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Development of a Method for Producing Self-Fluxing Nickel-Based Coatings by Detonation Spraying

This study investigated the influence of detonation spraying parameters on the structure and tribological and mechanical properties of self-fluxing coatings of the Ni–Cr–Fe–B–Si–C system. The investigated parameters included the barrel filling level (48–68%), the molar ratio of the working gases ($O/C = 1.026–1.856$), and the inter-shot delay (0–1 s). Morphological analysis of the coatings revealed a characteristic lamellar structure and a dependence of coating thickness and defect formation on the spraying conditions. A lower barrel filling level resulted in a denser coating structure with minimal porosity, whereas medium and high filling levels promoted the formation of microcracks, presumably due to increased residual stresses. Tribological tests showed that the minimum coefficient of friction was obtained at a barrel filling level of 48% ($\mu = 0.674 \pm 0.136$) and an O/C ratio of 1.026, but these conditions were also associated with increased wear. The highest wear resistance was obtained at an O/C ratio of 1.856 and an increased inter-shot delay of up to 1 s, resulting in a decrease in the specific wear rate to $0.000189 \text{ mm}^3/(\text{N} \cdot \text{m})$. Roughness analysis showed that increasing the inter-shot delay reduced R_a from 5.00 to $3.60 \text{ } \mu\text{m}$, which may be attributed to a reduction in thermal load and more favorable coating formation conditions. The maximum hardness, up to 905.6 HV, was obtained for a combination of parameters that promoted the formation of a dense structure and strengthening phases. The results indicate that optimizing the detonation spraying parameters requires a trade-off between reducing the coefficient of friction and increasing wear resistance. The findings can be used to develop technologies for the restoration and surface strengthening of machine components.

Keywords: self-fluxing alloys, detonation spraying, NiCrFeBSiC, heat treatment, AISI 321

Introduction

Thermal spraying is often used to extend the service life of tribomechanical systems, protecting new machine parts and restoring worn ones. This process creates surfaces with properties significantly superior to those of the base material [1]. Self-fluxing nickel-based alloys are widely used in thermal spraying technologies. These alloys are characterized by high strength and hardness, as well as excellent resistance to wear, heat, and corrosion. The presence of Cr, B, Si, and C in the structure creates hard phases dispersed in a viscous nickel matrix, which ensures good performance properties [2]. Nickel alloys with high chromium con-

tent are characterized by excellent corrosion resistance and high mechanical properties after hardening. Their corrosion resistance is ensured by a chromium oxide film formed on the alloy surface, which provides protection at elevated temperatures. These alloys are widely used in the power industry for the production of gas turbines and nuclear generators, as well as in motorsports for the manufacture of exhaust valves for racing engines, fasteners, spindles, and other components [3]. Coatings based on the Ni–Cr–Fe–B–Si–C system are widely used to improve the wear resistance of component working surfaces. NiCrFeBSiC alloys perform effectively under conditions of intense friction. Such coatings exhibit high resistance to adhesive wear and corrosion at both normal and elevated temperatures [4].

For the application of self-fluxing coatings, thermal spraying methods such as flame spraying, detonation spraying, and high-velocity oxy-fuel (HVOF) spraying can be used. However, detonation spraying offers a number of significant advantages, ensuring the formation of coatings with improved performance characteristics. Detonation spraying achieves the highest particle velocities (up to 800–1000 m/s), leading to intense plastic deformation of the particles upon impact with the substrate and the formation of a dense coating structure with minimal porosity, which is directly related to increased wear and corrosion resistance of the coatings. Furthermore, detonation spraying enables the formation of coatings with a finely dispersed structure and a uniform distribution of boride and carbide phases, which significantly increases resistance to abrasive and adhesive wear. Article [5] has shown that such structural features provide improved tribological properties compared to coatings obtained by the HVOF method. HVOF can lead to increased particle oxidation, especially when deviating from optimal spraying conditions, which negatively impacts the formation of the metal matrix and reduces the performance properties of the coating [6].

The formation of the required tribological properties of fused Ni–Cr–Fe–B–Si coatings is possible only under strictly specified heat treatment conditions (in the range of 1000–1373 K), since these alloys belong to eutectic systems and are highly sensitive to thermal exposure parameters [7, 8]. In this regard, the present work is devoted to the study and selection of optimal spraying parameters for NiCrFeBSiC coatings obtained by detonation spraying.

Experimental

Corrosion-resistant, austenitic structural steel grade AISI 321 was selected as the substrate material. This steel is often used in industry to manufacture components operating at temperatures up to 600 °C, welded equipment and vessels operating in dilute solutions of nitric, acetic, and phosphoric acids, alkaline and salt solutions, and other components operating under pressure at temperatures from –196 to +600 °C, as well as in aggressive environments. According to ASTM A240M, AISI 321 steel has the following composition (Table 1).

Table 1

Chemical composition of AISI 321 steel

C	Si	Mn	Ni	S	P	Cr	Cu	Ti	Fe
< 0.12	< 0.80	< 2	9–11	< 0.02	< 0.035	17–19	< 0.3	<1	base

A 30 mm diameter AISI 321 carbon steel rod was cut into 5 mm thick disks. The surface was mechanically processed by grinding with sandpaper of up to P400 grit. To improve the adhesion of the applied coating, the disk surface was additionally treated by abrasive blasting using fused alumina (Al_2O_3) with a particle size of 40 μm . After sandblasting, abrasive residue and dust were removed by blowing with compressed air. To remove organic and inorganic contaminants (oils, oxide films), the samples were cleaned in an ultrasonic bath using technical-grade ethanol. The ultrasonic cleaning duration was 10 minutes at a frequency of 40 kHz and a solution temperature no higher than 35 °C. Self-fluxing Ni–Cr–Fe–B–Si–C powder (produced in China) was used for spraying the coatings. This powder has a particle size of 100–150 μm , is perfectly spherical, and, as shown in Figure 1, exhibits a highly uniform element distribution. The powder composition is presented in Table 2.

