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Study the Effect of Twin Wire Arc Spraying Parameters on Surface Properties of Stainless Steel

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Abstract: Wire arc spraying is a widely used and cost-effective thermal spray technique that utilizes two metal wires fed into an electric arc. This study addresses a practical industrial issue observed at the Basra Refinery under the Ministry of Oil, where shafts of rotating and stationary equipment particularly at bearing contact zones suffer from frequent damage due to friction and wear. Traditional repair methods, including welding, have shown limited effectiveness, often resulting in distortion and degradation of mechanical properties caused by excessive heat exposure.As an alternative, this research explores the use of twin wire arc spraying to enhance the surface integrity and wear resistance of stainless steel components. The coating process was performed using the Arc Spray System Model BP400, manufactured by TAFA. Stainless steel 304 was selected as the substrate, coated with 55T-18/5 stainless wire (200 series), 1.6 mm in diameter. The study investigates the influence of key process parameters, particularly the spray distance, on the coating's surface characteristics. Spray distances of 10, 15, 20, and 30 cm were evaluated, while other parameters were fixed: 90° spray angle, 3.8 bar air pressure, 39 ±1 V, 124 ±1 A, and a spraying duration of approximately 30 ±5 seconds. Experimental evaluation focused on surface roughness, coating thickness, adhesion strength, microstructure (via SEM and optical microscopy), wear resistance, and Vickers hardness. The results showed that a spray distance of 15 cm yielded the best performance: hardness increased from 176.8 HV (substrate) to 367 HV, representing a 107% improvement. Additionally, the wear rate reached its lowest value at 15 cm (2.4×10^{-8} g/cm) indicating superior durability. At the same distance, the highest adhesion strength of 14.14 MPa (2051 psi) was recorded. These findings confirm that optimizing spray parameters particularly the spray distance can significantly improve the mechanical performance and service life of coated stainless steel components, providing an effective solution for industrial repair and surface enhancement in demanding environments.

Keywords: Thermal spraying, Stainless steel, Arc spraying, Vickers hardness, Coating

Introduction

Thermal spraying is one of the most efficient and widely adopted surface engineering techniques, offering a reliable solution for enhancing the functional properties of components exposed to harsh operating environments. Its effectiveness in mitigating wear, corrosion, oxidation, and thermal damage has made it indispensable across various sectors of manufacturing and heavy industry. The increasing demand for materials with enhanced surface performance, along with the method's cost-efficiency and adaptability, has further driven the development of thermal spray technologies (Fantozzi et al., 2017; Fauchais, 2015; Harrison, 1996; Li et al., 2004). Among the

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various technologies that are available, such as combustion-based, electrical, and kinetic processes, arc spraying remains one of the most advanced and industry-used methodologies. Initially developed by Max Ulrich Schupp in 1918 and commercially employed during the 1960s, arc spraying remains one of the preferred methods due to its simplicity of equipment, superb deposition efficacy, and its capability to be applied to an extensive range of metals and alloys. Perhaps its premier derivative to date remains the Twin Wire Arc Spraying (TWAS) process, which has been widely employed by the aerospace, petrochemical, and energy sectors. Its specific value-added proposition comes from its capacity to restore degraded components and to provide both heat and cold wear and corrosion protection. In the TWAS process, an electric arc is generated between two continuously fed conductive wires, melting their tips. The molten material is then atomized using a stream of compressed air or inert gas and propelled toward the substrate to form a coating (Ducos & Durand, 2001; Huchin, 1998; Rigney et al., 1998). The versatility of this process enables the utilization of diverse feedstock supplies, such as stainless steels, alloys, and metal matrix composites (MMC)s. Recent research confirms that process conditions, especially spray distance, voltage, and gas pressure, are very instrumental units that define coating quality and functionality. For example, Wagner (2021) determined that changes in standoff distance and air pressure, considerably and profoundly, affected the coating's hardness, porosity, and thickness while applying TWAS to steel coatings. Similarly, Nango-Blanco et al. (2024) indicated that a realization of optimal spray distance and carrier gas conditions resulted in considerable decreases in oxidation and improvements to Ti-6Al-4V coating microstructure. An extensive review by (Gaur & Kamari, 2024) further accentuates the growing industry importance of TWAS. It places emphasis on the need to fine-tune operating conditions to obtain workable and highly functional coating effects. Also, Arif et al. (2020) noticed that though surface roughness and coating microstructure are enhanced by rising voltage and standoff distance, the former instead decreases deposition efficiency. Johnston et al. (2013), among other researchers, verified that poor control over the parameters might yield undesirable characteristics, such as extensive porosity, oxidation, poor adhesion, and ill-formed coating profiles (Arizmendi-Morquecho et al., 2014; Boulos et al., 2021).

