

ADDITIVE MANUFACTURING OF INCONEL 625 SUPERALLOY PARTS VIA HIGH PRESSURE COLD SPRAY

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ABSTRACT: Cold gas dynamic spray (CGDS) or simply ‘cold spray’ (CS) is an emerging additive manufacturing technique, which is used in repair applications of metal components. The benefits of CS process are good metallurgical bonding with less heat-affected zone compared to traditional metal joining processes (i.e. welding, thermal spray etc.) or electron beam melting (EBM) or selective laser melting (SLM) additive manufacturing methods. In this study, Inconel 625 was deposited on Inconel 718 substrate via a high pressure cold spray system. The window of deposition for Inconel 625 particles, gas flow and particle acceleration behavior were investigated by numerical simulations. Powder and coating microstructures were investigated by a combination of optical microscopy and scanning electron microscopy. The bond strength between coating and substrate was tested according to ASTM C633. The hardness tests for both the substrate and the as-sprayed coating were conducted. The results showed that the CS Inconel 625 coatings had a low porosity level and an intimate interface. The bond strength between coating and substrate was greater than the maximum epoxy strength. The good quality of the CS Inconel 625 deposits showed a great application potential for the additive manufacturing of Ni-based superalloy parts.

KEYWORDS: High pressure cold spray; Additive manufacturing; Inconel 625 coating; Inconel 718 substrate.

1. INTRODUCTION

Cold gas dynamic spray or cold spray (CS) is an emerging additive manufacturing technique, which could be used as repair applications of metal components. In cold spray process, powder particles are accelerated to supersonic speed (Mach number ranging from 2~4). With high kinetic energies, the metal powder particles adhere to the substrate via metallurgical bonding or mechanical interlocking [1]. Compared with the traditional repair techniques such as welding or thermal spray, the main benefits of cold spray are good metallurgical bonding with less or no heated-affected zone, no oxidation, no distortion and thick material buildup.

Ni-based superalloy is widely used in marine and aerospace industries under high temperature circumstances. Inconel alloy 625 (hereafter called as “IN625”) is a nickel-based superalloy that has high strength properties at elevated temperatures. It also demonstrates remarkable protection against oxidation or corrosion [2]. Its ability to withstand high stress and a wide range of temperatures, both in and out of water, as well as being able to resist corrosion while being

exposed to high acidic environments makes it a fitting choice for nuclear and marine applications. Because of a high Niobium (Nb) level in the metal as well as its exposure to harsh environments and high temperatures, it was concerned with the weldability of IN625 [3].

In this study, IN625 coatings were deposited on IN718 substrates via a high pressure cold spray system. Both numerical and experimental methods were used to better understand the cold spray additive manufacturing (AM) process of the IN625. A numerical simulation was used to calculate the window of deposition for the IN625 particles, gas flow and particle acceleration behaviors. IN625 powder morphologies and size distributions were characterized by scanning electron microscope (SEM) and ColdSprayMeter (CSM) prior to cold spray deposition. The IN625 coating microstructures were investigated by a combination of optical microscopy (OM) and SEM. The coating quality was characterized by bond strength and hardness tests.

2. EXPERIMENTAL DETAILS

2.1 Materials

The feedstock power material used in this study was IN625 powder with an average particle size of about 35 μm . Table 1 shows the particle size distribution of the IN625 powder, where D10, D50 and D90 were defined as the particle sizes corresponding to cumulative size distribution at 10%, 50% and 90%, respectively [4]. The substrates used for microstructure, porosity and hardness characterization were cut from a 3mm-thick IN718 alloy sheet that was provided by AMP, Singapore. The substrates used for the bond tests were circular samples of $\text{\O}25$ mm x 5 mm. Prior to cold spray deposition, the substrate surfaces were polished according to the published work [5, 6]. The substrates were ultrasonically cleaned in an ethanol bath before cold spray deposition.

Table 1. Powder particle size distribution measured by using laser diffraction.

