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UDC 621.793

 <https://doi.org/10.31489/2026PH2/58-67>

Received: 12.02.2026

Accepted: 02.04.2026

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**Investigation of Detonation-Sprayed NiCr–Al Coatings
Tested under Real Operating Conditions of a Thermal Power Plant**

This study presents the experimental results of high-temperature oxidation testing under actual operating conditions in a thermal power plant of gradient and homogeneous composite NiCr–Al coatings produced by the detonation spraying method. To characterize the degradation mechanisms of the tested coatings, systematic analyses were performed, including phase composition evaluation, and detailed microstructural examination using scanning electron microscopy (SEM). The evolution of oxide layers and elemental redistribution across the coating thickness were also assessed to clarify the influence of coating architecture on protective performance. The experimental results demonstrated that the gradient composite NiCr–Al coatings exhibit superior resistance to high-temperature oxidation compared to homogeneous coatings. The gradient architecture effectively preserved structural integrity and promoted a more uniform distribution of aluminum and chromium within the coating thickness. This compositional optimization facilitated the formation of continuous and adherent protective oxide layers, predominantly Al₂O₃ and Cr₂O₃, which significantly reduced oxidation kinetics and inhibited coating degradation. In contrast, the homogeneous NiCr–Al coatings showed noticeable aluminum depletion, crack formation, and oxide scale spallation after prolonged exposure to high-temperature industrial conditions. The findings of this study confirm that gradient NiCr–Al coatings deposited by detonation spraying represent a promising protective solution for components operating in severe high-temperature and corrosive environments, offering improved durability and extended service life for industrial and energy related applications.

Keywords: NiCrAl coatings, detonation spraying technology, high temperature properties, thermal power plant

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Introduction

Structural steel components used in modern energy and heavy industrial sectors, particularly in coal- and biomass-fired thermal power plants, are subjected to complex degradation phenomena such as high-temperature oxidation, hot corrosion, erosion, and abrasive wear [1]. Boiler tubes, water walls, economizers, and superheaters, when operated for prolonged periods in aggressive gas environments containing sulfur, chlorine, alkali metal salts, and fly ash particles, undergo accelerated degradation, leading to a reduced service life of the equipment, increased maintenance and repair costs, and decreased efficiency of power generation systems. The synergistic nature of these degradation processes accelerates the breakdown of protective oxide layers, ultimately resulting in premature material failure [2–4].

One of the effective approaches to addressing these issues is the application of protective coatings on steel surfaces, which has become widely adopted. In recent years, coatings produced by thermal spraying techniques have gained particular importance for protection against high-temperature corrosion and oxidation. HVOF, HVAF, detonation, and plasma spraying technologies enable the deposition of dense coatings with high adhesion and relatively low porosity using metallic, ceramic, and cermet materials. In particular, FeCr-, NiCr-, and NiCrAl-based alloys, as well as carbide-based composite coatings (Cr_3C_2 -NiCr, WC-Co-Cr), are considered effective protective solutions against erosion and corrosion in power plant boilers [5-6]. In carbide-based systems, the protective effect is primarily provided by the physical barrier role of hard carbide phases (Cr_3C_2 , WC, W_2C), and such coatings exhibit high effectiveness under short- and medium-term cyclic exposure conditions [7]. However, during long-term high-temperature service, oxidation or decarburization of carbides may limit their protective performance. Consequently, recent studies have placed particular emphasis on aluminum-forming coatings, as the Al_2O_3 layer formed on their surface can significantly suppress oxidation and hot corrosion [8]. However, long-term tests conducted under industrial operating conditions have shown that, although pure Ni and nickel aluminide (Ni_2Al_3) coatings provide effective protection in the initial stages, their service life is limited due to the chemical instability of the γ - Al_2O_3 layer under the influence of KCl present in biomass combustion products, selective aluminum depletion, and the subsequent breakdown of the protective layer [9]. This indicates that the long-term stability of aluminum-forming systems is not determined solely by the formation of Al_2O_3 and that additional elements are required to enhance the chemical stability of the protective layer.

From this perspective, chromium-containing NiCrAl coatings are regarded as an intermediate and promising protective system. In such coatings, the Cr_2O_3 layer provides initial protection at low and intermediate temperatures, while the formation of an Al_2O_3 layer at higher temperatures enhances long-term stability. The presence of chromium partially compensates for the chemical instability of γ - Al_2O_3 and helps mitigate chlorine-induced corrosion. In addition, the dense microstructure and low porosity of NiCrAl coatings produced by detonation spraying and HVOF methods form an effective barrier against erosion-induced corrosion [10–12].

