Surface & Coatings Technology 335 (2018) 1–12

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Influence of feedstock powder and cold spray processing parameters on microstructure and mechanical properties of Ti-6Al-4V cold spray depositions

Venkata Satish Bhattiprolu[a], Kyle W. Johnson[b], Ozan C. Ozdemir[c], Grant A. Crawford[a,*]

[a] Department of Materials and Metallurgical Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
[b] VRC Metal Systems, 525 University Loop, Suite 211, Rapid City, SD 57701, USA
[c] Department of Mechanical and Industrial Engineering, Northeastern University, Boston, MA 02115, USA

ARTICLE INFO

Keywords:
Cold spray
Ti-6Al-4V
Feedstock powder
Microstructure characterization
Porosity
Adhesion strength

ABSTRACT

A high pressure cold spray system was used to deposit three Ti-6Al-4V feedstock powders (i.e., hydride de-hydride, plasma atomized, and gas atomized) on Ti-6Al-4V substrates while varying gas temperature and nozzle length. Particle impact temperature and particle velocity were calculated using a 1-D axial model. The microstructure of the feedstock powders and the cold spray depositions were characterized via optical and scanning electron microscopy. The hardness of the as-received powders was determined using nanoindentation. To assess deposition quality, coatings were characterized in terms of porosity, microhardness, and adhesion strength. Results showed that hydride de-hydride powders were characterized by an equiaxed alpha grain structure with intergranular beta phase regions while atomized powders were characterized by martensitic α phase structures. Cold sprayed coatings revealed two distinct microstructures. Regions that experienced low/moderate plastic strain retained the as-received powder microstructure while regions that experienced significant plastic strain were characterized either by a featureless microstructure (atomized coatings) or the presence of fine, elongated beta precipitates (hydride de-hydride coatings). Depositions performed using a long nozzle resulted in the best deposition quality, with porosity as low as 0.3% and adhesion strengths > 69 MPa. While atomized powders resulted in comparatively higher quality coatings for all process conditions, hydride de-hydride coatings of excellent quality (average porosity ≈ 0.6%, adhesion strength > 65 MPa) were achieved under optimal conditions. Thus, hydride de-hydride powders may hold promise as a cost effective alternative to atomized powders for Ti-6Al-4V cold spray depositions.

1. Introduction

Titanium (Ti) and Ti alloys are well known for their high strength-to-weight ratio and excellent corrosion resistance. Consequently, these materials are commonly used in the aerospace industry. In fact, a significant growth in Ti alloy raw material usage in the aerospace industry is projected over the next several years (173 million pounds in 2015 to 212 million pounds by 2020) [1]. This utilization would be even higher if not for the high cost of Ti alloys when compared to competing aerospace alloys such as aluminum and steel. A recent study shows that the production cost for a pound of Ti sheet to be 10–15 times higher than aluminum [2]. Owing to the high cost of manufacturing Ti and Ti alloy aerospace parts, a large market exists for maintenance repair and overhaul (MRO) of aerospace components [5]. One technology that has garnered significant interest in this regard is cold spray processing. The use of cold spray processing in repair and refurbishment of aerospace components is well documented and extensive case studies have been carried out previously [6,7], however, this technology is not yet mature for Ti and Ti alloys.

Cold spray is a solid state deposition process which relies on severe plastic deformation [8,9] of micron scale (< 100 μm) powder particles [10] upon impact with a target substrate, whereby the particles bond to the substrate through a combination of mechanical interlocking and metallurgical bonding [11]. As a solid state deposition process, one of the important advantages of cold spray is that thermally induced phase changes and stress development are limited during deposition. By contrast, high temperature thermal spray processes (e.g. plasma spray, high velocity oxy fuel) often result in the formation of thermal stresses and undesired oxides. The latter can be detrimental to oxygen sensitive materials such as Ti.

