The mechanical and corrosion properties of WCCo–Al coatings formed on AA2024 using the HVOF method

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Abstract
This paper investigates the microstructural, mechanical, and electrical-conductivity properties of WCCo–Al composite coatings produced on the Al alloy AA2024 using the high-velocity oxygen fuel (HVOF) thermal-spray method. In an experimental study, the amount of WCCo added to Al powders was varied between 25, 50, 75, and 100 wt%. The AA2024 used as the substrate material was cleaned in acetone solution and then subjected to a sanding process using Al2O3 sand that had a grain size of 24–35 mesh for improved bonding of the coating layer. Nitrogen was used as the powder-carrier gas. After the coating process, the substrates were cooled using high-pressure air jets. The coated samples were then compared in terms of their microstructure, phase composition, microhardness, electrical conductivity, and wear properties. The microstructure, phase composition, and surfaces of the coatings after abrasion were examined using a scanning electron microscope (SEM) and an x-ray diffractogram (XRD). The XRD results showed that the WCCo–Al coating layer was composed of Al, Al0.52Co0.48, Al30Mg23, Al0.47Co0.53, MgCuAl2, WCu2Al8, AlCo, Al12W, and BNi2 phases. The addition of WCCo increased the hardness of the coatings. For instance, the highest hardness value was measured as 1,335 HV0.2 in the coating produced using 100% WCCo. The amount of WCCo in the powder also affected the microstructure, phase composition, and hardness of the coatings. Moreover, the addition of WCCo lowered the electrical conductivity, wear rates, and friction coefficients of the coatings. In indentation tests, the hardness values of the coatings were generally found to increase with increasing applied load. In corrosion tests, the corrosion resistance of the coatings was observed to increase as the amount of WCCo in the coating layer increased. The highest peak depth was 36.94 μm in the sample coated with 100% Al, and the lowest peak depth was 6.82 μm in the sample coated with 100% WCCo. The coated materials had outstanding tribological performance compared to the uncoated ones. The increase in wear resistance provided by the coating was caused by a large amount of dispersed WC and Co.

1. Introduction

The aviation industry widely prefers 2XXX-series Al alloys because of the high strength and low density of these materials. Al alloys are used in the automotive, defense, and aviation sectors owing to their mechanical properties and low density [1]. Al is used in the construction sector and in vehicles such as airplanes and bicycles due to its low weight, and in electrical and electronic devices due to its high conductivity. Moreover, Al is considered to be the metal of the twenty-first century because its high strength-to-weight ratio in claddings has enabled new technologies. However, due to the low strength from mechanical properties, the use of pure Al in applications is uncommon.

For technical and economic reasons, interest in light structural metals has continued to increase. These metals offer many advantages over other engineering materials, such as low density, low electrical resistance, high thermal conductivity, nonflammability, high specific strength, weldability, recyclability, and excellent machinability. Research has primarily been conducted on the production of lighter vehicles that have improved
properties in the automotive and aviation industries. Some of the most important materials for this purpose are Al alloys [2]. A thesis study by Pinto found that, by reducing a vehicle’s weight by 100 kg, fuel consumption fell by 0.3 liters over 100 km, and CO₂ emissions decreased by 7.5–12.5 grams [3].

Cu is the essential alloying element of 2XXX-series Al alloys. The alloy AA2024 has high strength, high workability, and permanent strength. For these reasons, it is extensively preferred in threaded shafts, aerostructures, rocket parts, orthopedic tools, and scientific apparatus and instruments [4, 5]. AA2024 is a medium-strength alloy. Its main alloying elements are Cu and Mg, and its secondary alloying elements are Fe, Si, and Mn. The primary purpose of the Cu and Mg is to increase the strength of the material by forming precipitation [6]. Precipitate particles have an important role during deformation. Metal-matrix composites reinforced by ceramic particles are widely used in the aviation, automotive, and electronics industries owing to their excellent thermal conductivity, perfect wear resistance, and low density. WCCo particles are used in composite and coating production due to their high wear resistance, high melting degree, high hardness value, and excellent thermal stability [7].

