ORIGINAL STUDY

DEVELOPMENT AND CHARACTERIZATION OF WEAR-RESISTANT AL$_2$O$_3$-BASED COATINGS PRODUCED BY DETONATION SPRAYING

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Abstract. *In this study, Al_2O_3-based oxide coatings were deposited on 10Kh18N9 austenitic stainless steel using the detonation spraying method, and their structural, mechanical, corrosion, and tribological properties were investigated. The effect of barrel filling levels (53%, 58%, and 63%) on coating formation was examined. Phase analysis revealed that the α-Al_2O_3 phase was predominant under all spraying conditions, accounting for 77–80% of the coating composition. The highest microhardness was achieved at a barrel filling level of 58%, with a microhardness of 1362.3 HV and an elastic modulus of 190.0 GPa. Corrosion tests demonstrated that the coatings reduced the corrosion current density by up to two times compared with the untreated steel substrate, while the highest corrosion resistance was observed at a filling level of 63% (Icorr = 0.00725 A/cm^2). Tribological tests showed that the wear rate against a ZrO_2 counterbody was significantly lower than that against a 100Cr6 steel counterbody.*

Keywords: detonation spraying technology, aluminum oxide coating, wear-resistant coating, microhardness, corrosion resistance.

1. Introduction

At present, the intensive wear of pump equipment components operating in aggressive environments, such as abrasive and corrosive media, remains one of the most pressing engineering challenges. Such pumps are widely used for transporting hot and cold water, wastewater, slurries, and aggressive chemical solutions [1]. During operation, the most vulnerable components – including pump impellers, covers, and volute casings—are exposed to severe mechanical and chemical воздействия, resulting in significant material degradation and wear [2]. These components are commonly manufactured from 10Kh18N9 austenitic stainless steel. Although this material exhibits excellent corrosion resistance, its resistance to abrasive wear is relatively limited [3]. As a consequence, premature failure of pump components may occur, leading to reduced equipment reliability and shortened service life [4]. To address this issue, protective coatings with enhanced wear and corrosion resistance can be applied to the surfaces of pump components. Such coatings serve to mitigate the destructive effects of aggressive reagents and abrasive particles, thereby improving the durability and operational performance of the equipment [5–6].

Protective coatings based on aluminum oxide (Al_2O_3) are among the most widely used ceramic materials in industry due to their high hardness, chemical inertness, excellent wear resistance, and high melting point [7]. Owing to their outstanding chemical stability, Al_2O_3 coatings are extensively applied in acid-resistant pump impellers, pump casings, linings of acid-transport pipelines, and valves [8]. Al_2O_3 coatings produced by thermal spraying techniques are also widely utilized in various industrial sectors, including aerospace components, construction structures, and electrical and electronic applications [9].

At present, various thermal spraying technologies are widely employed for the production of wear- and corrosion-resistant coatings, including flame spraying using powder or wire feedstock, detonation spraying (DS), high-velocity oxy-fuel spraying (HVOF), and atmospheric plasma spraying (APS) [10–11]. Among these methods, APS is the most commonly used industrial technique for depositing Al_2O_3 ceramic coatings.

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However, due to the relatively low particle velocity achieved during atmospheric plasma spraying, the resulting coatings often exhibit high porosity. In addition, the elevated temperatures required to melt the particles promote the transformation of the initial α-Al_2O_3 powder into the thermodynamically metastable γ-Al_2O_3 phase. As a result, coating porosity typically remains within the range of 5–15%, leading to a deterioration of mechanical properties [12–13]. Among the thermal spraying technologies mentioned above, detonation spraying (DS) offers several advantages compared with alternative techniques such as high-velocity oxy-fuel spraying (HVOF) [14]. In the DS process, particles are accelerated by a detonation wave and impact the substrate surface at velocities of 800–1200 m/s. Upon collision with the metallic substrate, the particles form an exceptionally strong mechanical bond. Studies have confirmed that Al_2O_3 coatings produced by detonation spraying exhibit an adhesive strength exceeding 50 MPa and a porosity level of approximately 0.8% [15]. The high pressure generated during detonation, combined with rapid solidification, results in the formation of a highly dense coating layer. Consequently, detonation spraying enables the production of homogeneous coatings with porosity as low as 0.3% and strong adhesion to the substrate material [16].

