

ORIGINAL STUDY

EFFECT OF FLAME-SPRAYING TEMPERATURE ON THE PROPERTIES OF Ni–Cr–B–Si-BASED SELF-FLUXING COATINGS

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Abstract. The present study investigates the effect of flame-spraying process parameters on the microstructure and mechanical properties of Ni–Cr–B–Si-based self-fluxing coatings. Corrosion-resistant AISI 321 austenitic chromium–nickel steel was used as the substrate material. The coatings were deposited by flame spraying using a Metal Coat 6PM-II system. To vary the thermal conditions of the spraying process, the oxygen-to-acetylene (O_2/C_2H_2) ratio was adjusted to 1.0, 1.1, and 1.2. The spraying parameters were monitored using an Accuraspray 4.0 diagnostic system. The resulting coatings were characterized in terms of microstructure, porosity, microhardness, surface roughness, and adhesion strength. Increasing the O_2/C_2H_2 ratio resulted in densification of the coating structure and a decrease in porosity from $1.97 \pm 0.13\%$ to $0.90 \pm 0.09\%$. Concurrently, the surface roughness decreased from $4.70 \pm 0.09 \mu m$ to $2.99 \pm 0.11 \mu m$, while the adhesion strength increased from $22.14 \pm 4.3 MPa$ to $35.02 \pm 3.9 MPa$. The highest average microhardness of 1051.7 HV was obtained at an O_2/C_2H_2 ratio of 1.1. Among the investigated spraying conditions, the coating produced at $O_2/C_2H_2 = 1.2$ exhibited the lowest porosity and surface roughness together with the highest adhesion strength. The results demonstrate that controlling the O_2/C_2H_2 ratio provides an effective means of tailoring the microstructural and mechanical characteristics of flame-sprayed Ni–Cr–B–Si-based self-fluxing coatings.

Keywords: flame spraying; self-fluxing alloy; Ni–Cr–B–Si; AISI 321; mechanical properties.

1. Introduction

Metal components operating in the power engineering industry are exposed to severe degradation factors, including elevated temperatures, oxidizing environments, high-velocity gas flows, and erosive attack [1]. Under such operating conditions, high-temperature corrosion develops on metallic surfaces, resulting in material loss, changes in component geometry, and deterioration of mechanical properties. Consequently, the degradation rate of equipment increases, its service life is shortened, and maintenance and repair costs rise.

One effective approach to addressing this problem is the formation of corrosion- and wear-resistant protective coatings on component surfaces. According to previous studies, nickel-based Ni–Cr–B–Si self-fluxing alloys are considered promising materials for coatings intended for high-temperature applications [2]. Chromium enhances oxidation and corrosion resistance, whereas boron and silicon promote the self-fluxing behavior of the alloy and facilitate the formation of a denser coating structure.

Various technologies are currently employed for the deposition of protective coatings, including plasma spraying, high-velocity oxy-fuel (HVOF) spraying, laser cladding, and flame spraying. Plasma and HVOF spraying can provide coatings with low porosity and high adhesion strength [3]. However, these processes generally require sophisticated equipment, relatively high energy consumption, and precise control of processing parameters. In addition, the high gas consumption, equipment cost, and maintenance requirements associated with HVOF technology may limit its economic feasibility for certain industrial applications [4].

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Flame spraying provides an alternative approach that enables coatings to be deposited using comparatively simple and cost-effective equipment. In this process, powder particles are heated by an oxy-acetylene flame and accelerated toward the substrate surface. The major advantages of this technology include relatively simple equipment design, operational flexibility, ease of process control, and its applicability to the repair and restoration of power engineering components [5].

Previous studies have demonstrated that as-sprayed NiCrBSi coatings produced by flame spraying may exhibit relatively high porosity and limited adhesion strength to the substrate. For example, subsequent remelting has been reported to reduce coating porosity from approximately 15% to 3%, while induction remelting can further decrease porosity to approximately 1% [6]. These findings demonstrate that coating quality depends not only on the chemical composition of the feedstock material but also on the appropriate selection and optimization of spraying parameters. Therefore, controlling the thermal conditions during flame spraying represents an important approach for improving coating formation without necessarily introducing additional post-deposition processing [7].

Accordingly, the aim of the present study is to investigate the flame-spray deposition of Ni–Cr–B–Si-based self-fluxing coatings intended to protect power engineering components against high-temperature corrosion and to determine the influence of the principal processing parameters on coating properties [8]. Particular attention is given to the effect of flame temperature on coating porosity, microhardness, surface roughness, and adhesion strength to the substrate [9].