At present, it is becoming evident that the performance of single-layer coatings is limited in energy systems subjected simultaneously to high temperature, corrosion, and erosion. Consequently, multilayer and functionally graded thermally sprayed coatings are being considered as a promising approach. Such architectures reduce the thermal and mechanical mismatch between the coating and the substrate, improve adhesion, and decrease residual stresses [13]. The aim of this work is to test and comparatively investigate homogeneous and gradient NiCrAl coatings produced by detonation spraying under industrial operating conditions.

Materials and Methods

NiCr–Al coatings were deposited onto 12Kh1MF heat resistance steel substrates (ISO 4955 standard). The steel was machined into discs measuring 50 mm in diameter and 3 mm in thickness. Before the coating process, the substrate surfaces were sequentially ground with SiC sandpapers of 120–2000 grit size to obtain a uniform finish. To enhance the adhesion of the coatings, the prepared substrates were additionally subjected to sandblasting treatment. Composite powders were prepared using Ni75Cr25 alloy powder and high-purity Al powder (99.99 %). The powder mixture was homogenized and mechanically activated in a BML-6 ball mill. The average particle size of the NiCr–Al composite powder is 68 μm .

Homogeneous and gradient NiCr–Al coatings were produced using the CCDS2000 detonation spraying system. The study demonstrated that gradient-composition NiCr–Al coatings can be obtained by adjusting the filling volume of the detonation barrel with the explosive gas during detonation spraying [14-15]. The technological parameters for producing the coatings are presented in Table 1.

Table 1

Technological parameters for producing the NiCr–Al detonation coating

Coating structure	$\text{O}_2/\text{C}_2\text{H}_2$	Spray Distance, mm	Barrel Filling Volume, %	Number of Shots
Homogeneous	1.856	150	50	40
Gradient	1.856	150	50	10
			40	10
			30	10
			25	10

For the high-temperature tests, specimens with geometric dimensions of $15 \times 15 \times 3$ mm were prepared. The samples were fabricated by detonation spraying and fully coated with NiCr–Al on all six surfaces.

The high-temperature oxidation testing of the coatings was conducted in an industrial environment at the Sogra Thermal Power Plant (TPP) in Ust-Kamenogorsk, Kazakhstan. In this test, NiCr–Al coated specimens were placed in the high-temperature zone of the TPP (≈ 700 °C) and exposed to actual service conditions for a period of two weeks. The duration of exposure was selected based on literature data [16]. The industrial atmosphere of the thermal power plant is characterized by the presence of oxygen, water vapor, and combustion products, including sulfur- and chlorine-containing species, as well as fly ash particles. These factors create an aggressive high-temperature environment that promotes oxidation and corrosion processes. To ensure the reliability of the results, at least three coated samples were tested under identical conditions. The obtained results demonstrated good repeatability, as consistent trends in phase composition, oxide formation, and microstructural evolution were observed across all samples.

The phase composition of the coatings was examined using an X'Pert PRO X-ray diffractometer (PANalytical, Netherlands). X-ray diffraction analysis was performed with $\text{CuK}\alpha$ radiation under the following conditions: 40 kV accelerating voltage, 30 mA tube current, 1 s exposure time, step size of 0.02° , and a 2θ range of 10° – 90° . The obtained diffractograms were processed using HighScore software in conjunction with the PDF2 database. The surface microstructure and cross-sectional morphology of the coatings were investigated by scanning electron microscopy (SEM, SEM3200, China), while the elemental composition was determined by energy-dispersive X-ray spectroscopy (EDX, Bruker, USA).

Results and Discussion

Figure 1 presents the X-ray phase analysis results for the structure of homogeneous-composition and gradient-composition NiCr–Al coatings. It can be observed that the homogeneous-composition NiCr–Al coating consists mainly of the CrNi_3 phase. During the deposition process, the elevated temperatures prevented the formation of Al phases on the homogeneous-composition NiCr–Al coating surface. In contrast, the gradient-composition NiCr–Al coatings contains both CrNi_3 and Al phases. The appearance of the Al phase is attributed to the reduced filling volume of the detonation barrel with the explosive gas mixture during deposition [17].