Several studies on Al_2O_3 coatings produced by detonation spraying have previously been reported. In the work of Kantay et al., Al_2O_3 coatings were deposited on 12Kh18N10T stainless steel using detonation spraying with barrel filling levels ranging from 53% to 68%, and the influence of barrel filling on the phase composition and tribological properties of the coatings was investigated [17]. The authors found that the coating produced at a 53% filling level exhibited the highest wear resistance and concluded that an increase in the α-Al_2O_3 phase fraction led to enhanced hardness and wear resistance [18]. However, the corrosion resistance and adhesive strength of the coatings were not comprehensively evaluated in that study. In another study, Rakhadiov et al. produced gradient Al_2O_3 coatings by varying the barrel filling level with explosive gases to 53%, 56%, and 63%. It was established that coatings deposited at a 56% filling level were predominantly composed of the α-Al_2O_3 phase, whereas coatings produced at a 63% filling level were dominated by the γ-Al_2O_3 phase [19]. Nevertheless, corrosion testing and electrochemical characterization were not thoroughly investigated in this work either. Korobov et al. compared coatings with predominantly α-Al_2O_3 and γ-Al_2O_3 phase compositions. The researchers examined the possibility of increasing the α-phase content by adjusting the acetylene-to-oxygen ratio in the explosive gas mixture. However, they noted the limited availability of data on detonation-sprayed coatings in which α-Al_2O_3 is retained as the dominant phase [20]. Based on the analysis of the aforementioned studies, it can be concluded that the tribological performance and electrochemical corrosion resistance of Al_2O_3 coatings produced by detonation spraying under different barrel filling conditions have not yet been comprehensively evaluated.

Accordingly, the aim of this study was to deposit Al_2O_3 coatings on the surface of 10Kh18N9 austenitic stainless steel using the detonation spraying technique and to evaluate their wear and corrosion resistance.

2. Materials and methods

Austenitic stainless steel of grade 10Kh18N9 was selected as the substrate material for coating deposition. The chemical composition of the steel (wt.%) was as follows: chromium 17–18%; nickel 8–10%; carbon not more than 0.12%; manganese up to 2.0%; silicon up to 1.0%; and iron as the balance. The specimens were prepared in the form of discs with a diameter of 22 mm and a thickness of 5 mm. Prior to coating deposition, the 10Kh18N9 steel specimens underwent preliminary mechanical surface preparation. Specifically, the surfaces were subjected to grinding and polishing treatments. Subsequently, the specimens were grit-blasted to enhance surface roughness and improve coating adhesion. Al_2O_3 coatings were deposited using a CCDS2000 detonation spraying system. A general view of the installation is presented in Fig. 1.

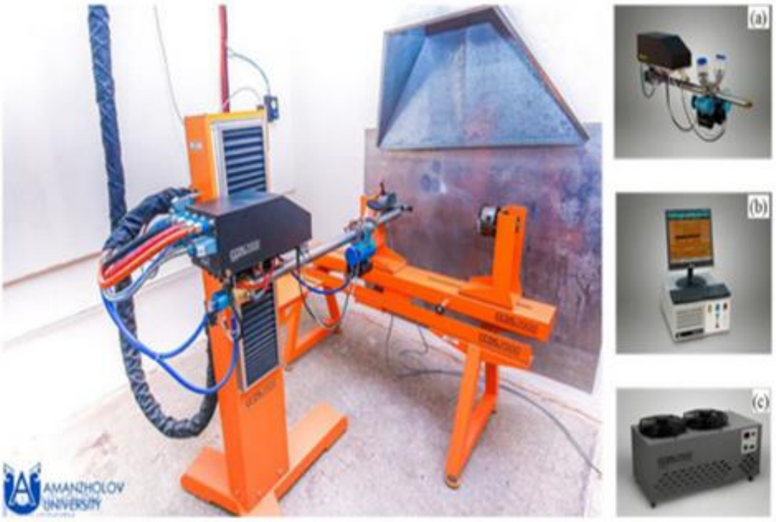


Fig. 1. CCDS2000 computerized detonation complex: (a) detonation barrel, (b) control unit, and (c) cooling system.