The high-velocity oxygen fuel (HVOF) method is a coating operation in which a powdered material is heated rapidly in a hot aeroform environment. Simultaneously, the powdered material is added to a prepared material surface where it gathers to produce the required coating by its high particle velocity. HVOF-sprayed coatings have been commonly used in the past decade (mostly for aviation and space technology, industrial applications, power plants, and the automotive industry) because the coatings states low porosity and oxide, high adhesion and hardness. The essential advantage of HVOF over other thermal-spray techniques is that the raw material can accelerate the molten powder particles to a relatively high velocity [8].

Thermal-sprayed WC coatings, such as WCCo coatings, have been researched widely owing to their high hardness values and good strength properties, and high-wear and violent-corrosion applications [9]. For long-term functional service, attention is mostly paid to further improving the mechanical properties of WCCo coatings. Among the processing approaches, HVOF is one of the best methods for superior mechanical performance of such coatings and minimal carbon removal from WC [10]. WCCo-based materials are used in many coatings produced by thermal-spray technologies. Of these technologies, the HVOF method is favored mainly because the properties of WCCo-based powders are not distorted due to their high velocity and low temperature. WCCo-based coatings are used in many applications that require good wear properties owing to their excellent wear resistance, high hardness values, and good strength properties. These coatings are also preferred as an alternative to hard chromium coatings. In WCCo-based coatings, the Co serves as a binder by bonding WC particles to the coating surface [11].

Some studies have been conducted to improve the hardness, wear, and corrosion properties of WCCo-based coatings [12, 13]. Magnani et al examined corrosion and wear resistance by coating WCCo on AA7050 T7 using the HVOF method. The authors produced coatings without cracks and reported that the coatings decreased the wear rate of the Al alloy by approximately ten times [14]. Lekatou et al conducted a comparative study on microstructure and surface properties by coating nanostructured and conventional WCCo powders on Al7075 using the HVOF technique. The authors found that both coating types showed high wear resistance and that nano-coating offered higher wear resistance than its conventional counterparts in terms of fewer wear marks, reduced wear-track width, and lower friction coefficient [15]. Ahmadi et al made vanadium and zirconium coatings on AA2024 and increased corrosion resistance [16]. Finally, Keshavamurthy et al investigated the wear properties of tungsten carbide and hard chrome coatings using the HVOF method. The authors determined that tungsten carbide coatings had better hardness and wear properties compared to hard chrome coatings [17].

The purpose of the current study was to prepare WCCo–Al coatings using the HVOF technique and to study their mechanical and corrosion properties. The surface properties of these coatings (such as their microstructure, phase formation, microhardness, electrical conductivity, and wear and corrosion resistance) have been investigated. In particular, the microstructure, wear, and corrosion properties of the coatings have been analyzed and compared.

2. Experiments

The HVOF spray method was used to produce WCCo-based coatings on the surface of Al alloy AA2024. Table 1 shows the chemical composition of the chosen substrate and powders. The average grain size of the WCCo powders was 45 ± 15 μm.

The substrates, which had dimensions of 20 mm × 5 mm × 130 mm, were cleaned in an acetone solution. They were then subjected to a sanding process using Al₂O₃ sand that had a grain size of 24–35 mesh to improve the bonding of the coating layer. The Metco Diamond Jet (DJ) 2600 HVOF spray system was used to produce the coatings. Table 2 shows the spraying parameters used in the coating process, which was carried out by
connecting the substrates to the mirror of the lathe. Nitrogen was used as the powder-carrier gas. After the coating process, the substrates were cooled using high-pressure air jets.

