Effect of voltage and spray–off distance of electric-arc spray technique on surface properties of nickel–chrome (Ni–Cr) coating developed on 304L stainless steel

A Inam, M A Raza, M A Hafeez, S B Shah, M Ishtiaq, M H Hassan, M Irfan, A Nasik, I Siddique, O M Butt, A Maqbool and W Haider

1 Department of Metallurgy & Materials Engineering, CEET, University of the Punjab, Lahore-54590, Pakistan
2 Department of Electrical Engineering, CEET, University of the Punjab, Lahore-54590, Pakistan
3 Department of Metallurgical & Materials Engineering, University of Engineering and Technology, Lahore, Pakistan
4 School of Engineering and Technology, Central Michigan University, Mount Pleasant, MI 48858 United States of America
5 Author to whom any correspondence should be addressed.
E-mail: aqil.ceet@pu.edu.pk

Keywords: nichrome coating, stainless steel, hardness, surface roughness, coating thickness, LOM, SEM

Abstract
Nickel–chrome coatings are widely used to improve surface properties and service life of engineering components made from different ferrous and non-ferrous alloys. Herein, an attempt has been made to investigate the impact of various voltages ranging from 26–30 V and spray–off distances ranging from 100–300 mm of electric-arc spray technique on the surface properties of Ni–Cr coating developed on 304L stainless steel. Thickness, porosity, surface morphology, surface roughness, and hardness of Ni–Cr coatings were determined to study the impact of deposition parameters. Coating deposition at 26 V exhibited the lowest porosity and the highest percentage of Cr nodules among all samples. The comparison study showed that coating deposit developed at 26 V and 100 mm spray–off distance has a maximum thickness, followed by coating developed at 30 V and 100 mm spray–off distance. This indicated that coating deposit developed at 100 mm spray–off distance results in thicker coatings. Maximum hardness was achieved at 30 V and 300 mm spray–off distance. The shorter spray–off distance revealed that coatings tend to be thicker and harder resulting in longer coating life.

1. Introduction
Low carbon low alloy steel components i.e. boiler components, engine, waste incinerator, gas turbine, and other thermal power plant components could fail early due to corrosion reactions or mechanical wear in intense service environments i.e. high temperature and pressure [1–4]. Thus, there is a need to protect their surfaces to avoid degradation mechanisms and failures [5]. Several coating techniques have been developed to enhance the service life of engineering components. These coating techniques include electric-arc spray deposition [6], electric-arc wire spraying, detonation gun spraying, high-velocity oxy-fuel spraying (HVOF) [7], and plasma spraying technique [8]. These processes are different in terms of their particle speed, temperature, spraying atmosphere, and coating properties i.e. morphology, porosity, bond strength, thickness, hardness, and oxide content [9–15]. Among all, electric-arc spray deposition technique is receiving much attention over the past few years. It is a widely used technique having the ability to deposit a variety of materials i.e. metals, ceramics, cermets and polymers. These coating materials are used in the form of wire, rod, or powder and melted to molten or semi-molten form to spray onto the surface of a component at high velocity with a spray gun [14].

Electric-arc spray technique is a low energy technique which uses a combustible gas as a heat source to melt the coating material. Electric-arc temperature ranges from 2500–3000 K and depends on oxygen to fuel ratio and pressure. The particle velocity achieved during this process is near to 100 m s\(^{-1}\) [14]. This process is characterized by the low capital investment, high deposition rate, low equipment cost, narrower working temperature range, thicker coatings, lower bond strength, adhesion strength, and oxide content between (6%–12%) [15–18]. However, these
properties can be further improved by the correct selection of the coating parameters. Voltage and spray–off distance are very important parameters for the deposition of good coatings, and in turn increasing service life of an engineering component [9]. By controlling these parameters, electric-arc spray deposition process can be optimized.

In current work, 304L stainless steel was used as a substrate and the impact of various voltages and spray–off distances of electric-arc spray technique on surface properties of Ni–Cr coating developed on 304L stainless steel was investigated. Morphological analysis was performed to evaluate the impact of these parameters on surface morphology and coating thickness. Coating roughness and hardness of Ni–Cr coating on 304L stainless steel were also determined.

