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ASSESSMENT OF NI-CR-AL HIGH-TEMPERATURE DETONATION COATINGS UNDER OPERATIONAL CONDITIONS

This study evaluates the high-temperature durability and oxidation resistance of homogeneous and gradient Ni-Cr-Al detonation coatings applied to 12Kh1MF steel substrates. Samples were exposed to operational conditions in a power plant for two weeks, simulating high-temperature industrial environments. The research utilizes X-ray diffraction (XRD) and scanning electron microscopy (SEM) to analyze phase stability, surface morphology, and structural integrity of the coatings before and after thermal exposure. Findings reveal that gradient coatings outperform homogeneous ones, demonstrating superior oxidation resistance and reduced susceptibility to thermal stress-induced microcracks. The multi-layered oxide structure and compositional gradient of the gradient coatings contribute to their enhanced thermal stability and long-term durability. In contrast, homogeneous coatings exhibited surface roughness and microcracks, which may compromise their longevity under extreme conditions. These insights emphasize the advantages of gradient Ni-Cr-Al coatings for high-temperature applications, highlighting their potential for improved performance and reliability in demanding industrial settings. The study bridges knowledge gaps regarding the long-term behavior of these coatings, aiding their optimization for critical applications.

Keywords: High-temperature coating, power plant, Ni-Cr-Al coating, detonation technology, steel 12Kh1MF.

Introduction

High-temperature detonation coatings based on the Ni-Cr-Al system have demonstrated remarkable effectiveness in resisting oxidation, corrosion, and wear, making them essential in industries such as aerospace, energy, and manufacturing. These coatings offer superior protection in environments where components are regularly exposed to high temperatures and harsh operational conditions [1; 2]. The unique combination of nickel, chromium, and aluminum forms a protective oxide layer, which significantly enhances the thermal and mechanical stability of the substrate [3; 4].

Detonation-sprayed Ni-Cr-Al coatings exhibit excellent adhesion to substrates and exceptional resistance to thermal cycling, making them ideal for applications requiring long-term durability in extreme conditions [5; 6]. This method produces dense, uniform coatings that effectively protect against wear and oxidation in demanding operational environments [7; 8]. Despite their recognized advantages, there remains a lack of comprehensive data on the long-term performance of these coatings in real-world conditions [9; 10].

This study aims to investigate the long-term durability of Ni-Cr-Al coatings under operational conditions. Understanding how these coatings perform in environments with temperature fluctuations and corrosive influences is critical for optimizing their applications in industrial sectors. This research will fill the gap in existing knowledge and provide important insights for future developments in protective coating technologies.

Materials and methods

The experiments were conducted using 12Kh1MF steel as the substrate, which was cut into cubic samples with dimensions of 1.5 cm on each side. The steel substrates were thoroughly cleaned to remove any contaminants that could affect coating adhesion. A Ni-Cr-Al coating was applied to all surfaces of the cubic samples using the detonation spraying method, which involves high-velocity particles being deposited onto the substrate, forming a dense, uniform layer. This technique ensures excellent adhesion and enhances the mechanical and thermal properties of the coated surface. A homogeneous Ni-Cr-Al coating was produced by filling 50 % of the barrel volume. Gradient coatings were created by gradually reducing the barrel filling volume with gas from 50% to 25%. A detailed procedure for obtaining a gradient coating can be found in our previously published work [6; 7].

After the coating process, the samples were transported to the Sogrinskaya Power Plant in Ust-Kamenogorsk. The samples were placed in high-temperature zones within the power plant, where they were exposed to operational conditions for a duration of two weeks (figure 1). The temperature in these zones reached up to 700°C, simulating real-world high-temperature environments to evaluate the coating's durability and resistance to thermal degradation.