Table 2

Chemical composition of Ni–Cr–Fe–B–Si–C powder

Ni	C	Cr	B	Si	Fe
Base	0.9	16–18	3.2	4	5

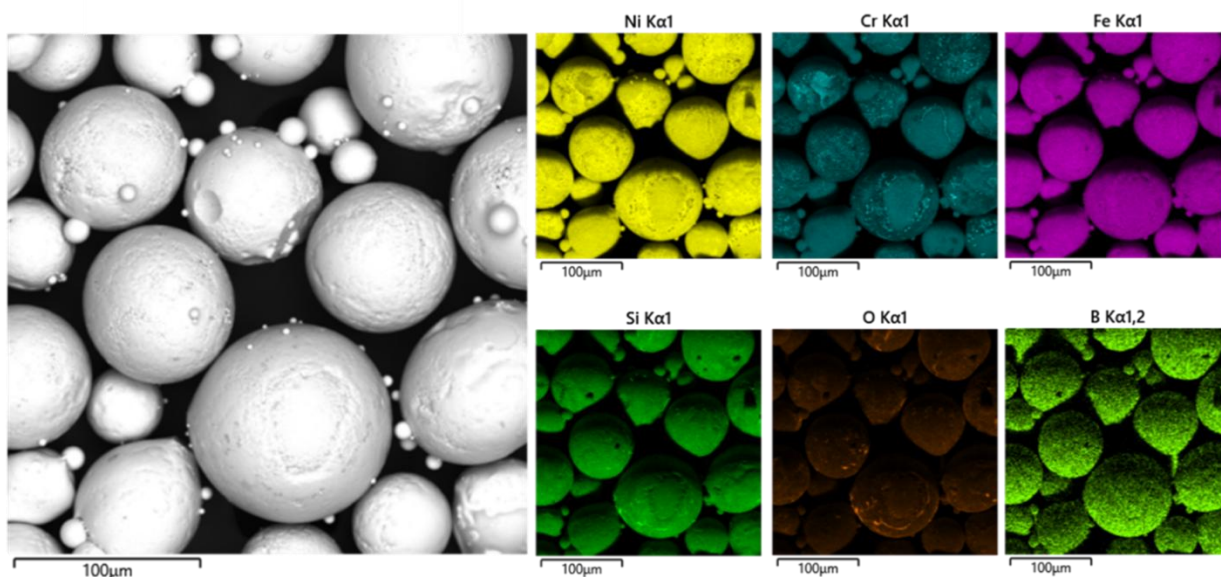


Figure 1. Morphology of Ni-Cr-Fe-B-Si-C powder

The CCDS-2000 detonation spraying system (Fig. 2) (Siberian Technologies of Protective Coatings, Novosibirsk) was used for coating production. The CCDS2000 system is designed to form high-quality coatings using detonation spraying, which is based on the cyclic combustion (detonation) of a gas mixture of fuel and oxygen in the barrel bore. The detonation generates a shock wave that accelerates powder particles. The system operates automatically and allows for precise adjustment of key process parameters, including:

- gas mixture composition and ratio;
- barrel fill level;
- interval between detonation pulses.

During spraying, powder is introduced into the detonation chamber, where it is captured by detonation products and accelerated along the barrel bore toward the substrate. Upon impact with the surface, the particles undergo intense plastic deformation, forming a dense coating with low porosity and high adhesive strength. The process is carried out in pulsed regime with a frequency of several shots per second, which ensures controlled heat input into the substrate and minimizes its thermal deformation.

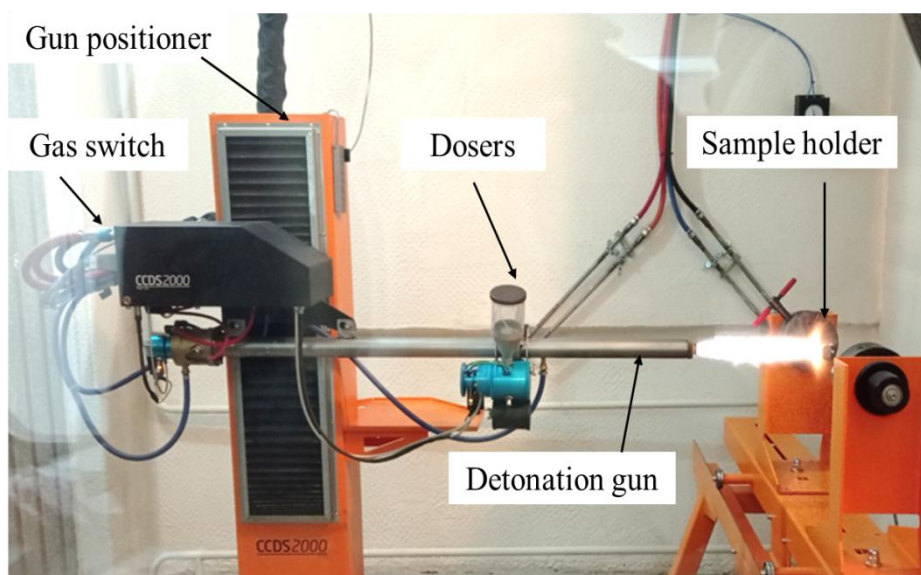


Figure 2. General view of the CCDS-2000 detonation spraying system

The coating morphology was examined using a SEM 3200 scanning electron microscope (China) equipped with an electron probe attachment for localized microanalysis and an EDS energy-dispersive spectrometer (BRUKER).

Tribological testing of the coatings was conducted using a ball-on-disk setup (Fig. 3) on an Anton Paar TRB3 tribometer (Austria). A 6 mm diameter 100Cr6 steel ball served as the counterweight. The load was 10 N, the rotation speed was 5 cm/s, the radius of curvature was 2 mm, and the friction path length was 100 m.

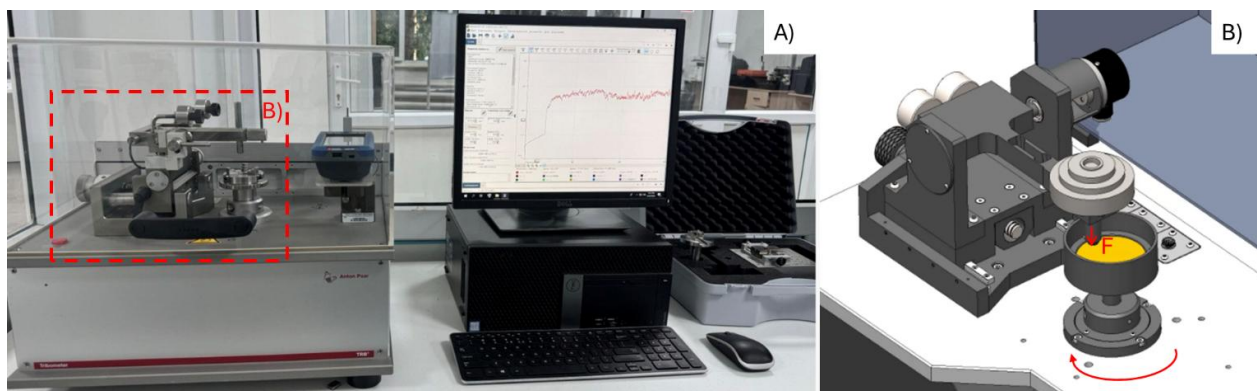


Figure 3. a) General view of the TRB3 tribometer; b) Ball-on-disk test setup.

