INFLUENCE OF STAND-OFF DISTANCE ON THE QUALITY OF STAINLESS STEEL COATINGS FORMED BY COLD SPRAY

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Abstract

Cold spray is a modern method of coating in which solid powder particles are accelerated by a supersonic gas jet and on impact with the substrate they deform plastically and adhere to the surface. This principle of coating formation is dependent on the critical velocity of the flying particles, which is influenced, among other things, by the distance of the coated material from the nozzle end. Therefore, this work investigates the effect of stand-off distance on the microstructure of austenitic stainless steel coatings deposited by cold spray technology. The Cold Spray CS EvoII 6/11 equipment was used in the experiment, using two convergent-divergent nozzles that differ from each other in length and expansion ratio. Different stand-off distances (10 mm, 30 mm, and 50 mm) were used in this work and their effect on the properties of the resulting coatings was observed, such as in particular the quality of the interface between the base material and the deposited coating, porosity, roughness, and coating thickness. The results showed that the stand-off distance of the coating significantly affects the quality and properties of the coating, with the best results obtained for samples deposited at a stand-off distance of 30 mm.

Keywords: Cold Spray technology, 316L, stand-off distance

1. INTRODUCTION

Stainless steel coatings, deposited by thermal spray technology, have been extensively used to enhance corrosion resistance due to their affordability and effectiveness. However, conventional thermal spray coatings are susceptible to high levels of porosity and micro-cracks, which can lead to reduced corrosion resistance when exposed to different corrosive environments [1]. To overcome these limitations, cold spray technology appears to be a suitable alternative for the future application of 316L austenitic steel coatings.

Cold spray technology is a high-speed solid-state coating and repair process that involves accelerating small particles of material, such as metals or ceramics, to supersonic speeds and then depositing them onto a surface. This process is carried out at ambient temperatures, which differentiates it from traditional thermal spray techniques that involve high-temperature heating. In cold spray technology, the particles are accelerated through a nozzle using a high-pressure gas, typically helium or nitrogen, and are propelled onto the substrate, where they adhere and form a dense, high-strength coating. The impact of the particles onto the surface also generates heat, causing the particles to deform and bond with each other, creating a metallurgical bond between the coating and substrate [2,3].

The quality and properties of coatings produced by cold spray technology are significantly influenced by its process parameters, including gas pressure, gas temperature, size distribution of powder particles, nozzle design, and stand-off distance [4,5]. This study will investigate the effect of three deposition distances (10 mm, 30 mm, and 50 mm) on the quality of 316L coating deposited by cold spray technology using two types of nozzles differing in length and expansion ratio.

2. MATERIALS AND METHODS

2.1 Powder feedstock

This study used 316L chromium-nickel austenitic steel powder (Sandvik Osprey®) as the feedstock. The details of this powder are given in the following table. The particle size distribution of this powder was characterized by a laser diffraction sizer (Mastersizer 2000 Malvern Instruments Ltd., UK) [6].

Table 1 Powder characterization [6]

Powder	**Fabrication method**		**Size distribution (µm)**					
316L	Gas atomized		d10 µm		d50 µm	d80 µm		d90 µm
			18.4		27.3	36.5		42.0
Chemical composition (wt %)								
Fe	**C**	**Cr**	**Ni**	**Mo**	**Mn**	**Si**	**P**	**S**
Bal.	≤ 0,03	16 - 18	10 - 14	2-3	≤ 2	≤ 1	≤ 0,045	≤ 0,03