Based on these results, the current work aims to address the optimal spray distance within the twin wire arc spraying process, since this has a fundamental function to regulate particle temperature, impact velocity, and microstructure of the coating. Optimal stand-off distance enables enhanced coating densification and bonding, thus directly enhancing hardness, adhesion, surface roughness, and wear resistance. By examining these relationships, the research aims to enhance the surface performance of stainless steel components in industrial applications.

Materials and Methods

Description of the Equipment Used

Twin Wire Arc Spray is one of the least expensive thermal spray techniques through the use of direct current. It operates by applying direct current to two feed wires. The molten material is then atomized and propelled toward the surface using compressed air, forming a dense and well-adhered coating. Thanks to its high deposition efficiency and relatively simple setup, this method is widely adopted across industrial applications.

Arc Spray System Model BP400manufactured by the TAFA coatings were applied with using 55T-18/5 stainless steel wire (200 Series, 1.6 mm in diameter), which complies with AWS C2.25/C2.25MFP5045 Type IV, Rev AB standards. The spraying was carried out using the BP-400 Arc Spray System, operated under the twin-wire arc configuration. Process parameters, including gas pressure (P), applied voltage (V), and the distance between the spray gun and the substrate, were adjusted to study their effects on the resulting coating. Throughout the spraying, the voltage was kept or maintained at 39 ± 1 V, and compressed air was used as the atomizing gas.

Table 1. Spraying parameters of stainless steel.

Parameters	Value
Arc voltage [V]	39 ±1
Arc current [A]	124 ±1
Atomizing gas	Air
Atomizing gas pressure [bar]	3.8
Spray distance [cm]	10, 15, 20, and 30

Characteristics of Materials Used and Sample Preparation

Stainless steel 304 substrates that had been prepared were sprayed with the coatings. Table 2 displays the chemical composition of substrate and steel wire.The substrates' surface was meticulously cleaned and prepard before to spraying.

Table 2. Chemical composition of the stainless steel 304 standard ASTM A-276, substrate stainless steel and steel wire 55T-18/5 stainless.

Element	C	Si	Cr	Ni	Mn	Fe
Stainless steel 304 standard(%)	0.08	1.0	18-20	8-10	2	Bal
Content of substrate (%)	0.08	1.0	19.7	8.00	2	Bal
Content of steel wire (%)	0.06	0.08	18.00	5	8	Bal

Methods for Evaluating the Characteristics of Coatings

To prepare the stainless steel specimens, surfaces were ground using silicon carbide (SiC) emery sheets with grit sizes of 400, 800, 1000, and 2000. The samples were then polished to a mirror-like finish using a polishing cloth and alumina powder. Afterward, the specimens were rinsed with distilled water and dried using a LABSC-D636 specimen drier. Microstructural analysis was performed using scanning electron microscopy (SEM) at various magnifications, as well as optical microscopy (MTM-1A). Coating thickness was measured using a thickness gauge (2103G933), and the average thickness was calculated based on three readings per sample. The Ra parameter (arithmetic mean roughness) was used to characterize surface roughness, measured using a portable contact profilometer (ISR-C300, separable type).

Adhesion strength was evaluated using a Posi Test AT-M pull-off tester. Steel dollies were bonded to the coated surfaces with strong epoxy adhesive, and a perpendicular tensile force was applied to detach the coating from the substrate. The adhesive strength was recorded as the force required for detachment. Microhardness was assessed using a digital micro-Vickers tester (TH714) in accordance with ASTM E384. A 500 g load was applied for 15 seconds. To evaluate wear resistance, A dry wear test was conducted Pin on Disc the disc steel (HRC52) to evaluate the resistance of the coated surfaces against friction under dry conditions. The wear rate was calculated using a load (10 N) for 10 min, and using the standard formula (ASTM G99-05, 2005):

$$W.R = \frac{\Delta W}{\pi \times D \times t \times N} \qquad \text{.............eq(1)}$$

Where ΔW = Change in weight (g); W0 = Original weight before wear (g); W1 = Weight after wear (g); π = 3.14; D = Disc diameter (cm); t = Duration of test (min); N = Rotation speed (rpm).

