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INVESTIGATION OF TRIBOLOGICAL PROPERTIES OF DETONATION Ni-Cr-Al COATINGS

This study explores the tribological properties of Ni-Cr-Al coatings applied through detonation spraying technology, with a focus on the comparison between gradient coatings and homogeneous coatings. Ni-Cr-Al coatings, widely used in aerospace, automotive, and energy industries like power plants, are valued for their exceptional hardness, wear resistance, and high-temperature stability. Gradient coatings, produced by tailoring the detonation spraying parameters, exhibit a microstructure combining a hard, wear-resistant surface with a softer, ductile subsurface, enhancing their load-bearing capacity and tribological performance. Experimental results reveal that gradient coatings achieve lower and more stable friction coefficients (0.3-0.4) compared to homogeneous coatings (0,4-0,5), attributed to their optimized stress distribution and reduced adhesive interactions. These findings underscore the superior wear resistance and durability of gradient Ni-Cr-Al coatings, making them highly suitable for applications involving prolonged operation under sliding conditions. This research contributes to the development of advanced coating systems optimized for demanding operational environments.
Key words: *detonation spraying, Ni-Cr-Al coatings, gradient coatings, homogeneous coatings, tribological properties.*

Introduction

High-performance coatings are essential for enhancing the durability and efficiency of engineering components, especially those exposed to extreme mechanical and thermal stresses. Among various coating systems, nickel-chromium-aluminum (Ni-Cr-Al) coatings have garnered significant attention due to their excellent combination of hardness, corrosion resistance, and high-temperature stability. These properties make Ni-Cr-Al coatings ideal for applications in aerospace, automotive, and energy sectors [1-2]. Detonation spraying is a thermal spray technique that effectively deposits Ni-Cr-Al coatings. Studies have shown that the degree to which the detonation gun barrel is filled with the gas mixture significantly influences the chemical composition and phase structure of the resulting coatings. For instance, higher filling degrees can decrease aluminum content, affecting the formation of Ni-Al phases, which are crucial for enhancing wear resistance [3-4].

The microstructure of Ni-Cr-Al coatings typically comprises a dense metallic matrix reinforced with hard intermetallic phases and oxides. This structure provides a synergistic balance of toughness and wear resistance, enabling the coatings to withstand significant mechanical loads without substantial deformation. Additionally, the formation of a self-healing oxide layer during operation enhances their high-temperature wear and oxidation resistance. Research has demonstrated that gradient Ni-Cr-Al coatings, produced by varying the detonation spraying parameters, exhibit high hardness and improved wear resistance compared to homogeneous coatings [5-6]. Recent investigations have also explored the effects of post-spray treatments on the properties of Ni-Cr-Al coatings. For example, pulsed plasma treatment has been employed to modify the surface characteristics of detonation-sprayed Ni-Cr-Al coatings, leading to enhanced hardness and tribological performance [7]. Furthermore, studies on the high-temperature oxidation behavior of these coatings have shown that both homogeneous and gradient Ni-Cr-Al coatings exhibit good resistance to oxidation at elevated temperatures, making them suitable for high-temperature applications [8].

Understanding the relationships between processing parameters, microstructural features, and tribological performance is essential for optimizing Ni-Cr-Al coatings for specific operational conditions. This study aims to investigate the tribological behavior of detonation-sprayed Ni-Cr-Al coatings under various wear conditions, providing insights into their wear mechanisms and contributing to the development of advanced coating systems for high-performance applications.