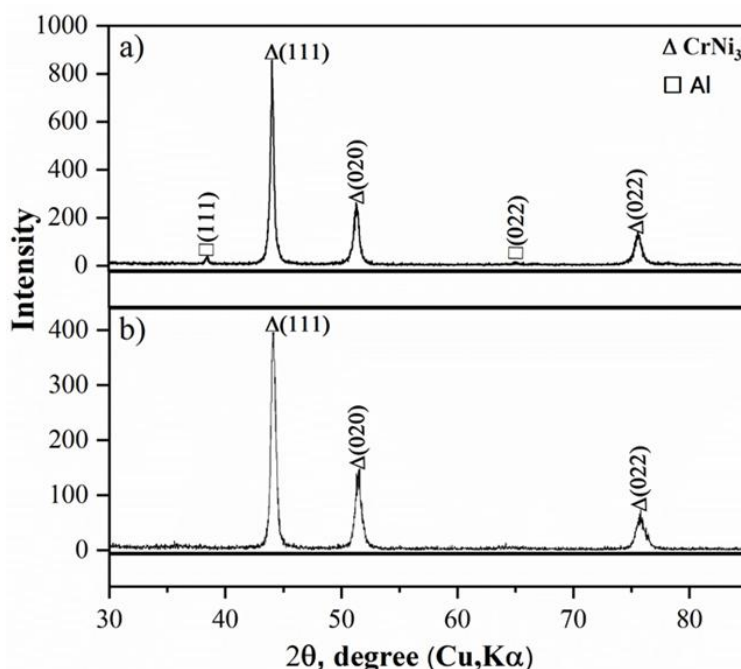


Figure 1. Results of the X-ray diffraction phase analysis for NiCr–Al coatings: a) Gradient; b) Homogeneous

Figure 2 presents cross-sectional micrographs of the homogeneous-composition and gradient-composition NiCr–Al coatings. In the microstructure of the homogeneous-composition NiCr–Al coating, distinct phase separation of the components can be observed. By progressively reducing the detonation

energy (from 50 % to 25 %), a gradient-composition NiCr–Al coatings was produced with an increased Al content in the surface layer, which contributed to a relatively high coating density (Fig. 2a). In contrast, the surface layer of the homogeneous-composition NiCr–Al coating exhibited a lower microstructural density. The study revealed that the coating obtained at a 50 % filling of the detonation barrel with explosive gases contained only a limited amount of Al. Consequently, the insufficient quantity of molten Al between CrNi₃ particles hindered the formation of a dense matrix, leading instead to a porous NiCr–Al coating (Fig. 2b) [18].

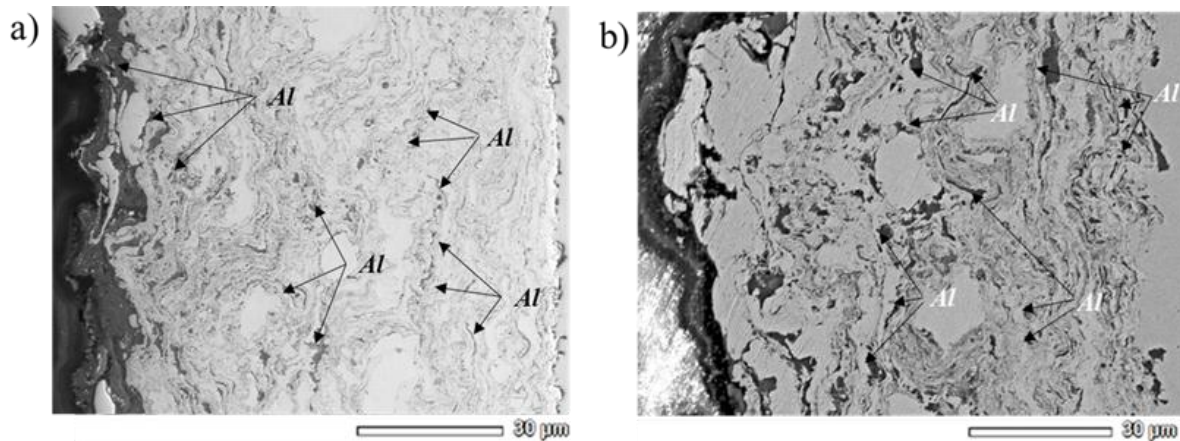


Figure 2. Cross-sectional microstructure of NiCr–Al coatings: a) Gradient; b) Homogeneous