Powder	D10 [μm]	D50 [μm]	D90 [μm]
IN625	21.8	34.6	54.5

2.2 Cold spraying

The spraying parameters (i.e. carrier gas temperature and pressure) were selected - by using the commercial software package KSS from Kinetic Spray Solutions (Buchholz, Germany) - in such a way as to obtain a proper velocity ratio ($\eta = v_p/v_{crit}$) [7]. The calculated particle velocities were cross checked by velocity measurements using a ColdSprayMeter from Tecnar (Saint-Bruno-de-Montarville, Canada) [7]. The selection of marginally proper spraying conditions was to assure good coating qualities. Cold spraying of IN625 was performed at a process gas pressure of 4.5 MPa and process gas temperature of 1000 $^{\circ}\text{C}$, corresponding to η value of 1.47. A high pressure cold spray system was used to perform the cold spray deposition, which consisted a De Laval convergent-divergent nozzle was used to accelerate the particles to supersonic speed. The feed rate of the IN625 powders was about 45 g/min. The detailed cold spray process parameters were selected according to the numerical simulation results.

2.3 Characterization

After the cold spray deposition, the cross-sectional microstructures of the IN625 coatings were analyzed by using optical microscopy. Prior to this process, the coated samples were hot-mounted and polished by following the standard metallographic procedures. The porosity level of the coatings was analyzed by using the ImageJ software, which was guided by ASTM E2109-01. The

images were captured with a magnification of 200× that allowed the voids in the coatings to be clearly resolved and the entire coating thickness properly displayed on the monitor screen. To calculate the porosity level, the optical images were converted into 32-bits black and white images. By adjusting the threshold function, the porosity levels of the coatings were determined. The interfacial bonding strengths of the coated samples were measured by using bond test which was compliant with the ASTM C633 Standard [8]. The microhardnesses of the substrates and coatings were measured by using a Vickers hardness tester (Future-tech FM-300e, Japan) under the load of 300 g. The microhardness values were averaged by taking ten measurements on each sample.

3. RESULTS AND DISCUSSION

3.1 Particle characterization

Fig. 1(a) and (b) show the SEM micrographs of IN625 feedstock powders that most of the IN625 particles have a spherical shape. However, some irregular particles and small-scale satellite particles can be seen, which can be attributed to the fabrication process of the powders by nitrogen gas atomization. These irregular particles not only affect the powder flowability but also affect the particle acceleration process due to different drag force coefficients of spherical and irregular particles. Fig. 1(c) shows the particle size distribution which was measured by laser diffraction method and it follows normal distribution and the average particle size is around 35 μm. Fig. 1(d) shows the particle velocity distribution which was measured by ColdSprayMeter and the average particle velocity is 725 m/s.

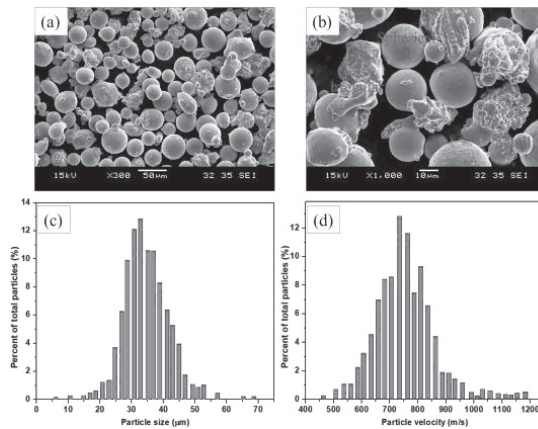


Fig. 1 (a & b) SEM micrographs showing IN625 feedstock powder: (a) at low-magnification and (b) at high-magnification. (c & d) Laser diffraction results showing: (c) particle size distribution and (d) particle velocity distribution.

3.2 Simulation results

In order to optimize the cold spray parameters for IN625, simulation of cold spray process was conducted, and the simulation results are shown Fig.2. Fig. 2(a) shows the window of deposition of IN625 particles as a function of particle temperature and particle velocity. Successful deposition can be achieved when the velocity and temperature of certain particles fall within the window of deposition. If the particle velocity is less than critical velocity, the particle will bounce back from the substrate and no deposition will be formed, which is quite similar with shot peening process. However, if the particle velocity is larger than erosion velocity, the particle will erode the substrate surface and no deposition will be formed either. Therefore, it is important to select