---

[*] Corresponding author.
E-mail address: grant.crawford@sdsmt.edu (G.A. Crawford).

https://doi.org/10.1016/j.surfcoat.2017.12.014
Received 27 July 2017; Received in revised form 5 December 2017; Accepted 6 December 2017
Available online 06 December 2017
0257-8972/ © 2017 Elsevier B.V. All rights reserved.

Cold spray technology is now well established for highly deformable face center cubic (FCC) alloys such as aluminum and copper [12–16]. Owing to their higher strength and somewhat limited capacity for plastic strain, Ti and Ti alloys are less amenable to cold spray processing and recent efforts have largely resulted in depositions with poor properties. In this regard, extensive work characterizing the deformation behavior of single particles (single splats) of commercially pure (CP)-Ti [10,17] and Ti-6Al-4V [18,19] have been conducted previously. Goldbaum et al. demonstrated that particles exhibit significant deformation during cold spray processing resulting in non-uniform hardness within the powder particles (i.e. high hardness in the impact region, lower hardness in the jetting region and in upper regions of the splats) [17]. In a separate study, Goldbaum et al. reported high adhesion strengths of up to 250 MPa for Ti-6Al-4V splats deposited using helium gas on Ti-6Al-4V substrates, pre-heated to 400 °C [18]. For this work, adhesion strength was measured using the splat adhesion technique (also known as modified ball bond shear test) [18]. While the measurement may be limited in the ability to predict full coating properties in some systems (considering it does not account for particle-particle interaction and associated porosity development during cold spray deposition), Goldbaum et al. have reported good correlation between splat adhesion strength and coating cohesion strength for titanium coatings sprayed on unheated substrates at low velocities (< 700 m/s) [18]. Blose et al. [4] conducted cold spray deposition of Ti-6Al-4V and reported porosities of roughly 5% and deposition efficiency of ~85%. The porosity reported by Blose et al. was the lowest observed in their study and resulted by increasing the stagnation gas pressure and temperature. It is well established that increasing gas temperature and pressure during cold spray depositions increases particle velocities and can result in improved deposition quality [20–22]. Blose et al. also reported a significant decrease in porosity (roughly 1 to 2%) with powder heating. Recently, porosity of $< 1\%$ was reported for cold sprayed Ti-6Al-4V coatings with helium carrier gas, deposited using plasma atomized powders [23]. While the low porosity reported by these authors is encouraging, the tensile strength and ductility of the coating was lower than bulk Ti-6Al-4V, even after applying a post-deposition heat treatment [23]. Clearly the use of a light gas like helium, instead of nitrogen, can effectively improve the deposition quality (especially porosity) [24]. The above studies show the potential for cold spray deposition of Ti-6Al-4V powders with good deposition quality. They also reinforce the importance of an in-depth understanding of the relationships between cold spray processing parameters and deposition quality/properties. Vidaller et al. [19] reported the influence of substrate material for deposition of Ti-6Al-4V splats and suggested the ideal combination to be deposition of Ti-6Al-4V powders on rough Ti/Ti-6Al-4V substrates. Grit blasting prior to cold spray deposition can serve two purposes, i.e. roughening the substrate and removing the inherent oxides on the substrate to improve bonding [25]. Detailed microstructure characterization of Ti-6Al-4V plasma atomized feedstock powder was reported by Birt et al. [26] for their use in cold spray applications. The same group of researchers reported the microstructure evolution of the powders during cold spray deposition and showed the presence of both textured and smooth regions within an individual particle that developed as a consequence of the degree of local plastic strain [27].