Coating hardness under various spraying conditions was measured using a Metolab 502 hardness tester (Russia) operating using the Vickers method in accordance with GOST 6507-1-2007, with a load of 0.1 kg and a hold time of 10 seconds.

Coating surface roughness was assessed using a contact profilometer. Measurements were performed by tracing a diamond stylus across the sample surface, followed by recording the roughness profile. The primary roughness parameter was the arithmetic mean deviation of the profile (R_a), which characterizes the average roughness height relative to the profile centerline. Measurements were conducted with a constant baseline length, followed by processing of the resulting profilograms. To enhance the reliability of the results, at least three measurements were taken for each sample in different surface areas, after which the mean values and standard deviation were calculated.

Results and Discussion

In order to select the optimal spraying regime for self-fluxing coatings using the detonation spraying method, the following parameters were varied: the volume of the barrel filled with a gas mixture (Table 3.1), the molar ratio of the working gases (Table 3.2), and the delay between shots (Table 3.3).

Table 3.1

Selecting the process parameter: barrel fill volume with gas mixture

Barrel fill volume with gas mixture	48 %	58 %	68 %
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Table 3.2

Selection of the process parameter: molar ratio of working gases

Molar ratio of working gases (O/C)	1.026	1.856
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Table 3.3

Selection of the process parameter: delay between shots

Delay between shots	no delay	0.25 s	0.5 s	0.75 s	1 s
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The process parameters for detonation spraying were selected to determine their impact on the structure formation and performance properties of Ni–Cr–Fe–B–Si–C coatings. The key variable parameters were: the barrel fill rate, the molar ratio of the working gases, and the delay between detonation pulses.

The barrel fill rate range (48–68 %) was selected based on the need to ensure a stable detonation process. The molar ratio of the working gases ($O/C = 1.026\text{--}1.856$) was varied to control the temperature and energy conditions of the process. Values close to stoichiometric ensure maximum temperature and velocity of the detonation products, while deviations from stoichiometry allow for control of the degree of heating and oxidation of the particles. This is especially important when spraying self-fluxing alloys, which are sensitive to overheating and changes in chemical composition. The delay time between shots (0–1 s) was selected taking into account the need to control heat transfer to the substrate. Increasing the interval between shots can promote temperature stabilization and improve coating formation conditions.

Thus, the selected ranges of process parameters allow for a comprehensive assessment of the influence of the energy and thermal conditions of detonation spraying on the morphology, structure, and properties of the coatings.

The cross-sectional morphology of Ni–Cr–Fe–B–Si–C coatings obtained at various degrees of barrel filling with the gas mixture during detonation spraying is shown in Figure 4. The morphology of the coatings on the surface of Ni–Cr–Fe–B–Si–C samples was described in a previous study [9].

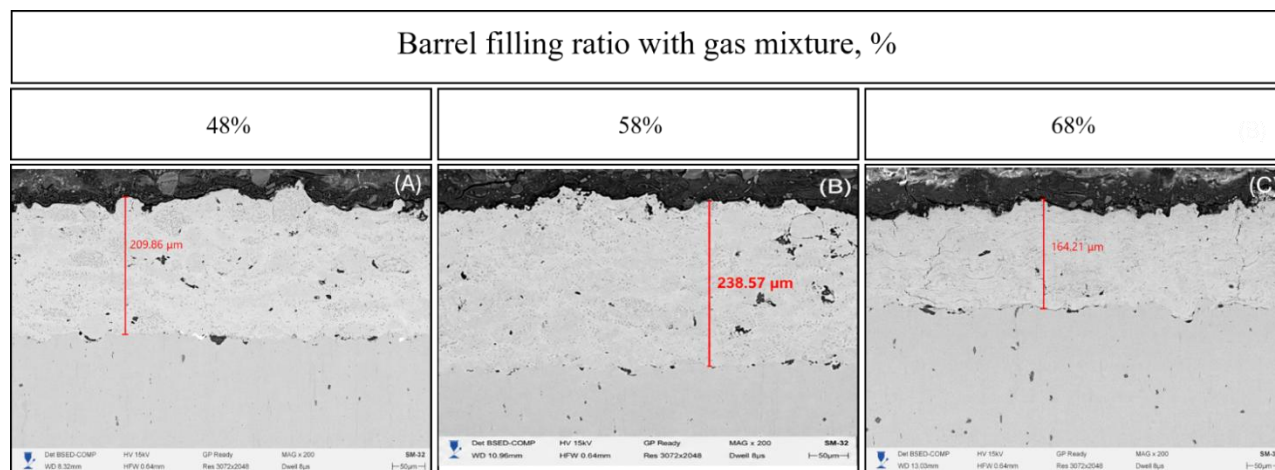


Figure 4. Coating thickness at different barrel fill rates with explosive mixture:

(a) fill rate — 48 %, (b) fill rate — 58 %, (c) fill rate — 68 %

Microstructure analysis revealed that at low fill rates (Fig. 4a), the coating structure develops a more uniform and dense structure with fewer pores. The reduced defect rate may be due to more stable deposition conditions and improved particle coalescence. At medium fill rates (Fig. 4b), despite the increased coating thickness, microcracks are observed, likely due to increased residual stresses arising from the high kinetic energy of the particles and rapid cooling. At higher barrel fill rates (Fig. 4c), cracks are also observed due to incomplete particle deformation upon impact with the substrate and increased microstresses. Thus, the degree of barrel filling with the gas mixture is one of the key process parameters determining the thickness, porosity, and defect level of the coatings. Optimization of this parameter ensures the formation of coatings with minimal porosity and high structural integrity.

The cross-sectional morphology of Ni–Cr–Fe–B–Si–C coatings obtained with various molar ratios of the gas mixture (propane/acetylene/oxygen) during detonation spraying is shown in Figure 5.