Before imaging the test samples using a scanning electron microscope (SEM), standard metallographic processes (namely, sanding, polishing, and etching) were applied. SEM and energy-dispersive spectrometer (EDS) analyses were taken from the ‘Fei Quanta 250 Feg’ brand device in the Kastamonu University Central Research Laboratory. X-ray diffraction (XRD) analysis was conducted using the ‘Bruker D8 Advance’ brand device in this same laboratory. The hardness measurements were performed using the ‘Shimadzu’ brand ‘Hmv-G21’ model microhardness measurement device under a load of 50 ve 200 g for a waiting time of 16 s. The hardness values of the materials were calculated according to the Astm-E92 standard.

The electrical-conductivity values were measured in units of m/Ω·mm² using the Sigma test 2.067 device at the Tubitak Marmara Research Center and were calculated according to the Astm-B193 standard.

In the wear tests, a back-and-forth wear test was applied to both the substrates and the coating layers, according to the Astm-G133 standard, using the Uts Tribometer T10 test device. These tests were carried out under room conditions with a shear distance of 350 m under a 10 N load. The data-collection rate was selected as 3 Hz. For abrasive balls, spherical steel balls that had a diameter of Ø6 mm and were made of 100Cr6 material were used. These balls were replaced for each experiment.

For the mechanical analysis of the coating samples, indentation experiments were conducted using the ‘Bruker’ brand ‘Umt’ model ultra-microhardness tester in the Kastamonu University Central Research Laboratory. This device analyzes the changes in a material caused by external forces and the behavior of the material under these effects. Loads of 1, 3, 5, 7, and 9 N were applied.

Corrosion measurements were made using the Gamry brand Reference 3000 Potentiostat–Galvanostat–Zra corrosion system. For the corrosion tests, the samples were sanded using coarse and fine sandpaper, polished using 3 μm and 1 μm solutions, and then cleaned using ethanol in an ultrasonic bath for 30 min. The samples were allowed to stand at room temperature (25 °C), 96.5% by weight in distilled water and 3.5% in NaCl solution, for 30 min to stabilize the surface. Then, the experiments were performed.

A conventional three-electrode cell was used for all electrochemical measurements. An Ag–AgCl electrode was used as the reference electrode, and a carbon electrode was used as the counter electrode. A potentiodynamic sweep was performed with a sweep speed of 1 mV s⁻¹ in the ± 0.25 mV potential range, according to Eocp. Three experiments were conducted for each sample. The new solution was used in each experiment, and the arithmetic mean of the results was taken. The corrosion rate was calculated according to the Astm-G102 standard.

### Table 1. Chemical composition of the substrate and powders.

| Chemical composition (wt%) | AA2024 (wt%) | WC-Co powder (wt%) | Al powder (wt%) |
|---------------------------|--------------|--------------------|----------------|
| Al                        | 90.7–94.7    | —                  | 99.0           |
| Cu                        | 3.8–4.9      | —                  | —              |
| Mg                        | 1.2–1.8      | —                  | —              |
| Fe                        | Max 0.5      | —                  | —              |
| Cr                        | Max 0.1      | —                  | —              |
| Mn                        | 0.3–0.9      | —                  | —              |
| Si                        | Max 0.5      | —                  | —              |
| Zn                        | Max 0.25     | —                  | —              |
| Ti                        | Max 0.15     | —                  | —              |
| W                         | —            | 82                 | —              |
| Co                        | —            | 12                 | —              |
| C                         | —            | 6                  | —              |

### Table 2. Spraying parameters.

| Spraying Distance | 30 cm |
|-------------------|-------|
| Nitrogen          | 0.8 Bar |
| Kerosene          | 26 l min⁻¹ |
| Oxygen            | 900 l min⁻¹ |
| Powder Feed Amount| 50 gr min⁻¹ |
| Coating Thickness | 350–400 μm |
| Surface roughness | 6.0–7.0 Ra |
3. Results and discussion

3.1. SEM examinations of the coatings

In the production of WCCo-based coatings on surfaces of the Al alloy AA2024, the HVOF spray method was used in an attempt to improve the surface properties after coating. Figure 1 shows SEM images of such surfaces.

