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Residual stresses in single particle splat of metal cold spray process – Numerical simulation and direct measurement

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ABSTRACT

This report provides the first quantitative evaluation and prediction of residual stress arising from a single particle deposition in the metal cold spray of Ti-6Al-4V. Micro-ring-core Focused Ion Beam–Digital Image Correlation (FIB-DIC) technique is employed to determine the residual stress variation experimentally, while finite element simulation with Johnson-Cook plasticity and dynamic failure model is employed to numerically predict the residual stress distribution within single particle, and they show good agreement with each other for different impact velocities. This provides a tight link between the validated description of microscopic phenomena and the ensuing macroscopic properties and processes of the deposit.

1. Introduction

The metal cold spray is an additive manufacturing technique with great potentials in surface functionalization [1], bulk component production [2] and restoration/repair [3]. The metallic powders (usually 5–50 μm in particle size) are accelerated to supersonic velocities (up to 1000 m/s) by the carrier gas of high pressure and temperature. The high-speed powders accelerated out of the convergent-divergent (de Laval) nozzle, impact on the substrate and form layers of coating through deformation-induced bonding [4]. One significant advantage of the cold spray technique is to keep the powder and substrate temperatures well below their melting points so that the initial physical and chemical properties of the materials can be retained [4]. The metallic bonding formed at the particle/substrate interface in cold spraying process is attributed to "adiabatic shear instability", which was proposed by Assadi et al. [5] and is widely accepted.

However, the coating fabricated by this process suffers from relatively low interfacial bonding strength [6,7]. Therefore, process optimization through numerical simulation and experiment is much needed to study the interaction between the particles and substrate during impact. In the simulation, axisymmetric 2D [8], symmetric ¼ -3D [9] and full 3D [10] models of single particle [11], multi particles [10] and multi-layers [12] were employed. Different numerical approaches, i.e. Lagrangian [11], Eulerian [13] and Smooth Particle Hydrodynamics (SPH) [10] were explored. Most of these models are validated indirectly through the link between microscopic simulation and macroscopic process parameters, namely the critical velocity and erosion velocity [14]. Some [10,12] are to link the macroscopic residual stress (in millimetre range) with the macroscopic analytical model of Tsai and Clyne for progressively deposited coatings [15]. Recently, *in situ* direct observation has been made on the single particle impact on the substrate [16], which again correlates microscopic impact behaviour with macroscopic critical velocity.

Up to date, no work has been reported on the comparison between the residual stresses in the single splat with the numerical model. Here we present the first quantitative validation of the single particle impact model by using the Focus Ion Beam (FIB) – Digital Image Correlation (DIC) technique to measure the microscopic residual stress (in micrometre range) in the single splat, which has shown a good agreement with the model, indicating a higher microscopic compressive stress in the in-plane direction.

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2. Material and methods

Ti-6Al-4V Grade 23 powder particle (15–45 μm) with average particle size of 32 μm was selected as the feedstock powder material and the substrate was Ti-6Al-4V Grade 5 block polished to mirror-like surface finish to promote interfacial bonding. The experimental setup follows the work of metal cold spray study of Ti-6V-4Al thin coating in Rolls-Royce@NTU Corporate Lab [17] and illustrated in Fig. 1a, with modification of reducing the powder feed rate down to 3 g/min and increasing the transverse scan speed up to 500 mm/s to promote single particle impact regions appearing in one raster. The substrate was firstly preheated to ~300 °C by the N_2 hot gas impingement, then the powder was fed to the hot gas gun and exited the nozzle at different flow speeds depending on the N_2 carrier gas temperature and pressure settings (700 °C, 4.5 MPa for ~700 m/s and 1000 °C, 4.5 MPa for ~800 m/s). The particle velocity was measured using Tecnar Cold Spray Meter. After the spray, the sample was examined by optical microscope to identify the single particle bonding region, then the cross section was cut by EDM slitting and electro-polished for further SEM study.

Prior to the residual stress measurements, the samples were electrochemically polished during 2 min with a current density of 2 kA/m^2 in an electrolyte containing 700 ml/l ethanol, 300 ml/l isopropanol, 60 g/l aluminium chloride and 250 g/l zinc chloride [18]. The residual stress profiles inside single splats were measured by parallel FIB-DIC micro-ring-core milling using a "double chocolate block" geometry, as shown in Fig. 1d. This technique, which is based on the parallel ring-core FIB-DIC method [19], involves parallel FIB milling of 3 vertical and 7 horizontal trenches of 1 μm width in 32 incremental steps of 125 nm, up to a total depth of 4 μm. This results in the formation of square "islands" of 4 by 4 μm. The main advantage of parallel FIB-DIC over pointwise micro-ring-core FIB-DIC is that the residual stress can be measured with a high point-to-point spatial resolution of 5 μm. The relief strain after each milling step was measured simultaneously for each 'island' by means of DIC analysis of SEM images. The surface contrast needed to ensure adequate DIC tracking was provided by electron deposition of Pt markers in a sunflower pattern. The total relief strain, measured at a milling depth of 4 μm, was used to calculate the residual stress that was present in each island, assuming an average Young's modulus of 110 GPa and Poisson coefficient of 0.3. A more detailed description of this technique has been provided elsewhere [20].