Based on the previous reports on cold sprayed Ti-6Al-4V coatings, it is apparent that processing parameters play a significant role in influencing the deposition quality (e.g. porosity). However, studies showing good deposition quality/properties are limited. Thus, there is a critical need for an in-depth understanding of the relationships between processing conditions and deposition quality/properties. Moreover, feedstock powder microstructure is known to significantly influence mechanical properties [28,29]. In this regard, gas atomization (GA), plasma atomization (PA), and hydride de-hydride (HDH) powders are extensively used in the powder metallurgy industry [30–32] and hence are viable options for cold spray. The atomization process involves the formation (i.e. breakup, dispersion, spheroidization) of micron scale liquid droplets from molten metal, followed by rapid cooling and associated solidification, resulting in highly uniform spherical metal powders. Among the various atomization processes, GA and PA are common; however, they differ significantly with respect to the form of the source metal, atomization mechanism, and cooling rates. In plasma atomization, Ti-6Al-4V is introduced as a wire (solid form) [31], whereas in gas atomization it is introduced in a liquid form [33]. As the name suggests, plasma is used for breakup and dispersion of molten metal in plasma atomization and argon gas (at high pressure and velocity) is used in the case of gas atomization. The cooling rates for plasma and gas atomization are 100–1000 °C/s [31] and 1000–10,000 °C/s [33], respectively. Hydride de-hydride (HDH) powder production is generally considered to be a lower cost process [32] and involves hydrogenation of Ti-6Al-4V at 650–700 °C, followed by milling and eventual de-hydrogenation at 350 °C in vacuum to form HDH Ti-6Al-4V powder. Due to the drastic difference in processing temperatures and cooling rates between atomization and HDH processes, the microstructure of the powders resulting from these processes are also different [28,31,34]. As such, the powders are expected to exhibit different deformation characteristics.

In the limited work reported on cold sprayed Ti-6Al-4V coatings, a comprehensive study on the influence of feedstock powder microstructure and cold spray processing conditions (e.g. nozzle length) on cold sprayed Ti-6Al-4V coating microstructure and properties has not been reported. Thus, this work has been conducted as a first step in gaining an understanding of the microstructure evolution and mechanical properties of Ti-6Al-4V cold spray coatings deposited using three feedstock powders (i.e. HDH, GA, and PA) while varying gas temperature and nozzle length.

2. Materials and methods

2.1. Cold spray processing

Three commercially available Ti-6Al-4V powders were used in this study: (1) gas atomized powder (Puris, LLC, West Virginia, USA), (2) plasma atomized powder (AP&C, Boisbriand, Quebec, Canada), and (3) hydride de-hydride powder (Phelly Materials Inc., New Jersey, USA). Cold spray deposition was performed on Ti-6Al-4V substrates (McMaster-Carr), using a VRC Gen III Max high pressure cold spray system (VRC Metal Systems, Rapid City, SD). All depositions were carried out using helium carrier gas with a gas pressure of 4.14 MPa. To evaluate the influence of particle velocity on deposition quality, gas temperature and nozzle length were varied. In this regard, three gas temperatures, i.e. 400 °C, 425 °C and 500 °C, and two nozzle lengths, i.e. 120 mm (short nozzle) and 200 mm (long nozzle), were used in this study. To prevent nozzle deterioration, high temperature depositions (i.e. 500 °C) were carried out using a two piece nozzle (tungsten-carbide converging section, polybenzimidazole (PBI) diverging section), while low temperature depositions were carried out using a PBI nozzle for both converging and diverging sections of the nozzle. All depositions were performed using a stand-off distance of 25 mm, travel speed of 200 mm/s, and deposition angle of 90°. The powder feed rate for atomized powders and hydride de-hydride powder were 5.7 g/min and 3.5 g/min, respectively. Finally, a 1-D axial model [35,36] was used to calculate particle temperature and velocity at impact, for each powder type, under the various processing conditions listed above. The particle velocity and temperature were tracked along the axis of the isentropic compressible gas flow in the nozzle [35,37]. The drag coefficient for flow around a sphere [38,39] and the forced convection heat transfer coefficient for a submerged sphere [40,41] were adopted from Bird [42].

Download English Version:

https://daneshyari.com/en/article/8024324

Download Persian Version:

https://daneshyari.com/article/8024324

Daneshyari.com