The images in Figure 1 demonstrate that the coating formation was successful. These coatings contained lamellar structures that resulted from melt and semi-melt particles deforming upon hitting the substrate and then solidifying. The thickness of these structures was greatest in their middle and decreased toward their ends, and the structures were parallel to each other [18]. As the WCCo rate increased in the SEM images, the bright and white structure also increased. Lekatou et al stated in their study entitled ‘A comparative study on the microstructure and surface property evaluation of coatings produced from nanostructured and conventional WC–Co powders HVOF-sprayed on Al7075’ that this structure was composed of Co and C contents [15].

Cracks that mostly extended to the AA2024 surface indicate that layer take place in some regions through the coating. Although cracks formed in both the AA2024 and the coating interfaces, there was strong adhesion between the AA2024 and the WCCo–Al coatings. The sandblast operation before the coating, whereby hard WC and Co grains hit the AA2024 surface at high velocity, roughened this surface, resulting in better adhesion. Similar investigations have been carried out by other researchers [19].

These researchers pointed out that the temperature of HVOF spraying needs to be low to melt the WC carbide, and, for this reason, semisolid WCCo particles scatter from the end of the HVOF spray gun. These particles first crash over the AA2024 surface and then into each other. When they crash into the AA2024 surface at high velocity, they diffuse into this surface. The amount of deformation increases by the time soft material is particularly used as a substrate. The hardness of the surface influences the deformation behavior of the particles.

Figure 1. SEM images of the coatings (a) Al, (b) Al + 25% WCCo, (c) Al + 50% WCCo, (d) Al + 75% WCCo, (e) 100% WCCo.
20. Because of the hot gas spray and the molten AA2024 and particles, regional melting can occur on the AA2024 surface, leading to perfect bonding between the AA2024 and the coating. Bolelli et al. in their investigation entitled ‘HVOF-sprayed WC-CoCr coatings on Al alloy: effect of the coating thickness on the tribological properties,’ stated that such a structure hampers instantaneous passing in the mechanical properties [19].

3.2. SEM—EDS analysis of the coatings

Figure 2 shows an SEM–EDS analysis of an AA2024 sample coated with 100% Al.

When figure 2 was examined, it was determined that the substrate material was AA2024, and the coating material was 100% Al. Figure 3 shows an SEM-EDS analysis of an AA2024 sample coated with Al + 25% WCCo.

When figure 3 was examined, it was determined that the substrate material was AA2024, and the coating material was Al + WCCo. Figure 4 shows an SEM-EDS analysis of an AA2024 sample coated with Al + 50% WCCo.
When figure 4 was examined, it was determined that the substrate material was AA2024, and the coating material was Al\textsuperscript{+}WCCo. Figure 5 shows an SEM-EDS analysis of an AA2024 sample coated with Al\textsuperscript{+}75\% WCCo.

When figure 5 was examined, it was determined that the substrate material was AA2024, and the coating material was Al\textsuperscript{+}WCCo. Figure 6 shows an SEM-EDS analysis of an AA2024 sample coated with 100\% WCCo. In figures 2–6, the peaks for Al, W, Co, and C that were also present in the coatings can be clearly seen. The matrix phase acquired a brighter contrast level for backscattered electrons in splats where WC dissolution was more pronounced\cite{21}. Oxides resulting from the high affinity of the substrate and coatings to oxygen were also found.

Bolelli et al\cite{21} reported that the addition of Cr to WCCo reduced the melting temperature of the powder substantially. In this situation, the number of molten particles in the coating spray (and therefore, sprawled splats in the coating) significantly increases. In this study, such a situation was seen. The sprayed WCCo–Al particles could spread on the AA2024 and each other more easily than could the WCCo–Al particles. Magnani

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{SEM-EDS analysis of Al + 50\% WCCo coated AA2024 material.}
\end{figure}

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure5.png}
\caption{SEM-EDS analysis of Al + 75\% WCCo coated AA2024 material.}
\end{figure}
et al \cite{14} reported that the dissolution of the new phases in the matrix contributed greatly to the development of this structure.