2. Materials and methods

2.1. Materials

304L stainless steel having chemical composition, given in table 1 was obtained from Peoples Steel Mill Limited, Karachi, Pakistan. Stainless steel plates of dimensions $305 \times 305 \times 3$ mm were wire–cut into coupons of

![Figure 1. SEM micrographs showing Ni–Cr coating deposited on 304L grade stainless steel at 26 V and 100 mm spray–off distance; (a) cross–section, (b) surface morphology, 200 mm spray–off distance; (c) cross–section, (d) surface morphology, and at 300 mm spray–off distance; (e) cross–section, (f) surface morphology.](image-url)
dimension $100 \times 70 \times 3$ mm for subsequent coating deposition and characterization. Nichrome wires having 80% Ni and 20% Cr was deposited on 304L stainless steel substrate through electric-arc spray technique.

### 2.2. Deposition procedure

Stainless steel coupons of dimensions $100 \times 70 \times 3$ mm were subjected to grit blasting to get adequate surface roughness of 5–6 μm by using alumina grits of particle size $\sim 5 \mu m$. Grit blasting was performed at a gun angle of 45°–90°, pressure 6 bar and gun distance of 50–100 mm. After grit blasting, air cleaning was carried out to remove all the left–over dust particles. After ultrasonic bath cleaning, samples were coated with Ni–Cr material using Sulzer Metco brand value LCAE (2004) S. No. GLCAE 100407-1 arc spraying system attached with a gun at various spray–off distances and various voltages given in table 2. Coatings were deposited by placing coating gun at an angle of 90° through 4–6 numbers of passes.

### 2.3. Characterization

Then the samples were wire–cut into size of $10 \times 10 \times 3$ mm for metallography. The samples were then ground using SiC grinding papers followed by polishing on Nylon and Velvet cloths using diamond pastes of

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**Figure 2.** SEM micrographs showing Ni–Cr coating deposited on SS–304L grade stainless steel at 28 V and 100 mm spray-off distance; (a) cross–section, (b) surface morphology, 200 mm spray–off distance; (c) cross–section, (d) surface morphology, and at 300 mm spray–off distance; (e) cross–section, (f) surface morphology.
grade 6, 3, 1 and 0.25 μm. Scanning electron microscope FEI brand model Inspect S50 was used to analyze the surface and cross–sectional morphology of coating deposit. Elemental composition and distribution of these coating elements were also characterized by spot analysis and EDS–mapping techniques using energy dispersive spectrometer attached with SEM. Coating thickness from light optical micrographs (captured by Leica Model DM 15000 M optical microscope) of each sample was measured by Gatan Digital Micrograph software. Average of three coating thickness values obtained from three different points of the coating cross–section was taken as

| Cr   | Ni  | O  | Fe  |
|------|-----|----|-----|
| 17.35| 8.58| 1.31| 74.35|

Figure 3. SEM micrographs showing Ni–Cr coating deposited on 304L stainless steel at 30 V and 100 mm spray off distance; (a) cross–section, (b) surface morphology, 200 mm spray–off distance; (c) cross–section, (d) surface morphology, and at 300 mm spray–off distance; (e) cross–section, (f) surface morphology.
thickness for each sample. Moreover, the hardness of the coating was measured using Insize ISH–R150 Rockwell hardness tester using steel ball indenter of 1/16 inch diameter. After coating, the surface roughness of the coated samples was measured using Surfcorder SE1700α surface profilometer equipped with a diamond tip of 2 μm radius operated at a speed of 1 mm sec⁻¹ for a length of 4 mm.

3. Results and discussion

3.1. Coating morphology

Ni–Cr coating was deposited on stainless steel plate by electric-arc spray technique under various voltages and spray–off distances. SEM–SEs images of cross–sectional and coating surfaces developed under various coating parameters are illustrated in figures 1–3. Whereas, the corresponding EDS spectra and EDS–maps of Ni–Cr coatings deposited at 30 V and various spray–off distances are also presented in figures 4–5. The morphologies of almost all the coatings comprised of lamellar with little porosity, few un–melted and semi-melted particles,
oxide inclusions and pores are visible as previously reported [19–23]. The interface between the coating and the substrate is clearly visible in all micrographs. In the SEM-SEs images, there are black spots presenting nodules of chromium, visible in figures 1–3.

A very thick Ni–Cr coating deposit was achieved at 26 V and 100 mm spray–off distance having a large number of Cr nodules and a smaller percentage of porosity as visible in figures 1(a)–(b). The reason behind the development of thickest coating is the minimum distance between the electric-arc spray gun and substrate. With further increase in the spray–off distance to 200 and 300 mm the percentage of porosity was increased and the number of Cr nodules was decreased as revealed in figures 1(c)–(f).

