings based on self-fluxing alloy of NiCrBSi system with the addition of SHS composites. *Norwegian Journal of Development of the International Science*, 121, 151. DOI: https://doi.org/10.5281/zenodo.10246. [ENG]

9 Simunovic, K., Havrlisan, S., Saric, T., & Vukelic, D. (2020). Modeling and optimization in investigating thermally sprayed Ni-based self-fluxing alloy coatings: A review. *Materials (Basel)*, 13(20), 4584. DOI: https://doi.org/10.3390/ma13204584. [ENG]

10 Kazamer, N., Muntean, R., Vălean, P. C., Pascal, D. T., Mărginean, G., & Șerban, V.-A. (2021). Comparison of Ni-based self-fluxing remelted coatings for wear and corrosion applications. *Materials (Basel)*, 14(12), 3293. DOI: https://doi.org/10.3390/ma14123293. [ENG]

11 Rukhande, S. W., Rathod, W. S., & Bhosale, D. (2021). Sliding wear investigation of Ni-based coating for high-temperature application. *Tribology in Industry*, 43(2), 247–258. DOI: https://doi.org/10.24874/ti.945.08.20.11. [ENG]

12 Orlov, P. V., Korotaev, D. N., Grinberg, P. B., Fedosov, V. V. (2018) Methodical complex for investigation dependencies between microstructure and macro properties of materials and operating characteristics of products. metodicheskiy-kompleks-dlya-issledovaniya-vzaimosvyazi-mikrostruktury-i-makrosvoystv-materialov-s-ekspluatatsionnymi-harakteristikami-izdeliy.pdf [In RUS]

AUTHORS' INFORMATION

Dastan Buitkenov - PhD, Leading Researcher, Scientific Research Center "Surface Engineering and Tribology" at Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan, ORCID iD: https://orcid.org/0000-0002-0239-5849. (e-mail: buitkenov@gmail.com)

Nurkhat Bimakhan - specialist of Scientific Research Center "Surface Engineering and Tribology" at Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan, ORCID iD: https://orcid.org/0009-0004-7221-7900. (e-mail: Nurhat130820@gmail.com)

Nurmahanbet Raisov - junior researcher of Scientific Research Center "Surface Engineering and Tribology" at Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan, ORCID iD: https://orcid.org/0009-0007-1698-957X. (e-mail: 2002raisov@gmail.com)