Available online at www.sciencedirect.com

ScienceDirect

Acta Materialia 59 (2011) 2693–2703

Acta MATERIALIA

www.elsevier.com/locate/actamat

Deposition mechanism of dry sprayed ceramic particles at room temperature using a nano-particle deposition system

Doo-Man Chun, Sung-Hoon Ahn *

School of Mechanical and Aerospace and Institute of Advanced Machinery and Design, Seoul National University, Seoul, Republic of Korea

Received 7 June 2010; received in revised form 27 December 2010; accepted 4 January 2011

Abstract

The nano-particle deposition system (NPDS) is a new dry spray process used to deposit metal and ceramic particles at room temperature. Low temperature deposition techniques for metals and ceramics that involve particle spraying include the NPDS, cold spray, and aerosol deposition methods. These are widely used to minimize thermal damage to the substrate when fabricating metal or ceramic layers. To optimize the process conditions for the intended applications and improve the deposition quality one must understand the mechanism of particle deposition at room temperature. The bonding mechanism in metal particle deposition by the cold spray method has already been researched. Adiabatic shear instability near the particle/substrate interface due to plastic deformation was reported to be the bonding mechanism for metal particles below the melting temperature. However, the bonding mechanism of ceramic particles has not been fully determined. This study assessed the bonding of ceramic particles by NPDS using numerical analysis and experimental results. A bonding mechanism is suggested after considering the experimental results for shock compaction, which is a process similar to that of the NPDS. The suggested deposition mechanism for ceramics involves the fragmentation of submicron ceramic particles into nanoparticles and the successive impact of submicron particles, which provides sufficient bonding energy, with heat and high pressure, to nanoparticles fragmented by the shock wave.

Keywords: Nano-particle deposition system; Aerosol deposition; Cold spray; Ceramic deposition; Bonding mechanism

1. Introduction

The deposition process for ceramic films and ceramic patterns using the high velocity impact of submicron sized ceramic powder at room temperature has been widely researched. The aerosol deposition (AD) method and nano-particle deposition system (NPDS) are typical deposition processes used to coat metal, ceramic, and polymer substrates with various ceramics, such as TiO_2, Al_2O_3, lead zirconate titanate (PZT), and hydroxyapatite [1–6]. The resulting fabricated films have various uses, such as photocatalytic films, actuators, capacitors, and biocompatible coatings.

The main advantage of these processes is that they are conducted at room temperature, so the substrate is free of thermal damage. The deposition procedure is simple. A high pressure carrier gas transports ceramic powder from a powder feeder to a nozzle, and the particles are accelerated through the nozzle. The particles strike the substrate in a vacuum. The entire process can be performed at room temperature.

The deposition mechanism of ceramic particles has been studied for the AD method by experimentation and numerical analysis, but the bonding mechanism has not been fully determined [1,7]. The phenomenon was initially termed room temperature impaction consolidation (RTIC) based on the experimental results, and involves particle fragmentation and bonding [7]. However, a source of sufficient energy for bonding could not be ascertained. A numerical simulation

* Corresponding author. Tel.: +82 2 880 7110; fax: +82 2 883 0179.
E-mail address: ahnsh@snu.ac.kr (S.-H. Ahn).

1359-6454/$36.00 © 2011 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.actamat.2011.01.007

of a single particle impact in AD showed that the maximum pressure was about 2.5 GPa and the maximum temperature 500 K [1]. These values, however, were too low to draw any conclusions regarding the deposition mechanism of ceramic particles and the simulation did not show particle fragmentation or reveal a source of sufficient energy for bonding.

In contrast, the bonding mechanism of a metal powder using a cold spray process that sprays metal powder at high velocity onto the substrate and creates a metal layer was proposed to be adiabatic shear instability. The high plastic strain at the interface results in softening due to adiabatic heating, so bonding between the particle and substrate is possible. The results were derived from a numerical analysis of metal particle impact. The deposition mechanism has not been determined experimentally because of the short impact duration and the particle size [8,9].