Analysis revealed that the resulting coatings have a layered (lamellar) structure characteristic of thermal spray methods, caused by the sequential layering of deformed particles, which is consistent with classical concepts of the coating formation mechanism [5].

The coating thickness in Figure 5a is approximately 244.12 μm , while in sample B it decreases to 180.01 μm , indicating the influence of spraying process parameters on particle deposition efficiency. As noted in [9], coating thickness is determined by particle velocity and the degree of their melting, which, in turn, depend on the energy parameters of the process. Sample A exhibits a relatively uniform structure with moderate porosity, indicating a sufficient degree of deformation and coalescence of the particles upon impact

with the substrate. According to [10], effective particle flattening facilitates the formation of dense coatings with good interlayer bonding.

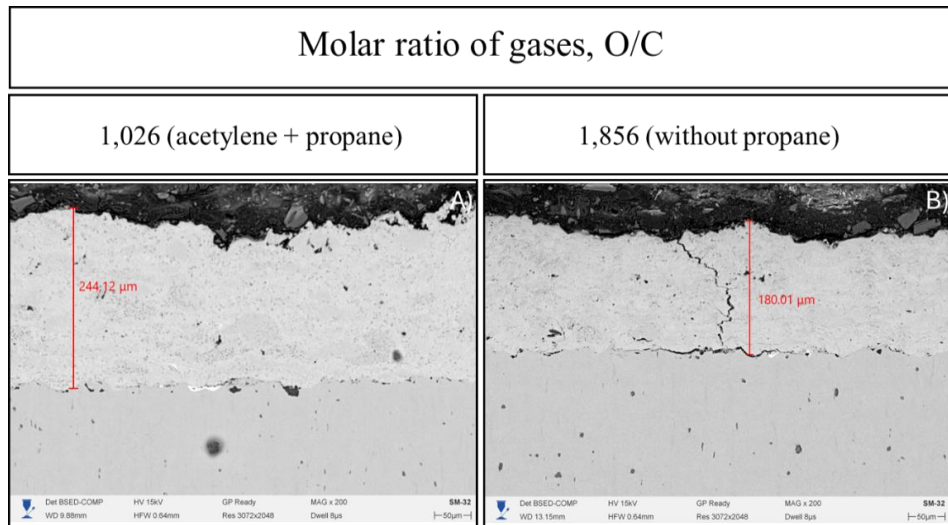


Figure 5. Coating thickness for different gas mixture molar ratios:
(a) 1.026 (oxygen/acetylene + propane mixture); (b) 1.856 (oxygen/acetylene mixture)

Figures 5b and 5c show microcracks propagating perpendicular to the surface, which may be associated with increased residual thermal stresses. As shown in [11], crack formation in thermal spray coatings is caused by rapid cooling and differences in the thermal expansion coefficients between the coating and the substrate. With insufficient propane content in the mixture (lean mixture), a decrease in the detonation temperature is observed, leading to incomplete melting of the powder particles. This results in a coating with increased porosity and insufficient interlayer bonding, as evidenced by the presence of pores and defects in the microstructural images.

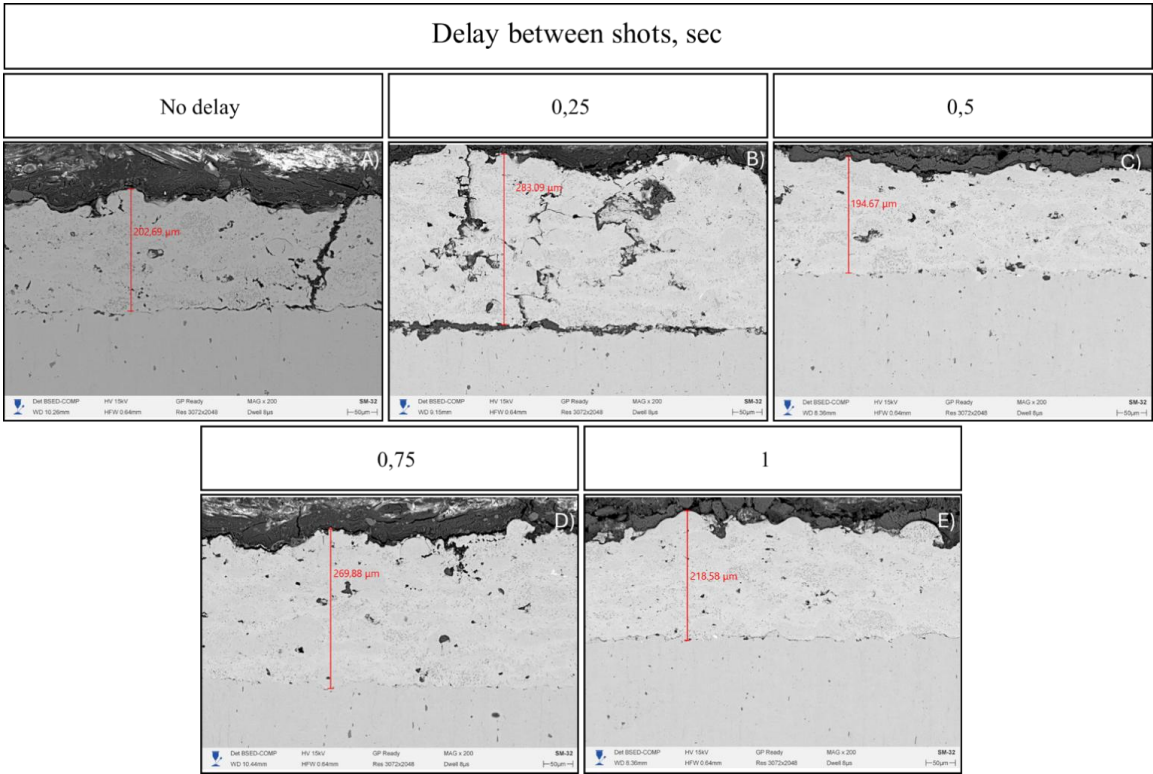


Figure 6. Coating thickness and morphology at different inter-shot delays:
(a) no delay; (b) 0.25 s; (c) 0.5 s; (d) 0.75 s; (e) 1 s