Materials and methods

Ferrite-pearlite steel 12Kh1MF was selected as the substrate material. The samples were ground using MIRKA grinding paper up to a grit size of 1200 to ensure a uniform and flat surface. Following the grinding process, the samples underwent sandblasting. Ni-Cr-Al coatings were prepared using a powder mixture of Ni-Cr (Ni20Cr80) and Al (99,99%) in the following mass proportions: 80% NiCr (Ni20Cr80) and 20% Al (99,99%). The particle size of the powders ranged from 30 to 45 microns. The coatings were deposited using the CCDS2000 detonation complex (LIH SB RAS, Novosibirsk, Russia), equipped with an electromagnetic gas valve system that precisely regulates the supply of fuel and oxygen, as well as purging operations. A high-precision, computer-controlled gas distribution system was used to fill the gun barrel with gases. Nitrogen served as the carrier gas for the process. A homogeneous Ni-Cr-Al coating was produced by filling the barrel to 50% of its volume. Gradient Ni-Cr-Al coatings were fabricated using a method developed and described in [6], which involves gradually varying the barrel filling volume with the explosive gas mixture during detonation deposition. The gradient coating was achieved by reducing the barrel filling volume progressively from 50% to 25%.

Friction tests were performed on a test stand designed at the Department of Fundamentals of Mechanical Engineering and Tribology, Wrocław University of Science and Technology (Figure 1). The apparatus allows for the evaluation of sliding friction in an alternating motion configuration [9]. During testing, a steel ball was pressed against a steel plate with the tested coating using a normal force F_n applied through weights.

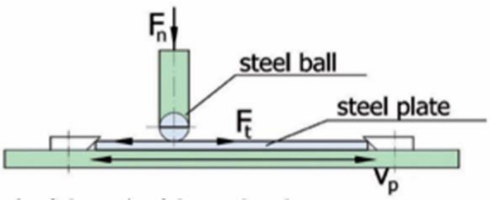

Figure 1 – Scheme of the test bench [10]

The plate movement system consisted of two carriages stacked on top of each other, equipped with bearings to facilitate motion in the same direction. The setup was powered by an electric actuator comprising a stepper motor and a helical gearbox. When extended, the actuator moved the larger carriage, which supported the smaller carriage. A strain gauge force sensor connected the larger carriage to the smaller one, transmitting the force of movement. The relative motion of the smaller carriage with respect to the larger one corresponded to the deflection of the force sensor and clamping components under the frictional force F_t. Each coated sample underwent three measurement series, with each series comprising 200 movement cycles. Each cycle consisted of two movements (one in each direction) at a maximum velocity (v_{smax}) of 5 mm/s. The duration of movement in each direction was 0.4 seconds. The normal load applied to the friction node was 20 N. Steel bearing balls with a diameter of 4 mm (measured at 3.969 mm) were used in the tests, conducted under dry friction conditions. Before the measurements, the coating surfaces were ground, polished, and cleaned to ensure uniform.

Results and discussion

The friction coefficient analysis of homogeneous (a) and gradient (b) Ni-Cr-Al detonation-sprayed coatings demonstrates distinct differences in tribological behavior (Figure 2). Both coatings exhibit an initial peak in the friction coefficient due to the break-in phase, with the homogeneous coating showing a slightly higher value, likely due to uniform composition and surface asperities. Over time, the gradient coating stabilizes at a significantly lower friction coefficient (0.3-0.4) compared to the homogeneous coating (0.4-0.5). This improved performance is attributed to the gradient coating's microstructural design, which combines a hard wear-resistant surface with a softer, ductile subsurface that enhances load-bearing capacity and reduces adhesive interactions. Consequently, the gradient Ni-Cr-Al coating is more effective in reducing friction and wear, making it highly suitable for applications requiring prolonged operation under sliding conditions.

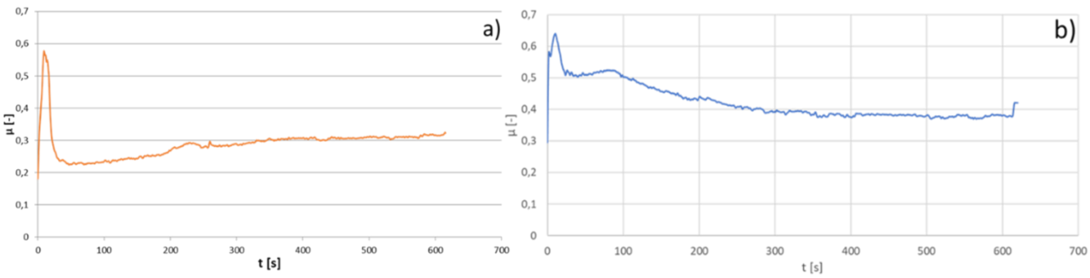

Figure 2 – The friction coefficient analysis of homogeneous (a) and gradient (b) Ni-Cr-Al detonation-sprayed coatings