2.2 Deposition process

The Impact Gun 6/11 EvoCSII cold kinetic spray system (Impact Innovations GmbH., DE) with an axial powder feeding system was used for coating. For the experiment, an OUT 1 nozzle with a length of 160 mm (expansion ratio 5.6) and an OUT 2 nozzle with a length of 109.7 mm (expansion ratio 9.97) were used. Nitrogen was used as a propellant and feedstock carrier gas. The values of parameters for all depositions were obtained in a preliminary in-house study. A gun traverse speed of 300 mm/s, a step distance of 1 mm, and stand-off distances of 10, 30, and 50 mm were used for the samples for metallographic evaluation. For all deposition, the propellant gas operated at a pressure of 45 bar and a temperature of 1000 °C. To find the width of a single coating profile, the gun traverse speed was 40 mm/s to obtain a very thick coating. Thus, only one layer of coating was applied on a plane substrate. The spray angle has been kept to 90°. Aluminium plates with dimensions of 60 x 20 x 5 mm were used as substrate. Due to the selection of aluminium substrate, the blasting step was skipped, and the substrate was degreased with acetone.

2.3 Sample characterization

Metallographic samples were prepared using a standard procedure for medium-hard coatings with a final polishing step using 1 µm diamond paste. Cross-sections of the samples were analysed using a light optical microscope (Arsenal), where the thickness of the coatings was also measured.

Hardness measurement was selected for testing the mechanical properties. The hardness of the coatings was measured by the Vickers method using a micro-hardness LECO tester (LM110AT). A load of 300 g (HV0.3) was selected for all samples. The measurements were carried out according to ČSN EN ISO 6507 - 1. Ten indentations were applied to calculate each sample's average hardness value.

3. RESULTS AND DISCUSSION

3.1 Effect of stand-off distance on coating microstructure

Metallographic cross-sections of cold-sprayed samples produced under the conditions mentioned above are displayed in **Figure 1** and **Figure 2**. **Figure 1** corresponds to samples deposited with nozzle OUT 1. The stand-off distance, which is the distance between the nozzle and the substrate, was varied between 10 mm, 30 mm, and 50 mm. The coating thickness was measured for each stand-off distance. The results show that the coating thickness for a stand-off distance of 10 mm was significantly lower than for the other distances. Specifically, the coating thicknesses were 466 µm, 1148 µm, and 1038 µm for stand-off distances of 10 mm, 30 mm, and 50 mm, respectively. The highest deposition efficiency, in terms of coating thickness, was observed for a stand-off distance of 30 mm. The resulting coatings contained a significant percentage of pores, but no cracks or other defects were found at the interface between the coating and the substrate. The particles were embedded sufficiently over the entire sample surface, regardless of the deposition distance.

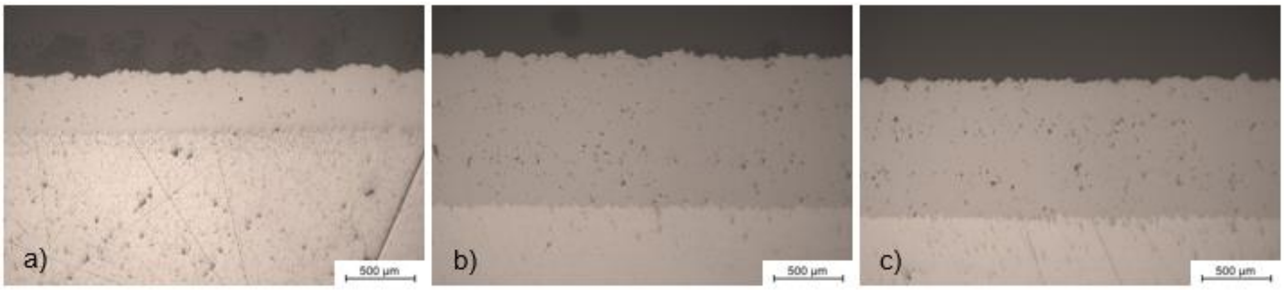

Figure 1 OM images of 316L coatings deposited by nozzle OUT 1 at stand-off distances of a) 10 mm (50x), b) 30 mm (50x), and c) 50 mm (50x)

Figure 2 demonstrates that changing the stand-off distance for nozzle OUT 2 has minimal effect on the coating's microstructure. The thicknesses of the coatings formed are nearly the same. At a deposition distance of 10 mm, the thickness was roughly 1081 µm, and at 30 mm and 50 mm, it was about 1049 µm and 1054 µm, respectively. A greater number of pores were present at the interface of each coating layer, including those in **Figure 1**. The interface of the coating with the substrate at a deposition distance of 10 mm did not contain pores or cracks, at larger deposition distances the quality of the interface decreased, and local delamination occurred.