The experimental work was carried out under three different regimes with barrel filling levels of explosive gases set at 53%, 58%, and 63%. For each regime, 100 detonation shots were performed. The distance between the barrel exit and the substrate surface was 250 mm. A stoichiometric oxygen/acetylene (O_2/C_2H_2) mixture with a ratio of 1.856 was used as the combustible gas mixture. Table 1 presents the deposition regimes for Al_2O_3 coatings produced by the detonation spraying method. The obtained samples were designated according to the barrel filling level as Al_2O_3_53%, Al_2O_3_58%, and Al_2O_3_63%.

Table 1. Detonation spraying regimes for Al_2O_3 coatings.

Samples	**Barrel filling with explosive gas (%)**	**Number of shots**	**Distance, mm**	**O_2/C_2H_2 ratio**
A_2O_3_53%	53	100	250	1,856
A_2O_3_58%	58	100	250	1,856
A_2O_3_63%	63	100	250	1,856

To determine the phase composition of the obtained coatings, X-ray diffraction (XRD) analysis was performed. The investigations were carried out using an X'Pert Pro diffractometer (Philips Corporation, Amsterdam, The Netherlands). Measurements were conducted using Cu-Kα radiation (λ = 1.5406 Å) at an accelerating voltage of 40 kV and a tube current of 40 mA. Diffraction patterns were recorded in the angular range of 20–90° (2θ) with a step size of 0.02°. The surface morphology and cross-sectional microstructure of the coatings were examined using a SEM3200 scanning electron microscope. To determine the elemental composition and the distribution profile of elements across the coating surface, energy-dispersive X-ray spectroscopy (EDS) analysis was performed using an XFlash Detector 730M-300 system. The hardness of the samples was measured using the FISCHERSCOPE HM2000 instrumented indentation system in accordance with the international standard DIN EN ISO 14577-1. During testing, the load was gradually increased to 2000 mN over a period of 20 s. Tribological properties of the coatings were investigated using a TRB^3 tribometer (Anton Paar, Graz, Austria) in a ball-on-disk configuration. ZrO_2 and 100Cr6 steel balls with a diameter of 3.00 mm were used as counter bodies. The applied load was set to 10.00 N, and the sliding speed was 3 cm/s, with a total sliding distance of 100 m. The corrosion properties of the samples were studied using electrochemical methods with an Autolab PGSTAT204 system in an HCl solution. Corrosion parameters were determined from the obtained polarization curves using the Tafel extrapolation method.

3. Results and discussion

The X-ray diffraction (XRD) analysis results of Al_2O_3 coatings obtained by detonation spraying at barrel filling levels of 53%, 58%, and 63% are presented in Fig. 2. Analysis of the diffractograms showed that all investigated samples contain two main polymorphic modifications of aluminum oxide: α-Al_2O_3 and γ-Al_2O_3 phases. The positions of the identified diffraction peaks are consistent with the reference data from the JCPDS database. The crystalline structure of the coatings is characterized by intense reflections corresponding to the crystallographic planes of the α-Al_2O_3 phase, namely (012), (104), (110), (113), (024), (116), (018), (300), (119), and (223). In addition, the presence of the γ-Al_2O_3 phase is confirmed by diffraction peaks corresponding to the (222), (400), and (440) planes. The clear presence of these reflections indicates that the obtained coatings possess a sufficiently well-crystallized structure.