The comparison of friction coefficients between homogeneous (a) and gradient (b) Ni-Cr-Al detonation-sprayed coatings highlights the influence of microstructural design on tribological behavior. The homogeneous coatings exhibit consistently higher average friction coefficients, ranging from approximately 0,4 to 0,45, as seen in the chart (Figure 3). This suggests a more uniform interaction between the coating surface and the counterbody, which could lead to higher adhesive and abrasive wear under sliding conditions. Conversely, the gradient coatings demonstrate lower average friction coefficients, typically around 0,3 to 0,35, attributed to their tailored microstructure. The gradient design provides a harder wear-resistant surface combined with a softer subsurface, which optimizes stress distribution, reduces localized frictional forces, and enhances wear resistance. The narrower error bars for the gradient coatings also indicate better stability in frictional performance compared to the homogeneous coatings.

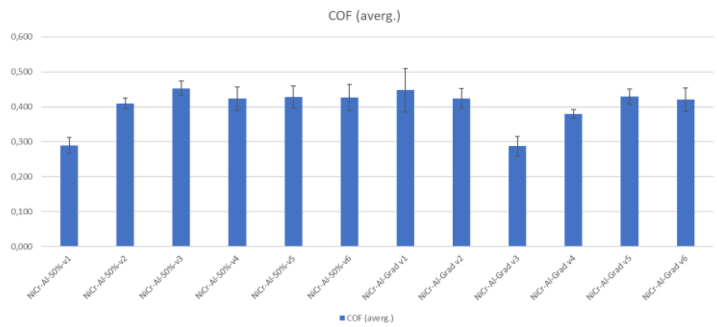

Figure 3 – The comparison of friction coefficients between homogeneous (a) and gradient (b) Ni-Cr-Al detonation-sprayed coatings

Conclusion

This study demonstrates that gradient Ni-Cr-Al coatings exhibit superior tribological performance compared to homogeneous coatings under sliding wear conditions. The tailored microstructure of gradient coatings, comprising a hard surface layer and a ductile subsurface, effectively reduces friction coefficients and enhances wear resistance. In contrast, homogeneous coatings, with their uniform composition, showed higher friction coefficients and greater susceptibility to adhesive and abrasive wear. The gradient coatings also demonstrated better stability in tribological performance, as evidenced by narrower variations in friction coefficient measurements. These results highlight the potential of gradient Ni-Cr-Al coatings for applications requiring high durability and reliability, particularly in industries such as aerospace, automotive, and energy, where components are subjected to extreme mechanical and thermal stresses. Future research should focus on further optimizing the detonation spraying parameters and exploring post-spray treatments to maximize the performance of these advanced coating systems.

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Ni-Cr-Al ДЕТОНАЦИЯЛЫҚ ЖАБЫНДАРЫНЫҢ ТРИБОЛОГИЯЛЫҚ ҚАСИЕТТЕРІН ЗЕРТТЕУ

Бұл зерттеуде детонациялық бүрку әдісімен алынған Ni-Cr-Al жабындарының трибологиялық қасиеттері зерттелді. Ni-Cr-Al градиентті және біртекті жабындарды салыстыруға ерекше назар аударылды. Ni-Cr-Al жабындары авиация, автомобиль және энергетика салаларында кеңінен қолданылады және олардың ерекше қаттылығы, тозуға төзімділігі мен жоғары температуралық *тұрақтылығы жоғары бағаланады. Детонациялық бүрку параметрлерін реттеу арқылы алынған градиентті жабындар қатты тозуға төзімді қабатты және жұмсақ пластикалық астарды біріктіретін микроструктураға ие, бұл олардың жүктемені көтеру қабілетін және трибологиялық қасиеттерін жақсартады. Эксперименттік нәтижелер бойынша градиентті жабындар біртекті жабындарға қарағанда төмен және тұрақты үйкеліс коэффициенттеріне (0,3-0,4) жететіні анықталды (0,4-0,5). Бұл нәтижелер градиентті Ni-Cr-Al жабындарының жоғары беріктік пен ұзақ қызмет етуін көрсетеді, бұл оларды ұзақ мерзімді пайдалану үшін өте қолайлы етеді. Бұл зерттеу экстремалды жағдайларға бейімделген жетілдірілген жабын жүйелерін әзірлеуге ықпал етеді.*