The distinctive feature of this study is the systematic evaluation of the structural and mechanical characteristics of Ni–Cr–B–Si-based self-fluxing coatings through controlled variation of the flame-spraying parameters [10,11]. The relationships between spraying temperature and coating porosity, microhardness, surface roughness, and adhesion strength are investigated to identify processing conditions that provide a favorable combination of coating integrity and mechanical performance. The obtained results are intended to establish effective flame-spraying regimes for producing protective coatings suitable for components operating under high-temperature corrosive conditions.

The scientific and practical significance of this study lies in establishing technologically accessible and economically viable deposition conditions for producing protective coatings capable of improving the high-temperature corrosion resistance and extending the service life of power engineering components [12].

2. Materials and methods

Corrosion-resistant AISI 321 austenitic chromium–nickel stainless steel was used as the substrate material. Prior to flame spraying, the substrate surfaces were prepared to promote uniform coating formation and improve adhesion between the coating and the substrate. The specimens were initially ground using abrasive papers ranging from P100 to P600, followed by sandblasting. After mechanical surface preparation, the specimens were ultrasonically cleaned in ethanol for 10 min at a frequency of 40 kHz and a temperature not exceeding 35 °C to remove residual abrasive particles and processing contaminants. The cleaned specimens were subsequently dried and prepared for the flame-spraying process.

Ni–Cr–B–Si-based self-fluxing powder coatings were deposited using a Metal Coat 6PM-II flame-spraying system. A schematic representation of the experimental setup is shown in Figure 1. The spraying system consisted of oxygen and acetylene cylinders equipped with pressure regulators, a compressed-air supply and control unit, gas supply lines, a flame-spray gun, and an MPF-700 powder feeder. Oxygen and acetylene were supplied separately to the flame-spray gun, where their combustion generated a high-temperature flame required for heating and melting the powder particles and accelerating them toward the substrate surface.

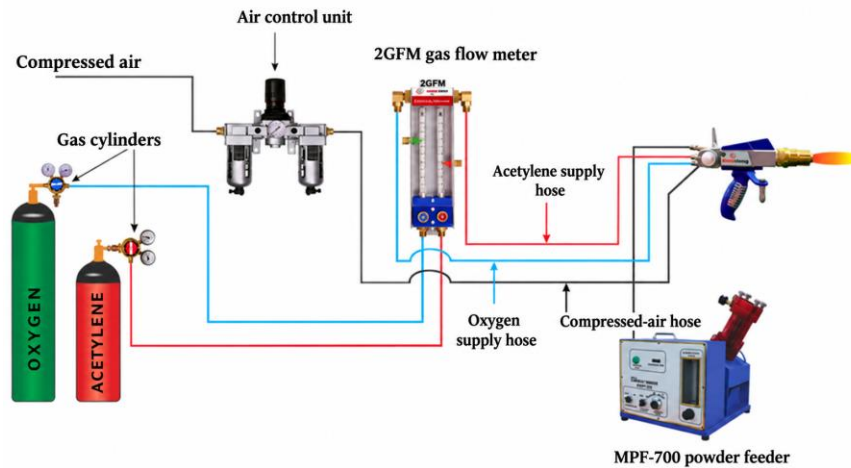


Fig. 1. Schematic diagram of the powder flame-spraying setup.

The thermal conditions of the flame-spraying process were controlled by varying the oxygen-to-acetylene (O_2/C_2H_2) ratio. Three O_2/C_2H_2 ratios of 1.0, 1.1, and 1.2 were investigated. The flame temperatures corresponding to the selected O_2/C_2H_2 ratios are presented in [Table 1](#).

The spraying process parameters were monitored using an Accuraspray 4.0 system. This system enabled non-contact monitoring of the thermal characteristics during flame spraying and ensured the stability and reproducibility of the selected processing conditions.

Table 1. Flame-spraying parameters.

Spraying condition	Flame temperature, °C	O_2/C_2H_2 ratio	Spray distance, mm	Carrier gas flow rate, NLPM
1	3800	1.0	150	20
2	4200	1.1		
3	4400	1.2		

Prior to coating deposition, the prepared AISI 321 steel substrates were preheated using the gas flame without powder feeding. Once the substrate reached the specified temperature, powder feeding was initiated using the MPF-700 powder feeder, and the coatings were deposited at the selected O_2/C_2H_2 ratios. The substrate temperature was monitored throughout the spraying process to maintain stable processing conditions for each experiment.