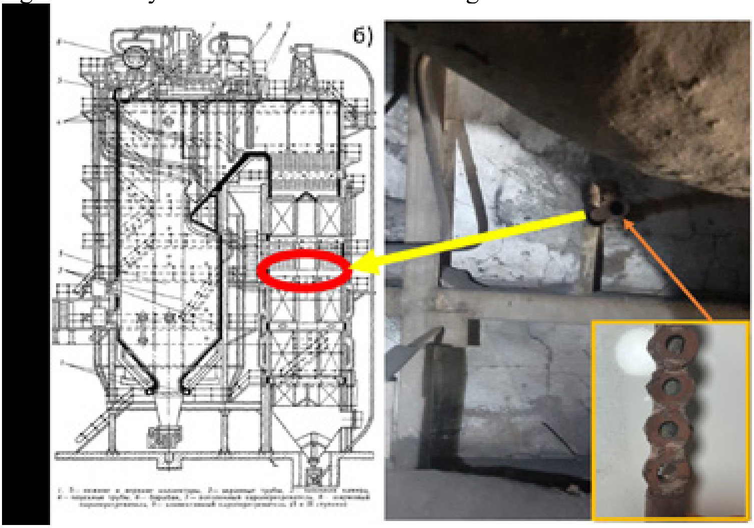

Figure 1 – The samples were placed in high-temperature zones within the power plant

Following the exposure period, the samples were retrieved for further analysis. To identify the phases formed in the coating after high-temperature oxidation, X-ray diffraction (XRD) analysis was performed using an X'PertPRO diffractometer with Cu-Kα radiation (λ = 1.54 Å) at 40 kV and 30 mA. The HighScore software analyzed the diffractograms, with measurements taken from 2θ = 20° to 90°, using a 0.02° step size and 0.5 seconds per step. After testing, the coating's cross-sectional morphology was examined using backscattered electrons (BSE) on a JSM-6390LV scanning electron microscope (Jeol, Tokyo, Japan).

Results and discussion

The SEM analysis provided insights into the surface morphology of both homogeneous and gradient Ni-Cr-Al coatings before and after exposure to high temperatures at the Sogrinskaya Power Plant (figures 2-3). Before thermal exposure, the homogeneous Ni-Cr-Al coatings displayed a relatively uniform surface, with densely packed particles and minimal porosity (figure 2a). After exposure to high temperatures, significant changes were observed in the surface morphology of the homogeneous coatings. SEM images show the formation of rounded features and surface roughness, indicating the onset of oxidation (figure

2b). Some microcracks were also observed, suggesting that the homogeneous coating experienced thermal stress due to temperature fluctuations. Despite these changes, the coating remained largely intact, demonstrating its ability to withstand high-temperature conditions without severe degradation.

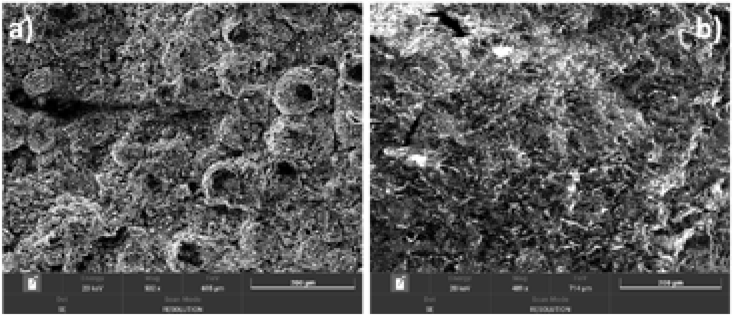

Figure 2 – Surface morphology of homogeneous Ni-Cr-Al coatings before (a) and after (b) exposure to high temperatures

The gradient Ni-Cr-Al coatings, before exposure, exhibited a more complex structure compared to the homogeneous coatings (figure 3a). The surface contained areas of varying particle sizes, reflecting the gradient nature of the coating where different layers contain varying concentrations of Ni, Cr, and Al. This gradient structure is designed to optimize thermal and mechanical properties, with outer layers providing high oxidation resistance and inner layers enhancing adhesion and toughness. Post-exposure SEM analysis revealed that the gradient coatings performed well under high-temperature conditions (figure 3b). While some oxidation features were observed, the gradient structure appeared to have mitigated the formation of large surface cracks. The presence of smaller oxide nodules suggests that the outer layers of the gradient coating formed protective oxides more effectively than the homogeneous coating. The gradient structure likely contributed to better thermal stress distribution, resulting in fewer microcracks and a more stable surface morphology after thermal exposure.

