Surface & Coatings Technology 302 (2016) 47–55

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Low pressure cold spraying under 6 bar pressure deposition: Exploration of high deposition efficiency solutions using a mathematical modelling

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ARTICLE INFO

Article history:
Received 1 January 2016
Revised 20 May 2016
Accepted in revised form 23 May 2016
Available online 25 May 2016

Keywords:
Cold spray
Low pressure
Deposition efficiency
Modelling
Copper

ABSTRACT

This paper investigates the improvement of the deposition efficiency (DE) for low pressure cold spraying. In the literature, some possibilities were studied (a long preheating of the powder feedstock, the use of irregular shaped particles, the combination of metallic particle with ceramics, or the laser assisted heating) but the DE is still weak, in the range of 10%, when working at around 6 bar. In this paper, the improvement possibilities depending on the gas conditions, the particle size and the nozzle geometry are explored. The deposition of spherical copper powder onto a copper substrate is considered. Experimental investigations evidence a low DE of about 0.1 and virtual tests computing the one-dimensional flow of the gas through the nozzle and the interaction with the particles are used to identify potential solutions increasing the DE. Air or nitrogen propellant gas has led to similar DE. The highest achieved value remains low even working at the maximum capacity of the low pressure system, i.e. a gas with an inlet pressure of 12 bar and a preheating temperature of 630 °C. Factors of improvement are suggested for the specific case of the standard pressure of 6 bar. Fine particles cause clogging and larger particles are difficult to be efficiently deposited. Successful combinations promoting the DE include a nozzle expansion ratio in between 1.2 and 2, a diverging part length in between 200 mm and 300 mm and the helium propellant gas preheated at 600 °C. Hence the DE can reach up to 100% for 10 μm sized copper particles according to the computation. If using larger particles (20 μm, 30 μm or 40 μm), the maximum DE is respectively 0.7, 0.5 or 0.3 approximately. This results give indications for the suitable conditions promoting the highest achievable DE for low pressure cold spraying.

1. Introduction

The cold spraying is a potential solution of additive manufacturing that gives access to new technological capabilities, particularly in terms of new properties development using standard materials, and in the advanced functionalization of surfaces for various applications in many industrial fields such as the biomedical, the energy sector, the engineering of MEMS device, the mechanical engineering, the decoration, and much more [1,2]. The cold spray (CS) method is found to be an alternative among the thermal spray processes with respect to the current technological and ecological perspectives. Several typical achievements reported in [1] evidence the growing interest in the development of the process. Conditions of high pressure, i.e. using a gas compressed beyond 10 bar, are generally considered to produce successful depositions for a wide range of materials including metals, ceramics and their combinations. The process parameters depending on tools characteristic such as the nozzle geometry and size are known so that finding the efficient projection conditions is no longer a major difficulty.

Nowadays, working at lower pressure is under exploration since it offers further innovative contributions. For instance, expected progresses are the development of hybrid deposit/substrate combination [3–5], the in-situ restoration thanks to the modernized CS set-up (portable system) [6], and the thermal sensitive material working [4,5]. The possibility to produce metallic [7–11], and MMCs [11–15] deposits have been demonstrated. However, unlike the high pressure cold spraying case, the low pressure cold spraying seems less efficient in terms of deposition capability. Ogawa et al. have characterized the low pressure cold spraying of 17 μm sized aluminium particles using a 6 bar compressed air [8]. The DE is low (~7%) due to the difficulty of the weak impingement force to break the inactive native oxide film on the aluminium surface. Ning et al. have established a situation that is more conducive to the deposition of copper particles onto an aluminium substrate [16]. The best efficiency conditions when working at 7 bar include the use of a 300 °C heated He as propellant gas, aggregates of irregular shaped particles, a granulometry with $d50 = 20$ μm, and a particle preheating at 500 °C during 1 h. However, the DE remains low, in the range of 30% [16]. Furthers findings in the literature are

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http://dx.doi.org/10.1016/j.surfcoat.2016.05.068

consistent with this tendency. Lagerbom et al. have experienced the deposition of dendritic shaped copper particles mixed with angular shaped Al_2O_3 fragments (mixing ratio of 50/50 and 80/20). The authors indicate a maximum DE of about 35% using a low pressure system working with a gas pressure and temperature up to 10 bar and 630 °C respectively [11]. According to Irissou et al., the overall DE of a ceramic/metal mixture decreases with the increase of ceramic content but there is an optimum content above which this DE decreases [17]. The hard/soft material combination allows the improvement of the DE by two contributions: (1) an easier adhesion of the angular shaped ceramic particles (hard phase) onto a ductile phase, and (2) a higher plastic deformation of the metallic particles (ductile phase) promoting their adhesion. Both mechanisms reduce the particles rebound and enhance the deposition so long as the new formed surface is ductile, i.e. containing more metallic proportion. For different concentrations of Al_2O_3 from 7% up to 70% mixed with spherical aluminium powder, the highest DE using a 6 bar nitrogen gas preheated at 500 °C corresponds to an optimum Al_2O_3 content of 30% giving a similar DE for the Al/Al_2O_3 mixtures and the Al particles. Effects of Al particle size on the overall DE is observed and the gain is weak even decreasing the Al particle diameter from 81 μm down to 36 μm. The maximum DE remains low: 6% and 12% approximately for the large and the small Al powders respectively [17]. Despite the collapse of the overall DE in the situation of metal/ceramic mixture, Melendez et al. have however noted that the DE of the ceramic particles increases [13]. For the case of WC/Ni sprayed with a 6 bar compressed air preheated at 550 °C, the DE of the WC varies from 7% to 68% with the WC content (50% to 96%). The change in the overall DE and its evolution were not however the main investigated aspect [13].