Coating achieved at 28 V and 100 mm distance possessed moderate porosity and Cr nodules in the matrix compared to other samples as revealed in figures 2(a)–(b). The reason behind the development of coating with moderate thickness is the minimum distance between the electric-arc spray gun and substrate and moderate voltage value. With further increase in spray–off distance to 200 and 300 mm, the percentages of porosity and Cr nodules were decreased compared to 100 mm distance but increased compared to 26 V and 200–300 m distance coatings as revealed in figures 2(c)–(f).

Coating achieved at 30 V and 100 mm distance possessed moderate Cr nodules in the matrix and highest porosity compared to other samples as revealed in figures 3(a)–(b). EDS spectrum of this sample validated the deposition of Ni–Cr and the presence of Cr nodules in the matrix by exhibiting 72.15% Ni and 16.98% Cr (figure 3(a)). EDS–map demonstrated the non–uniform distribution of Cr in the matrix of Ni as illustrated in figure 5(a). This is due to the fact that high voltage melts the Ni–Cr metal properly and accelerates the metal particles toward the substrate in a better way.

With further increase in the spray–off the distance to 200, the percentages of porosity and Cr nodules were decreased compared to 100 mm distance as visible in figures 3(c)–(d). EDS spectrum validated this fact by exhibiting reduced percentage of Cr (11.38%) in the spectrum (figure 3(b)). Whereas, EDS E–map presenting that the distribution of Cr in the matrix is still non–uniform throughout the coating surface (figure 5(b)).

Ni–Cr coating deposited at 30 V and 300 mm spray–off distance exhibited increased quantity of nodules compared to 100 and 200 mm distances (figures 3(e), (f)). Increased percentage of Cr (17.36%) in EDS spectrum is validated this fact (figure 4(d)). SEM EDS E-mapping exhibited that this coating has the most uniform distribution of all elements throughout the surface among all samples (figures 5(e), (f)).

### 3.2. Coating thickness

Light optical micrographs used for measuring Ni–Cr coating thickness are illustrated in figure 4 whereas; variations in Ni–Cr coating thickness with varying voltages and spray–off distances are plotted in figure 5. It was observed that coating developed at 26 V and 100 mm spray–off distance exhibited a significantly thick coating deposit of 200 μm. Increasing spray–off distance up to 200 and 300 mm significantly drop in the coating thickness up to 55 and 33 μm, respectively.

On the other hand, Ni–Cr coatings deposited at 28 V with varying spray–off distances demonstrated inverse behavior. At 100 and 200 mm spray–off distance, 81% and 58% reduction in coating thicknesses, 38 & 23 μm, respectively whereas, at 300 mm distance, 67% improvement in coating thickness, 55 μm were achieved, respectively.

Coating deposited at 30 V resulted in moderate coating thickness values under varying spray–off distances in comparison to other deposition voltages. At this voltage, 100 mm, spray–off distance produced Ni–Cr coatings with 47% reduction in thickness, 105 μm whereas; 200 mm spray–off distance caused significant improvement,
36% in thickness comparison to coating produced at 26 V and 200 mm spray–distance. Comparatively, very thin coating with a thickness of 15 μm was achieved at 300 mm spray–off distance.

The comparative study showed that the coating developed at 26 V and 100 mm spray–off distance resulted in maximum thickness, which is being followed by coating developed at 30 V and 100 mm spray–off distance. This indicates that coating developed at 100 mm spray–off distance results in thick coating deposits.

Table 3. Surface roughness Ry and Rz* of Ni–Cr coatings deposited on 304L stainless steel.

| Spray–off distance (mm) | Voltage (V) | Ry (μm) | Rz* (μm) |
|------------------------|-------------|---------|----------|
| 100                    | 26          | 68.04   | 46.20    |
| 200                    | 26          | 42.26   | 30.20    |
| 300                    | 26          | 53.24   | 40.40    |
| 100                    | 28          | 87.64   | 57.69    |
| 200                    | 28          | 70.27   | 48.32    |
| 300                    | 28          | 63.52   | 46.51    |
| 100                    | 30          | 98.81   | 76.17    |
| 200                    | 30          | 74.98   | 58.76    |
| 300                    | 30          | 61.32   | 44.80    |

Figure 5. SEM–EDS maps of Ni–Cr coatings deposited on 304L stainless steel at 30 V and spray–off distance (a) and (b) 100 mm, (c) and (d) 200 mm, and (e) and (f) 300 mm of electric–arc spray gun.
3.3. Surface roughness

Average surface roughness (Ra) values of Ni–Cr coatings deposited on 304L stainless steel under various voltages and spray–off distances are plotted in figure 6 whereas, corresponding Ry and Rz* are given in table 3. The coating developed at 26 V and 100 mm spray–off distance exhibited an average roughness of 13.51 μm, which implies that the surface of the coating is not very smooth and there in non-uniformity in the coating deposit. While the coatings developed at 200 and 300 mm spray–off distances showed 8.99 and 10.06 μm roughness presenting relatively smooth surface than 100 mm spray–off distance deposit surface.