proper CS parameters to guarantee optimum η values for different sizes. As can be seen from Fig. 2(a), the velocities of different particles ($D_{10}=22\ \mu\text{m}$, $D_{50}=35\ \mu\text{m}$ and $D_{90}=55\ \mu\text{m}$) fall within the window of deposition at a process gas pressure of 4.5 MPa and process gas temperature of 1000 °C. Fig. 2(b) shows the η value variations as a function of particle size. As shown in Fig. 2(b), if the particle size is smaller than 3 μm , the η value is less than 1.0, which means that a minimum particle size required for IN625 particle deposition is 3 μm due to the critical particle diameter required for adiabatic shear instability [1]. Since the IN625 powder particles used in this study range from 10 μm to 65 μm , moderate η values can be achieved for different particle sizes. Fig. 2(c) shows the gas velocity and particle velocity as a function of distance from the nozzle inlet. The gas velocity is much higher than the particle velocity and the smaller particle tends to have higher velocity than the larger particle. Both the gas velocity and particle velocity increase tremendously at the nozzle throat due to expansion effect of De Laval nozzle. The fluctuation of the gas velocity at the nozzle exit can be attributed to the shock wave formed at the nozzle exit. Fig. 2(d) shows the gas temperature and particle temperature variations along the nozzle axis. It can be seen that gas temperature is lower than particle temperature due to gas temperature decreases remarkably at the nozzle throat and nozzle divergent part. Since the particle is quite small, the particle surface area over volume is quite large and heat transfer between gas and particle is fast that the particle temperature can reach hundreds of Celsius degrees at the convergent part and cool down a little bit at the divergent part.

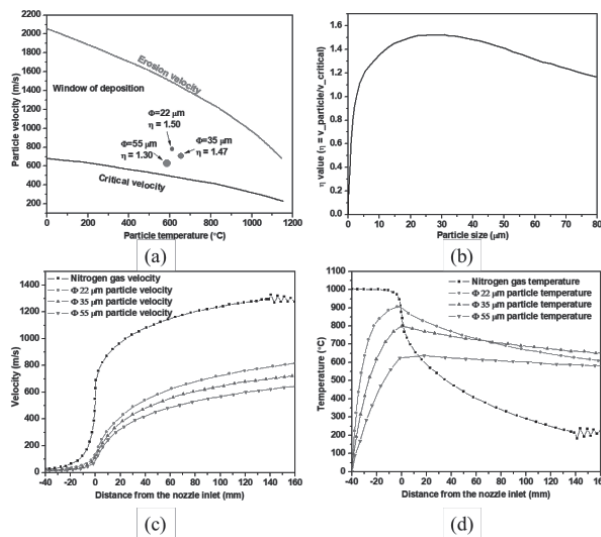


Fig. 2 Simulation results showing (a) window of deposition of IN625 feedstock powder, (b) η value as a function of particle size, (c) gas and particle velocities as a function of distance from the nozzle inlet, and (d) gas and particle temperatures as a function of distance from the nozzle inlet.

3.3 Experimental results

Fig. 3(a) shows the optical micrograph of cross-sectional view of IN625 coating on IN718 substrate. It can be seen that the coating thickness is around $770\pm 10\ \mu\text{m}$ with 5-layer deposition. The interface between IN625 coating and IN718 substrate is almost indistinguishable, which indicates a good bonding. A closer microstructure view of the IN625 coating is shown in Fig. 3(b), irregular micro pores can be observed, and the coating porosity is around $2.4\pm 0.3\%$. The micro pores probably can be attributed to insufficient impact energy for some particles and thus leading

to limited plastic deformation of those particles. Fig. 3 (c) shows the SEM micrograph of as-sprayed IN625 coating surface. It can be clearly seen that severe plastic deformation occurs for IN625 particles and materials jetting is obvious due to adiabatic shear instability during cold spray process [9]. Average surface roughness of as-sprayed of IN625 coating is around $14.6 \pm 0.3 \mu\text{m}$ as shown in Fig. 3(d).

