Surface & Coatings Technology 232 (2013) 587–599

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Effect of nitrogen flow rate on microstructures and mechanical properties of metallic coatings by warm spray deposition

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ARTICLE INFO

Article history:
Received 4 March 2013
Accepted in revised form 10 June 2013
Available online 15 June 2013

Keywords:
Warm spray
Tensile strength
Ductility
Aluminum
Copper
Titanium

ABSTRACT

In Warm Spraying (WS), the temperature of the combustion flame is controlled by injecting nitrogen gas into the combustion flame before the injection of spray powder. Temperatures of spray particles are kept under their melting points with moderately heated and thermally softened states. As compared to HVOF-spraying, the oxidation of particles can be significantly suppressed due to lower deposition temperatures, whereas, as compared to cold spraying, the degree of particle deformation upon impact can be enhanced by attaining higher particle temperatures. In the present study, the effects of particle temperatures on the coating microstructures and the mechanical properties were investigated for three metal coatings (Ti, Cu, and Al) by varying nitrogen flow rates during WS deposition. The mechanical properties of the coatings were evaluated by tubular coating tensile (TCT) and micro flat tensile (MFT) tests. For Ti and Cu coatings, a maximum in ultimate strength was reached for medium nitrogen flow rates, i.e. medium impact temperatures. For Cu, the maximum reflects a balance between the amount of bonded interfaces and softening by annealing. At lowest N_2 flow rates and thus highest impact temperatures, the elongation to failure of Cu coatings reached ~3%, and decreased with increasing nitrogen flow rates. Finally brittle fracture behavior was observed with the highest nitrogen flow rate. These results revealed how particle temperatures affect the microstructures and mechanical properties of WS coatings, and demonstrated that optimum spray conditions have to be balanced by adjusting particle temperatures, facilitating sufficient deformability while avoiding oxide formation.

1. Introduction

Warm spraying (WS) offers a wide range of attainable jet temperatures—about 700 to 2300 K—and bridges the gap between cold spraying (CS), where particles impact in the solid state, and conventional high velocity oxy-fuel (HVOF) deposition, in which particles are sprayed in molten or semi-molten state [1,2]. Thus, the method is attracting many interests from industries. By its higher particle temperature in comparison to CS, warm sprayed particles are more softened upon impact, thus reaching more deformation facilitating the formation of shear instabilities for bonding. As compared to HVOF-spraying, it can suppress various detrimental reactions such as oxidation. Thus, WS is expected to have advantages as compared to CS and HVOF spraying.

So far, substantial efforts were made to understand basic features of WS coatings and deposition mechanisms. Kawakita et al. [3] reported the microstructures of WS titanium (Ti) coatings and their corrosion resistance. The microstructures of Ti coatings showed a wide porosity range depending on particle temperatures. In combination with mechanical surface finishing, the results demonstrated a promising corrosion resistance. Chivavibul et al. [4–6] investigated the microstructures and mechanical properties of WC-Co coatings with various Co contents fabricated by WS and HVOF deposition. Particularly, the WS WC-17 and 25%Co coatings showed higher toughness than HVOF sprayed ones. Kim et al. [7,8] reported detailed observations of WS particle–particle and particle–substrate interfaces by transmission electron microscopy (TEM). These works revealed various types of interfacial bonding such as direct metal bonding and bonding with thin amorphous inter-layers depending on materials combinations. In addition, significant grain refinement was found depending on the degree of deformation implying the strong effects of particle temperatures on coating mechanical properties [7]. Tabbara et al. computationally investigated the interrelations between the gas and particle phases and highlighted the advantage of WS deposition [9]. However, correlations among spray conditions, coating microstructures and mechanical properties were not yet studied for WS metal coatings. The present

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0257-8972/$ – see front matter
http://dx.doi.org/10.1016/j.surfcoat.2013.06.034

research aims to investigate the effect of particle temperatures on mechanical properties of aluminum (Al), copper (Cu), and titanium (Ti) coatings deposited by warm spraying and to reveal the dominant factors for coating formation. Al, Cu, and Ti were chosen as spraying materials because of their quite different melting temperatures, which should allow a more general view of the influence on building-up coatings by the impact of solid or semi-liquid material. Apart from the scientific background, Al, Cu and Ti are also of a high interest for industrial applications.

2. Experimental procedure

2.1. Materials

Three commercially available metal powders of Al (Al #350 M-45, Fukuda Metal Foil & Power Co. Ltd., Kyoto, Japan), Cu (Cu AT 350, Fukuda Metal Foil & Powder Co. Ltd., Kyoto, Japan), Ti (TILOP -45 μm, Sumitomo Titanium Co. Ltd., Tokyo, Japan) were used as feedstock materials. The particle size distributions were measured by laser scattering (Microtrac 9320-X100, Microtrac Inc., FL, US). All powders had a gaussian powder size distribution from 15 to 45 μm and the average particle sizes of Al, Cu, and Ti were 30, 33, and 31 μm, respectively. All the powders were manufactured by gas atomization. The powder morphologies are shown in Fig. 1. The Al powder (Fig. 1(a)) had irregular shapes and the Cu and Ti powders were spherical (Fig. 1(b) and (c)). The oxygen and nitrogen contents in all powders were analyzed by an inert gas fusion method (LECO TC-600, Leco corp., MI, US).