To objectively evaluate the effect of the O_2/C_2H_2 ratio on coating formation, the other principal spraying parameters were maintained constant. The microstructure, porosity, hardness, adhesion strength, and tribological properties of the deposited coatings were characterized using a comprehensive set of experimental techniques. Cross-sectional microstructural characterization was performed using an Olympus BX53M optical metallographic microscope. The obtained metallographic images were used to evaluate the microstructural features of the coatings, coating uniformity, the integrity of the coating–substrate interface, and porosity.

The adhesion strength of the coatings was determined using a Shimadzu AGS-X 100 kN universal testing machine. The tests were performed in accordance with ASTM C633, using a tensile method in which the coating was loaded normal to the substrate surface until failure occurred. The adhesion strength was calculated as the ratio of the maximum load at failure to the bonded area and was expressed in MPa.

The tribological properties of the coatings were evaluated using an Anton Paar TRB³ tribometer (Anton Paar GmbH, Austria) in a *ball-on-disk* configuration. A 100Cr6 steel ball with a diameter of 6 mm was used as the counterbody. The tests were conducted under a normal load of 10 N, a linear sliding velocity of 5 cm/s (0.05 m/s), and a wear-track radius of 2 mm. The total sliding distance was 100 m. During testing, the coefficient of friction was continuously recorded as a function of sliding distance to evaluate the friction and

wear behavior of the coatings. To ensure the reproducibility of the experimental results, tribological tests were performed three times ($n = 3$) for each coating under identical conditions. The coefficient of friction and wear rate are reported as the mean values obtained from three independent measurements.

3. Results and discussion

Prior to coating deposition, the AISI 321 steel substrates were preheated using a gas flame, followed by powder spraying under the selected processing conditions. Visual inspection confirmed the formation of continuous coatings over the substrate surface under all investigated spraying conditions.

To evaluate the effect of the flame-spraying conditions on the structural characteristics of the Ni–Cr–B–Si coatings, microscopic examination of the coating cross-sections was performed. Figure 2 presents the cross-sectional microstructures of the coatings deposited under different thermal conditions, together with the results of the quantitative porosity analysis.

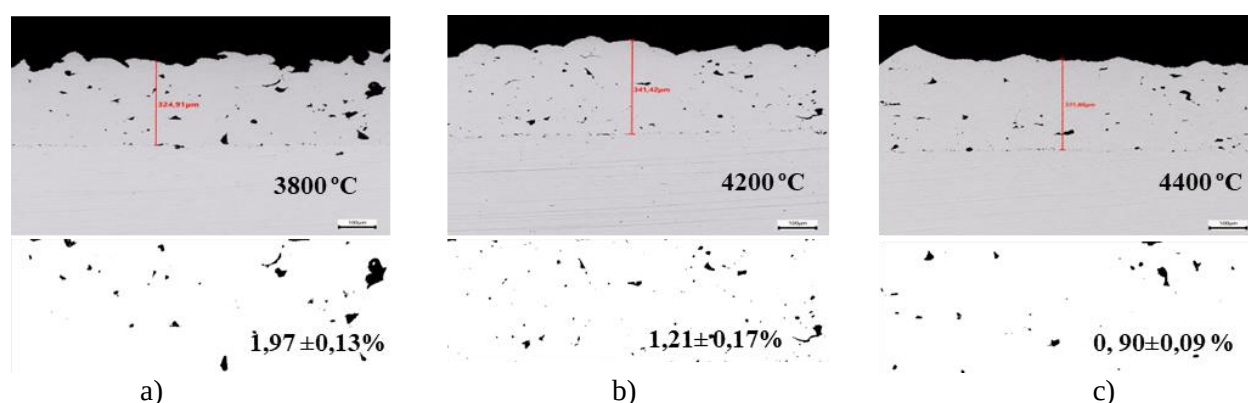


Fig. 2. Cross-sectional microstructure and porosity of Ni–Cr–B–Si coatings obtained at different flame-spraying temperatures: (a) 3800 °C – $1.97 \pm 0.13\%$; (b) 4200 °C – $1.21 \pm 0.17\%$; and (c) 4400 °C – $0.90 \pm 0.09\%$.