Meanwhile, for ease of the direct comparison, all the model setup parameters in ABAQUS/Explicit were kept the same as that in the experiment. The diameter of spherical particle (d_p) was set to be 30 μm to correspond to the average size of the sprayed powder particles. In order to reduce the computational effort while maintaining the numerical accuracy, the cylindrical substrate was set to be 120 μm in diameter and 60 μm in height, with mesh element size set to 0.3 μm (1/100 of the particle diameter d_p) at the impact centre and gradually increased to 1.0 μm (1/30 d_p) at the edge of the part [21]. An 8-node hexahedral element with reduced integration and stiffness hourglass control (C3D8R) was used as the meshing element type. The outer side face of the substrate was only allowed vertical movement while the bottom was fixed in all directions as the boundary condition. In addition, the particle impacted vertically onto the substrate in the current simulation. Although a number of researchers prefer 2D axisymmetric model [11] for vertical impact, 3D model was chosen as more flexible and capable of simulating impacts with tilt angle and self-spin. An isometric view of the full 3D model before impact is shown in Fig. 1b. Fig. 1c provides the cross sectional view of the particle during impact, with the centreline plot as the data point for the residual stress evaluation.

In the simulation, all the material properties of Ti-6Al-4V were taken from the literature [22] and provided in Appendix A. Notes have to be taken that since the complete deformation process is kept within dozens of nanoseconds, the thermal diffusivity distance is much shorter than the characteristic dimension of the elements in the particle and substrate, and hence the particle/substrate impact is assumed to be an adiabatic process where thermal conduction is considered to be zero during the deformation. The inelastic heat fraction in the Appendix A is determined from the fraction of plastic work converted to heat during deformation. Besides, it should be noticed that the values of

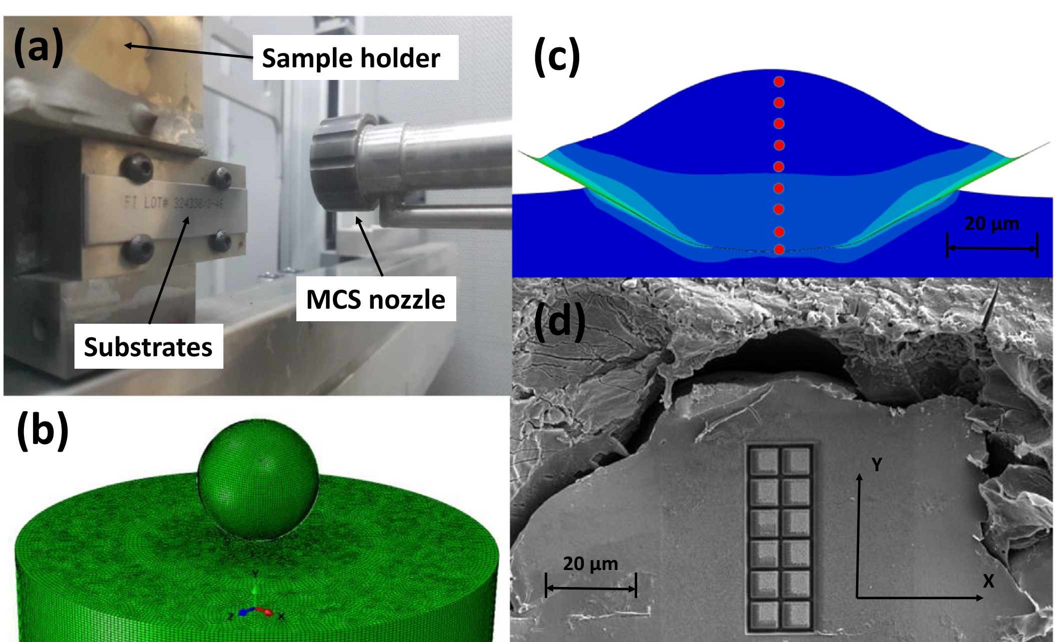

Fig. 1. (a) Metal cold spray experiment setup (b) isometric view of the full 3D model (c) deformed particle with data points for residual stress evaluation (d) SEM image of the measurement points in the FIB-DIC micro residual stress evaluation.