Deposition characteristics of cold sprayed Inconel 718 particles on Inconel 718 substrates with different surface conditions

Sun, Wen; Tan, Adrian Wei Yee; Bhowmik, Ayan; Marinescu, Iulian; Song, Xu; Zhai, Wei; Li, Feng; Liu, Erjia

2018

Sun, W., Tan, A. W. Y., Bhowmik, A., Marinescu, I., Song, X., Zhai, W., . . . Liu, E. (2018). Deposition characteristics of cold sprayed Inconel 718 particles on Inconel 718 substrates with different surface conditions. *Materials Science and Engineering A*, 720, 75-84.
doi:10.1016/j.msea.2018.02.059

<https://hdl.handle.net/10356/98684>

<https://doi.org/10.1016/j.msea.2018.02.059>

© 2018 Elsevier B.V. All rights reserved. This paper was published in *Materials Science and Engineering A* and is made available with permission of 2018 Elsevier B.V.

Downloaded on 26 Apr 2023 15:37:08 SGT

Deposition characteristics of cold sprayed Inconel 718 particles on Inconel 718 substrates with different surface conditions

Wen Sun^{1,2}, Adrian Wei Yee Tan^{1,2}, Ayan Bhowmik^{1,2*}, Iulian Marinescu⁴, Xu Song³, Wei Zhai³, Feng Li⁴, Erjia Liu^{2*}

¹Rolls-Royce@NTU Corporate Lab, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

²School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

³Singapore Institute of Manufacturing Technology, 73 Nanyang Dr, Singapore 637662, Singapore

⁴Advanced Technology Centre, Rolls-Royce Singapore Pte Ltd, 1 Seletar Aerospace Crescent, Singapore 797565, Singapore

*Email: abhowmik@ntu.edu.sg (A. Bhowmik)

*Email: mejliu@ntu.edu.sg (E. Liu), Tel: +65-67905504

Abstract

This article examined the coating/substrate interface characteristics of IN718 coatings deposited on IN718 substrates using a high pressure cold spray technique. The study was aimed at a greater insight into the coating/substrate bonding mechanism under varying substrate conditions, namely surface roughness and surface preheating, from both experimental data and simulations. The coating/substrate interface microstructure and bonding strength were systematically investigated. The coating/substrate strengths were measured by using tensile and shear tests. A finite-element model on the single particle impact was used to explain and validate the experimental data and analyze the particle bonding behavior with the substrate at different preheating temperatures. The analysis of the coating/substrate interface revealed that a polished IN718 substrate surface could promote adiabatic shear instability as well as the formation of material jetting and thus resulting in a high interface bonding strength. In addition, the preheating of the substrates could increase the metallurgical bonding and promote the coating/substrate adhesion strength.

Keywords: Inconel718; High pressure cold spray; Substrate preheating; Surface roughness; Finite-element modeling; Interface bonding

Highlights

- IN718 powder was cold sprayed on IN718 substrates of different surface conditions.
- Coating/substrate bonding characteristics were investigated using both numerical and experimental methods.
- IN718 coating on polished IN718 substrate obtained a high adhesion strength.
- A flexible ceramic substrate heater was used to preheat substrates prior to deposition.
- Substrates preheated prior to cold spraying showed an enhanced bonding strength with coating.
- Experimental and numerical results showed a good agreement.

1. Introduction

Cold spray is a low temperature ($<400\text{ }^{\circ}\text{C}$) deposition technique using which powder particles are impacted on substrate with supersonic velocities [1]. With high kinetic energies, the particles adhere to the substrate to form a dense coating [2]. In cold spray, successful bonding between powder particle and substrate is achieved via high strain rate deformation and adiabatic shear instability (ASI) [3]. Due to low heat input during deposition, cold spray process has the potential to form thick and dense metal coatings with low oxide contents and low thermal stresses [4]. Thus, cold spray technology has become increasingly attractive for the applications of repairing damaged parts, which could reduce manufacturing costs and improve performances of the repaired parts.

Ni-based superalloys are widely used materials at elevated temperatures due to their high strength, good resistance to corrosion or oxidation and good surface stability. In particular, Inconel 718 (hereafter called as 'IN718') is a typical nickel chromium superalloy that can be used at up to $650\text{ }^{\circ}\text{C}$ [5]. Cold spraying IN718 coatings could provide a viable solution for the repair of damaged IN718 components. However, there is limited literature available on cold sprayed IN718 coatings and many process parameters that affect the IN718 coating qualities are still not clear. So, extensive study on cold sprayed IN718 coating deposition characteristics is necessary.

