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ScienceDirect
Applied Surface Science 252 (2006) 7809–7814
applied surface science
www.elsevier.com/locate/apsusc

The bond strength of Al–Si coating on mild steel by kinetic spraying deposition

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Received 31 August 2005; received in revised form 12 September 2005; accepted 12 September 2005
Available online 3 July 2006

Abstract

Kinetic spraying (or cold gas dynamic spraying) works by accelerating small solid particles to supersonic velocities, and then impacting them onto a substrate. These high impact velocities, and low particle temperatures are the principal attributes of kinetic spraying technology. However, only recently has this technology's interfacial behavior, due to particle/substrate impaction, become well understood. In order to investigate the particle/substrate bond behavior, Al–Si feedstock was deposited onto mild steel, over a range of particle velocities; next, their respective coating bond strengths were measured by the stud pull coating adherence test. The effects of the particle velocity and the substrate surface roughness on the coating bond strength were presented, and a model of the particle/substrate bond generation was discussed in an effort to estimate the bond strength.

Keywords: Kinetic spraying; Cold gas dynamic spraying; Bond strength; High velocity impact

1. Introduction

Kinetic spraying works by accelerating small solid particles to supersonic velocities, and then impacting them onto a substrate; where the critical particle velocity is key in characterizing the process. In these processes, dense coatings are produced without significant heating of the spray powder or substrate material, therefore the kinetic energy of the particles plays a major role in the behavior of impaction and deformation. After over a decade of development, kinetic spraying has been successful in depositing a wide range of pure metals, metal alloys, polymers, composites and nano-materials onto a variety of substrate materials [1–3].

The bonding mechanisms associated with high velocity impaction can be explained by shear instabilities caused from thermal softening, which in turn are caused by adiabatic heating during high strain rate deformation. Numerous experimental studies [4–6] have shown that particles require a minimum critical velocity in order to deposit onto a substrate, while also suggesting that higher impact velocities yield a better coating bond strength and lower coating porosity. From computer modeling, Assadi et al. [4] have provided an equation to estimate the critical particle velocity as a function of the feedstock material properties, such as density, melting point, ultimate strength, and initial particle temperature; but not interfacial bonding.

Until now, the interfacial reactions due to high velocity impaction have not been well understood; even though many different interfacial reactions have been documented by experimental and theoretical investigations. In early research interfacial melting was observed, but was proved not to be a dominant mechanism in the high-speed particle/substrate bonding [6,7]. Since most depositing in kinetic spraying occurred in the solid state, with a high interfacial pressure and large extents of plastic deformation; atomic length-scale phenomena, atomic diffusion, and surface adhesion were all considered to be the dominant bonding reactions. In Bolestal et al. [8] and Xiong et al.'s [9] studies, the boundary phase of the intermetallic compound was checked by XRD, and indicated that an interface boundary, which included atomic diffusion, occurred during the kinetic spraying process. Furthermore, Bolestal observed that the thickness of the film interface was 20–50 nm. However, in most kinetic spraying processes, particle impaction is completed within 0.1 μs, during

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0169-4332/$ – see front matter
doi:10.1016/j.apsusc.2005.09.015

which the atomic diffusion was not significant. For example, the thickness of an Al–Cu inter-diffusion (with an inter-diffusion coefficient of 10^{-15} to 10^{-14} m^2/s) layer in 0.1 μs is less than 1 nm; which suggests that the atomic diffusion may not be a dominant mechanism of kinetic spraying after all.

Clean surfaces and high contact pressures, which come from high-speed impaction and large plastic deformation along the interface, made the two contact surfaces mutually conforming so that surface adhesion could occur. Metallic bonding was observed in the coatings, and therefore surface adhesion was believed to play an important role in the particle bonding. In Grujicic et al.'s [6] computational analysis of the interfacial bonding in a cold-gas dynamic-spray process, nano/micro-scale material mixing and mechanical interlocking were both identified and used to explain the enhancement of interfacial bonding. These phenomena can be exemplified by the interfacial roll-up and vortices observed during high shear and high viscous flow along the interface. Grujicic's mechanism is useful in explaining the coating of two materials with weak repulsive or attractive atomic interactions, which is generally difficult to explain solely by surface adhesion.