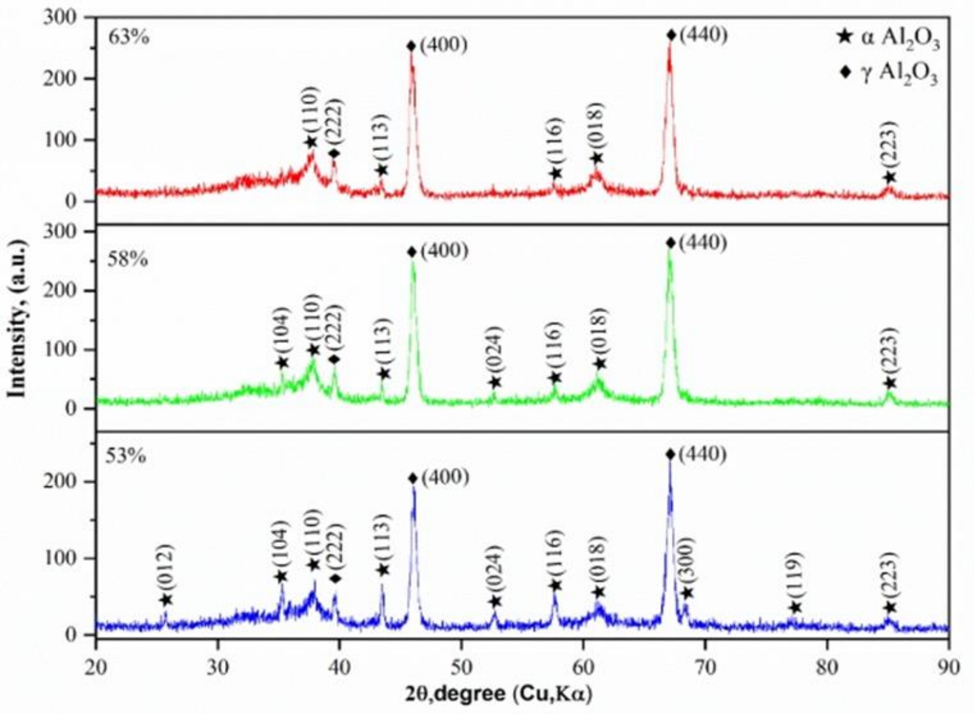


Fig. 2. X-ray diffraction patterns of Al_2O_3 coatings obtained at different detonation barrel filling levels.

According to the quantitative phase analysis results, the coatings obtained at barrel filling levels of 53%, 58%, and 63% contained 80.2%, 77.3%, and 79.1% of the α-Al_2O_3 phase, respectively. The corresponding fractions of the γ-Al_2O_3 phase were 19.8%, 22.7%, and 20.9%, respectively (Table 2). No significant differences in phase composition were observed between the investigated regimes, indicating that variations in barrel filling level do not substantially affect the phase state of aluminum oxide coatings. In all cases, α-Al_2O_3 remained the dominant phase. Such behavior can be explained by the high-temperature conditions generated during the detonation spraying process and the intensive heating of powder particles, which promote the stabilization of the α-Al_2O_3 phase.

Table 2. Phase composition of α-Al_2O_3 and γ-Al_2O_3 at different detonation barrel filling levels.

Samples	**α-A_2O_3, %**	**γ-A_2O_3, %**
A_2O_3_53%	80,2	19,8
A_2O_3_58%	77,3	22,7
A_2O_3_63%	79,1	20,9

The analysis of the elemental line distribution of Al_2O_3 coatings (Fig. 3) revealed the formation of two distinct regions corresponding to the coating and the substrate in all investigated samples. For coatings obtained at barrel filling levels of 53%, 58%, and 63%, the concentrations of aluminum and oxygen were uniformly distributed across the coating thickness. At the coating – substrate interface, the intensities of Al and O sharply decreased, while the content of Fe, Cr, and Mn – main elements of the 10Kh18N9 steel substrate – increased significantly. The clearly defined transition zone indicates a high coating density and good adhesion between the coating and the substrate. The elemental distribution profiles of samples produced at 58% and 63% barrel filling levels appeared more homogeneous compared with those obtained at 53%. This suggests that an increase in barrel filling level leads to a higher degree of particle melting during spraying and improves coating homogeneity. In addition, the coating thickness was found to depend on the barrel filling level: 188.1 ± 15.1 µm for the 53% regime, 502.7 ± 25.1 µm for the 58% regime, and 370.5 ± 11.1 µm for the 63% regime. The maximum coating thickness was observed at 58% filling. The reduction in thickness at the 63% filling level, despite the increased powder feed, may be explained by partial particle loss due to splashing during spraying and incomplete participation in coating formation. As a result, the coating growth rate decreases, leading to a reduced final thickness.