Microstructural analysis showed that, under all investigated spraying conditions, the coating formed as a continuous layer over the substrate surface. At the same time, increasing the flame temperature had a pronounced effect on the internal defect structure of the coatings. At a flame temperature of 3800 °C, the coating exhibited a porosity of $1.97 \pm 0.13\%$, which was the highest value among the investigated conditions. The corresponding microstructure contained clearly visible dark pores distributed throughout the coating.

When the flame temperature was increased to 4200 °C, the coating porosity decreased to $1.21 \pm 0.17\%$, indicating a substantial reduction compared with that obtained at 3800 °C. A further increase in temperature to 4400 °C resulted in a porosity of $0.90 \pm 0.09\%$, which was approximately 2.2 times lower than that of the coating deposited at 3800 °C ($1.97 \pm 0.13\%$).

The observed decrease in porosity may be associated with changes in the thermal state of the powder particles as the flame temperature increases. Higher flame temperatures can promote a greater degree of particle melting, thereby facilitating particle deformation upon impact with the substrate and improving contact between the resulting splats. Consequently, interlamellar voids may be reduced, leading to the formation of a denser coating structure. However, since direct confirmation of this mechanism would require independent measurements of the in-flight particle temperature and velocity, this explanation should be regarded as a plausible mechanism underlying the observed microstructural changes.

Thus, within the investigated range, increasing the flame temperature from 3800 to 4400 °C resulted in progressive coating densification and a decrease in overall porosity.

The densification of the coating structure was accompanied by changes in its mechanical characteristics. The microhardness values of the coatings obtained at different O_2/C_2H_2 ratios are summarized in Table 2.

At an O_2/C_2H_2 ratio of 1.0, the average coating microhardness was 954.1 HV. Increasing the gas ratio to 1.1 resulted in an increase in microhardness to 1051.7 HV. When the O_2/C_2H_2 ratio was further increased to 1.2, the microhardness slightly decreased to approximately 1015.0 HV, although it remained higher than that obtained at an O_2/C_2H_2 ratio of 1.0.

These results indicate that the microhardness did not exhibit a monotonic dependence on the O_2/C_2H_2 ratio. The highest average microhardness was obtained at $O_2/C_2H_2 = 1.1$. Under this condition, the relatively low porosity and improved structural integrity of the coating may have contributed to the higher hardness. However, despite the further decrease in porosity at $O_2/C_2H_2 = 1.2$, a slight reduction in microhardness was observed, indicating that coating hardness is not governed solely by porosity. Other factors, including phase composition, oxide formation, and the melting and subsequent solidification behavior of the sprayed particles, may also contribute to the observed variation in microhardness.

To evaluate the influence of the flame-spraying parameters on the surface condition of the coatings, the surface roughness was measured, and the corresponding results are presented in [Table 2](#).

The coating deposited at $O_2/C_2H_2 = 1.0$ exhibited a surface roughness of $4.70 \pm 0.09 \mu\text{m}$, whereas a value of $4.95 \pm 0.13 \mu\text{m}$ was obtained at $O_2/C_2H_2 = 1.1$. The difference between these two conditions was relatively small. However, increasing the O_2/C_2H_2 ratio to 1.2 resulted in a pronounced decrease in surface roughness to $2.99 \pm 0.11 \mu\text{m}$.

This trend is consistent with the porosity results: the coating deposited at $O_2/C_2H_2 = 1.2$ exhibited both the lowest porosity ($0.90 \pm 0.09\%$) and the lowest surface roughness ($2.99 \pm 0.11 \mu\text{m}$). This behavior may be attributed to the enhanced melting of the powder particles under the higher thermal input, which can promote more effective deformation and spreading upon impact with the substrate. Improved particle flattening may consequently reduce surface irregularities and contribute to the formation of a more homogeneous and relatively smooth coating surface.

To assess the influence of the flame-spraying parameters on the mechanical integrity of the coating–substrate system, the adhesion strength of the coatings was determined. The corresponding results are presented in [Table 2](#).

Table 2. Mechanical and surface characteristics of Ni–Cr–B–Si coatings obtained under different flame-spraying conditions.