Coating quality is usually characterized by 'particle/substrate interface strength' and 'particle/particle cohesive strength'. Particle/substrate interface strength is influenced by material properties and process parameters, such as supersonic gas stream temperature and pressure. In addition, substrate conditions also influence the bonding behavior, such as substrate surface roughness and temperature prior to deposition. Particle/substrate bonding strength is strongly influenced by the first few layers deposition, which may vary with substrate surface conditions. For softer substrate materials (i.e. Al, Cu), higher surface roughness may result in better adhesion strength and higher deposition efficiency [6, 30] due to more contact areas. For harder substrate materials (i.e. Ti6Al4V), a polished surface is preferred as a rough surface restricts jet formation in the powder particles, thus, resulting in poor bonding [7, 8]. Furthermore, bonding characteristics between coating and substrate are also affected by substrate temperature. Xie et al. [9] had

demonstrated that in cold sprayed SS316L coatings, adhesive strength was improved by substrate preheating due to the abundant plastic deformation and the metallurgical bonding that occurred in the particles and substrates. Watanabe et al. [10] investigated the effects of substrate temperature on different materials, which showed that substrate heating could enhance the adhesion strength under several material conditions although oxide layers were formed by exposure to a high temperature. Suo et al. [17], however, showed that in cold sprayed Mg coatings, changing Al substrate temperature did not influence coating porosity and microhardness. The coating bond strength increased compared to that without substrate preheating due to the increases in area of mechanical interlocking and also metallurgical bonding.

Thus, in light of the above few reports, the surface condition of the substrate clearly plays a decisive role in good quality bonding of the cold-sprayed layer. Therefore, the aim of this study is to clarify the effects of substrate conditions in terms of substrate surface roughness and temperature on bonding behavior between IN718 coating and substrate. Thus far, no reports in literature have outlined the effects of these surface parameters on cold-spraying behavior of this technologically important class of Ni-alloys. Through systematic experimental trials, the variations of bonding strength with these parameters have been established. Additionally, finite element modeling has been employed to complement and corroborate the experimental results.

2. Experimental and modelling procedures

2.1. Experiments

2.1.1. Surface preparations

The substrates used in this study were a commercially available IN718 bulk material. For adhesion test, the samples had a diameter of 25 mm and a thickness of 5 mm. For other experiments, the substrates used are 50 mm × 50 mm × 10 mm flat plates. For the study of substrate surface roughness effect, the substrate surfaces were prepared by four different methods, namely,

- (1) sandblasting by using 80 μm Al_2O_3 particles;
- (2) grinding by using P180 grade sand paper;

(3) milling by using a face milling cutter; and

(4) polishing by P320 grade SiC sand paper, followed by 9 and 3 μm diamond suspensions on Struers MD Largo and MD Chem polishing discs, respectively [21-23].

For the study of the substrate preheating temperature effect, the substrates with the polished surfaces were used. The surface topographies and roughnesses were measured by using surface profilometer (Talyscan 150) with a diamond stylus of 4 μm in diameter.

2.1.2. Cold spraying

A commercial IN718 powder was used to prepare the cold sprayed IN718 coatings. The chemical compositions of the IN718 powder and IN718 substrates are shown in Table 1. The morphology of the particles is shown in Fig. 1(a) and the cross-sectional micrograph of the as-polished powder particles is shown in Fig. 1(b), which show that the IN718 particles were spherical and free of internal pores. A high pressure cold spray system (Impact Innovation, Germany) was used for the deposition of the IN718 coatings on the IN718 substrates. N_2 was used as the propelling gas while the standoff distance between the spray nozzle exit and the substrate surface was 30 mm and the spray gun was held perpendicular to the substrate surface [24]. The spray gun with a De Laval nozzle was controlled by a robot with the scanning speed of 500 mm/s over the substrate surfaces.

Table 1 Chemical compositions of IN718 substrate and IN718 powder.

Material	Chemical composition (wt.%)										
	Ni	Cr	Fe	Nb + Ta	Mo	Ti	Al	Mn	Cu	C	Others
IN718 powder	53.0	18.7	18.3	4.92	3.00	0.97	0.48	0.17	0.11	0.05	<0.3
IN718 substrate	53.6	18.8	17.4	5.10	2.89	0.94	0.61	0.07	0.12	0.03	<0.4

Fig. 1 SEM micrographs of (a) IN718 powder feedstock and (b) cross-sectional view of as-polished IN718 powder particles.

The spraying parameters were selected by using the commercial software package KSS from Kinetic Spray Solutions (Buchholz, Germany) [14] to obtain a velocity ratio η ($\eta = v_p/v_{crit}$, with v_p being the particle velocity and v_{crit} being the particle critical velocity) within the deposition window [28]. For the study of substrate surface roughness effect, the optimized cold spray parameters were used, i.e. carrier gas temperature of 1000 °C and gas pressure of 4.5 MPa. For the study of substrate preheating effect, the spraying conditions were chosen to ensure moderate coating quality, and thus, to increase the sensitivity of the results to the substrate preheating [25]. Fig. 2(a) shows the IN718 particle deposition window with respect to the parameters for carrier gas pressure of 4.0 MPa and gas temperature of 800 °C. The particle velocities were within the deposition window with moderate η values as expected. The substrates were fixed by substrate holders and preheated by using a 16-kW ceramic heater attached to the back sides of the substrates. The ceramic heating pad used here could be applied for heating either curved or flat components. To control the substrate surface temperature, K-type thermocouples were mounted on the substrate surface, which were monitored by a 6000A Eurotherm Temperature Recorder [25]. Fig. 2 (b) shows the measured thermal histories during cold spraying at each substrate preheating temperature.