Analysis showed that changing the inter-shot delay has a significant impact on the coating thickness, structural homogeneity, and defect content. Without inter-shot delay (Fig. 6a), the coating thickness is approximately 202.69 μm . A developed network of microcracks extending from the coating surface into the coating is observed. The formation of such defects is associated with heat accumulation during continuous spraying, which leads to the development of significant residual thermal stresses due to rapid cooling (Pawlowski, 2008). With an increase in the holding time to 0.25 s (Fig. 6b), the coating thickness increases to 283.09 μm , but at the same time the maximum degree of defects is recorded, including pronounced microcracks and localized structural discontinuities. This effect can be caused by a combination of the high substrate temperature and the significant kinetic energy of the particles, which leads to an intense accumulation of stresses and a violation of the continuity of the coating. With a further increase in the holding time to 0.5 s (Fig. 6c), the coating thickness decreases to 194.67 μm , while a noticeable decrease in the number of cracks and a more uniform structure are observed. This indicates partial stabilization of the thermal regime and a decrease in the level of residual stresses [12]. With a holding time of 0.75 s (Fig. 6d), the coating thickness again increases to 269.88 μm , while the structure becomes denser and the number of defects decreases. The improved morphology is due to the optimal combination of substrate cooling between shots and maintaining sufficient particle energy for efficient deposition. The most favorable structure is observed with a delay of 1 s (Fig. 6e), where the coating thickness is approximately 218.58 μm . The coating is characterized by minimal porosity and the absence of pronounced microcracks, indicating stabilization of the deposition process and reduced thermal stress.

Thus, increasing the time between shots reduces the thermal load on the substrate and decreases residual stress, which positively impacts the integrity of the coating. However, excessively long delays can be accompanied by a decrease in coating thickness due to reduced heat accumulation and particle deposition efficiency.

Tribological tests were conducted to assess the wear resistance of the coatings. The results are presented in Figure 7. Based on the results of tribological tests with dry friction, it was found that subsequent heat treatment reduces the friction coefficient, thus thermal gas flame heating and furnace treatment reduced the friction coefficient by 6 times on average for both types of treatment.

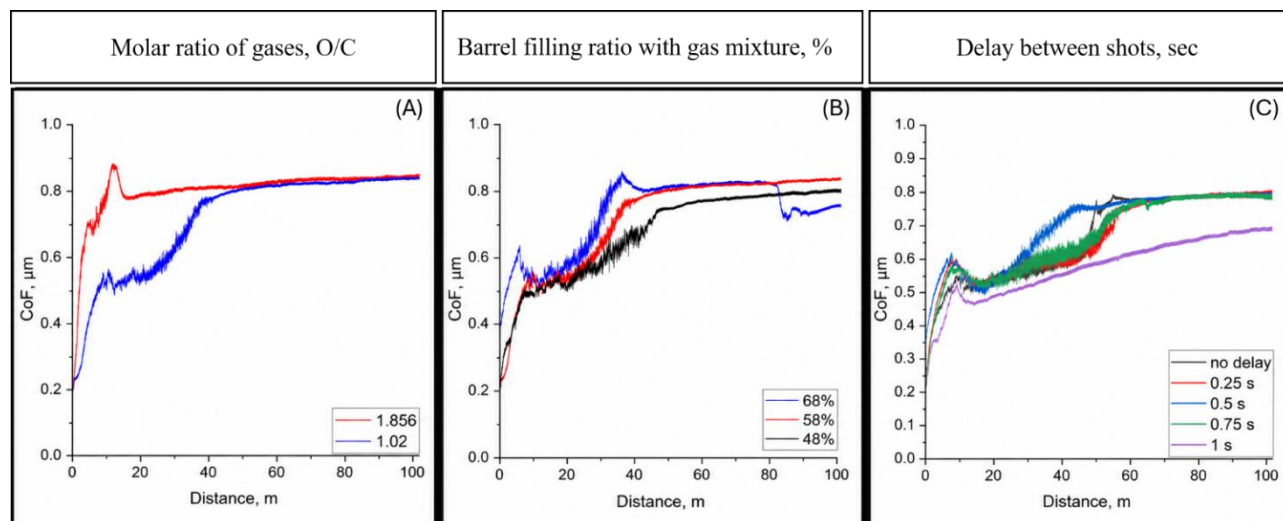


Figure 7. Graphs of the friction coefficient versus the distance for different detonation spraying process regimes

Table 4.1

Results of tribological tests of coatings with different barrel filling volumes of gas mixture

Barrel filling volume with gas mixture	48 %	58 %	68 %
Friction coefficient	0.674±0.136	0.713±0.151	0.729±0.111
Wear volume, μm^2	30852.7	36317.5	96530.7
Wear intensity, $\text{mm}^3/(\text{N}\cdot\text{m})$	0.000387	0.000456	0.001213

Table 4.2

Results of tribological tests of coatings with different molar ratios of working gases

Molar ratio of working gases (O/C)	1.026	1.856
Friction coefficient	0.713±0.151	0.799±0.076
Wear volume, μm^2	96530.7	26017.7
Wear intensity, $\text{mm}^3/(\text{N}\cdot\text{m})$	0.001213	0.000326

Table 4.3

Results of tribological tests of coatings with different delay between shots

Delay between shots	No delay	0.25 s	0.5 s	0.75 s	1 s
Friction coefficient	0.703±0.110	0.678±0.093	0.671±0.130	0.672	0.671±0.120
Wear volume, μm^2	27724.5	31779.8	28902.0	23115.9	15083.5
Wear intensity, $\text{mm}^3/(\text{N}\cdot\text{m})$	0.000348	0.000399	0.000363	0.000290	0.000189