Results

Microstructure

The microstructure of steel 304 was evaluated after surface preparation using an optical microscope (OPM). It can be depicted that austenite (γ-Fe) and twinning were observed in some grains. as shown in Figure 1.

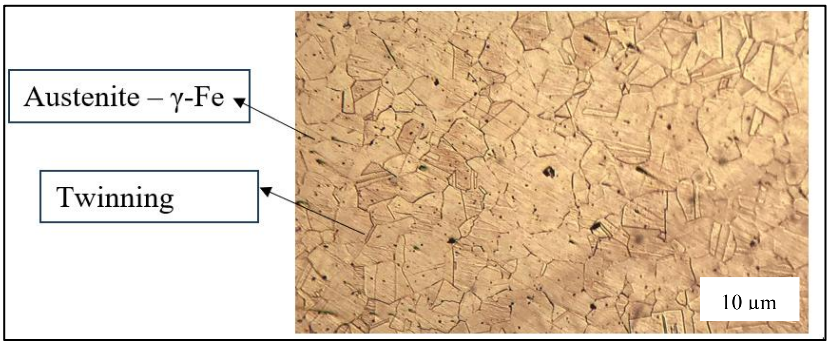


Figure 1. The OPM image reveals the microstructure of the stainless steel 304 substrate.

The XRD pattern confirms a face-centered cubic (FCC) structure, typical of austenitic γ-Fe in AISI 304 stainless steel. The sharp peak at 2θ ≈ 44.5° corresponds to the (111) plane, with additional peaks at ≈ 50.7° and ≈ 74.6°

matching the (200) and (220) planes. These results indicate a stable, well-crystallized FCC phase with no significant transformation or oxidation, ensuring good corrosion resistance and mechanical reliability as illustrated in Figure2.

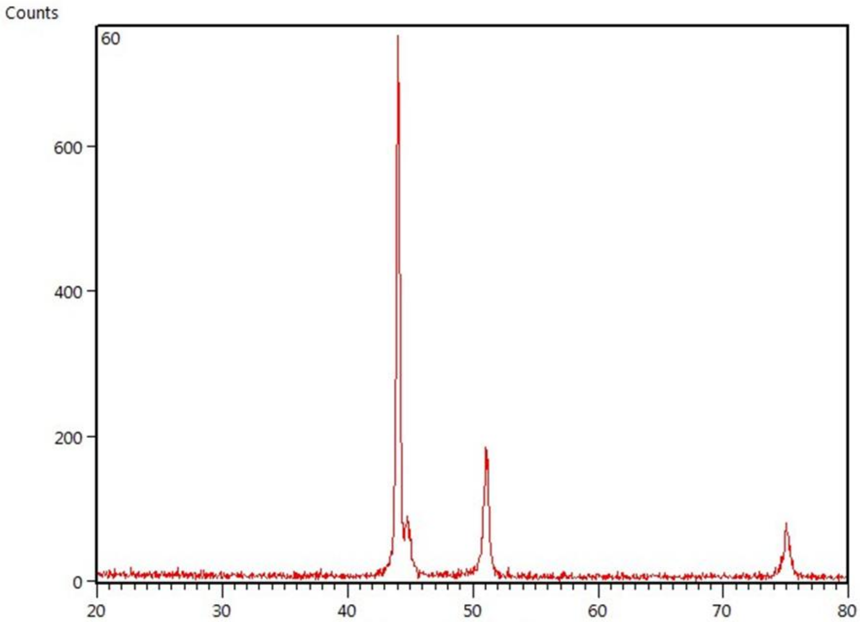
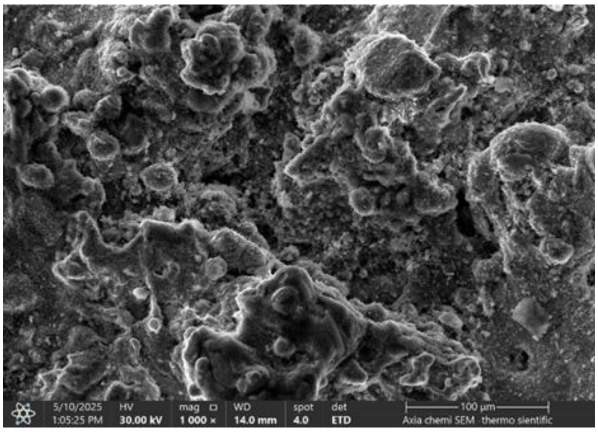
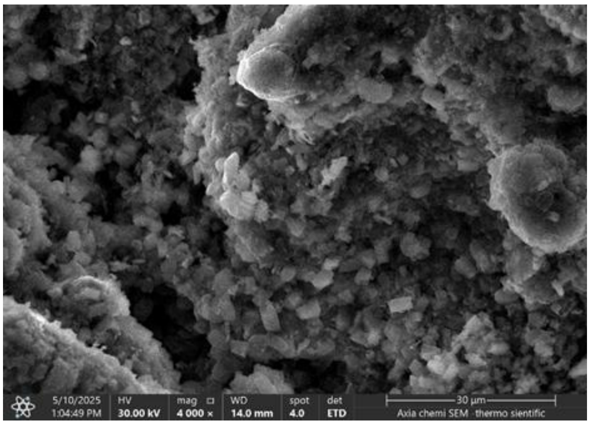