Figure 3 shows the X-ray phase analysis results of homogeneous-composition and gradient-composition NiCr–Al coatings after high-temperature testing under industrial conditions. As can be seen, the gradient-composition NiCr–Al coating (Fig. 3a) is dominated by the CrNi₃ intermetallic phase, which indicates its high thermal stability. In addition, protective oxides such as Cr₂O₃ and Al₂O₃ were formed on the coating surface. This phase composition demonstrates the enhanced oxidation and corrosion resistance of the gradient-composition NiCr–Al coatings. Furthermore, the CrO₃ oxidized chromium phase, which typically forms under aggressive oxidation conditions, was also detected on the coating surface. In contrast, for the homogeneous-composition NiCr–Al coating, although the CrNi₃ phase was retained, oxidation-resistant oxides (Al₂O₃, Cr₂O₃) were either scarce or not detected at all. This indicates the weaker ability of the homogeneous-composition NiCr–Al coating to form a protective layer.

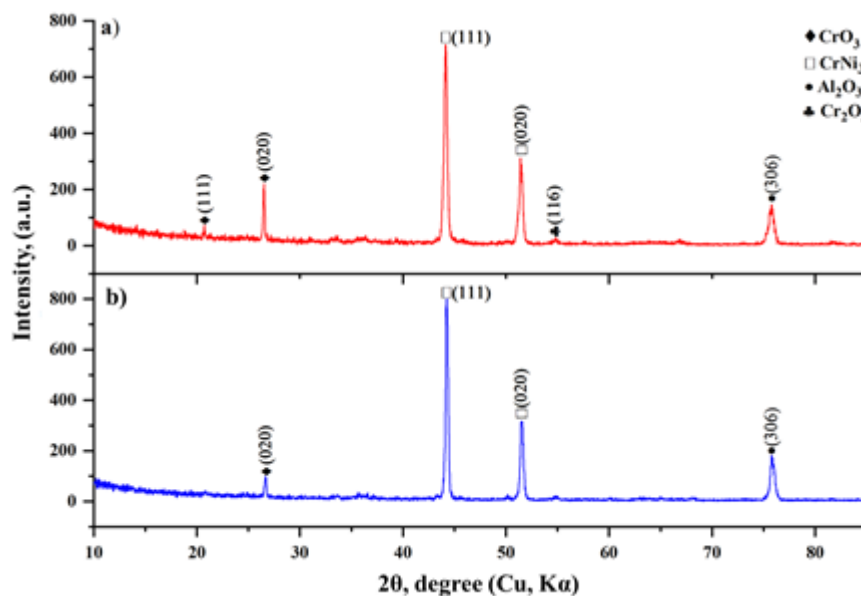


Figure 3. X-ray phase analysis results of NiCr–Al coatings after high-temperature testing under industrial conditions: a) homogeneous; b) gradient

Figure 4 presents the SEM cross-sectional images of homogeneous-composition and gradient-composition NiCr–Al coatings after high-temperature testing under industrial conditions. These results provide an assessment of the internal structure and structural changes of the coatings after thermal exposure. In the cross-section of the homogeneous-composition NiCr–Al coating (Fig. 4a), cracks, porosity, and fragmented regions are clearly visible within the coating. In some areas, structural disintegration is observed. These changes indicate that oxidation and thermal fatigue processes occurred intensively under high temperature and aggressive atmospheric conditions. In contrast, the gradient-composition NiCr–Al coating (Fig. 4b) exhibits fewer microcracks and pores, and no signs of fragmentation or delamination are observed in the internal regions of the coating. A certain degree of surface oxidation is present, but this is attributed to the formation of a protective oxide layer, which helps to suppress coating degradation.