**Figure 6.** Light optical micrographs showing thickness of Ni–Cr coatings deposited on 304L stainless steel at (a) 26 V and 100 mm distance, (b) 26 V and 200 mm distance, (c) 26 V and 300 mm distance, (d) 28 V and 100 mm distance, (e) 28 V and 200 mm distance, (f) 28 V and 300 mm distance, (g) 30 V and 100 mm distance, (h) 30 V and 200 mm distance, and (i) 30 V and 300 mm distance.

**Figure 7.** Plot of average coating thickness produced on 304L stainless steel at various voltages and spray off distances.
Ni–Cr coatings deposited at 28 V and varying spray–off distances were observed to be rougher than the coating deposited at 26 V. Coating produced at this voltage and 100 mm of spray–off distance offered relatively rough surface having 17.94 μm roughness compared to coating produced at 26 V and 100 mm distance. Distance of 200 mm offered 48.83% rougher coating surface (13.38 μm) than coating produced at 26 V and 200 mm whereas, 300 mm distance developed 22.76% rougher surface (12.35 μm) than coating surface produced at 26 V and 300 mm distance. This fact indicates that the surface is non–uniform, which is due to the presence of un–melted deposit particles.

Coating produced at 30 V and 100 mm spray–off distance exhibited rough surface having 20.18 μm roughness, while 200 mm distance developed relatively smooth surface (14.27 μm). Spray–off distance of 300 mm produced the smoothest surface among all samples exhibiting 12.02 μm surface roughness.

3.4. Coating hardness
Rockwell hardness of Ni–Cr coated 304L grade stainless steel was observed to be highly sensitive to voltage and spray–off distance of deposition gun. Variations in Rockwell hardness of Ni–Cr coating with varying voltage and spray–off distance are plotted in figure 7. Coatings deposited at 26 V exhibited lowest hardness values at all spray–off distance among all voltages. At 100, 200, and 300 mm distance, these coatings resulted in hardness 41, 53, and 45 HRF values, respectively.
Coatings produced at 28 V were observed to have moderate hardness values at all spray-off distances. Coatings deposited at 28 V and 100 mm spray-off distance exhibited 46% improvement, at 200 mm showed 18% whereas, 300 mm distance showed 6% improvement in hardness value compared to coatings deposited at 26 V. Deposition process involving 30 V and various spray-off distances exhibited the highest hardness values among all samples. Coatings deposited at this voltage and 100 mm spray-off distance showed 59% improvement, 200 mm showed 13% improvement, and 300 mm showed 53% improved and highest hardness among all samples. The hardness acquired is associated with the material deposited and the values acquired are similar to data available in the scientific literature for thermal spray coatings [24–26].

4. Conclusions

Following were the extracted conclusions from this work;

Thicker and harder coatings are developed using small spray-off distances at three of the selected voltages. Coating developed at 28 V using 100–300 mm spray-off distances showed more roughness than the rest of the two opted voltages. While coating developed at 30 V using 100–300 mm spray-off distances show less roughness and 26 V has roughness intermediate of the rest of the two. While coating developed at 8 inch spray-off distance shows less roughness which is followed by 300 mm and then 100 mm. Considering thickness, hardness and roughness of the coating, it is concluded that the Ni–Cr coating developed at 30 V and 200 mm spray-off distances on 304L stainless steel shows a good combination of properties. It shows good thickness and hardness with less–surface roughness. Hence, we can conclude that coating at 100 mm distance helps to develop thick coatings resulting in long service life. SEM EDS E–mapping exhibited that this coating has the most uniform distribution of all elements throughout the surface among all samples (figures 5(e), (f)) developed at 30 V and spray-off distance of 300 mm.

ORCID iDs

A Inam https://orcid.org/0000-0001-6112-6131
M A Raza https://orcid.org/0000-0002-3496-0283
M A Hafeez https://orcid.org/0000-0001-7337-7595
W Haider https://orcid.org/0000-0003-4235-3560

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