The results of tribological tests of Ni–Cr–Fe–B–Si–C coatings (Tables 4.1–4.3) indicate a complex effect of the process parameters of detonation spraying on the friction coefficient and wear resistance. It was found that with an increase in the degree of filling of the barrel with a gas mixture from 48 to 68 %, an increase in the friction coefficient is observed from 0.674 ± 0.136 to 0.729 ± 0.111 (Fig. 7a), accompanied by a significant increase in the wear volume from 30852.7 to $96530.7 \mu\text{m}^2$ and wear intensity from 0.000387 to $0.001213 \text{ mm}^3/(\text{N}\cdot\text{m})$, which indicates a deterioration in wear resistance at high filling values due to the formation of a more defective and less stable coating structure. The effect of the gas molar ratio is opposite (Fig. 7b): at $\text{O/C} = 1.026$, a lower friction coefficient is observed (0.713 ± 0.151), wear reaches maximum values ($96530.7 \mu\text{m}^2$; $0.001213 \text{ mm}^3/(\text{N}\cdot\text{m})$), whereas at $\text{O/C} = 1.856$, a coating is formed with a higher friction coefficient (0.799 ± 0.076), but significantly lower wear ($26017.7 \mu\text{m}^2$; $0.000326 \text{ mm}^3/(\text{N}\cdot\text{m})$), which indicates the formation of a harder and more destruction-resistant structure with an increased oxygen content. When analyzing the effect of the delay between shots, it was found (Fig. 7c) that the friction coefficient changes insignificantly and is in the range of 0.671–0.703, while wear demonstrates a pronounced dependence on this parameter: an increase in the delay from none to 1 s leads to a decrease in the wear volume from 27.724.5 to 15.083.5 μm^2 and wear intensity from 0.000348 to $0.000189 \text{ mm}^3/(\text{N}\cdot\text{m})$, which is due to a decrease in thermal accumulation, a decrease in residual stresses and the formation of a denser and more uniform coating structure. Thus, it was found that a decrease in the friction coefficient is achieved with lower barrel filling values and when using a more reducing gas environment, while an increase in wear resistance is associated with an increase in the oxygen potential of the mixture and optimization of the thermal regime due to an increase in the interval between shots, which confirms the need for comprehensive optimization of the process parameters to obtain coatings with specified performance characteristics [13].

The results of the study of the dependence of the filling volume of the gas mixture and the roughness profile during detonation spraying are presented in Figure 8.

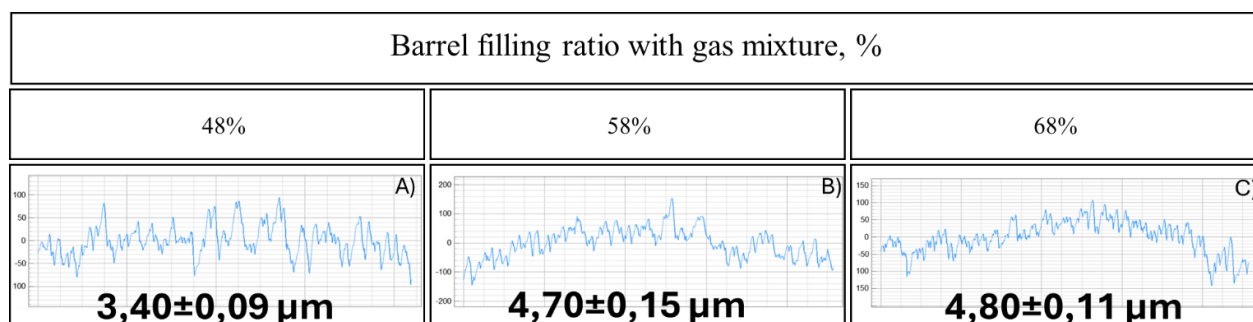


Figure 8. Surface profiles for different barrel fill volumes with explosive mixture:
 (a) fill volume — 48 %, (b) fill volume — 58 %, (c) fill volume — 68 %

It was found that at a barrel fill volume of 48 % (Fig. 8a), the average roughness value is $R_a = 3.40 \pm 0.09 \mu\text{m}$, with the profile characterized by a relatively uniform distribution of irregularities with a moderate oscillation amplitude. This surface structure indicates a sufficient degree of particle deformation and their uniform distribution over the surface. With an increase in the fill volume to 58 % (Fig. 8b), the roughness increases to $R_a = 4.70 \pm 0.15 \mu\text{m}$, while an increase in the amplitude of irregularities and a more pronounced waviness of the profiles are observed. This may be due to the increased energy of the particles and their uneven deformation upon impact, which leads to the formation of a more developed surface relief. With a further increase in fill to 68 % (Fig. 8c), the roughness reaches a maximum value of $R_a = 4.80 \pm 0.11 \mu\text{m}$. The surface profile is characterized by significant height variations and the presence of pronounced peaks and valleys, indicating the formation of a coarser and more heterogeneous coating structure. This may be due to worsening detonation conditions, partial melting of particles, and their agglomeration.

The results of studying the relationship between the molar ratio of the gas mixture and the roughness profile during detonation spraying are presented in Figure 9.

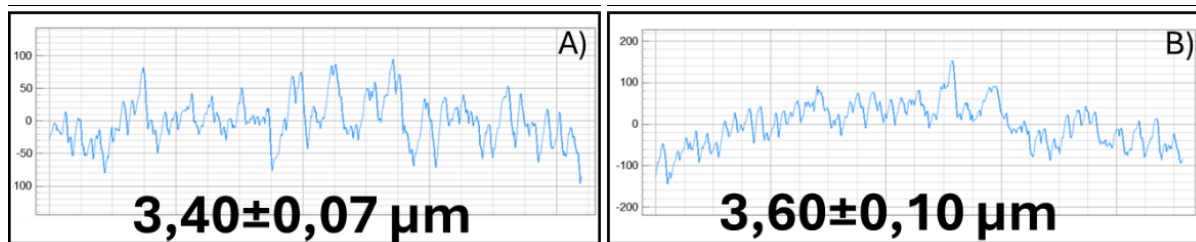


Figure 9. Coating profiles for different gas mixture molar ratios:
(a) 1.026 (oxygen/acetylene + propane mixture); (b) 1.856 (oxygen/acetylene mixture)

For sample A, the average roughness value was found to be $R_a = 3.40 \pm 0.07 \mu\text{m}$. The surface profile is characterized by a moderate oscillation amplitude and a relatively uniform distribution of irregularities, indicating a stable particle deposition process and sufficient plastic deformation upon impact with the substrate. For sample B, the roughness increases to $R_a = 3.60 \pm 0.10 \mu\text{m}$, with an increase in the profile oscillation amplitude and the appearance of more pronounced peaks and valleys. This indicates the formation of a more developed surface relief, which may be associated with changes in the energy conditions of spraying and uneven particle deformation.