Түйін сөздер: *детонациялық бүрку, Ni-Cr-Al жабындары, градиентті жабындар, біртекті жабындар, трибологиялық қасиеттер.*

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ИССЛЕДОВАНИЕ ТРИБОЛОГИЧЕСКИХ СВОЙСТВ ДЕТОНАЦИОННЫХ ПОКРЫТИЙ Ni-Cr-Al

В данном исследовании изучены трибологические свойства покрытий Ni-Cr-Al, нанесённых методом детонационного напыления, с акцентом на сравнение градиентных и однородных покрытий. Покрытия Ni-Cr-Al, широко используемые в аэрокосмической, автомобильной и энергетической отраслях, ценятся за их исключительную твёрдость, износостойкость и стабильность при высоких температурах. Градиентные покрытия, созданные путём настройки параметров детонационного напыления, имеют микроструктуру, которая сочетает твёрдую износостойкую поверхность с мягким пластичным подслоем, что улучшает их способность выдерживать нагрузки и трибологические свойства. Экспериментальные результаты показывают, что градиентные покрытия достигают более низких и стабильных коэффициентов трения (0,3-0,4) по сравнению с однородными покрытиями (0,4-0,5). Эти результаты подчеркивают превосходную износостойкость и долговечность градиентных покрытий Ni-Cr-Al, что делает их особенно подходящими для применения в условиях длительной эксплуатации. Данное исследование способствует разработке усовершенствованных систем покрытий, оптимизированных для работы в экстремальных условиях.

Ключевые слова: *детонационное напыление, покрытия Ni-Cr-Al, градиентные покрытия, однородные покрытия, трибологические свойства.*

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АГРОХИМИЧЕСКОЕ ИССЛЕДОВАНИЕ ПЛОДОРОДИЯ ПОЧВЫ ДЛЯ ОПТИМИЗАЦИИ ЗЕМЛЕДЕЛИЯ В АГРОБИОЛАБОРАТОРИИ

Аннотация: *В статье приведены результаты исследования агрохимических показателей плодородия пахотного горизонта (0-20 см) каштановой почвы агробиолаборатории НАО «Университет имени Шакарима города Семей». Проведены механический, элементный и гравиметрический анализы 40 почвенных проб с 7 участков под посевами зерновых, бобовых и овощных культур. Установлены оптимальные показатели содержания органического вещества (4,49%), макроэлементов (общий азот – 71,81 кг/га; подвижный фосфор – от 0,37 до 0,88 мг/г; подвижный калий – от 0,26 до 0,47 мг/г; Na – 0,16-0,54 мг/г; Ca – 2,29-3,57 мг/г; Mg – 0,43-1,64 мг/г; Al – 0,82-2,41 мг/г) и микроэлементов питания (Mn – 0,12-0,39 мг/г; Cr – 0,10-0,11 мг/г; Fe – 0,43-0,80 мг/г), показателя pH почвенного раствора ($pH_{водн.}$ 7,7, $pH_{сол.}$ 6,7). По результатам исследований лимитирующими факторами почвенного плодородия являются влажность и механический состав. В настоящее время необходима разработка мелиоративных мероприятий для улучшения низкой влажности (11,72%,) и плохой структурности (агрегаты размером от 1 до 5 мм составляют 10-30%) почвы. Результаты агрохимического анализа проб почвы позволили создать базу почвенных данных агробиолаборатории для дальнейших мониторинговых исследований.*

Ключевые слова: *каштановая почва, органическое вещество, pH почвы, элементный состав, полевая влажность, минеральный азот, фракционный состав.*