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POTENTIAL OF COLD SPRAY AS ADDITIVE MANUFACTURING FOR TI6AL4V

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ABSTRACT: Cold spray can be regarded as a high build-speed (300-400 cm^3/h) additive manufacturing technology that is capable of non-thermal freeform fabrication on any surface profile. It uses a high pressured and preheated gas stream to accelerate the microparticles via a converging-diverging nozzle to supersonic speeds and impact onto the substrate. The micro-particles will then plastically deform and bond with the substrate. Cold spraying of Ti6Al4V (or Ti64) would be beneficial for many industries because of the build speed and minimal material wastage. However, recent studies showed that cold spraying of Ti64 coating is challenging due to the coating's poor interfacial bonding to the substrate surface, limited coating thickness and relatively high porosity level from 5 to 20%. In this work, we have successfully deposited high-quality cold sprayed Ti64 coatings on Ti64 substrates. The microstructure and mechanical properties of the Ti6Al4V coatings were systematically investigated.

KEYWORDS: High-pressure cold spray, Additive manufacturing, Ti6Al4V coating, Ti6Al4V substrate, Microstructure, Mechanical properties

1 INTRODUCTION

Additive manufacturing (AM) technologies are used to fabricate freeform components on a layer-by-layer basis. For the production of metallic component, AM technologies such as selective laser sintering (SLS), direct metal deposition (DMD), and electro-beam melting (EBM) are commonly used. However, as these techniques use high temperature for either sintering or melting and re-solidification, their products suffer from detrimental effects such as large residual stresses, poor mechanical properties, unwanted phase transformations and part distortion (Amon et al., 1993). Several thermal spraying techniques have also been applied to the fabrication of free-standing components, including plasma spraying (PS) (Devasenapathi et al., 2002) and high velocity oxy-fuel (HVOF) spraying (Stokes et al., 2001); however, they too involve melting and solidification. Cold spray (CS) has shown the capability to perform non-thermal freeform fabrication (Pattison et al., 2007) at high build speed, although being a thermal spray process.

Cold spray process is based on gas flow physics, deformation of materials and thermo-mechanical dynamics (Papyrin et al., 2006). A cold sprayed layer or coating is achieved with a de-Laval type of nozzle through which pressurized (1 to 5 MPa) and preheated (up to 1100°C) nitrogen (N_2) or helium (He) propellant gas undergoes compression and expansion, imparting supersonic velocities (300 to 1200 ms^{-1}) to the feed stock powders (40 to 60 μm). When directed towards a substrate, the ballistic impact events that result cause massive plastic deformation in both the incident particles and the underlying material. This process disrupts thin surface films such as oxides and exposes fresh, active material, which when brought into intimate, conformal contact under high localised pressures, undergoes adiabatic shear instabilities to form strong atomic bonds (Assadi et al., 2003). Despite large preheated gas temperature, the gas temperature significantly lowers (about 100°C) when expanded to the nozzle divergent section. Consequently, the temperature of the feedstock powder particles remains below their macroscopic melting point and, therefore, the resulted coating is formed in the solid state.

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As CS operates with low heat, this process is suitable to deposit temperature sensitive materials such as nano-crystalline and amorphous materials (Ajdelsztajn et al.; C. J. Li et al., 2005), as well as oxygen-sensitive materials such as aluminium and titanium. Recently, cold spraying of Ti64 coatings has been researched as it can be potentially used in many applications. Some studies have been carried out to understand the splat deformation of cold sprayed Ti64 particles. Goldbaum et al. (Goldbaum et al., 2011) observed that Ti64 splats deposited on Ti64 substrate were highly deformed but demonstrated poor particle adhesion. Li et al. (W. Y. Li et al., 2007) reported cold sprayed Ti64 coatings having a high porosity level of about 22.3 %, especially at the boundaries of the deposited microparticles. On the other hand, Luo et al. demonstrated that cold sprayed Ti64 using He gas can create a denser coating with only about 2.7% porosities, but He gas is not economical as compared to N_2 gas due to cost.

Limited work has been reported on high-quality cold sprayed Ti64 coatings that are needed to meet the need of industries. In this work, thick and dense cold sprayed Ti64 coatings were successfully deposited on Ti64 substrates at a critical velocity via optimum parameters. The microstructure, thickness, surface roughness, hardness and interfacial bond strength of the Ti64 coatings were systematically investigated.

2 EXPERIMENT DETAILS

2.1 Materials

Ti64 (Grade 5) pieces with dimensions of 50 mm × 50 mm × 8 mm were used as the substrates. The substrates were ground and degreased sequentially prior to spraying for the purpose of disrupting the oxide layers on the substrate surfaces and promoting better particle–substrate interfacial bonding. The powder used as feedstock was a plasma atomized Ti64 ELI (Grade 23), with particle size of 15 to 45 μm.

