Surface & Coatings Technology 252 (2014) 15–28

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Analysis of the residual stress and bonding mechanism in the cold spray technique using experimental and numerical methods

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ARTICLE INFO

Article history:
Received 11 October 2013
Accepted in revised form 27 April 2014
Available online 9 May 2014

Keywords:
Cold spray
Neutron diffraction
Residual stress
FE modelling
SPH

ABSTRACT

In the current study, numerical solutions were used to simulate multi-particle deposition in the cold spray (CS) process, and to investigate some of the physical attributes of the deposition process of AA-6061-T6 particles deposited on an AA-6061-T6 substrate. Earlier experimental results are presented, with varying substrate and cladding combination; a subset of these results is analysed using single particle impact simulation, a more traditional approach in simulations of cold spray, and the smooth particle hydrodynamic (SPH) formulation to simulate multi-particle deposition. In a single particle impact simulation, a strong correlation between temperature and plastic deformation of the CS particles during the deposition process was found. The authors were able to correlate the onset of adiabatic shear instability with pronounced reduction in the flow stress with an inversely proportional relation exhibited for both temperature rise and plastic deformation. In the simulation of multiple particle impact, 400 particles, several bulk characteristics were extracted as through-thickness functions: density, equivalent plastic strain and stress profile. Stress profile from the simulation was contrasted against neutron diffraction measurements of residual stress, along with the analytical model of Tsui and Clyne, and is shown to achieve good correlation and providing validation of the results of simulations. Furthermore it was found that these stresses originate from a delicate balance between (a) the strain rate hardening and thermal softening and (b) the shot peening effects induced by the impact of CS particles. Analysis of particle morphologies in the simulation suggests a strong influence of temperature rise at the periphery of CS particles during deposition and dynamic recrystallization with the strong jetting of molten metal allowing for inter particle mixing and substrate adhesion.

1. Introduction: cold spray

Cold spray is a material deposition technique in which particles of metal powder are accelerated up to speeds of 500–1000 m/s by injecting them into a carrier gas stream which impacts a metallic substrate and is bonded to the surface. In this process metallurgical bonding can occur only when the particle velocities reach a critical limit that is defined by the material properties and process conditions. The impact of particles onto a substrate and cohesion of the particle on a substrate, or, in other words, formation of metallurgical bonding, is a key part and a basis of the CS or the kinetic spraying technique.

There are a number of major ideas [1–6] as to the deformation sequences and the bonding mechanism associated with the CS technique. The major theories look at the interface temperature and the large adiabatic instabilities developed during the plastic deformation of both the particles and the substrate [2,3]. Other theories [2,7] have concluded that successful bonding can only occur if a critical velocity is reached which governs both the contact area and the contact time.

A factor and a distinctive feature of the CS process, which is closely related to the coating integrity and linked to the boding mechanism, is the residual stress that builds up in the material

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http://dx.doi.org/10.1016/j.surfcoat.2014.04.059
0257-8972/

during spraying. It was shown in several studies [8–11] that CS produces compressive residual stress, which can be beneficial when it is of moderate magnitude. However, large compressive stresses can also lead to the coating failures (e.g. through delamination) and the question of effective stress control through tuning the spray process parameters and material properties is important, provided that bonding is not compromised. Thus, understanding of the bonding mechanism together with the stress formation might be decisive for improving the overall integrity or performance of the coating

In earlier works [6,12,45,46] the authors attempted to interpret the measured values based on the kinetics of the spray process and material properties without finite element calculations, but the focus of the current study is the single- and multi-particle impact using finite element (FE) simulation. These can demonstrate some microscopic features of the particle bonding mechanism and the local stress distribution on a 60 μm thick substrate. In this study we also present measurements of residual stress in macroscopically thick AA-6061-T6 CS coatings, 3–4 mm thickness, produced using two slightly different spraying techniques. The experimentally determined through thickness stress profiles by neutron diffraction on macroscopically thick coatings were used to validate FE calculations made for 100 μm thick coatings. This was done by using the progressive deposition model of Tsui and Clyne [7] to correlate the experiments and simulations. Combining complementary approaches, experimental and modelling, some new insight into CS deformation was achieved.

2. Sample production and characterization

Two samples were of interest and these were characterized by a similar particle speed of ~600 m/s, although they were sprayed by two different CS techniques. The first sample was produced by a kinetic metallization (KM), a commercially available low-pressure CS system that uses a convergent barrel nozzle and operated under choked flow conditions with the gas speed through the nozzle barrel ~Mach 1. The AA-6061-T6 powder, with 15 μm diameter spherical particles produced by atomisation, was used to feed the spray system and deposited the particles onto an AA-6061-T6 substrate as shown in Table 1.