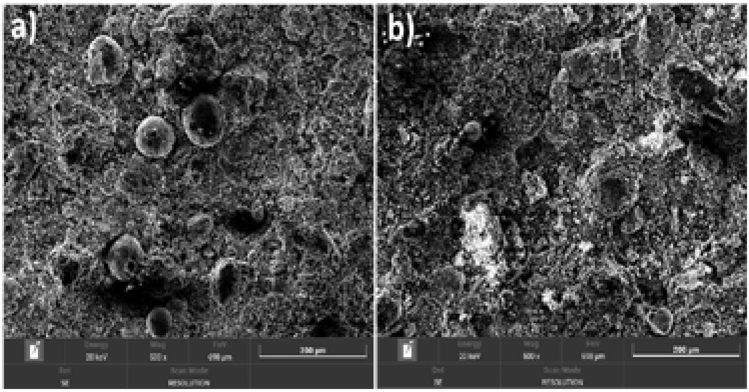

Figure 3 – Surface morphology of gradient Ni-Cr-Al coatings before (a) and after (b) exposure to high temperatures

A cross-section SEM figures of the homogeneous and gradient Ni-Cr-Al detonation coatings after two weeks of exposure in the power plant reveals distinct differences in their structural responses and oxidation resistance figure 4. The homogeneous coating, examined through cross-sectional SEM analysis, shows the formation of a continuous oxide layer primarily consisting of Cr_2O_3 and Al_2O_3 (figure 4a). However, the high thermal stress from prolonged exposure led to surface roughness and the development of microcracks extending from the surface into the coating. These microcracks indicate that the homogeneous structure struggles to manage thermal expansion, potentially compromising its long-term durability. While the coating maintained its structural integrity to some extent, the presence of microcracks poses a risk for deeper oxidation over time. In contrast, the gradient Ni-Cr-Al coating displayed a more robust response to the same high-temperature conditions (figure 4b). The cross-sectional SEM analysis highlights a multi-layered oxide structure, with higher concentrations of Cr_2O_3 and Al_2O_3 near the surface, providing enhanced oxidation resistance. The gradient structure allows for better distribution of thermal stress across the layers, resulting in fewer and smaller microcracks compared to the homogeneous coating. This graded composition minimizes thermal mismatch and helps accommodate expansion, preserving the coating's integrity and reducing susceptibility to deep oxidation.

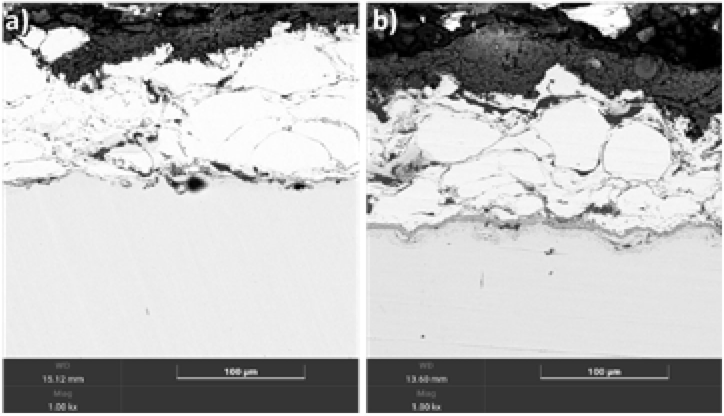

Figure4 – A cross-section SEM figures of the homogeneous (a) and gradient (b) Ni-Cr-Al detonation coatings after two weeks of exposure in the power plant