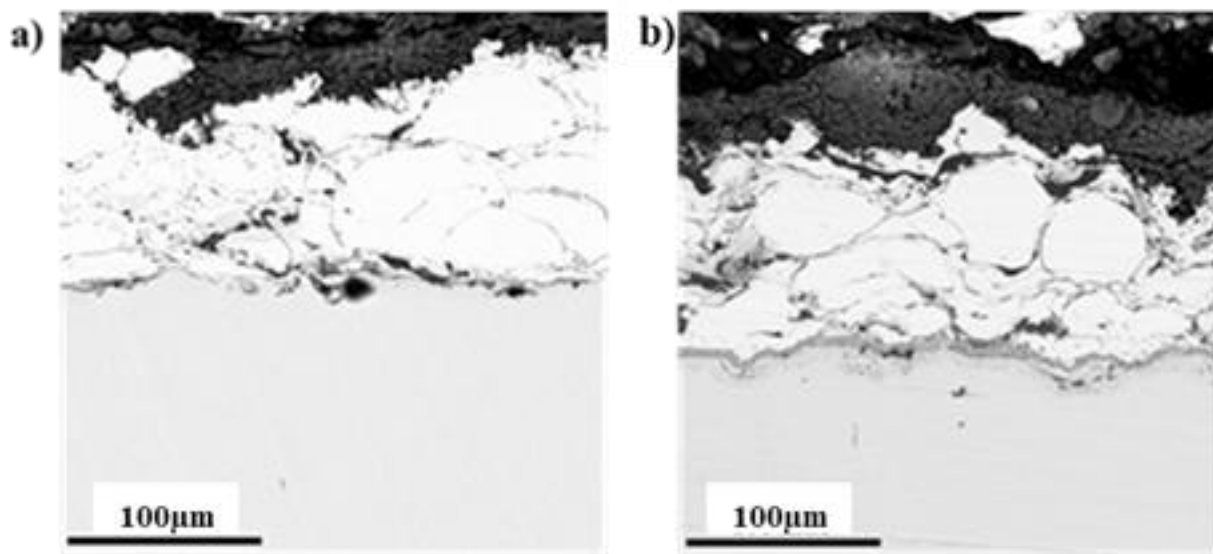


Figure 4. SEM cross-sectional image of NiCr–Al coatings after high-temperature testing under industrial conditions: *a*) homogeneous; *b*) gradient

Figure 5 shows the EDS results of the cross-section of the homogeneous-composition NiCr–Al coating after high-temperature testing under industrial conditions. Within the coating, Cr and Ni elements are uniformly distributed, representing the main constituents of the coating. According to the spectral analysis, the Al content in the coating is relatively low, with a noticeable concentration only near the surface. This indicates the formation of a protective Al_2O_3 oxide layer on the surface during high-temperature oxidation. The elemental mapping results reveal that oxygen (O) and aluminum (Al) are concentrated in the upper region of the coating, confirming the presence of an oxide layer. Based on the line scan analysis, Fe content sharply increases within $\sim 100\ \mu\text{m}$ from the coating surface, which marks the boundary between the coating and the substrate. Overall, the EDS analysis demonstrates that, after high-temperature exposure under industrial conditions, the homogeneous-composition NiCr–Al coating underwent oxidation and formed a surface oxide protective layer. However, the low aluminum content in the coating suggests insufficient capability for long-term protection of the substrate.

Figure 6 presents the EDS results obtained from the cross-section of the gradient-composition NiCr–Al coatings after high-temperature testing under industrial conditions. The analysis reveals the elemental distribution between the coating and the substrate, the oxidation process, as well as the advantages of the gradient structure. According to the line scan profile, aluminum (Al) and chromium (Cr) are highly concentrated in the surface layer of the coating, which facilitates the formation of protective oxides such as Al_2O_3 and Cr_2O_3 . Spectral analysis taken at different points from the substrate toward the coating surface shows that the aluminum content gradually increases toward the surface. Elemental mapping demonstrates that nickel (Ni) and chromium (Cr) are uniformly and predominantly distributed within the inner regions of the coating, while iron (Fe) is localized in the bottom region, clearly indicating the boundary between the substrate and the coating. These EDS results confirm that the gradient-composition NiCr–Al coatings possess high oxidation resistance and good structural integrity under industrial high-temperature conditions.