2.2 Cold spray process

The Ti64 powders were sprayed using cold spray system 5/11. The spraying experiments were carried out using N_2 as the propellant gas. The gas pressure and temperature used were 4.5 MPa and 1100°C, respectively. Three Ti64 coated samples were prepared with coating thickness of about 3 mm.

2.3 Characterisation of Powders and Coatings

The surface roughness of the as-sprayed samples was measured with a contact mode surface profilometer (Taylor Hobson Talyscan). For cross-section analysis, the cold spray samples were cut into pieces with dimensions of 2 cm × 1 cm × 8 mm (L × W × H) each. The cut samples were then cold mounted (Struers Specifix-20, cured for 12 hours), ground and polished to mirror-like surface using the Struers package. The cross-sections of the samples were etched to reveal their microstructure using Kroll's reagent by immersion method for 10 to 15 s after porosity analysis. Microstructures and porosities of the samples were observed under optical microscopy (OM, Axioskop 2 MAT optic microscope) and/or scanning electron microscopy (SEM, JEOL JSM-5600LV) operated at 20 kV. Porosity measurement was processed using the open source software ImageJ by National Institutes of Health.

Elemental compositions of the samples were analysed using Energy Dispersive Spectroscopy (EDS, Oxford Instrument, attached to SEM). Phase analysis of the cold spray samples was carried out using X-ray diffraction (XRD, Panalytical Empyrean) with CuKα radiation at 40 kV and 40 mA, from 20 to 90 degrees of 2θ. Microhardness profiles across the coating and substrate cross sections (Figure 4a) of the Ti64 samples were evaluated using a Vickers microindenter (Future-Tech FM-300e) with 300 g load applied to a diamond indenter tip.

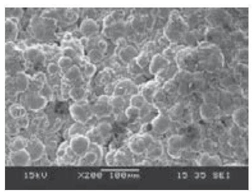
Adhesion strength tests were guided by a ASTM C633 standard (ASTM C633-13, 2008). First, the samples were wire cut into circular buttons with a diameter of 24 mm and the buttons were ground down to make them flat. Next, the button surfaces and fixtures were sand blasted with P80 alumina particles, cleaned with ethanol and assembled. The assembled sets were then placed at a tilt angle of 35° in an oven in which the sets were cured at 200°C under a weight of 380 g for 100 min. After curing, the sets were cooled at room temperature. Finally, the sets were mounted on a tensile test machine (Instron 5569) with a load cell of 50 kN for tensile tests at an extension rate of 0.8 mm/min till the sets failed.

3 RESULT AND DISCUSSIONS

3.1 As-sprayed surface analysis

The as-sprayed Ti64 coatings on the Ti64 substrates have a surface roughness (R_a) of about 57.1 µm, measured from a surface area of 20 mm × 20 mm (Figure 1b). Such a high surface roughness is because the Ti64 particles are difficult to completely deform upon impact due to their high yield strength (Figure 1a).

a)



b)

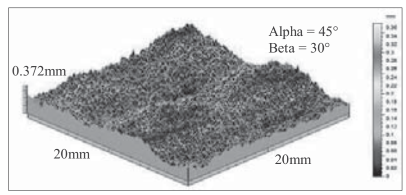


Figure 1. (a) SEM micrographs and b) surface profile of as-sprayed Ti64 coating surface

3.2 EDS and XRD analysis

Both EDS and XRD results show that the as-sprayed Ti64 coatings have no impurities or phase transformation compared to both the raw Ti64 powder and the uncoated Ti64 substrate (Table 1 and Figure 2). The cold spray is a supersonic deposition process in which particle interlocking or thermal bonding can occur within nanoseconds. However, such a short exposure of the powder particles to the environment cannot induce significant atomic diffusion, such as the diffusion of nitrogen or oxygen(Assadi et al., 2003).

Table 1. EDS results of Ti64 coating

Element	Weight%
Al	5.3
Ti	90.5
V	4.2
Total	100.0

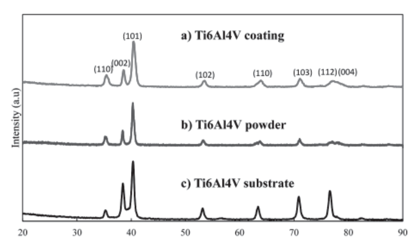


Figure 2. XRD spectra of a) Ti64 coating, b) Ti64 powder and c) Ti64 substrate

3.3 Cross section analysis

The polished samples show an average porosity level of about 2.6% with no cracking or interface delamination (Figure 3a), which is low compared to other reported works with porosities from about 5 to 20% (Blose et al., 2006; Perton et al., 2012; Vo et al., 2013). A lower porosity level (~2.4%) is observed towards the coating-substrate interface. The dense coatings are attributed to the high impact energy of the particles, which have promoted accumulative intensive plastic deformation, thus enhancing the cohesion of the particles and preventing the formation of porosities

a) b)