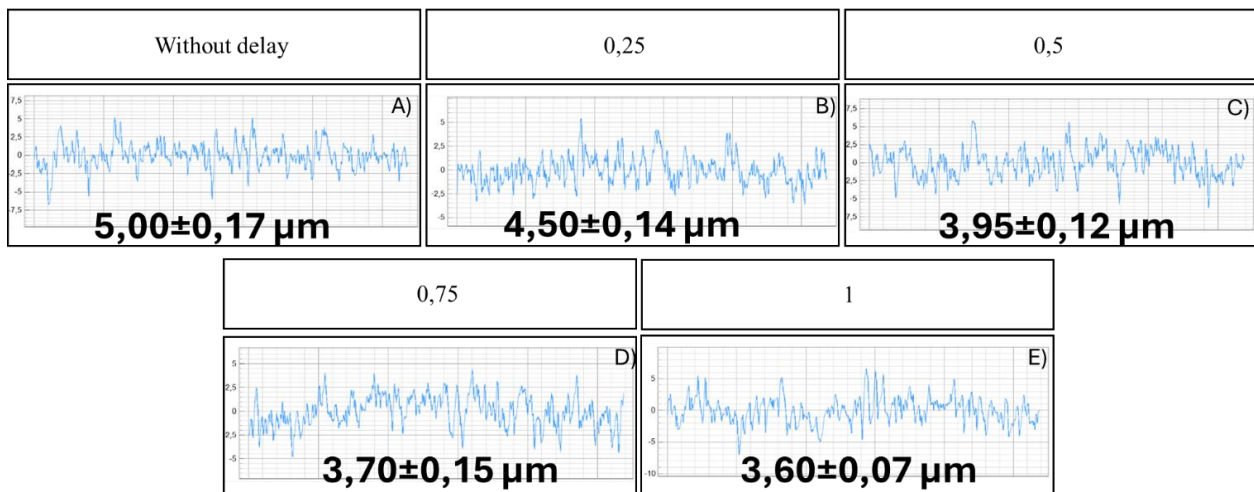


Figure 10. Coating profiles with different delays between shots:
(a) no delay (b) 0.25 s (c) 0.5 s (d) 0.75 s (e) 1 s

It was found that without a delay between shots (Fig. 10a), the roughness reaches a maximum value of $R_a = 5.00 \pm 0.17 \mu\text{m}$, with the profile characterized by significant fluctuations and the presence of pronounced peaks and valleys. This is due to surface overheating and unstable particle deposition conditions,

leading to the formation of a rough relief. With a delay of 0.25 s (Fig. 10b), a decrease in roughness to $Ra = 4.50 \pm 0.14 \mu\text{m}$ is observed, indicating partial stabilization of the thermal regime and improved conditions for coating formation. A further increase in the holding time to 0.5 s (Fig. 10c) leads to a decrease in roughness to $Ra = 3.95 \pm 0.12 \mu\text{m}$, while the profile becomes more uniform, and the amplitude of the irregularities decreases. With a holding time of 0.75 s (Fig. 10d), the roughness continues to decrease to $Ra = 3.70 \pm 0.15 \mu\text{m}$, which indicates the formation of a denser and more uniform coating structure. The minimum roughness value is achieved with a holding time of 1 s (Fig. 10e) and is $Ra = 3.60 \pm 0.07 \mu\text{m}$. The surface is characterized by the smallest oscillation amplitude and the most uniform distribution of irregularities, which indicates stabilization of the spraying process and optimal thermal conditions [14].

Thus, increasing the delay between shots leads to a systematic decrease in surface roughness, which is due to a decrease in thermal accumulation, a decrease in residual stresses and an improvement in the conditions for deformation and coalescence of particles upon impact with the substrate.

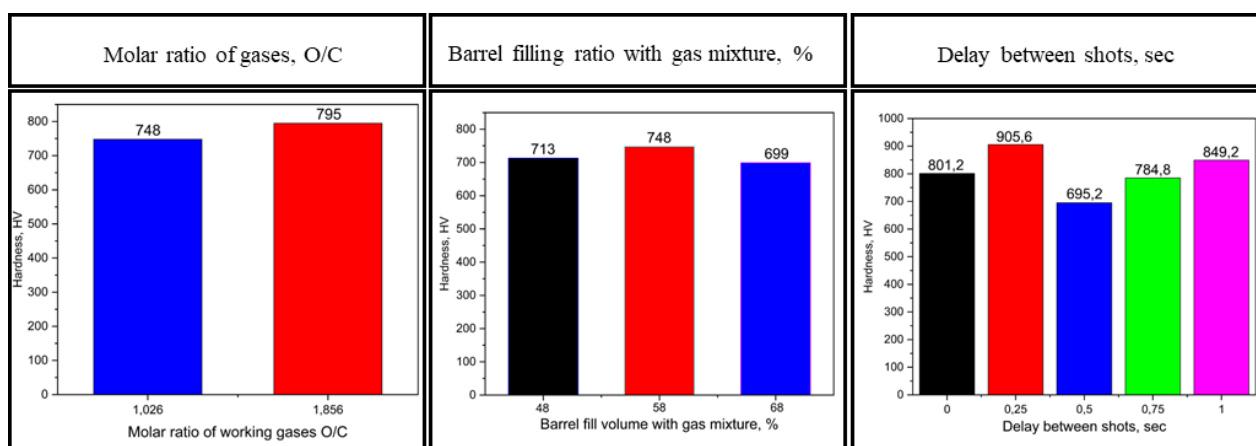


Figure 11. Coating hardness measurement results for various detonation spraying process regimes

The microhardness measurements for Ni–Cr–Fe–B–Si–C coatings (Fig. 11) showed a pronounced dependence of this parameter on the detonation spraying process regimes. It was found that with a change in the gas molar ratio, the hardness increased from 748 HV at O/C = 1.026 to 795 HV at O/C = 1.856, indicating the formation of a denser and more reinforced coating structure at a higher oxygen content due to the higher process temperature and improved particle melting. An analysis of the barrel fill factor influence revealed that the maximum hardness value (748 HV) is achieved at 58 %, whereas a decrease and increase in fill to 48 % and 68 % results in a decrease in hardness to 713 HV and 699 HV, respectively. This may be due to the fact that an average fill factor provides optimal conditions for particle acceleration and deformation, ensuring the formation of a dense structure, whereas deviations from the optimum lead to increased porosity and coating heterogeneity. The most significant influence is exerted by the delay between shots: an increase in the interval from 0 to 0.25 s leads to an increase in hardness from 801.2 to 905.6 HV, after which a decrease to 695.2 HV is observed at 0.5 s, and a further increase in delay to 0.75–1 s leads to a repeated increase in hardness to 784.8–849.2 HV. This nature of the change is explained by the complex influence of the thermal regime: with a short delay, heat accumulation and partial softening of the structure occur, whereas with an optimal delay, effective cooling and the formation of hardening phases (borides and carbides) are ensured, increasing the hardness of the coating [15]. Thus, maximum hardness values are achieved with an increased oxygen ratio, an average barrel filling level, and an optimal delay between shots, which confirms the decisive role of energy and thermal process parameters in the formation of the mechanical properties of coatings.