Figure2. X-ray diffraction of stainless steel 304 substrate that shows the microstructure phases (γ-Fe).

The coatings created by twin wire arc spraying exhibit a rough surface morphology with thin, tightly packed polyhedral to subcubic particles, as determined by SEM and EDS investigations. Rapid solidification and fast cooling rates during spraying limit grain expansion and encourage the creation of thin crystalline phases, resulting in this microstructure, which is clearly visible at a spraying distance of 150 mm in Figure 3. These characteristics align with earlier research indicating enhanced coating qualities as a result of the uniform and refined structure attained by rapid thermal quenching (GRANT, 2007).



(a)



(b)

Figure 3. Scanning electron microscope image of the coating layer on stainless-steel substrate.

Table 3. EDX analysis of stainless-steel substrate coating layer.

Element	Atomic %	Weight %
O	51.3	26.9
Al	11.4	10.1
Si	4.7	4.3
Cr	7.8	13.3
Mn	1.7	3.1
Fe	23.1	42.3

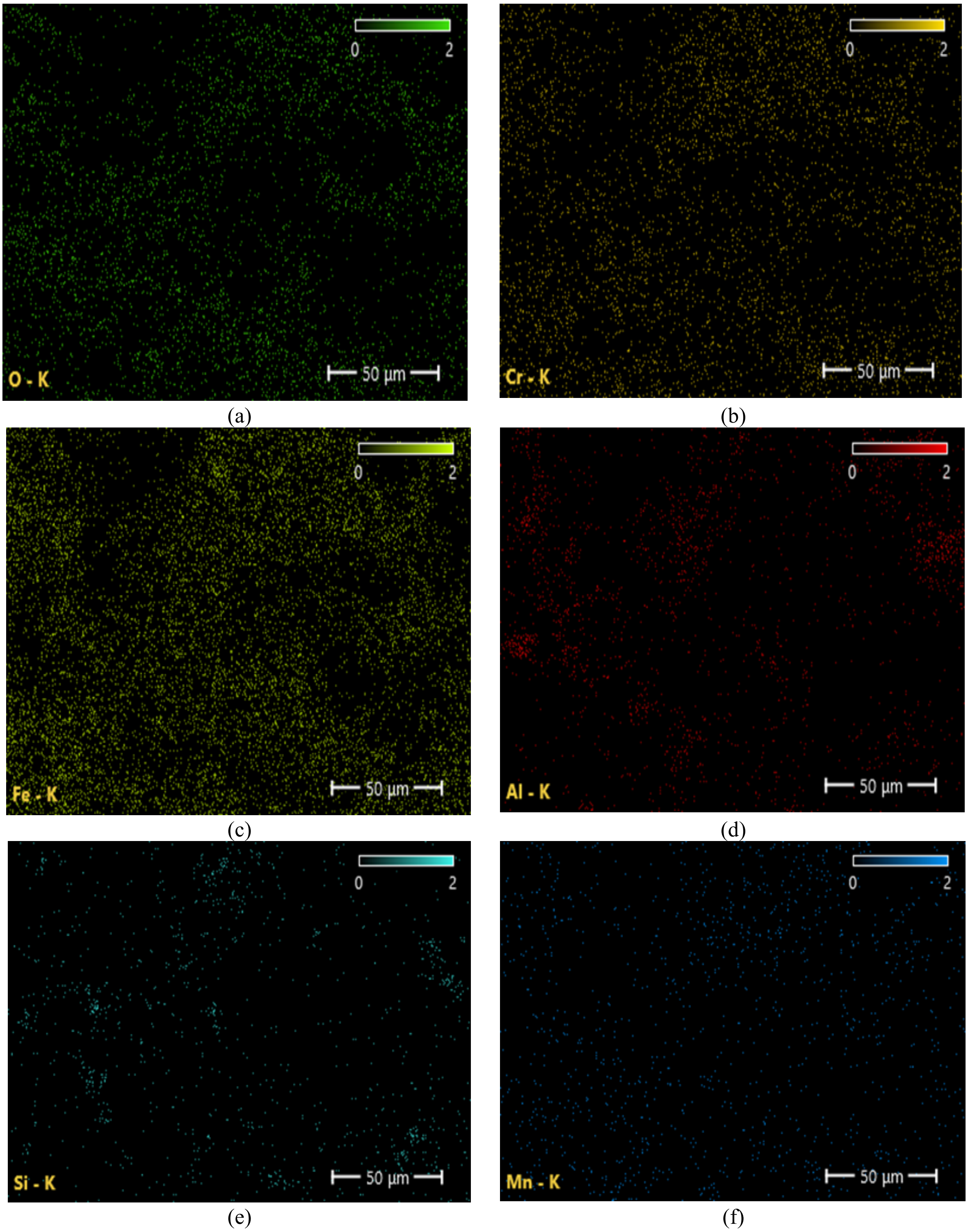


Figure 4. Morphology and elemental distributions measured by SEM/EDX of the coating layer on stainless-steel substrate.

(EDS) Analysis of the coated surface reveals the presence of several key elements, including iron (Fe), chromium (Cr), manganese (Mn), aluminum (Al), silicon (Si), and oxygen (O), illustrated in Table 3. Iron is the dominant element, consistent with the base material and feedstock wire composition. The detection of Cr and Mn indicates that the coating potentially offers better corrosion protection and better mechanical performance, whereas the detection of Al and Si