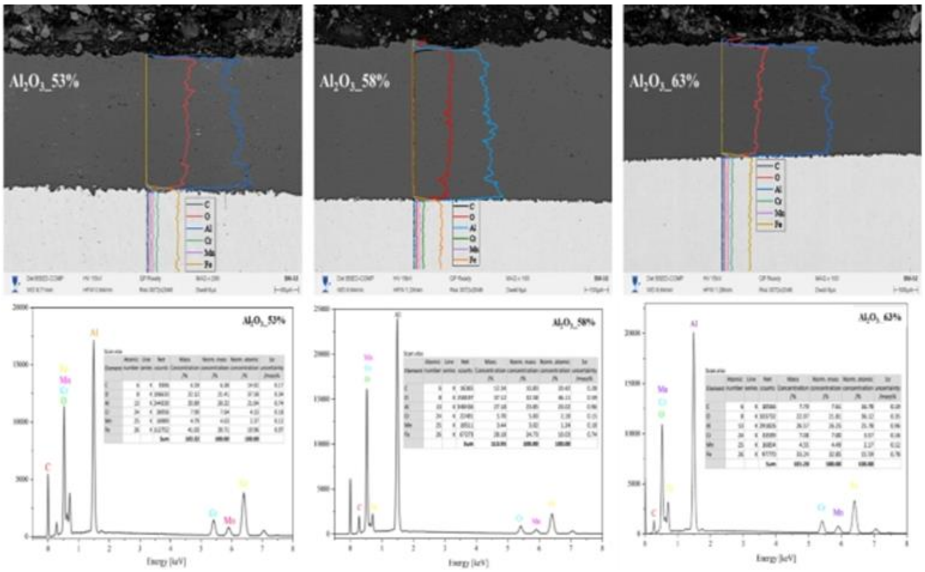
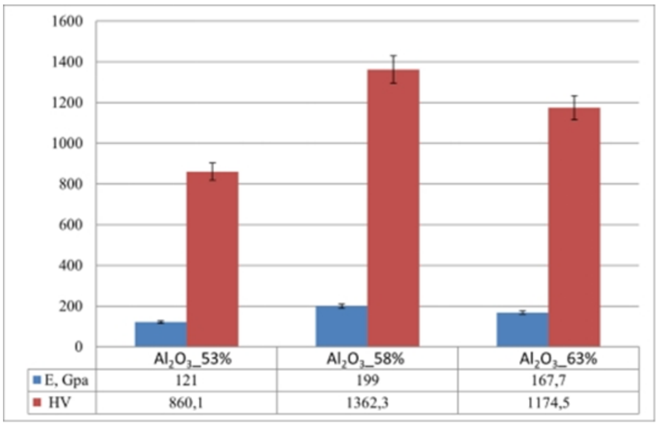


Fig. 3. Microstructure of Al_2O_3 coatings obtained at different detonation barrel filling levels.

Mechanical testing results demonstrated that the coating properties strongly depend on the spraying regime (Fig. 4). At a barrel filling level of 53%, the coatings exhibited a Young's modulus of 121.0 GPa and a hardness of 860.1 HV. The highest values were recorded for the 58% barrel filling regime, where the Young's modulus reached 190.0 GPa and the hardness increased to 1362.3 HV. This improvement is associated with the formation of a denser and more homogeneous coating structure. In contrast, at a 63% barrel filling level, both the Young's modulus and hardness decreased to 167.7 GPa and 1174.5 HV, respectively. This reduction can be explained by a decrease in coating density caused by particle splashing and partial loss of material during deposition.



	Al$_2$O$_3$_53%	Al$_2$O$_3$_58%	Al$_2$O$_3$_63%
🟦 E, Gpa	121	199	167,7
🟥 HV	860,1	1362,3	1174,5

Fig. 4. Microhardness and Young's modulus of Al_2O_3 coatings obtained at different detonation barrel filling levels.

The corrosion test results (Fig. 5) demonstrated that the obtained coatings significantly improve corrosion resistance compared with the initial 10Kh18N9 stainless steel substrate. The corrosion current density (Icorr) for the uncoated steel was 0.01343 A/cm², whereas for the coatings produced at barrel filling levels of 53%, 58%, and 63%, this value decreased to 0.01210 A/cm², 0.00873 A/cm², and 0.00725 A/cm², respectively. The reduction in Icorr indicates a slowdown of the electrochemical corrosion process and an enhancement of the protective properties of the coatings. A similar trend was observed for the calculated corrosion current density values, which decreased by approximately two times when transitioning from the uncoated substrate to the coating obtained at 63% barrel filling. In addition, the corrosion rate (CR) also decreased gradually: for the uncoated steel, the value was 2.08×10^{-4} mm/year, while for coatings produced at 53%, 58%, and 63% barrel filling levels, it decreased to 1.88×10^{-4} mm/year, 1.35×10^{-4} mm/year, and 1.12×10^{-4} mm/year, respectively. These results confirm that the coatings provide effective protection against aggressive environments and significantly reduce the intensity of corrosion damage.