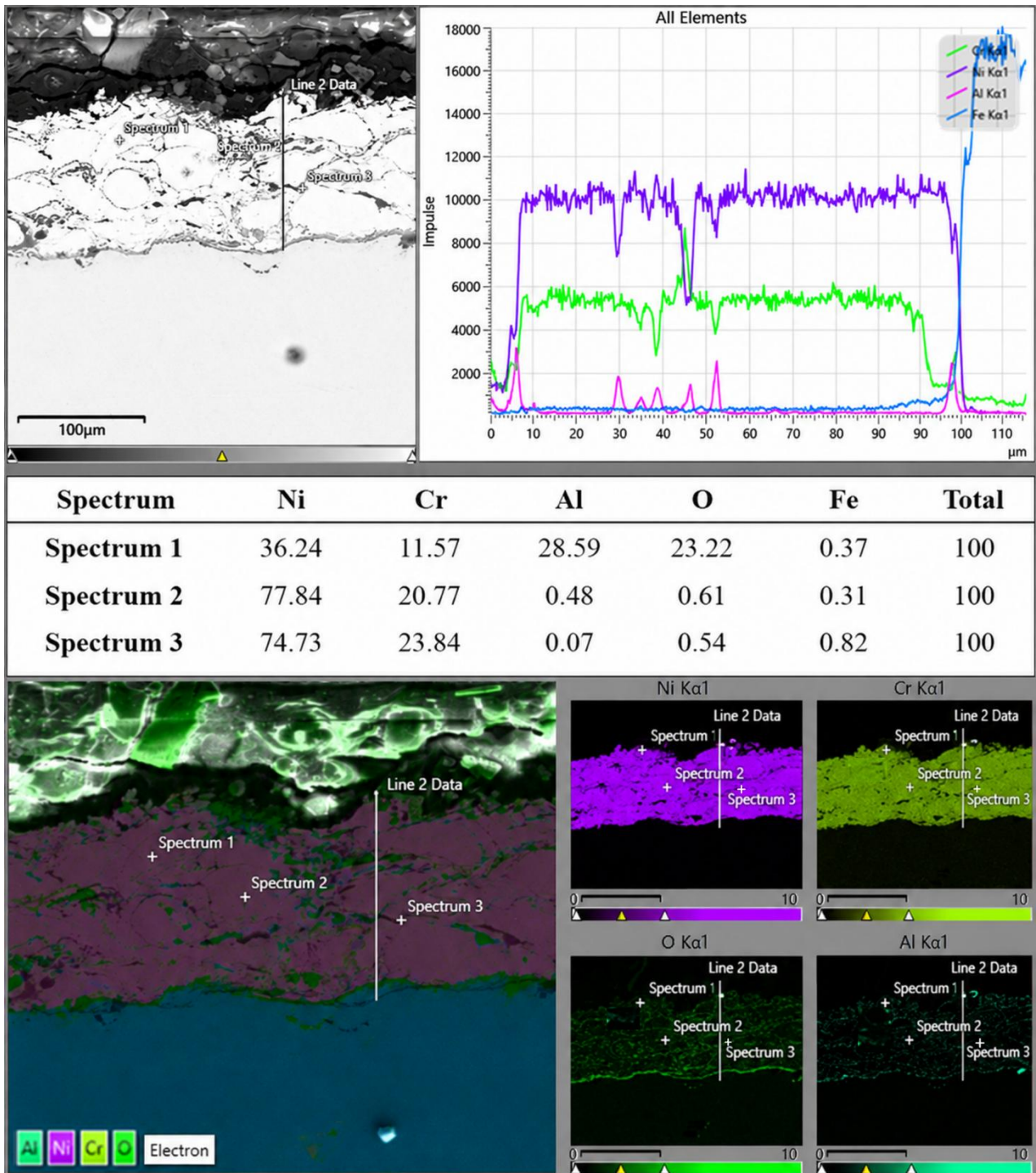


Figure 5. Cross-sectional EDS analysis of the homogeneous-composition NiCr–Al coating after exposure to high-temperature testing in an industrial environment