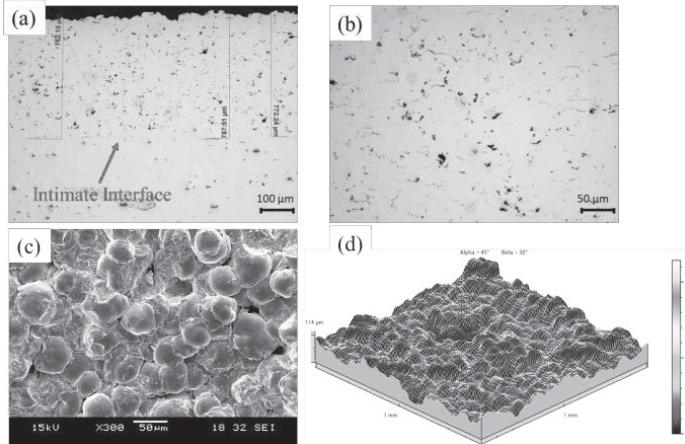


Fig. 3 (a & b) Optical micrographs showing (a) cross-section of IN625 coating on IN718 substrate, (b) top surface of IN625 coating, (c) SEM micrograph showing as-sprayed IN625 coating surface morphology and (d) surface profile of as-sprayed IN625 coating.

Mechanical properties of CS IN625 coating are evaluated in terms of hardness, adhesion strength and cohesion strength. Fig. 4(a) shows the micro hardness of IN718 substrate and IN625 coating and the coating hardness is around $450 \pm 21 \text{ HV0.3}$ while the substrate hardness is about $263 \pm 15 \text{ HV0.3}$, which indicates that the cold sprayed IN625 coating can act as a surface enhancement of IN718 substrate. Fig. 4(b) shows the setups of cohesion test and adhesion test. The cohesion test is also named as Tubular Coating Tensile (TCT) test. Fig. 4(c) shows the results of cohesion test and adhesion test, and the cohesion strength of CS IN625 coating is around $307 \pm 15 \text{ MPa}$ while the adhesion strength of CS IN625 coating is larger than 68 MPa due to glue failure occurs rather than coating/substrate interface failure. The mechanical property test results show good quality of CS IN625 coating.

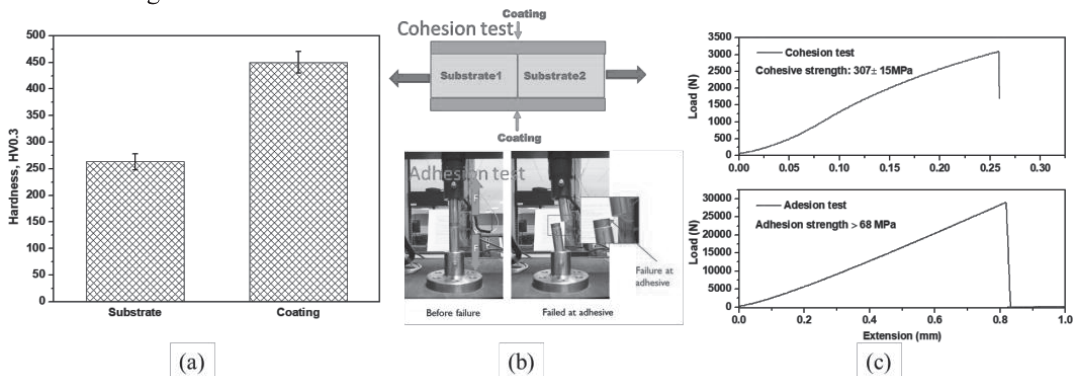


Fig. 4 (a) Microhardnesses of as-sprayed IN625 coating and IN718 substrate, (b) cohesion and adhesion test setups and (c) cohesion and adhesion test results.

4. CONCLUSIONS

In this study, IN625 coatings were successfully deposited on IN718 substrates via a high pressure cold spray process. A numerical method was used to optimize the spraying process and the window of deposition was achieved. At the nozzle exit, the gas and particle temperatures were around 200 and 600 °C, respectively, and the gas and particle velocities were around 1200 and 700 m/s, respectively. The microstructure, microhardness, adhesion strength and cohesion strength of the IN625 coatings were systematically investigated. The porosity level of the coatings was around $2.41 \pm 0.3\%$ with limited irregular micropores. The hardness of the IN625 coatings was much higher than that of the IN718 substrates due to the work hardening of the coatings during cold spraying. The adhesion strength of the coatings was more than 68 MPa and the interparticle cohesive strength was around 307 ± 15 MPa. The good quality of the cold sprayed IN625 coatings shows that cold spray is a promising additive manufacturing technique for repair applications of Ni-based superalloy parts [10].

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