might suggest oxide formation or likely contamination while spraying. The level of oxygen indicates extensive oxidation during the thermal spray processing, which is a common phenomenon applicable to arc spraying within atmospheric conditions. The oxide phase formation might have an effect on the coating's hardness and adhesion. The general elemental distribution confirms the detection of fine polyhedral particles from the SEM images, which are commonly associated with solidification on a fast scale and partial oxidation (Gan & Berndt, 2013).

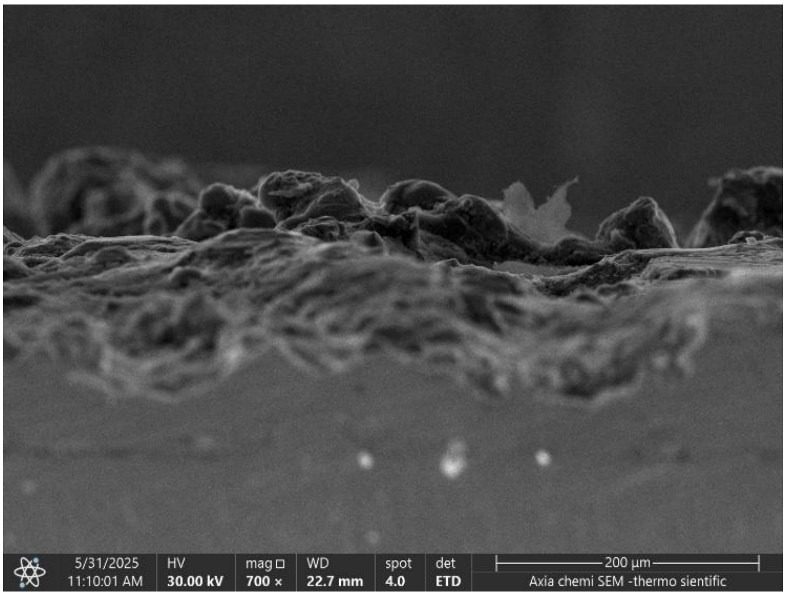


Figure 5. SEM of a cross-section of stainless steel and coating layer thickness 531µm at 15 cm spray distance.

The image of SEM for the cross-section shows good proof of the best deposition parameters resulting in a fine microstructure, which is evident from Figure 5. The compacted microstructure and even dispersion of the particles favorably to the mechanical integrity and characteristics of the coating. Also, the fact that no extensive voids or delamination areas are evident within the monitoring location testifies to the fact that there was good adhesion between splats and a coating structure that was relatively uniform. This morphology is favorable for corrosion and wear resistance, aligning well with the intended functional performance of the coated layer. The presence of faceted, polyhedral particles is consistent with rapid solidification behavior typically reported in literature for arc-sprayed coatings. This structure is expected to enhance the mechanical stability and environmental durability of the applied layer.