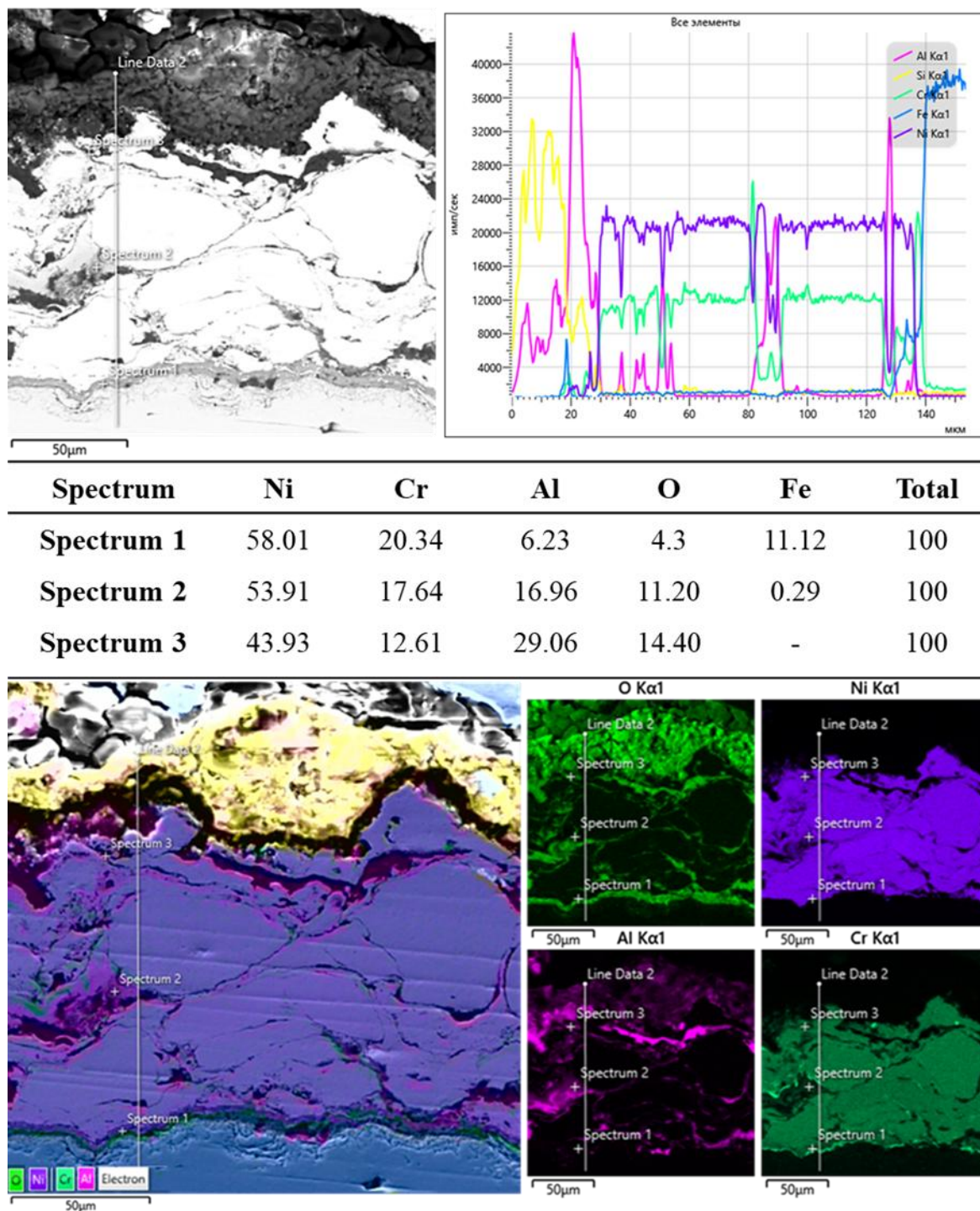


Figure 6. Cross-sectional EDS analysis of the gradient composition NiCr–Al coating after exposure to high-temperature testing in an industrial environment

Conclusion

Based on the results following conclusions can be drawn:

– After high-temperature oxidation testing under industrial operating conditions, the homogeneous composite NiCr–Al coating exhibited a pronounced reduction in aluminum concentration accompanied by structural degradation, including crack formation and oxide scale spallation. In contrast, the gradient composite NiCr–Al coating showed a more favorable elemental distribution along the coating thickness, particularly for aluminum and chromium.

– The optimized compositional gradient promoted the formation of continuous and adherent protective oxide layers, primarily Al_2O_3 and Cr_2O_3 , on the coating surface. These oxides acted as effective diffusion barriers, significantly improving oxidation resistance and mitigating further material degradation at elevated temperatures.

– The superior performance of the gradient composite NiCr–Al coating can be attributed to the combined effect of its tailored chemical architecture and enhanced thermomechanical compatibility between coating layers, which reduces thermal stresses and improves long-term stability under severe service conditions.

Funding

This research has been funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP22688426).