Fig. 2 (a) Window of deposition (gas temperature: 800 °C, gas pressure: 4.5 MPa) for the IN718 particles of different sizes (i.e. 25, 32 and 46 μm) and the calculated particle velocities, particle temperatures and velocity ratios, and (b) the measured thermal histories of cold spraying processes at varying substrate temperatures by using a 6000A Eurotherm Temperature Recorder.

2.1.3. Interfacial bonding characterization

The coating cross-sections were examined by optical microscopy (Zeiss Axioskop 2 U.S.A). The porosities in the coatings were measured by ImageJ software [7]. The particle heights after single splat deformation were measured by optical surface profilometer (Alicona Infinite Focus, Alicona Imaging GmbH, Austria). The coating bonding strength was characterized with both adhesion test (in accordance with ASTM C633 [15]) and shear test (in accordance with ČSN EN 15340 [16]). Additional details about the shear test are available elsewhere [18]. An average of three measurements was taken for each test. Scanning electron microscopy (SEM, JEOL-JSM-5600LV, Japan) was used to observe the single splat morphology and analyze the fractured surfaces.

2.2. Modelling

ABAQUS/Explicit finite element analysis software was used for the 3D modelling of particle/substrate impact process for IN718. The particle velocity and temperature were estimated from the KSS software [14]. The particle impact velocity was 672 m/s while the particle temperature was 507 °C (for cold spray

parameters: 800 °C and 4.0 MPa for N₂ propellant gas) and the substrate temperature varied from 25 °C to 450 °C. The particle size was fixed at 30 µm for the simulations and the substrate diameter was 5 times larger than the particle size. The mesh size of the substrate ranged from 0.3 µm at the impact center to 1 µm at the edge wall, while the particle mesh size was set as 0.3 µm. Fig. 3 shows an isometric view to better illustrate the meshes and the exact positions of the particle and substrate.

Fig. 3 (a) Finite element mesh of the full 3D model for a single particle normal impact upon substrate and (b) a zoom-in cut-view of particle/substrate interface.

Since the complete deformation process was constrained within few tens of nanoseconds (typically of the order of 40 ns), the thermal diffusivity distance was much shorter than the characteristic dimensions of the elements in the particles and substrates. The particle-substrate impact was thus assumed to be an adiabatic process where thermal conduction was not considered during the deformation process. The inelastic heat fraction determined the fraction of plastic work converted to heat during the deformation. Since the specific heat and Young's modulus for IN718 varied with temperature, the exact temperature-dependent values of these parameters were used to ensure the accuracy of the simulation results.

To describe the plastic deformation of the particles and substrates, the Johnson – Cook plasticity model was used to determine the effects of strain hardening, strain rate hardening and thermal softening on the equivalent plastic deformation resistance. The equivalent plastic stress of the material is as follows [11]:

$$\bar{\sigma} = [A + B(\bar{\epsilon}^P)^n] \left[1 + C \ln \left(\frac{\dot{\bar{\epsilon}}^P}{\dot{\bar{\epsilon}}_0^P} \right) \right] \left[1 - \left(\frac{T - T_{ref}}{T_m - T_{ref}} \right)^m \right] \quad (1)$$

where:

$\bar{\sigma}$: equivalent plastic stress (MPa)

$\bar{\epsilon}^P$: equivalent plastic strain

$\dot{\bar{\epsilon}}^P$: equivalent plastic strain rate (s^{-1})

$\dot{\bar{\epsilon}}_0^P$: reference equivalent plastic strain rate (s^{-1})

T_m : melting temperature of the material (K)

T_{ref} : reference temperature, normally taken as room temperature (K)

A, B, C, m and n : material constants determined by mechanical tests.

The ABAQUS/Explicit also provides the Johnson – Cook dynamic failure model for simulating progressive damage and failure of materials. During the high velocity impact process, excessive deformation and distortion occurred at the contact interface which led to material failure. The failure model expressed below [12] was therefore included in the material properties definition for the complete analysis.

$$\bar{\epsilon}_f^P = \left[D_1 + D_2 \exp \left(D_3 \frac{p}{q} \right) \right] \left[1 + D_4 \ln \left(\frac{\dot{\bar{\epsilon}}^P}{\dot{\bar{\epsilon}}_0^P} \right) \right] \left[1 + D_5 \left(\frac{T - T_{ref}}{T_m - T_{ref}} \right)^m \right] \quad (2)$$

where:

$\bar{\epsilon}_f^P$: equivalent fracture strain

$\frac{p}{q}$: dimensionless pressure-deviatoric stress ratio where p is the pressure stress and q is the Mises stress

$D_1 - D_5$: failure parameters determined by mechanical tests.

All the material properties for IN718 were obtained from [13] and summarized in Table 2.