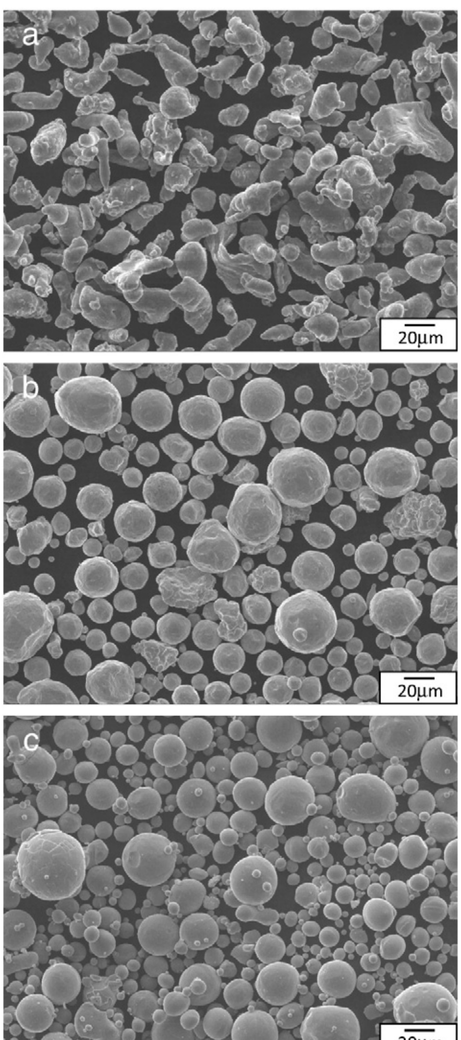

Fig. 1. Scanning electron microscope (SEM) images of feedstock powders: (a) aluminum, (b) copper, and (c) titanium.

2.2. Warm spraying

Warm spraying (WS) was developed by modifying a conventional HVOF equipment (JP5000, Praxair Technology Inc., USA), in which a mixing chamber was inserted between the combustion chamber and the powder feed ports in order to mix the combustion gas with nitrogen gas so that the combustion gas temperature can be controlled in a wide range [1,3]. The schematic of the system is shown in Fig. 2. WS allows to control the gas jet temperature and to keep impact temperatures of sprayed particles under their melting point in moderately heated but thermally softened states. Details of the process can be found elsewhere [1,3]. In the present study, the powders were sprayed under various nitrogen flow rates of 0.5, 1.0, 1.5, and 2.0 m^3/min. The spraying conditions are listed in Table 1. All substrate surfaces were grit blasted by alumina, degreased by ultrasonic cleaning in acetone, and dried before spraying. For tubular coating tensile (TCT) tests, a set of two cylindrical copper substrates with a diameter of 25 mm was used. For micro-flat tensile (MFT) tests and for microstructure analysis, the coatings were sprayed on carbon steel plates (JIS SS400, 100 × 50 × 5 mm^3). Detailed explanations of both tests will be given below. The target thickness of the coatings was 0.4 mm for the TCT samples, and 2 mm for the MFT ones.

2.3. Mechanical properties

2.3.1. Tubular coating tensile (TCT) test

The tubular coating tensile (TCT) tests [10], were carried out to investigate the tensile strength of the coatings. The advantage of the test method is to obtain data in a fast and cost-efficient way. In the TCT test configuration, two cylindrical copper substrates with a diameter of 25 mm and a length of 25 mm were fixed face-to-face by a screwable jig as shown in Fig. 3(a). By using a precise parallel vice during screwing, any misalignments between the girthed surfaces of two substrates were carefully avoided. The girthed surfaces of the screwed samples were grit-blasted before spraying. The surface topography was digitally measured along the axial direction and was evaluated before and after grit blasting in order to confirm that there is no detectable joint patch after surface treatment. By rotating the copper substrates with 420 rpm, coatings were deposited on the girthed surfaces by warm spraying. After deposition, the screw inside was removed and the tensile test jigs were attached to grip the specimen as shown in Fig. 3(b). Tensile tests were carried out with a loading rate of 1 mm/min by a universal mechanical test device (Autograph, Shimadzu, Japan). For each spraying condition, three specimens were tested.

2.3.2. Micro-flat tensile (MFT) test

In the TCT test, the abutted faces of the two copper substrates are only fixed by the coating and act like a crack during loading. Thus, they cause a stress concentration in the coating that fails at lower load as compared to purely tensile ultimate strength. For CS, multiplying TCT strengths with a stress concentration factor of 1.6 supplies respective ultimate tensile strengths [11]. Since such factor might vary depending on individual spray configurations, tensile tests of miniaturized free-standing-coating specimens, so called micro flat tensile (MFT) tests [10], were performed, in addition to the TCT tests. Fig. 4 shows the specimen geometry of the MFT test, which was prepared by spark erosion out of the coating. The thickness of the specimens was 0.5 mm, and the gauge length and width were 12 mm and 2 mm, respectively. The direction of the applied "in plane" stress was parallel to the traverse spray lines. In the case of