O_2/C_2H_2 ratio	Temperature, °C	Microhardness, HV	Surface roughness, Ra, μm	Adhesion strength, MPa
1,0	3800	954,1	954,1	954,1
1,1	4200	1051,7	1051,7	1051,7
1,2	4400	1015,0	1015,0	1015,0

A systematic increase in coating adhesion strength was observed with increasing flame temperature. At 3800 °C, the adhesion strength was $22.14 \pm 4.3 \text{ MPa}$, whereas increasing the temperature to 4200 °C resulted in an increase to $27.84 \pm 5.4 \text{ MPa}$. The highest adhesion strength of $35.02 \pm 3.9 \text{ MPa}$ was obtained at 4400 °C. Thus, increasing the flame temperature from 3800 to 4400 °C resulted in an approximately 58% increase in the mean adhesion strength.

The improvement in adhesion strength may be associated with the progressive densification of the coating structure. In particular, as the flame temperature increased from 3800 to 4400 °C, the coating porosity decreased from $1.97 \pm 0.13\%$ to $0.90 \pm 0.09\%$. Under higher-temperature spraying conditions, an increased degree of particle melting and deformation upon impact may increase the effective contact area between the deposited particles and the substrate, thereby promoting mechanical interlocking and improving the integrity of the coating–substrate interface.

Overall, the obtained results demonstrate that variation in the O_2/C_2H_2 ratio during flame spraying has a combined effect on the microstructural, surface, and mechanical characteristics of Ni–Cr–B–Si coatings. Within the investigated range, increasing the O_2/C_2H_2 ratio from 1.0 to 1.2, accompanied by an increase in flame temperature, resulted in a decrease in coating porosity from $1.97 \pm 0.13\%$ to $0.90 \pm 0.09\%$, a reduction in surface roughness from 4.70 ± 0.09 to $2.99 \pm 0.11 \mu\text{m}$, and an increase in adhesion strength from 22.14 ± 4.3 to $35.02 \pm 3.9 \text{ MPa}$. In contrast to these monotonic trends, the microhardness reached its maximum average value of approximately 1051.7 HV at $O_2/C_2H_2 = 1.1$.

These findings indicate that the investigated coating properties do not respond uniformly to changes in the O_2/C_2H_2 ratio. The coating deposited at $O_2/C_2H_2 = 1.2$ exhibited the lowest porosity and surface roughness together with the highest adhesion strength, whereas the maximum average microhardness was achieved at $O_2/C_2H_2 = 1.1$. Therefore, selection of the flame-spraying conditions should take into account the specific performance requirements of the coating rather than relying on a single property as the optimization criterion.

4. Conclusion

In this study, Ni–Cr–B–Si-based self-fluxing coatings were deposited onto AISI 321 austenitic stainless steel substrates by flame spraying, and the effect of varying the O_2/C_2H_2 ratio from 1.0 to 1.2 on their microstructure and properties was investigated. Increasing the gas ratio and the corresponding thermal input was found to promote progressive densification of the coating structure.

As the O_2/C_2H_2 ratio increased from 1.0 to 1.2, the coating porosity decreased from $1.97 \pm 0.13\%$ to $0.90 \pm 0.09\%$, while the surface roughness decreased from $4.70 \pm 0.09 \mu\text{m}$ to $2.99 \pm 0.11 \mu\text{m}$. At the same time, the adhesion strength increased from $22.14 \pm 4.3 \text{ MPa}$ to $35.02 \pm 3.9 \text{ MPa}$. These changes may be attributed to improved melting and deformation of the powder particles under higher thermal input, resulting in reduced structural defects and improved interfacial contact between the coating and the substrate.

The dependence of microhardness on the O_2/C_2H_2 ratio was non-monotonic. The highest average microhardness of 1051.7 HV was obtained at $O_2/C_2H_2 = 1.1$, whereas a slightly lower value of 1015.0 HV was measured at $O_2/C_2H_2 = 1.2$. This behavior indicates that the mechanical response of the coatings is governed not only by porosity but may also be affected by microstructural and phase transformations occurring during the spraying process.

Among the investigated conditions, the coating deposited at $O_2/C_2H_2 = 1.2$ exhibited the lowest porosity ($0.90 \pm 0.09\%$), the lowest surface roughness ($2.99 \pm 0.11 \mu\text{m}$), and the highest adhesion strength ($35.02 \pm 3.9 \text{ MPa}$), whereas the maximum microhardness was achieved at $O_2/C_2H_2 = 1.1$. Overall, the results demonstrate that controlling the O_2/C_2H_2 ratio provides an effective technological approach for tailoring the microstructure and functional properties of flame-sprayed Ni–Cr–B–Si-based self-fluxing coatings.

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Conflict of interest

The authors declare that they have no competing interests.

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