For the KM samples, the speed was estimated using Dykhuizen and Smith formalism [37] through velocity integration along the nozzle barrel. The particle drag coefficient was calculated according to the local Reynolds number and Henderson's correlation by evaluating the particle nozzle exit velocity based on the gas stagnation temperature, pressure, and the He gas thermodynamic properties using a 1-dimensional isentropic model. In the case of the samples sprayed using the supersonic CGT system, the particle exit velocities were calculated using the commercially-available computational fluid dynamic code FLUENT 3D.

The coatings were characterized by optical metallography in order to measure the amount of plastic deformation in the cold sprayed material. It was found, by assuming initial spherical shape of the particle and fitting deformed shape with an ellipsoid, that for both samples the

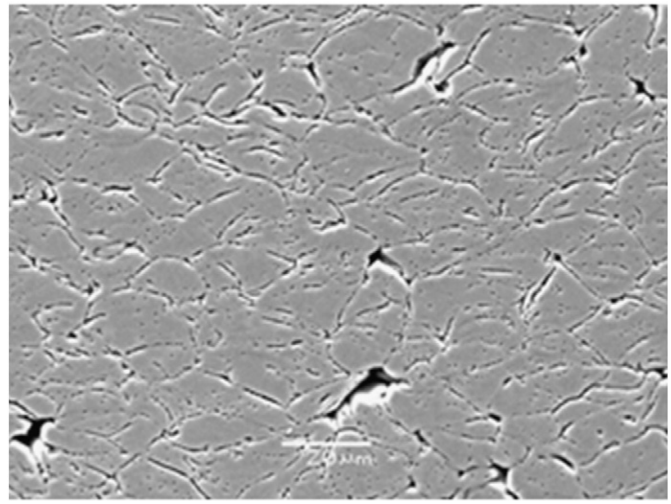

Fig. 1. Microstructure of the KM AA-6061-T6 on AA-6061-T6 system with the coating material showing the elongated grains (grey areas are single phase Al with limited porosity appearing as black areas). The image is taken 0.1 mm above the substrate/coating interface.

plastic deformation was about the same, 50%, as demonstrated in Fig. 1. The analysis of aspect ratios $l_\parallel/l_\perp$ of multiple particles (~50 measurements for each sample) allowed the authors to evaluate the average equivalent plastic strain, $\bar{\varepsilon} = \frac{2}{3}\ln\left(\frac{l_\parallel}{l_\perp}\right)$. Exact values are reported in Table 2 together with measured densities, measured using Archimedes' method, and the Young's modulus, measured using the impulse excitation technique [44] according to ASTM standard E1876, these methods were utilised in earlier studies of the cold spray technique by the current authors [45,46]. The values are shown as percentages of bulk values.

3. Neutron stress measurements

The neutron diffraction residual stress measurements were carried out at the OPAL research reactor, Australian Nuclear Science and Technology Organisation, using the KOWARI strain scanner. A gauge volume of 0.5 × 0.5 × 18 mm was used in allowing to measure the stress profile with fine enough through-thickness resolution. At the same time it was sufficient to measure strains with statistical uncertainty ~5 × 10^{-5}, within reasonable experimental time.

A 90° geometry ($2\theta_B$ ~ 90°) was chosen to rectify localisation of the gauge volume. To maintain this, the take-off angle $2\theta_M$ of the Si (400) monochromator (or the neutron wavelength) was varied according to the material (see Table 3). The measurements were done in several different through-thickness locations to cover the entire sample thickness, forming a line profile with 0.3 mm spacing between points. For each measurement point, d-spacings (diffraction peak positions) were measured in the two principle directions, normal to the surface and in-plane. From the measured d-spacings, in-plane stresses were calculated using the assumption of a balanced biaxial plane stress state, following the procedure described in [48]. The diffraction elastic constants used for stress calculation were computed using the self-consistent method of Kröner [47], and are reported in Table 3.

Table 1
Materials and process parameters used for cold spray.

Powder material/ substrate	Cold spray process	Average particle size (μm)	Driving gas	Driving pressure (kPa)	Nozzle temp. (°C)	Nozzle gas speed (m/s)	Calc. impact speed [m/s]
AA6061-T6/AA-6061	KM	15	He	620	~140	1025	585
Pure Al/Mg	KM	15	He	620	132	1025	585