3.3. XRD analysis of the coatings

Figure 7 shows XRD graphs of Al-WCCo and WCCo coatings produced using the HVOF spray method. When figure 7 was examined, peaks for Al, Al\textsubscript{0.52}Co\textsubscript{0.48}, Al\textsubscript{3}Mg\textsubscript{23}, Al\textsubscript{0.47}Co\textsubscript{0.53}, MgCuAl\textsubscript{2}, WCu\textsubscript{2}Al\textsubscript{8}, AlCo, Al\textsubscript{12}W, and BNi\textsubscript{2} were identified. García-Hernández et al \cite{22} found similar peaks in their study on the effect of the Cu-to-Mg ratio on plastic deformation in the strengthening mechanism and precipitation behaviors of AA2024. The dominant phases seen in the graphs were Al, Al\textsubscript{0.52}Co\textsubscript{0.48}, Al\textsubscript{3}Mg\textsubscript{23}, Al\textsubscript{0.47}Co\textsubscript{0.53}, MgCuAl\textsubscript{2}, WCu\textsubscript{2}Al\textsubscript{8}, AlCo, Al\textsubscript{12}W, and BNi\textsubscript{2}. When all the peaks were studied, it was found that, as the amount of WCCo in the coatings increased, the intensity of the Al peaks decreased. The WCu\textsubscript{2}Al\textsubscript{8}, AlCo, and Al\textsubscript{12}W phases, which are likely to occur at high temperatures, formed in the coating layer. The release of W and Co from decarburization of the WCCo phase resulted in the
generation of the Al_{0.52}Co_{0.48}, Al_{0.47}Co_{0.53}, WC_{0.5}Al_{0.5}, AlCo, and Al_{12}W phases. The sprayed WCCo powder was thought to have partially decomposed during spraying.

3.4. Microhardness test results of the coatings

Figure 8 shows the microhardness graph for the samples. Figure 9 presents the microhardness profiles along the cross section of the coatings as a function of distance from the coating–substrate interface.

The hardness measurements were taken along a line through the substrate, intermediate layer, and coating regions. Non-uniform melting of WCCo particles during spraying supported microstructural heterogeneity in the WCCo coatings [23]. The hardness of the substrate material was measured to be about 165 HV_{0.05}. The hardness of the intermediate layer increased as more WCCo was added. The hardness of the coating layer varied from 59.6 HV_{0.05} to 1,335 HV_{0.2}, depending on the amount of WCCo.

As seen in figure 8, the hardness of the coatings increased as more WCCo was added. In particular, when the amount of WCCo was raised to 100%, the hardness value became much higher. This increase was associated with the presence of carbide and hard phases in the coating layer. The addition of WCCo resulted in the formation of WC_{0.5}Al_{0.5}, AlCo, and Al_{12}W phases and thus caused the hardness to increase. However, when the SEM–EDS and XRD analyses were examined, it was realized that, due to the difference in density, the lack of coating in the desired ratio (because all the powders could not reach the material to be coated) and the partial decomposition of all the powders changed the hardness values.

3.5. Electrical-conductivity test results for the coatings

Figure 10 shows the electrical-conductivity results for the coatings as percentage (%) IACS. These results were determined by taking the average value of three measurements. The electrical conductivity of the coatings was calculated using equation (1) [24]:

\[
W = \frac{L_s}{R \cdot S \cdot 5 \cdot 8 \cdot 10^{-7}} \cdot 100\%
\]

where:
- \(W\) = Electrical conductivity (%IACS)
- \(L_s\) = Length of the sample (m)
- \(R\) = Electrical resistance (\(\Omega\))
- \(S\) = Transverse section area of the sample (m²)