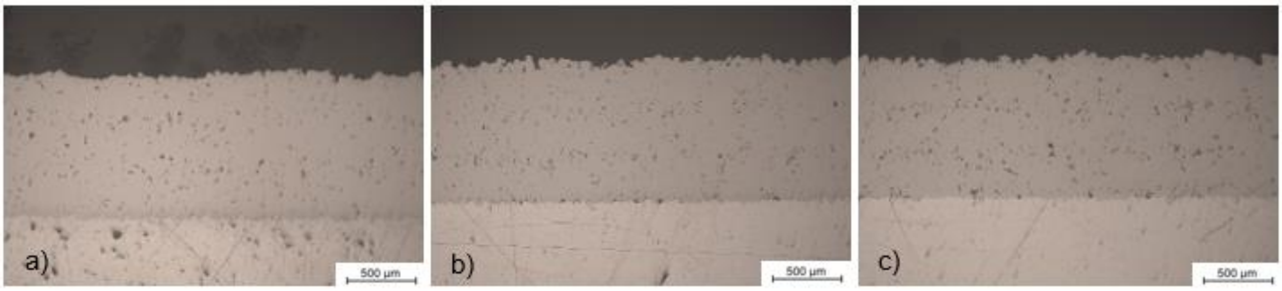

Figure 2 OM images of 316L coatings deposited by nozzle OUT 2 at stand-off distances of a) 10 mm (50x), b) 30 mm (50x), and c) 50 mm (50x)

3.2 Effect of stand-off distance on coating microhardness

The microhardness values of the coatings are presented in **Table 2**. The coatings deposited using nozzle OUT 1 exhibit higher microhardness values compared to those deposited using nozzle OUT 2. Specifically, the difference is most significant at a deposition distance of 50 mm, whereas the lowest difference is observed at a deposition distance of 30 mm.

Table 2 Microhardness values for different stand-off distances

Type of nozzle	**Stand-off distance**		
	10 mm	**30 mm**	**50 mm**
OUT 1	385 HV0.3	390 HV0.3	394 HV0.3
OUT 2	375 HV0.3	386 HV0.3	361 HV0.3

3.3 Effect of stand-off distance on the width of single pass deposit

The distance of the nozzle from the substrate surface affects the single track profile, which together with the kinematic parameters of the robot has a significant effect on the homogeneity of the coating thickness. The single track profile is determined by the material properties, spray distance from the nozzle to the substrate, spray angle, substrate properties, substrate deformation caused by local heat transfer, etc [7].

Figure 3 and **Figure 4** show the width of the single track at selected deposition distances. For a stand-off distance of 10 mm for both nozzles, the single track is the narrowest with sharp edges. At higher deposition distances, the edge sharpness decreases. The single coating profile for nozzle OUT 1 and a stand-off distance of 10 mm was the only one without a visible highest point in the middle of the pass. This sample achieved the lowest thickness, which correlates with the thickness measurements from the metallographic cross-sections. It is possible that for this stand-off distance and type of nozzle, the critical particle velocity was not achieved, resulting in the inability to form a good quality coating [8,9]. For all other depositions, the track had a typical profile with the greatest thickness in the middle.