Table 2 Johnson-Cook parameters for IN718

Nomenclature	Symbol	Unit	Value
Density	ρ	kg/m ²	8150
Specific Heat	c	J/(kg·K)	Temperature Dependent

Melting Temperature	T_m	K	1609
Solidus Temperature	T_s	K	1533
Young's Modulus	E	GPa	Temperature Dependent
Poisson's Ratio	ν	Dimensionless	0.33
Thermal Conductivity	k	W/(m·k)	0
Latent Heat of Fusion	L_f	J/kg	210000
Inelastic Heat Fraction	η	Dimensionless	0.9
Johnson-Cook Plasticity Model Parameters	A	MPa	1200
	B	MPa	1284
	C	-	0.012
	n	-	0.54
	m	-	1.2
Johnson – Cook Dynamic Failure Model Parameters	D_1	-	0.11
	D_2	-	0.75
	D_3	-	-1.45
	D_4	-	0.04
	D_5	-	0.89

3. Results and discussion

3.1. Experimental evidence of the effect of surface roughness on bonding characteristics

Fig. 4 shows the 3D substrate surface morphologies after different surface preparations. The average surface roughness for (1) sand-blasted sample was $R_a=2.33 \pm 0.20 \mu\text{m}$; (2) ground surface $R_a=1.13 \pm 0.12 \mu\text{m}$; (3) milled surface $R_a=0.36 \pm 0.05 \mu\text{m}$; and (4) polished surface $R_a=0.04 \pm 0.01 \mu\text{m}$. The sand-blasted surface has a large fraction of uniformly distributed peaks and valleys. The ground surface has some remnant materials from the grinding and wear tracks. The milled surface is characterized by uniform and fine milling tracks. The polished surface is very smooth with the least surface roughness.

Fig. 4 Topographies of IN718 substrate surfaces prepared with (a) sandblasting, (b) grinding, (c) milling and (d) polishing.

Fig. 5 shows the cross-sectional microstructures of the IN718 coatings deposited on the different substrates. It can be seen that the interfaces between the coatings and substrates of these specimens show different morphologies. The interface between the sand-blasted substrate and its coating has a wavy morphology and a continuous delamination line (red arrow in Fig. 5(a)), indicating a poor bonding. For the ground sample, the interface is relatively flat, but the delamination line is still visible. However, for the milled and polished samples, the interfaces are intimate with little or no signs of delamination, indicating a strong bonding. Furthermore, the porosity levels of the coatings on the substrates with different surface conditions are quite similar ($\sim 1.7\%$), which indicates that the substrate surface roughness possibly affects the deposition behavior of the first few layers and has an insignificant effect on subsequent deposition and hence the porosity levels.

Fig. 5 Optical micrographs showing cross-sectional microstructures of cold sprayed IN718 coatings on IN718 substrates prepared by (a) sand-blasting, (b) grinding, (c) milling and (d) polishing.

In order to measure the bonding strengths between coating and substrate, pull-off tensile tests were conducted. Fig. 6 shows the variations of adhesion strength between the IN718 coatings and substrates with different surface conditions. Both the IN718 coatings on the sand-blasted and ground IN718 substrates fail at the coating/substrate interfaces and their adhesion strengths are about 23.7 MPa and 45.4 MPa, respectively. The adhesion strengths of the IN718 coatings deposited on the polished and milled IN718 substrates exceed the glue strength, which means that the coating bond strengths are at least more than 65 MPa. The reason for this is that a smoother substrate provides a flat surface with a greater area of contact for the impacting particles to deform and adhere to the substrate surface by formation of an adiabatic shear instability (ASI) zone, which results in a better bonding [31, 32]. In addition, due to the identical substrate and particle constitution, the IN718 particles are not able to penetrate the substrate and be mechanically interlocked with the substrate, which means that ASI plays a very important role in particle bonding. However, rougher surface conditions act as a barrier for the particles to deform with jetting (bonding occurred at jetting region), which results in poor bonding [33].

Fig. 6 Adhesion strengths of cold sprayed IN718 coatings on IN718 substrates prepared by sand-blasting, grinding, milling and polishing. The strength of the glue used to fix the sample to the tensile fixtures has a strength of ~60-80 MPa.

3.2. Experimental evidence of effect of substrate preheating on bonding characteristics

3.2.1. Single splat

Fig. 7 shows the cross-sections of the single IN718 particles deposited on the IN718 substrates with and without preheating. For the non-preheated substrate as shown in Fig. 7(a), about half of the IN718 particles are bonded to the IN718 substrate surface and there is no obvious sign for the jetting feature [26, 34]. The deformation of the substrate is not significant, and it is obvious that there is a gap and a microcrack on both sides of the interface. As the substrate preheating temperature is increased to 100 °C, the particles bond better to the substrate but the gap at the interface still could be seen. When the substrate temperature is increased to 200 °C, no gap is observed at the interface and material jet is formed on the right side of the interface, which is usually considered as a positive indication for a sound coating-substrate bonding [29, 30, 34]. However, the discontinuous bonding line between the particle and substrate still could be distinguished. When the substrate temperature is further increased to 450 °C, the formed metal jet becomes more obvious and the entire IN718 particle is almost bonded to the underlying substrate.