When figure 10 was examined, it was found that the coating that had 100% Al had the highest electrical conductivity, and the coating that had 100% WCCo had the lowest conductivity. Pores and microcracks that formed in the coatings made using the HVOF method and carbides in the composite coatings made on AA2024 decreased the conductivity. The main reason for this effect was the failure to spray carbides on the substrate at the desired rate, owing to the density during the coating. Because the interaction between nuclei and free electrons in metals is weak, the electrons can move easily. Therefore, the conductivity of metals is high. By contrast, electrons in carbides are firmly attached to nuclei and cannot move easily. As a result, carbides have low electrical conductivity [25]. It is thus expected that the conductivity decreases as carbides are added.
3.6. Wear analysis of the coatings

Wear tests were conducted using the procedure given in section 2. Figures 11 and 12 show the wear rate calculated as the volume loss and the coefficient of friction (COF) of the produced samples at the end of the sliding distance against the applied loads. The friction coefficient varied from 0.43 to 0.58 under an applied load of 10 N for the AA2024 substrate. These values suggest that the WCCo particles had an abrasive-wear property and decreased the COF relative to the substrate.

The highest wear rate was obtained for the 10 N load and pure-Al coating. The presence of WCCo particles was clearly seen to improve the wear behavior of the AA2024 matrix. Coating WCCo particles on the matrix can decrease the friction between the sliding surfaces and lower the wear rate significantly. WCCo-coated AA2024 had higher hardness and better wear resistance than uncoated samples. This observation is consistent with Archard’s Law, confirming that harder materials have better wear performance than softer ones [26].

The friction coefficient is a key quantity for interpreting the wear and friction performance of materials [27]. When figure 12 was examined, it was clearly seen that there was a general tendency for the friction coefficient to decrease when WCCo was added. Indeed, the sample coated with 100% WCCo had the lowest COF value under a 10 N load. The worn material was subjected to plastic deformation against the opposite material. As the load increased, the material structure exhibited micro-cracks, fractures, and separation of hard phases from the sample.
matrix. The load level increased the extent of these damages. It varied from 23.62 μm to 1.17 μm for the sample containing 100% WCCo [28].

The COF is important for understanding the wear and friction performance of materials [27]. In figure 12, the COF generally decreases as the applied load increases. However, there is no significant change in COF values for WCCo-reinforced coatings versus sliding speed, possibly because of insufficient solid lubricant on the contact surface [29].

3.7. SEM and SEM-EDS analysis after wear test
Figure 13 presents the wear-profile results for the coatings. Figure 14 shows the morphology of the worn surfaces of the substrate and coating layers under a 10 N load. When figures 13 and 14 were examined, both abrasive and adhesive wear types were clearly seen in the coating layers. When the SEM images were studied, it was found that the wear tracks were most distinct in the pure-Al coating and became increasingly less visible as the amount of WCCo increased. It was determined in post-wear SEM images that there were material losses, micro-cracks, plastic deformation, and debris in all the coating samples.

Wang et al reported similar wear mechanisms for WCCo coatings [30]. The degree of material losses, plastic deformation, and debris was lower in the wear surfaces of the coatings containing WCCo compared to the other coatings due to the low wear rates and friction coefficients that resulted from the hardness of the coating layer.
Berger et al found that the wear resistance was improved when Co was used as a binder metal \[31\]. Gangatharan et al reported that the formation of wear debris between the specimen and the disc reduces the wear rate. The wear rates and friction coefficients of all HVOF coating performed specimens were lower than those of the AA2024 substrate. An increase in the amount of WCCo powder positively affected the wear rate and friction coefficient of the specimens \[32\].