Thickness and Roughness

At various spray operating distances, the coating thickness and surface roughness (Ra) of FP5045 stainless steel wire coatings applied to stainless steel 304 substrates using the Twin Wire Arc Spraying (TWAS) technique were assessed. Table 4 summarises the findings.

Table 4. Spray distance, surface roughness (Ra), and coating thickness on stainless steel substrate.

Spray Distance (cm)	Ra (µm)	Thickness **(**µm**)**
10	10.660	484.0
15	30.354	529.6
20	25.743	531.0
30	21.097	264.3

Reveal that the spray distance strongly influences both parameters. The surface roughness exhibited a clear nonlinear trend concerning spray distance. At a short distance of 10 cm, the roughness was relatively low (Ra = 10.660 µm) due to the high temperature and velocity of the molten particles, which promotes extensive splat flattening and a smoother surface finish. Increasing the spray distance to 15 cm resulted in a significant rise in roughness to 30.354 µm, indicating the best balance between particle temperature and solidification rate, which encourages more aggressive particle impact and surface texturing. Beyond this point, further increases in spray distance to 20 cm and 30 cm led to a gradual decline in roughness values (25.743 µm and 21.097 µm, respectively), which can be attributed to particle cooling and partial oxidation during extended flight time, reducing their impact energy and surface deformation capability.

A similar dependency was observed for coating thickness. The maximum thickness was recorded at 15 cm and 20 cm (529.6 µm and 531 µm, respectively), while the thickness at 10 cm was slightly lower (484 µm). At the longest spray distance of 30 cm, a significant decrease in coating build-up occurred (264.3 µm). These variations can be explained by the behavior of molten particles during flight: at shorter to moderate distances, particles retain sufficient thermal and kinetic energy to flatten and stack effectively, resulting in higher deposition efficiency and thicker coatings. At excessive distances, particles lose energy due to cooling and oxidation, reducing deposition efficiency. Overall, these results demonstrate that a moderate spray distance around 15 cm provides the best conditions for achieving both average surface roughness and significant coating thickness, which are desirable for promoting good mechanical interlocking and adhesion. These findings are consistent with previous studies highlighting the importance of controlling spray parameters to tailor coating morphology and performance. These results agree with (Yan et al., 2025) , who found that changing the spray distance affects the structure and properties of arc-sprayed stainless steel coatings.

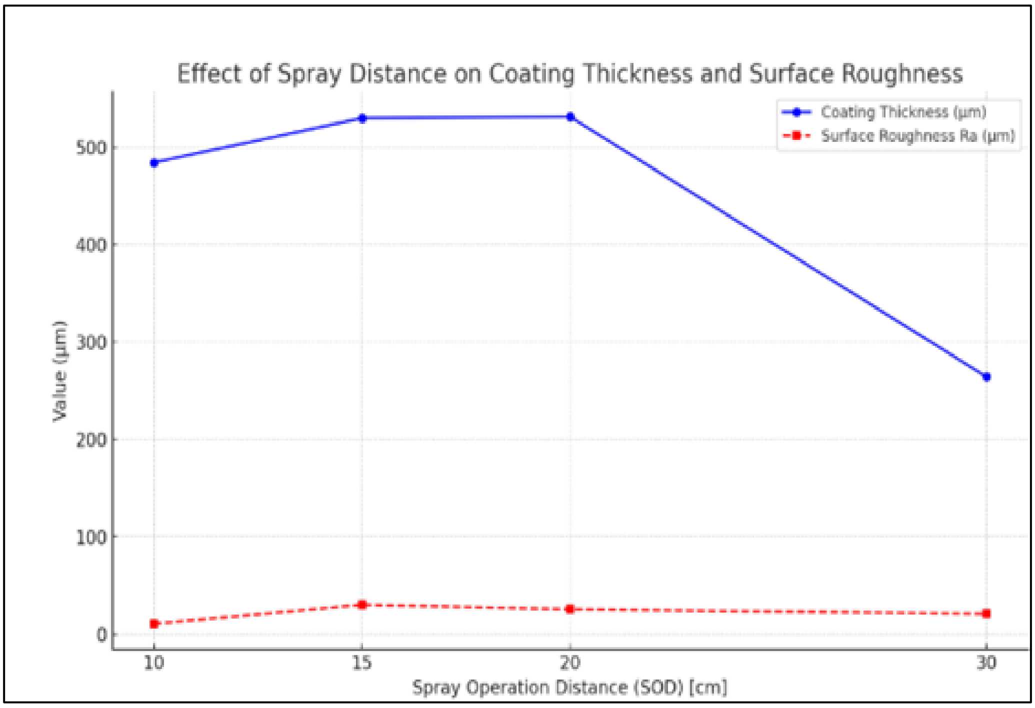


Figure 6. Variation of coating thickness and surface roughness with spray distance for coating on stainless steel 304.