Conclusion

The study found that detonation spraying process parameters have a decisive influence on the morphology, structure, and performance properties of Ni–Cr–Fe–B–Si–C coatings.

It was shown that the degree of filling of the barrel with the gas mixture significantly influences coating formation: at 48 %, the most uniform structure with minimal porosity is formed, while at 58–68 %, defects increase and an increase in the friction coefficient and wear is observed.

It was found that the gas molar ratio determines the balance between the friction coefficient and wear resistance. At $O/C = 1.026$, the friction coefficient is minimal, but wear intensity increases, while at $O/C = 1.856$, a harder and more wear-resistant coating structure is formed.

The delay between shots is a key parameter regulating the thermal regime of the process. Increasing the interval to 1 s leads to a reduction in roughness, a decrease in residual stresses, and a nearly twofold reduction in wear intensity, due to the formation of a denser and more uniform structure.

It has been shown that maximum coating hardness is achieved with an optimal combination of parameters, ensuring efficient particle melting and the formation of strengthening phases (borides and carbides).

Thus, it has been established that producing coatings with desired tribological characteristics requires comprehensive optimization of the energy and thermal parameters of detonation spraying. Optimal conditions ensure the formation of coatings with high structural integrity, reduced roughness, and increased wear resistance, making them promising for the restoration and strengthening of mechanical engineering components.

Acknowledgments

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Никель негізіндегі өздігінен балқитын жабындарды детонациялық бүрку әдісімен алу негіздерін әзірлеу

Мақалада Ni–Cr–Fe–B–Si–C жүйесіндегі өздігінен балқитын жабындардың құрылымы мен трибомеханикалық қасиеттеріне детонациялық бүркудің технологиялық параметрлерінің әсері зерттелді. Айнымалы параметрлер ретінде газ қоспасымен оқпанның толтырылу көлемі (48–68 %), жұмыс газдарының молярлық қатынасы ($O/C = 1,026\text{--}1,856$) және атулар арасындағы уақыт (0–1 с) қарастырылды. Жабындардың морфологиялық талдауы жүргізіліп, нәтижесінде ламеллярлы құрылымның қалыптасатыны анықталды, сондай-ақ жабын қалыңдығымен ақаулылығының бүрку режимдеріне тәуелділігі көрсетілді. Оқпанның төмен толтырылу деңгейінде минималды кеуектілігі бар тығыз құрылым қалыптасатыны, ал орташа және жоғары толтыру кезінде қалдық кернеулердің артуына байланысты микрожарықшақтардың пайда болатыны анықталды. Трибологиялық сынақтар нәтижесінде ең төмен үйкеліс коэффициенті 48 % толтыру кезінде ($\mu = 0,674 \pm 0,136$) және $O/C = 1,026$ қатынасында байқалатыны анықталды, алайда бұл жағдайда тозу жоғары болады. Ең жоғары тозуға төзімділік $O/C = 1,856$ және атулар арасындағы уақыт аралығын (1 с дейін) арттыру кезінде қамтамасыз етіледі, бұл кезде тозу қарқындылығы $0,000189 \text{ мм}^3/(\text{Н} \cdot \text{м})$ дейін төмендейді. Беткі кедір-бұдырлықты талдау атулар арасындағы уақыт аралығының ұлғаюы Ra мәнінің 5,00-ден 3,60 мкм-ге дейін төмендеуіне әкелетінін көрсетті. Максималды қаттылық (905,6 HV дейін) тығыз құрылыммен беріктендіруші фазалардың қалыптасуын қамтамасыз ететін параметрлердің оңтайлы үйлесімі кезінде байқалады. Детонациялық бүрку параметрлерін оңтайландыру үйкеліс коэффициентін төмендетумен тозуға төзімділікті арттыру арасындағы компромисті талап ететіні көрсетілді. Алынған нәтижелер машина бөлшектерін қалпына келтіру және беріктендіру технологияларын әзірлеуде қолданылуы мүмкін.

Кілт сөздер: өздігінен ағатын қорытпалар, детонациялық бүрку, никель қорытпалары, NiCrFeBSi, жылулық өңдеу, AISI 321 болат

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Разработка метода получения самофлюсующихся покрытий на основе никеля методом детонационного напыления

В работе исследовано влияние технологических параметров детонационного напыления на структуру и трибомеханические свойства самофлюсующихся покрытий системы Ni–Cr–Fe–B–Si–C. В качестве варьируемых параметров рассматривались объём заполнения ствола газовой смесью (48–68 %), молярное соотношение рабочих газов ($O/C = 1,026\text{--}1,856$) и выдержка между выстрелами (0–1 с). Проведён морфологический анализ покрытий, показавший формирование характерной ламеллярной структуры, а также выявивший зависимость толщины и дефектности от режимов напыления. Установлено, что при низком заполнении ствола формируется более плотная структура с минимальной пористостью, тогда как при среднем и высоком заполнении наблюдается образование микротрещин вследствие роста остаточных напряжений. Трибологические испытания показали, что минимальный коэффициент трения достигается при заполнении 48 % ($\mu = 0,674 \pm 0,136$) и соотношении $O/C = 1,026$, однако при этом наблюдается повышенный износ. Наиболее высокая износостойкость обеспечивается при $O/C = 1,856$ и увеличенной выдержке между выстрелами (до 1 с), при которой интенсивность износа снижается до $0,000189 \text{ мм}^3/(\text{Н} \cdot \text{м})$. Анализ шероховатости показал, что увеличение выдержки между выстрелами приводит к снижению Ra с 5,00 до 3,60 мкм, что связано с уменьшением тепловой нагрузки и улучшением условий формирования покрытия. Максимальная твёрдость (до 905,6 HV) достигается при оптимальном сочетании параметров, обеспечивающем формирование плотной структуры и упрочняющих фаз. Показано, что оптимизация параметров детонационного напыления требует компромисса между снижением коэффициента трения и повышением износостойкости. Полученные результаты могут быть использованы при разработке технологий восстановления и упрочнения деталей машин.

Ключевые слова: самофлюсующиеся сплавы, детонационное напыление, никелевые сплавы, NiCrFeBSi, термическая обработка, сталь AISI 321

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