The present study tried to clarify the effects of particle velocity and substrate surface roughness on the coating bond strength. In addition, a model, of the particle/substrate bond generation, used to estimate the bond strength during high velocity impact was discussed.

2. Experimental procedures

2.1. Spraying system

In this study, a commercially available CGT kinetic spraying system was used. The equipment and the coating process are described in detail in the literature [1–3]. A de Laval type nozzle with a converging/diverging inner form was used (standard nozzle type is when exit throat exit diameter ratio is 3.15). Nitrogen was used for both the process and feedstock carrier gas; where the pressure ranged between 0.3 and 3.0 MPa, and the temperature was fixed at 400 °C. The feedstock was Al–12Si powder with a mean particle size of 25 μm, a physical density of 2.66 g/cm^3, and a feed rate of 8 g/min. The micrograph and size distribution of the Al–Si powder feedstock are shown in Fig. 1. Mild steel was used as the substrate, and two kinds of surface conditions were prepared by either polishing or grit-blasting the surface. The roughness R_a of the as-polished surface and the grit-blasted surface were 1.52 and 17.98, respectively, which was measured with a laser scan microscope. Finally, the target substrate distance was fixed at 30 mm in front of the nozzle exit.

2.2. Analysis

During our experiments, the SprayWatch system (Oseir Ltd., Finland) was used to measure the velocity of in-flight particles. With this system, images of the flying particles were taken with a high-speed camera; then from the particle flying distance and camera exposure time a particle velocity could be calculated. While the particle size, distance to the nozzle exit, radial position, and other factors affected the particles' velocity; only the effect of the mean particle velocity was analyzed for the purpose of simplification. In an effort to capture the most accurate representation of the process, the mean particle velocity was determined from a large number (>300) of measured flying particles. The remaining experimental analysis was accomplished with optical microscopy, X-ray diffraction (XRD), and scanning electron microscopy (SEM).

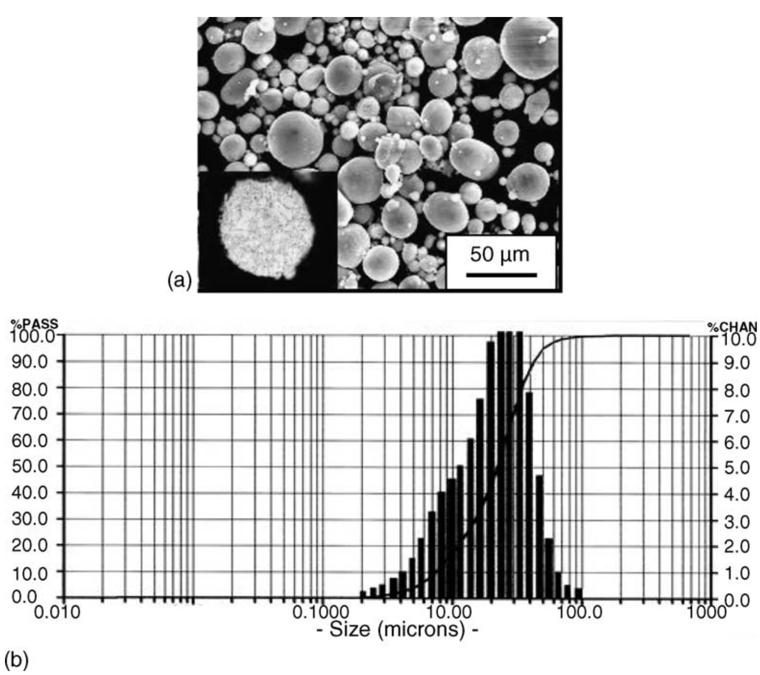

Fig. 1. Feedstock: Al–Si (wt.% 78:12), spherical, +5 to 45 μm (mean size 25 μm): (a) SEM micrograph of Al–Si powder morphology; (b) laser scatter value of Al–Si powder size distribution (volume fraction).