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Жылу электр станциясының нақты жұмыс жағдайларында сыналған детонациялық бүрку арқылы алынған NiCr–Al жабындарын зерттеу

Жұмыста детонациялық бүрку әдісімен алынған градиентті және біртекті композициялық NiCr–Al жабындарының жылу электр станциясының нақты жұмыс жағдайларында жоғары температуралық тотығуға төзімділігі бойынша жүргізілген эксперименттік зерттеулердің нәтижелері ұсынылған. Сынақтан өткен жабындардың деградация механизмдерін сипаттау мақсатында фазалық құрамды бағалау және сканерлеуші электрондық микроскопия әдісін қолдана отырып, микроқұрылымды талдау сияқты жүйелі зерттеулер жүргізілді. Қорғаныштық тиімділікке жабын құрылымының әсерін нақтылау мақсатында жабын қалыңдығы бойынша оксидтік қабаттардың өзгерісі мен элементтердің таралуы бағаланды. Эксперименттік нәтижелер градиентті композициялық NiCr–Al жабындарының біртекті жабындармен салыстырғанда ыстық коррозияға және жоғары температуралық тотығуға төзімділігі жоғары екенін көрсетті. Градиентті жабын құрылымдық тұтастығын тиімді түрде сақтауға мүмкіндік беріп, жабын қалыңдығы бойымен алюминий мен хром элементтерінің неғұрлым біркелкі таралуын қамтамасыз етті. Мұндай құрамдық онтайландыру негізінен Al_2O_3 және Cr_2O_3 типтес үздіксіз әрі адгезиясы жоғары қорғаныш оксидтік қабаттардың қалыптасуына ықпал етіп, тотығуды төмендетті және жабынның деградациялануын тежеді. Ал біртекті NiCr–Al жабындарында жоғары температуралық өнеркәсіптік жағдайларда ұзақ уақыт әсер ету нәтижесінде алюминийдің айқын сарқылуы, жарықшақтардың түзілуі және оксидтік қабаттың қабыршақтанып бөлінуі байқалды. Зерттеу нәтижелері детонациялық бүрку әдісімен алынған градиентті NiCr–Al жабындарының жоғары температуралық және коррозиялық әсері күшті ортада жұмыс істейтін бөлшектерді қорғау үшін перспективалы екенін көрсетті, бұл өнеркәсіптік және энергетикалық қолданбаларда олардың ұзақ мерзімділігін арттырып, қызмет ету мерзімін ұзартады.

Кілт сөздер: NiCr–Al жабыны, детонациялық бүрку технологиясы, жоғары температуралық қасиеттер, ЖЭС

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Исследование покрытий NiCr–Al полученных методом детонационного напыления испытанных в реальных условиях эксплуатации теплоэлектростанции

В данной работе представлены экспериментальные результаты испытаний на высокотемпературное окисление в реальных условиях эксплуатации теплоэлектростанции градиентных и однородных композиционных покрытий NiCr–Al, полученных методом детонационного напыления. Исследуемые покрытия подвергались воздействию агрессивных промышленных сред с целью оценки их структурной стабильности, стойкости к окислению и коррозионной стойкости в условиях повышенных температур. Для характеристики механизмов деградации исследуемых покрытий были проведены систематические анализы, включающие оценку фазового состава и детальное исследование микроструктуры с использованием сканирующей электронной микроскопии (SEM). Для уточнения влияния архитектуры покрытия на его защитную эффективность также были оценены эволюция оксидных слоёв и перераспределение элементов по толщине покрытия. Экспериментальные результаты показали, что градиентные композиционные покрытия NiCr–Al по сравнению с однородными покрытиями обладают более высокой стойкостью к высокотемпературному окислению. Градиентная архитектура эффективно сохраняла структурную целостность покрытия и способствовала более равномерному распределению алюминия и хрома по всей толщине покрытия. Данная оптимизация состава способствовала формированию непрерывных и хорошо адгезированных защитных оксидных слоёв, преимущественно Al_2O_3 и Cr_2O_3 , что существенно снизило кинетику окисления и подавило деградацию покрытия. В отличие от этого, однородные покрытия NiCr–Al после длительного воздействия высокотемпературных промышленных условий демонстрировали заметное истощение алюминия, образование трещин и отслаивание оксидной окалины. Результаты настоящего исследования подтверждают, что градиентные покрытия NiCr–Al, нанесённые методом детонационного напыления, представляют собой перспективное защитное решение для компонентов, работающих в условиях высоких температур и агрессивных корро-

зионных сред, обеспечивая повышенную долговечность и увеличение срока службы в промышленном и энергетическом применении.

Ключевые слова: покрытия NiCr–Al, технология детонационного напыления, высокотемпературные свойства, ТЭЦ

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