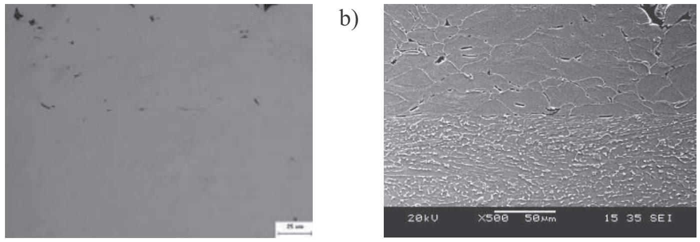


Figure 3. a) OM of polished and b) SEM of etched of cross-section at coating/substrate interface

The etched Ti64 coatings also reveal that the individual impacted particles are heavily deformed (Figure 3b) with the flattening ratios (width/height of particle) of about 1.67 to 2.78 towards the coating-substrate interface. With reference to the Ti64 splat study conducted by Goldbaum et al, the flattening ratios of 1.67 to 2.78 correspond to a particle velocity of about 750 to 850 ms^{-1}, which are the required critical velocities (Goldbaum et al., 2011; Schmidt et al., 2006). Such high impact energy allows localised interfacial melting and bonding of the impacted particles to other particles or interfaces.

3.4 Hardness analysis

The microhardness of the Ti64 coatings is similar to or exceeds that of the powder particles (~350 Hv). The microhardness of the coatings across their cross-sections varies from about 325 to 400 Hv while the hardness of the substrate is about 300 to 350 Hv as shown in Figure 4b, which are comparable with the reported works (Luo et al., 2015; Vo et al., 2013). The large deviations of the hardness values are due to the porosities at the indention locations.

a) b)

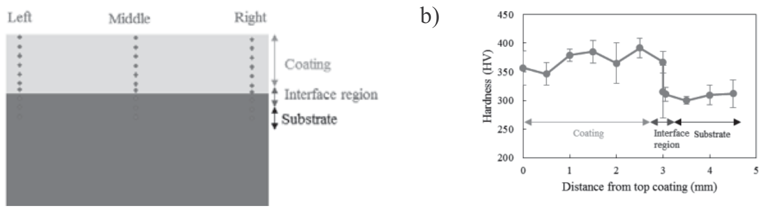


Figure 4. a) Hardness indentation location and b) Hardness profile across cross-section of coating

3.5 Adhesion strength test

The bond strength (exceeded 60 to 70 MPa) of the cold sprayed Ti64 coatings to their substrates is much stronger than that (about 50 MPa) of the reported thermal sprayed coatings (Zakharov et al., 2002). It is observed that the failure of the assembled sets happens at the adhesive instead of the coating-substrate interfaces (Figure 5), which is in agreement with the literature (Costil et al., 2010). The adhesion strength of the coatings is mainly contributed by the metallurgical bonding between the particles and the substrates. However, the current adhesion test standard with the ASTM C633 cannot precisely evaluate the effective bond strength of the cold sprayed Ti64 coatings to the Ti64 substrates, which needs future implementations.

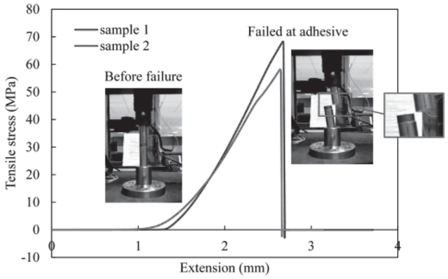


Figure 5: Adhesion test results before and after adhesive failure

4. CONCLUSIONS

High-quality cold sprayed Ti64 coatings are promising for many potential applications. The 3mm thick Ti64 coatings used in this study showed a high surface roughness (R_a) of about 57.1 µm. XRD and EDS analyses proved that there were no phase changes and impurities in the cold sprayed Ti64 coatings with reference to the pristine Ti64 powder and substrate. The cross-sections of the Ti64 coatings showed a low porosity level of about 2.6% and highly deformed particles, which were attributed to the high impact energy of the particles sprayed at their critical velocity. Such an impact energy promoted metallurgical bonding and mechanical interlocking as observed in the coatings. The hardness across the cross-sections of the Ti64 coatings was in the range of 325Hv to 400HV, higher than that of the Ti64 substrate and Ti64 powder due to the cold work hardening. The adhesive strength of the Ti64 coatings to their substrates exceeded 70 MPa (due to failure at adhesive), which is higher than that of many thermal sprayed Ti64 coatings.

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