Fig. 7 SEM cross-section views of cold sprayed IN718 single splats deposited on IN718 substrates with temperatures of (a) 25 °C, (b) 100 °C, (c) 200 °C and (d) 450 °C.

Fig. 8 exhibits the substrate surface morphologies following pull-out of the coatings from the substrates with different preheating temperatures. For the non-preheating substrate, the particle deposition efficiency is relatively low. Some particles are deposited on the substrate surface, while others fail to deposit with some observable craters left on the substrate surface [33] as shown in Fig. 8(a). This is an indication of poor bonding between the particles and substrate without preheating. Also, these craters may be produced by the particles with a velocity lower than the critical velocity [17]. However, with the substrate preheating temperature of 100 °C, the particle deposition efficiency increases, and more particles are attached to the substrate surface as several craters are observed. Furthermore, a fraction of small white points, which indicates the deposition of some small particles, can be found on the substrate surface as shown in Fig. 8(b). When the substrate preheating temperature is 200 °C, the particle deposition efficiency is further increased

and only two craters can be observed within the region of interest as shown in Fig. 8(c). Besides, when the substrate is preheated to 450 °C, almost all the particles are deposited on the substrate [33]. The fraction of the smaller particles as indicated by the circles in Fig. 8(c & d) significantly increases in comparison to the case of 100 °C. Based on these facts, it is obvious that substrate preheating can truly promote the bonding between cold sprayed particles and substrate, which is consistent with the discussion on the shear test and simulation results in the later section [33].

Fig. 8 SEM micrographs showing surface morphologies of the IN718 substrates impacted by individual IN718 particles with respect to substrate preheating temperatures: (a) 25 °C, (b) 100 °C, (c) 200 °C and (d) 450 °C.

In order to measure the contour heights of the deposited particle after single splat deformation, Alicona Infinite Focus is used. Fig. 9 shows the typical 3D surface morphologies of the IN718 substrates impacted by the individual IN718 particles with respect to different substrate preheating temperatures. From Fig. 9(a) (i.e. the substrate preheating temperature: 25 °C), the maximum particle height above the substrate is ~16

μm and the material jetting can be observed. However, when the substrate preheating temperature is increased to $450\text{ }^{\circ}\text{C}$, the maximum particle height above the substrate is $\sim 20\text{ }\mu\text{m}$ and the material jetting is more obvious as shown in Fig. 9(b). This means that the particle deformation ratio decreases with increasing substrate preheating temperature, which is probably due to the IN718 substrate material softening at higher temperature. In addition, the material jetting indicates the occurrence of adiabatic shear instability [20] and high substrate preheating temperature promotes the adiabatic shear instability process. These results have been verified by the modelling in the later section.

Fig. 9 3D optical micrographs showing surface morphologies of the IN718 substrates impacted by IN718 particles with and without substrate preheating: (a) $25\text{ }^{\circ}\text{C}$ and (d) $450\text{ }^{\circ}\text{C}$.

3.2.2. Shear test

Fig. 10 shows the coating/substrate shear strength as a function of substrate temperature. Obviously, the preheating of substrate is found to improve the bonding strength because of the better metallurgical bonding. According to the ČSN EN 15340 standard [16], shear strength is defined as the shear load resistance of the coating when the shear adhesive or adhesive/cohesive or cohesive strength of the coating or the coating system is exceeded. Without preheating, the average shear strength between the coating and substrate is $66 \pm 5\text{ MPa}$. However, when the substrate preheating is $100\text{ }^{\circ}\text{C}$, the shear strength is found to be $95 \pm 10\text{ MPa}$. When the substrate preheating temperature is increased to $450\text{ }^{\circ}\text{C}$, the shear strength

dramatically increases to 218 ± 19 MPa. The measured shear strength data shown in Fig. 10 confirm that the substrate preheating plays a very crucial role in the final coating bonding strength.

Fig. 10 Interfacial shear strengths of cold sprayed IN718 coatings deposited on IN718 substrates with different preheating temperatures.

In order to better understand the fracture mechanisms during the shear tests, the fractured surfaces after shear tests are investigated. The typical morphologies of the fractured substrate surfaces with and without substrate preheating are shown in Fig. 11. A few retained IN718 particles are found on the surface of the substrate without preheating as shown in Fig. 11(a). This means that the fracture of the IN718 coating occurs at the interface of the coating and substrate under this condition. A high magnification view of the crater in Fig. 11(a) is shown in Fig. 11(c), where the crater presents shallow dimples at the edge and a smooth area at the center. When the substrate preheating temperature is 450 °C, more IN718 particles are found retained on the fractured surface as shown in Fig. 11(b), which means that the bonding strength between the coating and substrate is stronger than the coating cohesive strength in some areas following substrate preheating. This is a direct reason for a higher bond strength between the coating and the preheated substrate. A closer view of the crater in Fig. 11(d) shows that more enlarged dimples are present at the edge of each particle, which correlates with the enhanced bond strength. In addition, the retained material from

the particle is found at the crater edge, which implies that fracture occurs within the particle. This is another direct proof that the bonding strength is stronger under this condition.