The XRD patterns for both the homogeneous and gradient Ni-Cr-Al coatings reveal significant insights into the phase stability and oxidation resistance under high-temperature conditions. The gradient Ni-Cr-Al coating (figure 5a) exhibits similar peaks for the $CrNi_3$ phase, but with a higher intensity for the Al_2O_3 (306) peak, indicating a more pronounced oxidation at the surface. This is consistent with the gradient structure, which may facilitate gradual compositional changes that enhance oxidation resistance on the surface. The enhanced Cr_2O_3 layer likely provides better protection against thermal oxidation, suggesting that the gradient structure promotes improved thermal and oxidative stability over homogeneous coatings under real (Power plant) conditions. In the gradient Ni-Cr-Al coating, the presence of a CrO_3 peak indicates additional oxidation products forming on the surface. CrO_3, a higher oxidation state of chromium oxide, suggests that the gradient structure facilitates oxygen diffusion deeper into the coating, forming CrO_3 in addition to Cr_2O_3. This phase is known for its high-temperature stability but is typically less thermally stable than Cr_2O_3, which might influence the coating's performance. The gradient composition likely aids in managing oxidation, creating a multi-layered oxide structure that enhances thermal resistance under real (Power plant) conditions. Homogeneous Ni-Cr-Al Coating's major peaks at positions corresponding to the $CrNi_3$ phase indicate that the coating retains its primary structure (figure 5b). However, smaller peaks attributed to Cr_2O_3 and Al_2O_3 suggest a minor oxidation layer on the surface, which likely enhances thermal stability. The presence of the $CrNi_3$ (111) peak as the dominant phase implies good structural integrity under prolonged thermal exposure, as well as stable adherence to the substrate.

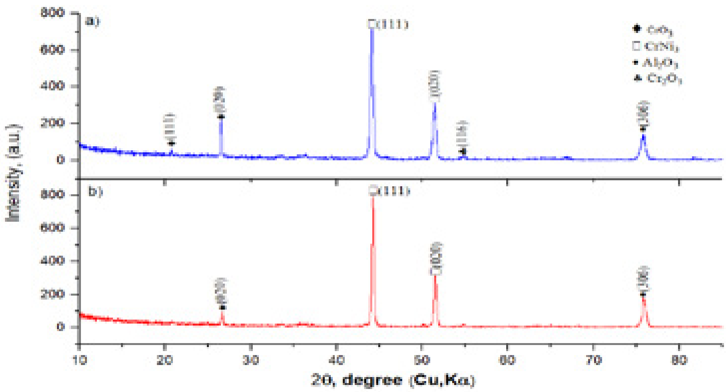

Figure 5 – XRD results of coatings after exposure to high temperatures: (a) gradient Ni-Cr-Al coating and (b) homogeneous Ni-Cr-Al coating.

The SEM linear analysis of the gradient Ni-Cr-Al coating after two weeks of exposure in a power plant reveals distinct elemental distributions across the cross-section. The intensity of Al and Cr signals is high near the surface, indicating a protective oxide layer enriched in these elements, likely due to oxidation processes. The Ni signal is stronger in deeper layers, suggesting the underlying coating retains its nickel-rich matrix. This gradient in elemental distribution supports enhanced oxidation resistance and thermal stability in the surface region of the coating.

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Conclusion

This comparative study highlights the effectiveness of gradient Ni-Cr-Al coatings over homogeneous ones in high-temperature environments, as shown through two weeks of exposure in a power plant. The gradient coating's multi-layered oxide structure, enriched in Cr_2O_3 and Al_2O_3 near the surface, provided enhanced oxidation resistance and minimized microcracking due to improved thermal stress distribution. In contrast, the homogeneous coating, though effective, displayed surface microcracks that may compromise long-term durability under thermal cycling. The gradient coating's structure allows for better management of oxygen diffusion and thermal expansion, promoting structural integrity and resistance to oxidation. These findings underscore the gradient Ni-Cr-Al coating as a more robust solution for applications requiring high durability in extreme conditions.