**Figure 12.** Coefficient of friction of coated samples.

**Figure 13.** Wear profiles results of the coatings (a) Al, (b) Al + 25% WCCo, (c) Al + 50% WCCo, (d) Al + 75% WCCo, (e) 100% WCCo.
Figure 15 shows the results of SEM–EDS for sample surfaces subjected to a wear test under a 10 N load. When the EDS results were examined, oxide formation was observed in all the samples except for the sample coated with 100% WCCo. The resulting oxide layer could have caused the friction coefficients to decrease through a tribolayer effect. The formation of different wear mechanisms was determined by the breaking of the oxide layers under an excessive load. Torgerson et al. emphasized the formation and tribolayer effect of these oxide layers in their study entitled ‘Room and elevated temperature sliding wear behavior of cold sprayed Ni-WC composite coatings’ [33]. Due to thermomechanical processes and thermal reason in the material, an oxide layer is formed on the material surface. This layer acts as a lubricant on the material surface, causing the friction coefficient to decrease [34].

The load and contact-depth graphs for the coatings are given in figure 16. These graphs also show the values of the applied load and indentation modulus for all the coating samples.

The mechanical properties (applied load, depth of contact, hardness, and indentation modulus) of all the coatings are listed in table 3.

As previously mentioned, loads of 1, 3, 5, 7, and 9 N were applied to the coatings. It was previously found that, as the amount of applied load and WCCo increases, the hardness values of the coatings generally increase [35]. As a result, these values were determined according to the applied load. Kaya et al. in their study entitled
Enhanced mechanical properties of yttrium doped ZnO nanoparticles as determined by instrumental indentation technique, demonstrated that the degree of hardness increases as the applied load increases [36].

WCCo is considered to be a hard material. As shown in table 3, the highest hardness value was measured in the sample coated with 100% WCCo. Different hardness values can be obtained at different application loads. As shown in figure 16, the highest peak depth was 36.94 μm in the sample coated with 100% Al, and the lowest peak depth was 6.82 μm in the sample coated with 100% WCCo.

The corrosion tests of the coatings were carried out in a prepared 3.5% NaCl solution. Potentiodynamic polarization curves resulting from the experiments are given in figure 17.
The potential was applied to the open-circuit potential after \(-0.25\ \text{mV}\) to \(0.25\ \text{mV}\). An immersion time of 30 min was applied. Tafel curves were used to determine \(E_{\text{corr}}\) (the corrosion potential), \(I_{\text{corr}}\) (the corrosion current), \(\beta_a\) (the anodic tafel curve), \(\beta_c\) (the cathodic tafel curve) and the corrosion rate. The value of \(R_p\) (the corrosion resistance) was calculated using the Stern–Geary equation (equation (2)) [37].

$$I_{\text{corr}} = \frac{\beta_a \times \beta_c}{2.303 \times R_p(\beta_a + \beta_c)} \quad (2)$$

The electrochemical results for the coatings are given in table 4.

When examined in table 4 and figure 17, the sample with the coating of 100% WCCo had the greatest corrosion resistance (\(-598\ \text{mV}\)). Among the other coatings, the lowest resistance was \(-874\ \text{mV}\) for the sample coated with 100% Al. As the amount of WCCo in these coatings rose, the corrosion resistance of the coatings increased. As a result, there was a reaction between the AA2024, Al, and WCCo. The corrosion resistance of the sample coated with 100% Al was 1.55 kΩ·cm², whereas the value for the sample coated with 100% WCCo was 40.92 kΩ·cm². It is clear from the data obtained that, as the amount of WCCo in the coating layer increases, the
corrosion resistance of the coating also increases. Similar results for WCCo coatings have been reported in the literature \[10, 38\].

4. Conclusions

In this study, WCCo–Al composite coatings were produced on the Al alloy AA2024 using the HVOF thermal spray method. SEM images of these coatings revealed lamellar structures that were parallel to each other. In an EDS analysis, peaks for Al, W, Co, and C present in the coatings were clearly seen. XRD graphs showed peaks for