Fig. 11 SEM micrographs showing fracture morphologies of IN718 on the substrate sides after shear tests at (a & c) room-temperature (25 °C) and (b & d) preheating temperature of 450 °C.

3.3. Impact simulation

In cold spray, the particle kinetic energy and thermal energy are determined by the particle velocity and particle temperature, respectively. The particle kinetic energy is mainly converted into local adiabatic heat energy at the particle-substrate interface upon impact on the substrate [14, 20, 27]. Furthermore, a small percent of the initial kinetic energy is stored as recoverable strain energy in the particle and substrate [20]. Given that only a small quantity of initial kinetic energy of the particle is dissipated as elastic wave propagations [31], it is neglected in this study. The kinetic energy and internal energy variations of the impact particles are displayed in Fig. 12(a). It is evident from the figure that increasing substrate preheating temperature has little effect on the impact time (~40 ns for different cases). However, the corresponding

maximum substrate temperature increased as a function of substrate preheating temperature as shown in Fig. 12(b). From the results, without preheating the substrate, the maximum substrate temperature at the impacting interface is found to be 585 °C. However, as the substrate preheating temperature is increased to 450 °C, the maximum substrate temperature increases to 1034 °C.

Bae et al. [20] mentioned that local adiabatic heating at the particle-substrate interface contributes to particle bonding process, and the elastic strain energy triggers the particle debonding from the substrate [20]. Wu et al. [19] showed that the elastic strain energy is related to the elastic modulus of the particle and substrate materials. Fig. 12(c) reveals that the recoverable strain energy decreases, and plastic dissipation energy increases with substrate preheating temperature. The reason for this is that the flow stress of the material decreases during adiabatic heating and the resultant thermal softening becomes more obvious with increasing substrate preheating temperature [20]. Without preheating the substrate, the relatively high fraction of recoverable strain energy affects the coating bonding strength. However, with preheating, the additional thermal energy of the substrate renders a positive effect on bonding criteria by increasing the plastic dissipation energy and decreasing the flow stress and elastic strain energy, which clearly indicates the role of substrate temperature in the cold spray bonding process [14].

On the other hand, the crater depths and particle deformation ratios vary with substrate preheating temperatures as shown in Fig. 12(d). The rise in the initial temperature softens the substrate, which generates a larger crater depth under the same impact velocity. While the deformation of the particle decreases as the substrate gets softened with increasing temperature. The larger crater depths would increase the contact area thus promoting the particle/substrate bonding. Fig. 12(e & f) shows the Von Mises stress and temperature distributions at ~40 ns of the cold spray particle impacted on the substrates with room temperature and 450 °C, respectively. The maximum stress value and maximum temperature at contact is lower for 450 °C, which is due to the fact that less particle deformation is caused for the 450 °C case.

Fig. 12 (a) Kinetic energy and internal energy variations of the IN718 particles impacted on IN718 substrates at different preheating temperatures, (b) maximum substrate temperatures at the impacted interfaces upon impact obtained from the modelling, (c) recoverable strain energy and plastic dissipation energy at different substrate preheating temperatures, (d) crater depths and particle deformations at different substrate temperatures and (e & f) Von Mises stress and temperature distributions in the particles deposited on (e) substrate at room temperature and (f) substrate at 450 °C.

Fig. 13 shows the deformed splats and substrates at different substrate preheating temperatures. The results show that the periphery of the particle has a higher temperature than the center [6], which agrees well with the experimental results shown in Fig. 11 that the bonding occurs at the periphery of the particle. However,

around the ‘south pole’, a lower temperature is observed, and such temperature is insufficient to create sound bonding at the ‘south pole’ zone. Such a weakly bonded area can be observed from the SEM image of the peeled-off fractured surface, that shows a ductile fractured surface at the periphery of the crater and a smooth fractured surface at the center. Fig. 13(a) and (b) show that the maximum temperature on the particle side is close to the material melting point, which is higher than that of the substrate side. Furthermore, the modelling results exhibit a more flattened particle with a less deformed substrate for the room temperature case (Fig. 13(a & c)) and a less deformed particle and more deformed substrate for the 450 °C case (Fig. 13(b & d)) – this is in line with the 3D optical micrographs that show an increased deformation ratio at the low temperature. In addition, for the 450 °C case, the wider high-temperature areas both on the substrate and particle sides than that of the room temperature case would probably increase the adiabatic shear instable areas and thus leading to a greater bonding strength.

Fig. 13 Simulated deformed splats and substrates at different substrate preheating temperatures: (a & c) room temperature and (b & d) 450 °C.