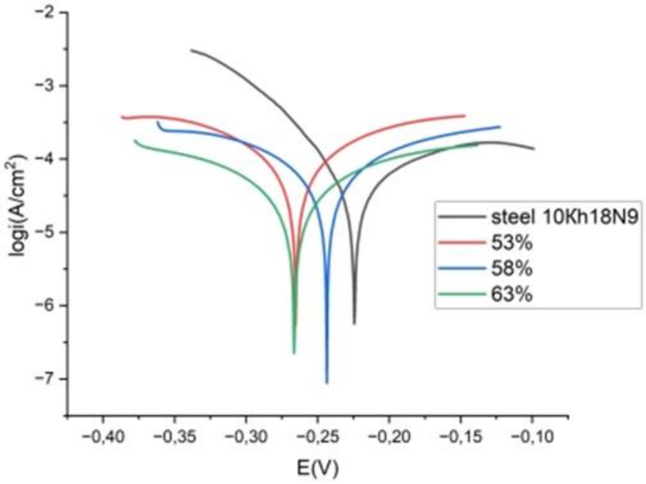


Fig. 5. Potentiodynamic polarization test results of Al_2O_3 coatings obtained at different detonation barrel filling levels.

Tribological test results demonstrated that the wear behavior of the coatings strongly depends on the counter-body material used. During interaction with the ZrO_2 counter-body, all investigated samples exhibited relatively low wear intensity (Fig. 6), characterized by small cross-sectional areas of the wear tracks. For coatings obtained at barrel filling levels of 53%, 58%, and 63%, the wear track areas were 3421.1 µm², 4407.1 µm², and 6377.0 µm², respectively. The coefficient of friction remained stable within the range of 0.55–0.60, with no significant fluctuations observed during the tests. Analysis of the wear track microrelief revealed a relatively smooth profile with a limited number of abrasive grooves. This indicates a low degree of surface damage and confirms that the coatings maintain a high level of wear resistance during contact with the ZrO_2 counter-body.

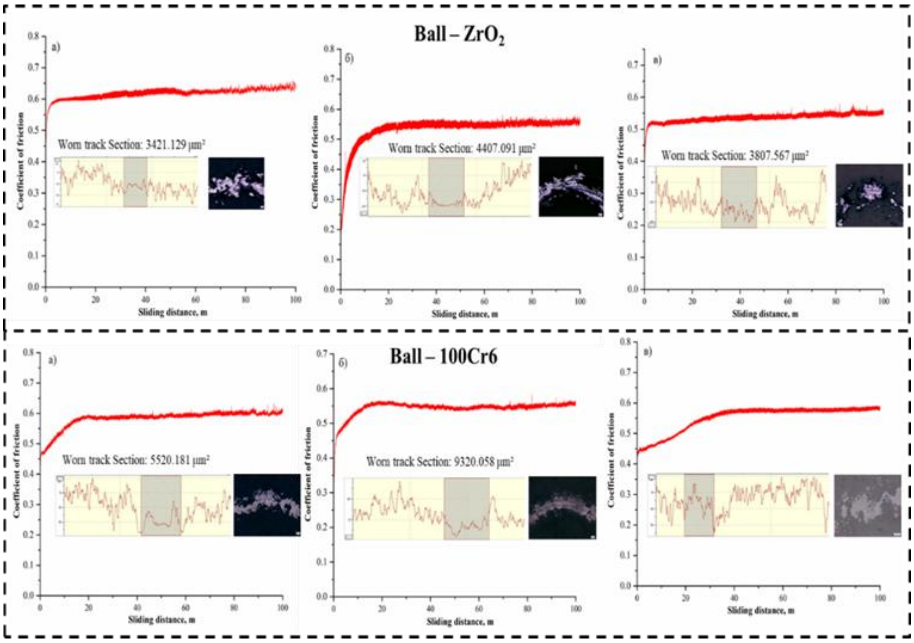


Fig. 6. Friction coefficient curves and wear track profiles of Al_2O_3 coatings tested with ZrO_2 and 100Cr6 counter-bodies: (a) Al_2O_3_53%, (b) Al_2O_3_58%, (c) Al_2O_3_63%.