Hardness and Adhesion Strength

Vickers microhardness is used to evaluate the tracks before and after TWAS on substrates that are done at various distances from the spray the test done by applaying 500-g load for 15 seconds . The hardness increased after applying wire arc spray, as shown in Table 5.

Table 5. The microhardness results at each spray distance, vickers microhardness analysis.

Hardness (Hv) of Substrate as base metal	Spray Distance (cm)	Hardness result (Hv)
	10	257.7
176.8	15	367.3
	20	261.5
	30	302.8

All recorded microhardness values after the coating process were higher than those of the stainless steel 304 substrate, with the highest value observed at a spray distance of 15 cm. This increase in hardness is consistent with findings reported by (Ismail et al., 2024), who showed enhancements in mechanical properties of coatings deposited via TWAS depending on process parameters.

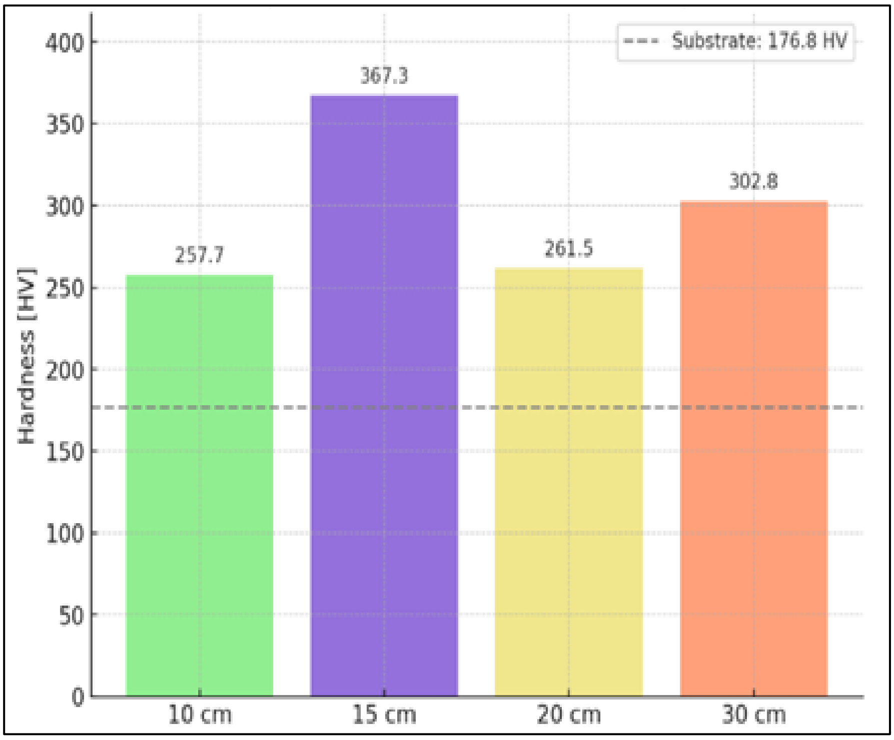


Figure 7. The microhardness results, vickers microhardness analysis.

The adhesion electricity (Lod) of the chrome steel (FP5045) cord coatings deposited by using Twin Wire Arc Spraying (TWAS) on chrome steel 304 substrates at one of the kind spray distances is summarized in Table 6. The effects indicate that adhesion is considerably influenced by the spray distance.

Table 6. Adhesion strength (Lod, psi) of arc-sprayed coating on stainless steel 304 at different spray distances.