4. Conclusions

The deposition characteristics of cold sprayed IN718 particles on IN718 substrate surfaces prepared with different methods at different preheating temperatures were explored by means of both experimental characterization and finite element modelling. Based on the results obtained from the study, the following conclusions were drawn:

- Substrate surface roughness played an important role in adiabatic shear instability process. A smoother substrate surface allowed a particle to undergo adiabatic shear instability without constraint, hence leading to better interface bonding. However, a rougher substrate surface acted as a barrier for the particle to deform by jetting (bonding occurred in a jetting region), which resulted in poor interface bonding.
- Preheated IN718 substrates were conducive to a good quality bonding resulting in a higher bonding strength under shear loading condition.
- It was found that with the increase of substrate preheating temperature, craters formed on the substrate surface, and metal jets, formed at the rim of the substrate/particle interface, became increasingly prominent as a result of enhanced thermal softening. The single splat on the 450 °C substrate formed an intimate, defect-free bond with the substrate.
- The modelling results indicated that increasing the substrate preheating temperature would probably promote the adiabatic shear instability process and thus leading to greater bonding strength. Without preheating, a relatively high amount of recoverable elastic strain energy may contribute to a poor bonding strength.
- From the shear test results, the coating-substrate bonding strength increased with the substrate preheating temperature – a significant increase in shear strength of the bond was noted from 66 ± 5 MPa at room-temperature to 218 ± 19 MPa when the substrate was preheated to 450 °C. Besides, the fractured surfaces revealed that the fracture occurred only at the coating/substrate interfaces for the samples without preheating while the fracture occurred both at the interfaces and in the coatings

for the preheated samples. In addition, deeper dimples were observed in the jetted areas, which further indicated that metallurgical bonding more easily formed on the substrate surfaces preheated at higher temperatures.

Acknowledgements

This work was financially supported by the National Research Foundation (NRF), Rolls-Royce (RR), and Nanyang Technological University (NTU), Singapore, with the research grant number of NRF-RR-NTU M-RT3.1. Wen Sun was grateful for the PhD scholarship from the Rolls-Royce @ NTU Corporate Lab and the Nanyang Technological University, Singapore.

References

- [1] A. Papyrin, V. Kosarev, K.V. Klinkov, A. Alkhimov, V.K. Fomin, Cold Spray Technology, Elsevier Ltd., Oxford, 2006.
- [2] V.F. Kosarev, S.V. Klinkov, A.P. Alkhimov, A.N. Papyrin, On some aspects of gas dynamics of the cold spray process, *J. Therm. Spray Technol.* 12 (2003) 265–281.
- [3] M. Grujicic, C.L. Zhao, W.S. DeRosset, D. Helfricht, Adiabatic shear instability based mechanism for particles/substrate bonding in the cold-gas dynamic-spray process, *Mater. Des.* 25 (2004) 681–688.
- [4] J. Pattison, S. Celotto, R. Morgan, M. Bray, W.O. Neill, Cold gas dynamic manufacturing: a non-thermal approach to freeform fabrication, *Int. J. Mach. Tools Manuf.* 47 (2007) 627–634.
- [5] R. Singh, K.-H. Rauwald, E. Wessel, G. Mauer, S. Schrufer, A. Barthd, S. Wilson, R. Vassen, Effects of substrate roughness and spray-angle on deposition behavior of cold-sprayed Inconel 718, *Surf. Coat. Technol.* 319 (2017) 249–259.
- [6] C.W. Ziemian, M.M. Sharma, B.D. Bouffard, T. Nissley, T.J. Eden, Effect of substrate surface roughening and cold spray coating on the fatigue life of AA2024 specimens, *Mater. Des.* 54 (2014) 212–221.
- [7] W. Sun, A.W.Y. Tan, N.W. Khun, I. Marinescu, E. Liu, Effect of substrate surface condition on fatigue behavior of cold sprayed Ti6Al4V coatings, *Surf. Coat. Technol.* 320 (2017) 452–457.
- [8] T. Marrocco, D. G. McCartney, P. H. Shipway, A. J. Sturgeon, Production of titanium deposits by cold-gas dynamic spray: Numerical modeling and experimental characterization, *J. Therm. Spray Technol.* 15 (2006) 263–272.
- [9] Y. Xie, M.-P. Planche, R. Raoelison, H. Liao, X. Suo, and P. Herve, Effect of Substrate Preheating on Adhesive Strength of SS 316L Cold Spray Coatings, *J. Therm. Spray Technol.* 25 (2016) 123–130.
- [10] Y. Watanabe, C. Yoshida, K. Atsumi, M. Yamada, M. Fukumoto, Influence of substrate temperature on adhesion strength of cold-sprayed coatings, *J. Therm. Spray Technol.* 24 (2014) 86–91.
- [11] H. Assadi, F. Gartner, T. Stoltenhoff, H. Kreye. Bonding Mechanism in Cold Gas Spraying. *Acta Mater.* 51(2003) 4379–4394.