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NI-CR-AL ЖОҒАРЫ ТЕМПЕРАТУРАЛЫҚ ДЕТОНАЦИЯЛЫҚ ЖАБЫНДАРЫН ЖҰМЫС ЖАҒДАЙЫНДА БАҒАЛАУ.

Бұл зерттеуде 12Х»МФ болат негіздерге алынған Ni-Cr-Al негізіндегі біртекті және градиентті детонациялық жабындардың жоғары температураға төзімділігі мен тотығуға қарсы тұрақтылығы бағаланады. Үлгілер екі апта бойы жылу электр станциясындағы эксплуатациялық жағдайларға ұшырап, жоғары температуралы өндірістік ортада сыналды. Зерттеуде фазалық тұрақтылықты, беткі морфологияны және жабындардың құрылымдық тұтастығын термиялық әсерге дейін және кейін талдау үшін рентгендік дифракция (XRD) және сканерлік электрондық микроскопия (SEM) әдістері қолданылды. Нәтижелер көрсеткендей, градиентті жабындар біртекті жабындарға қарағанда жақсырақ, тотығуға қарсы жоғары тұрақтылықты және термиялық кернеу нәтижесінде пайда болатын микрожарықтарға аз бейімділікті көрсетеді. Градиентті жабындардың көпқабатты оксидті құрылымы мен құрамдық градиенті олардың термиялық тұрақтылығын және *ұзақ мерзімді беріктігін жақсартады. Ал біртекті жабындар бетінің кедір-бұдырлығын және микрожарықтарды көрсетті, бұл олардың төзімділігін экстремалды жағдайларда төмендетуі мүмкін. Бұл нәтижелер градиентті Ni-Cr-Al жабындарының жоғары температуралық қолданулар үшін артықшылықтарын көрсетіп, оларды күрделі өндірістік жағдайларда тиімділік пен сенімділікті арттыру әлеуетіне ие екенін дәлелдейді. Зерттеу нәтижелері мұндай жабындардың ұзақ мерзімді қолдану туралы ақпаратты толтырып, олардың негізгі қолдануларға оңтайландырылуына үлес қосады.*

Кілт сөздер: жоғары температуралық жабын, ЖЭС, Ni-Cr-Al жабыны, детонациялық технология, 12Х1МФ болаты.

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ОЦЕНКА СВОЙСТВ ВЫСОКОТЕМПЕРАТУРНЫХ ДЕТОНАЦИОННЫХ ПОКРЫТИЙ NI-CR-AL В УСЛОВИЯХ ЭКСПЛУАТАЦИИ

В данном исследовании оценивается высокая температурная стойкость и устойчивость к окислению однородных и градиентных детонационных покрытий на основе Ni-Cr-Al, нанесенных на стальные подложки 12Х1МФ. Образцы подвергались эксплуатационным условиям на теплоэлектростанции в течение двух недель, имитируя высокотемпературные промышленные среды. В ходе исследования использовались рентгеновская дифракция (XRD) и сканирующая электронная микроскопия (SEM) для анализа фазовой стабильности, морфологии поверхности и структурной целостности покрытий до и после термического воздействия. Результаты показывают, что градиентные покрытия превосходят однородные, демонстрируя высокую стойкость к окислению и меньшую подверженность термическим трещинам. Многослойная оксидная структура и градиент состава градиентных покрытий способствуют их *улучшенной термической стабильности и долговечности. В отличие от этого, однородные покрытия показали шероховатость поверхности и микротрещины, что может ухудшить их долговечность в экстремальных условиях. Эти результаты подчеркивают преимущества градиентных покрытий Ni-Cr-Al для высокотемпературных применений, указывая на их потенциал для повышения производительности и надежности в сложных промышленных условиях. Исследование восполняет пробелы в знаниях о поведении таких покрытий в долгосрочной перспективе, способствуя их оптимизации для ключевых приложений.*

Ключевые слова: Высокотемпературное покрытие, ТЭЦ, Ni-Cr-Al покрытие, технология детонации, сталь 12Х1МФ.

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