The improvement of the DE was differently processed by Kulmala et al. The authors have chosen an in-situ heating of the sprayed particles using a laser irradiation that simultaneously interacts with the particle spot ahead the collision zone on the substrate [18]. A pyrometer measures the temperature of the spot. The DE is evaluated based on coating thickness depending on the laser heating. Cu/Al_2O_3 and Ni/Al_2O coatings with an initial mixture ratio of 50/50 are thus produced using a 6 bar compressed air heated at 445 °C for the Cu/Al_2O_3 mixture and 650 °C for the Ni/Al_2O_3. There is approximately a two-fold increase of the coating thickness from a pyrometer temperature of 0 °C (without laser heating) up to 800 °C (laser assisted heating). However the DE values have not been specified.

This paper explores the DE improvement possibilities depending on the gas conditions, the particle size and the nozzle geometry. The limitations of the experimental DE are evidenced and different improvement situations are suggested using virtual tests. The variance of computed DE addresses an overview of the potential alternatives of the DE improvement for the low pressure cold spraying process.

Table 1
Particle size distribution given by dry measurement laser granulometry.

Size range: 1.5–56.4 μm	d10	d50	d90
Cu	11.058 μm	21.915 μm	40.242 μm

2. Material and method

2.1. Material and cold spray system details

In-house spherical pure copper production (Fig. 1) is used as powder feedstock and sandblasted copper plates with a thickness of 2 mm as substrate. The powders were manufactured by atomisation. Table 1 gives the particle size distribution measured by dry laser granulometry. The deposition is performed using a portable DYMET 423 system composed of a vibrational powder feeder, a control unit and a compact spraying gun that contains the gas heater and the supersonic nozzle. This CS unit was supplied by DYCOMET Corporation. The device is able to work with a gas pressure and temperature up to 12 bar and 630 °C respectively. A coating is produced on a substrate surface of 40 mm^2 (Fig. 2). Using a CNC robot arm, the nozzle moves with a speed of 100 mm/s and a step of 1 mm between two tracks. Those kinematic parameters are an in-house standard to provide a continuous coating covering the substrate. The nozzle performs a horizontal track, moves vertically with the displacement of 1 mm and then forms the next horizontal track toward the opposite direction, and so on. At most, two passes are produced. Those conditions have been considered in this paper.

2.2. Spraying conditions and experimental DE

The copper deposit is produced using a De Laval nozzle exhibiting a diverging part length of 130 mm and an expansion ratio of 1.275. The standoff distance is set to 10 mm. The propellant gas consists of a 6 bar compressed air preheated at different temperatures (430 °C, 530 °C, and 630 °C). The DE corresponds to the weight ratio of the deposited particles and the initial powder feedstock. Note that the work station displays a pressure of 5.2 bar which is slightly lower than the real inlet gas pressure of 6 bar due to the pressure loss within the system. The experimental results evidenced the difficulty to obtain an efficient deposition, and particularly at the standard gas pressure of 6 bar. The DE is 4% for a gas preheated at 430 °C and slightly increases to 10% at 630 °C (Table 2). The next sections attempt at identifying some improvement conditions using the same nozzle, as well as other potential solutions that merit to be explored. A one dimensional computational procedure is considered for this purpose.

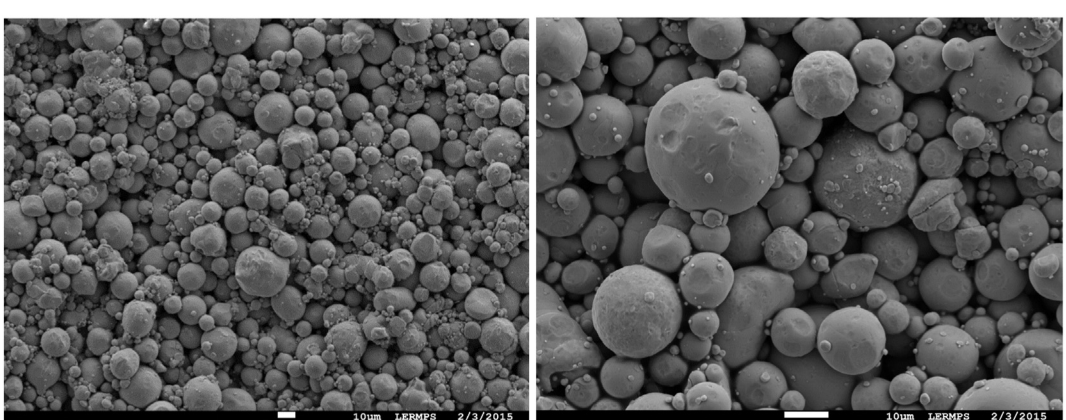

Fig. 1. SEM observation of the spherical Cu powders.