- [12] Office of Aviation Research Washington, D.C. 20591. Experimental Investigations of Material Models for Ti-6Al-4V Titanium and 2024-T3 Aluminium. National Technical Information Service (NTIS), September 2000.
- [13] B. E. Echavarri, Flow and fracture behavior of high performance alloys, Doctoral thesis, Universidad Politecnica de Madrid, 2012.
- [14] S. Kumar, M. Ramakrishna, N.M. Chavan, S.V. Joshi, Correlation of splat state with deposition characteristics of cold sprayed niobium coatings, *Acta Mater.* 130 (2017) 177–195.
- [15] ASTM C633-13, Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings, 2017.
- [16] ČSN EN 15340, Thermal Spraying - Determination of Shear Load Resistance of Thermally Sprayed Coatings, 2007.
- [17] X.K. Suo, M. Yu, W.Y. Li, M.P. Planche, H.L. Liao, Effect of substrate preheating on bonding strength of cold sprayed Mg coatings, *J. Therm. Spray Technol.* 21 (2012) 1091–1098.
- [18] W. Sun, A.W.Y. Tan, I. Marinescu, W. Q. Toh, E. Liu, Adhesion, tribological and corrosion properties of cold-sprayed CoCrMo and Ti6Al4V coatings on 6061-T651 Al alloy, *Surf. Coat. Technol.* 326 (2017) 291–298.
- [19] J. W. Wu, H. Y. Fang, S. H. Yoon, H. J. Kim, C. H. Lee, The rebound phenomenon in kinetic spraying deposition, *Scripta Mater.* 2006 (54) 665–669.
- [20] G. Bae, Y. M. Xiong, S. Kumar, K. Kang, C. H. Lee, General aspects of interface bonding in kinetic sprayed coatings, *Acta Mater.* 2008 (56) 4858–4868.
- [21] N.W. Khun, A.W.Y. Tan, K.J.W. Bi, E. Liu, Effects of working gas on wear and corrosion resistances of cold sprayed Ti6Al4V coatings, *Surf. Coat. Technol.* 302 (2016) 1–12.
- [22] N.W. Khun, A.W.Y. Tan, W. Sun, E. Liu, Effect of heat treatment temperature on microstructure and mechanical and tribological properties of cold sprayed Ti-6Al-4V coatings, *Tribol. Technol.* 60 (2017) 1033–1042.

- [23] A.W.Y. Tan, W. Sun, Y. P. Phang, M. H. Dai, I. Marinescu, Z. L. Dong, E. Liu Effects of Traverse Scanning Speed of Spray Nozzle on the Microstructure and Mechanical Properties of Cold-Sprayed Ti6Al4V Coatings, *J. Therm. Spray Technol.* 26 (2017) 1484–1497.
- [24] N.W. Khun, A.W.Y. Tan, W. Sun, E. Liu, Wear and Corrosion Resistance of Thick Ti-6Al-4V Coating Deposited on Ti-6Al-4V Substrate via High-Pressure Cold Spray, *J. Therm. Spray Technol.* 26 (2017), 1393–1407.
- [25] Z. Arabgol, M. Villa Vidaller, H. Assadi, F. Gartner, T. Klassen, Influence of thermal properties and temperature of substrate on the quality of cold-sprayed deposits, *Acta Mater.* 127 (2017) 287–301.
- [26] T. Hussain, D.G. McCartney, P.H. Shipway, Impact phenomena in cold-spraying of titanium onto various ferrous alloys, *Surf. Coat. Technol.* 205 (2011) 5021–5027.
- [27] R. Ghelichi, S. Bagherifard, M. Guagliano, M. Verani, Numerical simulation of cold spray coating, *Surf. Coat. Technol.* 205 (2011) 5294–5301.
- [28] F. Raletz, M. Vardelle, G. Ezo, Critical particle velocity under cold spray conditions, *Surf. Coat. Technol.* 201 (2006) 1942–1947.
- [29] D. Goldbaum, J.M. Shockley, R.R. Chromik, A. Rezaeian, S. Yue, J.-G. Legoux, E. Irissou, The effect of deposition conditions on adhesion strength of Ti and Ti6Al4V cold spray splats, *J. Therm. Spray. Technol.* 21 (2012) 288–303.
- [30] T. Stoltenhoff, C. Borchers, F. Gartner, H. Kreye, Microstructures and key properties of cold-sprayed and thermally sprayed copper coatings, *Surf. Coat. Technol.* 200 (2006) 4947–4960.
- [31] I. M. Hutchings, Energy absorbed by elastic waves during plastic impact, *J Phys. D: Appl. Phys.*, 12 (1979) 1819–1824.
- [32] A.W.Y. Tan, W. Sun, N.W. Khun, I. Marinescu, Z.L. Dong, E. Liu, Potential of Cold Spray as Additive Manufacturing for Ti6Al4V, *Proc. of the 2nd Intl. Conf. on Progress in Additive Manufacturing*, 02 (2016) 403–408
- [33] Y. Shuo, X.K. Suo, Z.W. Guo, H.L. Liao, X.F. Wang, Deposition features of cold sprayed copper particles on preheated substrate, *Surf. Coat. Technol.* 268 (2015) 252–256.

[34] Y. Shuo, X.K. Suo, Y.C. Xie, W.Y. Li, R. Lupoi, H.L. Liao, Effect of substrate temperature on interfacial bonding for cold spray of Ni onto Cu, *J. Mater. Sci.* 50 (2015) 7448–7457.