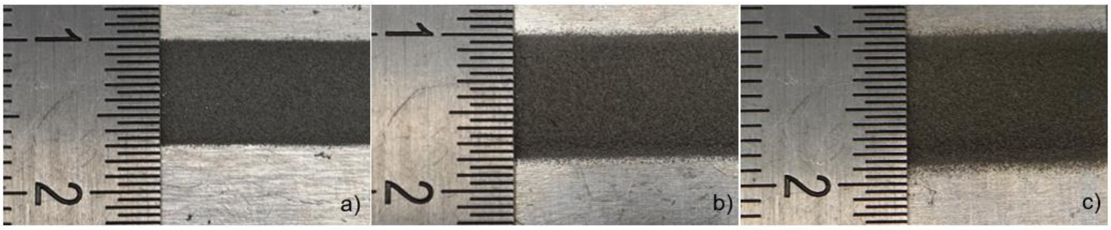

Figure 3 the width of a single track of 316L coatings deposited by nozzle OUT 1 at stand-off distances of a) 10 mm, b) 30 mm, and c) 50 mm

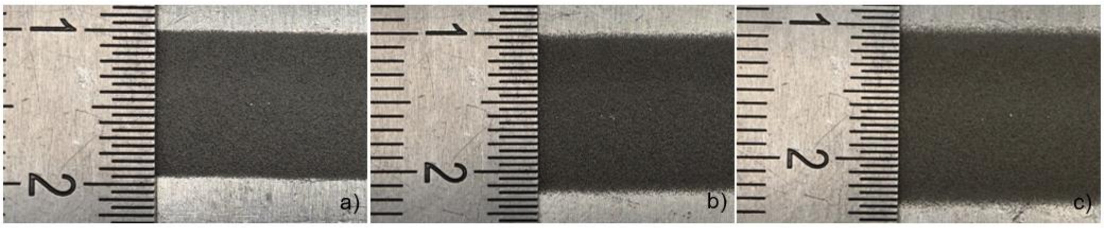

Figure 4 the width of a single track of 316L coatings deposited by nozzle OUT 1 at stand-off distances of a) 10 mm, b) 30 mm, and c) 50 mm

Figure 5 and **Figure 6** show the surface of the coatings deposited by the three layers. For nozzle OUT 1, the profile roughness initially increased at a stand-off distance of 30 mm and then decreased again with a further increase in stand-off distance. For nozzle OUT 2, the profile roughness gradually decreased with an increasing stand-off distance.

Figure 5 The surface of the coatings deposited by nozzle OUT 1 at stand-off distances of a) 10 mm, b) 30 mm, and c) 50 mm

Figure 6 The surface of the coatings deposited by nozzle OUT 2 at stand-off distances of a) 10 mm, b) 30 mm, and c) 50 mm

4. CONCLUSION

The aim of the experiment was to investigate the effect of three stand-off distances (10 mm, 30 mm, and 50 mm) on the quality of austenitic stainless steel coatings deposited by cold spray technology using two types of convergent-divergent nozzles. The study focused on evaluating the coating quality and interface with the substrate, as well as measuring the coating thickness to compare deposition efficiency among samples. Additionally, the width of the single coating profile and its influence on the final coating surface were examined. According to the experimental data obtained in this study, the following conclusions can be drawn.

- When deposited by nozzle OUT 1, the coating thickness at a stand-off distance of 10 mm was significantly lower than that at other distances, possibly because the critical particle velocity had not been reached.
- For the samples deposited with the OUT 1 nozzle, the most suitable deposition distance in terms of porosity, coating thickness, and the quality of the interface between the coating and the substrate was found to be 30 mm.
- For OUT 2 nozzle deposition, a stand-off distance of 10 mm is optimal in terms of interface quality and coating thickness.
- In terms of hardness, it can be concluded that deposition with nozzle OUT 1 will produce harder coatings than for nozzle OUT 2, at the same deposition distances.
- For a deposition distance of 10 mm for both nozzles, the coating profile is the narrowest with sharp edges. At higher deposition distances, edge sharpness decreases and profile width increases.
- In terms of surface roughness, for nozzle OUT 1, the profile roughness initially increased at a stand-off distance of 30 mm and then decreased with a further increase in deposition distance. For nozzle OUT 2, the profile roughness gradually decreased with an increasing deposition distance.

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