Spray distances (cm)	MPa
10	10.81
15	14.14
20	10.69
30	9.89

The maximum adhesion was determined at a spraying distance of 15 cm, attaining 14.14 MPa. This indicates that this distance creates the best conditions for strong mechanical interlocking and proper deposition of the particles. At this point, the particles retain sufficient heat and velocity to bond effectively with the substrate surface. It was observed that at a distance of 20 cm, the adhesion decreased to 10.69 MPa. As the distance increased, the adhesion decreased. Similarly, at 30 cm, the adhesion decreased to 9.89 MPa. This is likely due to the particles losing heat and oxidizing during their longer flight, which reduces their bonding capacity. These results are consistent with previous studies by (Hussein Ataiwi, 2008; Zhang et al., 2015), which confirmed that there is an optimal spray distance for strong bonding; distances that are too short or too long tend to weaken adhesion due to poor interaction between particles and the substrate. This concept is also supported by (Arif et al., 2020), who highlighted the critical role of spray parameters especially spray distance in controlling adhesion strength. Moreover, the outcomes align with the work of (Ismail et al., 2024; Rakhadilov et al., 2024), who emphasized the importance of an optimal spray distance to achieve strong bonding and warned against the negative effects of inappropriate distances on adhesion.

Wear Behavior

The wear performance of the coating applied using the Twin Wire Arc Spraying (TWAS) technique on stainless steel 304 substrates was evaluated under dry sliding conditions. The test was conducted using a disc with a diameter of 14 cm, a duration of 10 minutes, and a rotational speed of 490 rpm. The wear rate was calculated based on weight loss measurements taken before and after the test, following the ASTM G99-05 standard, as shown in Table 7. The results demonstrate that the coating offers significant resistance to frictional wear, indicating the effectiveness of the TWAS process in enhancing surface durability under operational conditions.

Table 7. Wear results of the coating layer on stainless steel substrates.

Spray distance (cm)	W0 (g)	W1 (g)	ΔW	W.R (g/cm)
10	57.9632	57.9540	0.0092	4.27×10^{-8}
15	59.2753	59.2701	0.0052	2.4×10^{-8}
20	56.7612	56.7501	0.0111	5.15×10^{-8}
30	38.8012	38.7851	0.0161	7.47×10^{-8}

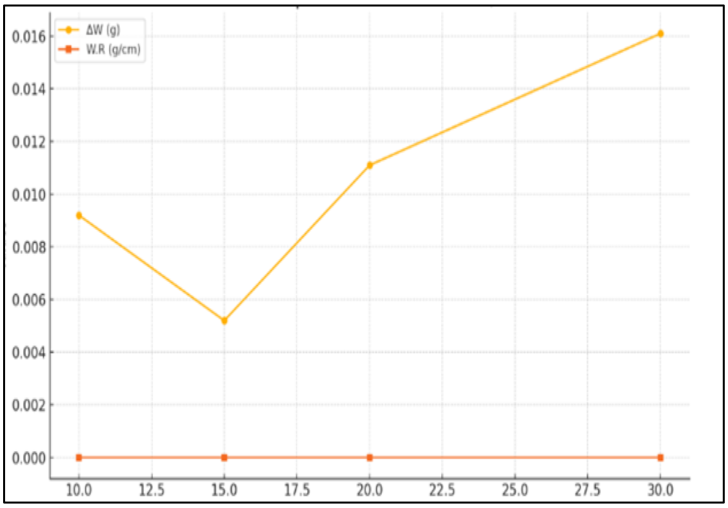


Figure 8. Relationship between spray distance and wear results

Conclusion

1. The findings demonstrate that a moderate spray distance of 15 cm provides the most favorable balance among all tested parameters, showing that the microhardness peaked at 367.3 HV, significantly higher than that of the base metal, and the adhesion strength reached its maximum at 2051 psi, confirming robust bonding between the coating and the substrate.
2. The wear rate was the lowest at this distance (2.4×10^{-8} g/cm), indicating excellent resistance to material loss under dry friction conditions. These results suggest that the balance between particle energy, temperature, and solidification rate at 15 cm best the deposition efficiency and microstructural quality of the coating layer.
3. At same distance 15 cm, maximum coating thickness (529.6 µm), the coating was achieved the average surface roughness (Ra = 30.354 µm). The lowest surface roughness was recorded at the shortest spray distance of 10 cm, which can be attributed to the higher particle temperature and velocity, resulting in smoother layer formation.
4. Selecting an appropriate spray distance is crucial for tailoring coating performance to meet the desired mechanical and tribological properties. Among the distances investigated, 15 cm was identified as the best condition for achieving a coating with superior hardness, strong adhesion, suitable roughness for interlocking, and improved wear resistance. This highlights the importance of carefully controlling spraying parameters to ensure high-quality coatings for industrial applications.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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