In the presented study we performed a numerical analysis of ceramic particle impact and compared this with experimental results to suggest a bonding mechanism. The deposition mechanism was suggested from the numerical analysis. The suggested deposition mechanism for ceramics involves the fragmentation of submicron ceramic particles into nanoparticles and the successive impact of submicron particles, which provides sufficient bonding energy, with heat and high pressure, to fragment nanoparticles. The experimental results confirm this deposition mechanism of fragmentation followed by bonding at high heat and pressure. The numerical analysis and experiment considered an Al_2O_3 powder and an Al_2O_3 (sapphire wafer) substrate. Al_2O_3 is a typical material used for ceramic deposition in AD and in the NPDS and its material properties have been well researched, enabling explicit analysis.

2. Nano-particle deposition system (NPDS)

2.1. System configuration

The NPDS was designed to deposit metals and ceramics at room temperature. Deposition of metals and ceramics such as Ni, Sn, TiO_2, and Al_2O_3 have been reported [2,4,10,11]. AD has mainly been studied for depositing ceramics [1,7], while cold spraying has been studied for depositing metals and ceramics [12]. However, no single system can easily deposit both ceramics and metals. In the cold spray process a supersonic flow at atmospheric pressure with a high pressure carrier gas creates a strong shock wave around the substrate that small, light particles cannot penetrate [13]. The minimum particle size is approximately 10 μm for cold spraying, while large ceramic particles can erode the substrate, as in powder blasting mechanical etching [14,15]. In AD the nozzle cannot control the supersonic flow, although metal particles require a high critical velocity, which exceeds the speed of sound in air [1,16]. To minimize the strength of the shock wave and to control the supersonic flow in NPDS a converging-diverging nozzle was used in vacuo. This high speed feature means that NPDS can use more diverse deposition materials than AD. In addition, the aerosol generators used for AD have low controllability of the powder feed rate, especially for heavy powders, so a fluidized bed powder feeder is used in NPDS.

The NPDS consists of a compressor for the carrier gas, powder feeders, nozzles, a vacuum chamber, a vacuum pump, and controllers, as shown in Fig. 1. The compressor supplies pressurized air that carries particles from the powder feeders to the nozzles. The particles are sprayed through the nozzle at room temperature under low vacuum conditions and strike the substrate. For economic reasons the NPDS used commercial compressed air (<1 MPa) and a low vacuum (>25 Torr). In addition, the vacuum minimizes the effect of the shock wave near the substrate, especially for small particles. Fig. 2 compares the pressure in the deposition chamber and the pressure of the carrier gas for cold spraying, the NPDS, and AD.

2.2. Process parameters

Al_2O_3 powder was deposited on an Al_2O_3 substrate using a NPDS for comparison with the numerical analysis.

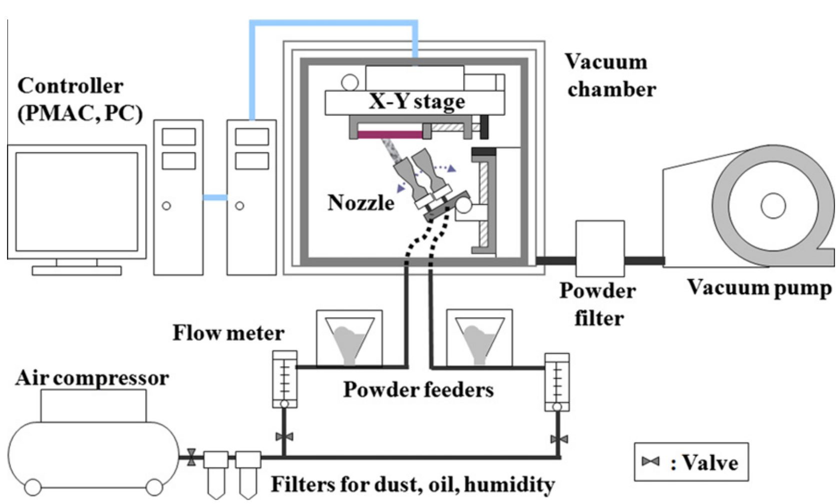

Fig. 1. Schematic view of a nano-particle deposition system.