| Table 3. Mechanical properties of coatings. |
|--------------------------------------------|
| Coating samples | Load (N) | Contact depth (μm) | Hardness (GPa) | Indentation modulus (GPa) |
|-----------------|----------|-------------------|----------------|--------------------------|
| 100% Al         | 1        | 13.6222           | 0.2265         | 15.6081                  |
|                 | 3        | 19.5285           | 0.3166         | 25.1011                  |
|                 | 5        | 21.3931           | 0.4385         | 40.4248                  |
|                 | 7        | 26.4823           | 0.4007         | 37.7974                  |
|                 | 9        | 36.9446           | 0.2658         | 34.4180                  |
| Al + 25% WCCo   | 1        | 12.7565           | 0.2643         | 21.7270                  |
|                 | 3        | 20.4104           | 0.2929         | 74.5119                  |
|                 | 5        | 26.3467           | 0.2910         | 37.5482                  |
|                 | 7        | 19.5860           | 0.7353         | 55.6708                  |
|                 | 9        | 23.5378           | 0.6514         | 55.4039                  |
| Al + 50% WCCo   | 1        | 17.9089           | 0.1300         | 32.8504                  |
|                 | 3        | 16.2925           | 0.4561         | 60.5373                  |
|                 | 5        | 22.7040           | 0.3912         | 59.6950                  |
|                 | 7        | 17.4527           | 0.9280         | 90.4957                  |
|                 | 9        | 26.1613           | 0.5293         | 64.8489                  |
| Al + 75% WCCo   | 1        | 10.4937           | 0.3787         | 57.1086                  |
|                 | 3        | 19.3379           | 0.3234         | 72.1691                  |
|                 | 5        | 19.1488           | 0.5503         | 83.2865                  |
|                 | 7        | 23.0338           | 0.5313         | 80.4995                  |
|                 | 9        | 28.9566           | 0.4733         | 404.3450                 |
| 100% WCCo       | 1        | 6.8241            | 0.9257         | 55.4630                  |
|                 | 3        | 9.4692            | 0.9257         | 80.8072                  |
|                 | 5        | 11.2524           | 0.9257         | 91.4875                  |
|                 | 7        | 11.7709           | 0.9257         | 387.1773                 |
|                 | 9        | 9.9970            | 0.9257         | 234.0813                 |

Figure 17. Tafel curves of coated materials.
Al, Al0.52Co0.48, Al30Mg23, Al0.47Co0.53, MgCuAl2, WCu2Al8, AlCo, Al12W, and BNi2. The hardness of the coating layer varied from 59.6 HV0.05 to 1,335 HV0.2, depending on the amount of WCo. The highest electrical conductivity was measured in the coating made with 100% Al. From corrosion tests, it was determined that, as the amount of WCo in the coating particles was found to improve the wear resistance of the AA2024 matrix. In an SEM–EDS analysis after wear, both abrasive and adhesive wear types were seen in the coating layers. From indentation tests, it was determined that the hardness values of the coatings generally increased as the amount of applied load increased. The highest peak depth was 36.94 μm in the sample coated with 100% Al, and the lowest peak depth was 6.82 μm in the sample coated with 100% WCo. From corrosion tests, it was determined that, as the amount of WCo in the coating layer increased, the corrosion resistance of the coating also increased.

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Table 4. Electrochemical results of the coatings.

| Coating samples | Ecorr (mV) | Icorr (μA/cm2) | β3 (mV) | β1 (mV) | Corrosion rate (mpy) | Corrosion resistance (kΩ·cm²) |
|-----------------|------------|----------------|---------|---------|---------------------|-----------------------------|
| 100% Al         | −874       | 2.25           | 0.999   | 0.439   | 2.144               | 1.55                        |
| Al + 25% WCCo   | −763       | 0.302          | 0.032   | 0.072   | 0.331               | 3.18                        |
| Al + 50% WCCo   | −740       | 0.243          | 0.828   | 0.077   | 2.932               | 12.58                       |
| Al + 75% WCCo   | −717       | 0.181          | 0.130   | 0.159   | 0.158               | 17.15                       |
| 100% WCCo       | −598       | 0.413          | 0.405   | 10,000  | 9.954               | 40.92                       |
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