It was found that, compared with the ZrO_2 counterbody, the use of a 100Cr6 steel counterbody leads to a significant increase in the wear intensity of the coatings and higher material loss (Fig. 7). The cross-sectional areas of the wear tracks for the samples obtained at detonation barrel filling levels of 53%, 58%, and 63% with explosive gas were 5520.2 µm², 9320.1 µm², and 6377.0 µm², respectively, which are considerably higher than the values obtained when using the zirconium oxide counterbody. The coefficient of friction stabilized in the range of 0.55-0.65 and was characterized by pronounced fluctuations during the test. Analysis of the microprofiles of the wear tracks revealed features typical of microplastic deformation, abrasive microcutting, and local spalling mechanisms. These phenomena can be explained by the intensified mechanical action on the coating surface caused by the high hardness and abrasive activity of 100Cr6 steel. As a result, the use of the 100Cr6 counterbody causes an increase in friction-induced loading, intensive degradation of the coating, and a higher wear rate. The obtained results indicate that the properties of the counterbody material are among the key factors determining the tribological behavior of the coatings.

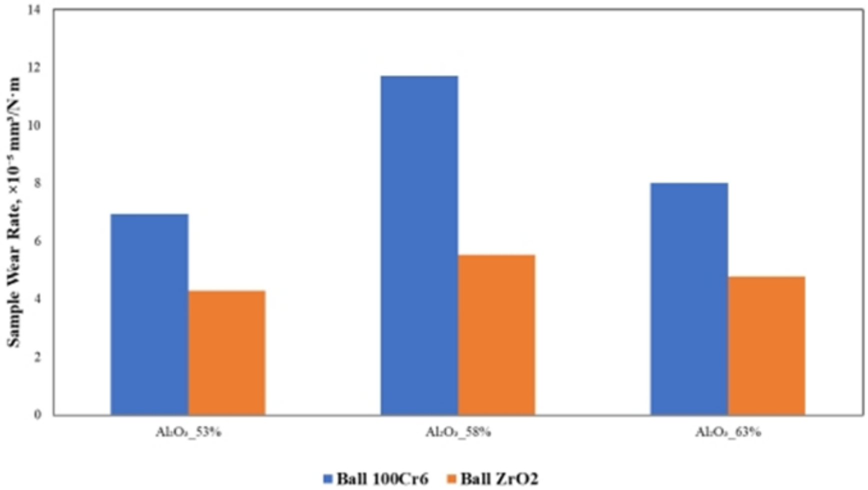


Fig. 7. Specific wear of Al_2O_3 coatings obtained at different filling volumes of the detonation barrel with explosive gas under testing conditions against 100Cr6 and ZrO_2 counterbodies.

4.Conclusion

As a result of the study, it was established that the structure, mechanical properties, and tribological characteristics of Al_2O_3 coatings obtained by detonation spraying directly depend on the filling level of the detonation barrel with explosive gas. When the filling level of the detonation barrel with explosive gas was increased to 58%, the microstructure of the coating improved significantly: the coating became denser, and the degree of particle melting increased. As a result, the microhardness (1362.3 HV) and elastic modulus (190.0 GPa) reached their maximum values, indicating an improvement in mechanical properties. In addition, under the 58% filling condition, the corrosion current density decreased significantly compared with the initial steel. Although the highest corrosion resistance (I_{corr} = 0.00725 A/cm^2) was observed at the 63% filling level, the mechanical properties decreased compared with those obtained at 58%. The reduction in coating thickness can be explained by the scattering and loss of part of the powder during the spraying process. Tribological tests showed that the wear rate against the ZrO_2 counterbody was significantly lower than that against the 100Cr6 steel counterbody, confirming that the counterbody material has a direct influence on the wear behavior of the coating. Thus, a barrel filling level of 58% is the optimal regime for obtaining Al_2O_3 coatings.

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Conflict of interest

The authors declare that they have no competing interests.

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