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Full Length Article

Interfacial bonding mechanisms between aluminum and titanium during cold gas spraying followed by friction-stir modification

F. Khodabakhshi[a,*], B. Marzbanrad[b], H. Jahed[b], A.P. Gerlich[b]

[a] School of Metallurgical and Materials Engineering, College of Engineering, University of Tehran, P.O. Box: 11155-4563, Tehran, Iran
[b] Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON, Canada

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ABSTRACT

This paper closely evaluates the interfacial bonding mechanism between titanium particles deposited on an aluminum alloy substrate by cold gas spraying followed by friction-stir processing (FSP). After cold spraying and FSP modification, the produced Al/Ti interface was studied using focus ion beam-transmission electron microscopy (FIB-TEM) analysis and auger electron spectroscopy. Formation of a well-bonded titanium aluminide reaction layer was observed at the interface with a thickness in the range of 10–20 nm and a coherent interface associated with an inter-diffusion distance of about 600 nm. The results of this study showed that the physical bonding phenomenon during cold spraying according to the well-known adiabatic shear instability at the interface can be associated with chemical bonding and formation of an intermetallic layer at the interface during FSP modification. This is aided by the induced thermo-mechanical processing and deformation-assisted solid-state diffusion-based reactions. Also, these possible interfacial bonding and intermetallic layer formation mechanisms were discussed based on the inter-diffusion of elements at the Al/Ti interface based on the well-established Boltzmann-Matano theory and kinetics models correlated with experimental observations. The main findings of this research highlight the role of FSP on the performance of cold spray coatings as a post-processing technique to promote densification and homogenization during processing by promoting nano-scale interfacial mechanisms and chemical bonding at the interface.

1. Introduction

Cold gas dynamic spraying is a new and versatile solid-state coating technology which can be easily implemented in the field. It utilizes the high velocity kinetically impact of particles upon the substrate to achieve bonding without melting. It only relies on severe plastic shear deformation to achieve deposition of the powder materials with minimum possible oxidation, structural/compositional changes, and undesirable phase transformations when compared to conventional high temperature thermal spraying technology [1,2]. Beneficial residual stress induced by the peening process [3] and potentials for fatigue life enhancement of substrate [4] have added to the attractions of cold spray coating. Also, this technology can be implemented to repair the damaged structures and for rapid/additive layer by layer manufacturing with higher deposition rates as compared to the selective laser/electron-beam melting based methods [5–7].

During the build-up of material by cold spraying, the adhesion of coated material is influenced by the cohesion and adhesion strengths mainly due to "particle to particle compaction" between the layers as well as the "particle to substrate interaction" in the first layer, respectively [8,9]. Highly pressurized nitrogen or helium inert? gas streams in the range of 1.5 MPa are usually employed to fluidize and transfer the typically micro-sized particles on the substrate surface and accelerate them through a convergent-divergent type nozzle with a high velocity impact in the range of 500–1200 m/s to produce strain rates in the order of 0.5×10^9/s for nanosecond durations on impact, depending on the type of substrate, particles, carrier gas, flow gas temperature and nozzle design [10,11].

This new technology has attracted considerable attention in the academia for about ten years, which has spurred new industrial applications aside from thermal spraying methods, considering the unique performance of the coatings as well as the economic efficiency [12]. Improvement of surface characteristics including indentation hardness, wear resistance, fatigue fracture, corrosion, electrical resistivity, and

* Corresponding author.
E-mail address: fkhodabakhshi@ut.ac.ir (F. Khodabakhshi).

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Table 1
Chemical composition for the studied AA5083 aluminum alloy as substrate (*wt* %).

Element	Al	Mg	Zn	Mn	Fe	Si	Ti
AA5083 alloy	Base	4.5	0.7	0.85	0.11	0.08	0.015

thermal conductivity were the main objects of cold spray depositions [13,14]. The first application of cold gas spraying technology has involved manufacturing of dense and strongly bonded oxygen-free copper coatings with superior physical and mechanical properties [15]. Thereafter, it was extended to other materials sensitive to oxidation and heat, such as titanium, magnesium, metastable and nanocrystalline materials [16,17].

Since the integrity and performance of cold sprayed coatings can be controlled by the bonding quality between particles and substrate during high velocity impact process, understanding the nature of bonding mechanism is essential to explore new coating applications [18]. Mechanisms used to explain bonding during explosive welding [19] or shock wave powder compaction [20] processes are very similar to those involved during cold gas spraying, in terms of formation of material flow jet upon impact, subsequent widespread severe plastic deformation, and the related phase transformation phenomena at the interface. The required heat and material flow controlling interfacial bonding are generated by adiabatic shear instability and subsequent thermal softening [18,21]. Adiabatic shear instability is a well-known micro-mechanism which has been introduced by Assadi et al. [22], and is a dominant feature of bonding during particle impact in cold spraying. This heating is induced by the high strain rate severe plastic deformation at the interface without any melting in a time period of less than 100 ns. Physical bonding involving this mechanism is achieved using gas flow rates higher than a critical impact velocity which depend on the gas pressure and temperature, as well as the powder and substrate thermo-mechanical characteristics, which all depend on the temperature, strain, and strain-rate fields produced during particle impingement on the surface [23,24].

Friction-stir processing (FSP) is an innovative and energy efficient adaption of friction-stir welding (FSW), which was introduced by Mishra et al. [25,26] mainly for the aim of localized surface microstructural modifications in metallic materials. In this solid-state processing technique, a non-consumable and specially designed rotating tool is forged on the surface of substrate, leading to localized frictional heating mainly due to the contact between shoulder and substrate. This causes the material to soften under the shoulder surface and around the pin as a result of induced severe plastic shear straining, and by traversing the tool along the pre-defined path, material is transferred from the leading edge to trailing, such that upon cooling a modified stirred zone is produced with a refined microstructure [27].

This modification technique has been employed for the purpose achieving desirable material properties, including; (*i*) fabrication of ultra-fine grained metals to attain high strain rate superplasticity [28,29], (*ii*) production of metal-matrix nanocomposites [30–33], (*iii*) homogenizing of powder metallurgy products [34–36], and (*iv*) eliminating the casting defects [27]. More recently, FSP was implemented as an effective post-processing technique to consolidate pores and remove the micro-cracks, enhance the uniformity, refine the microstructure, and subsequently improve the mechanical performance of cold sprayed

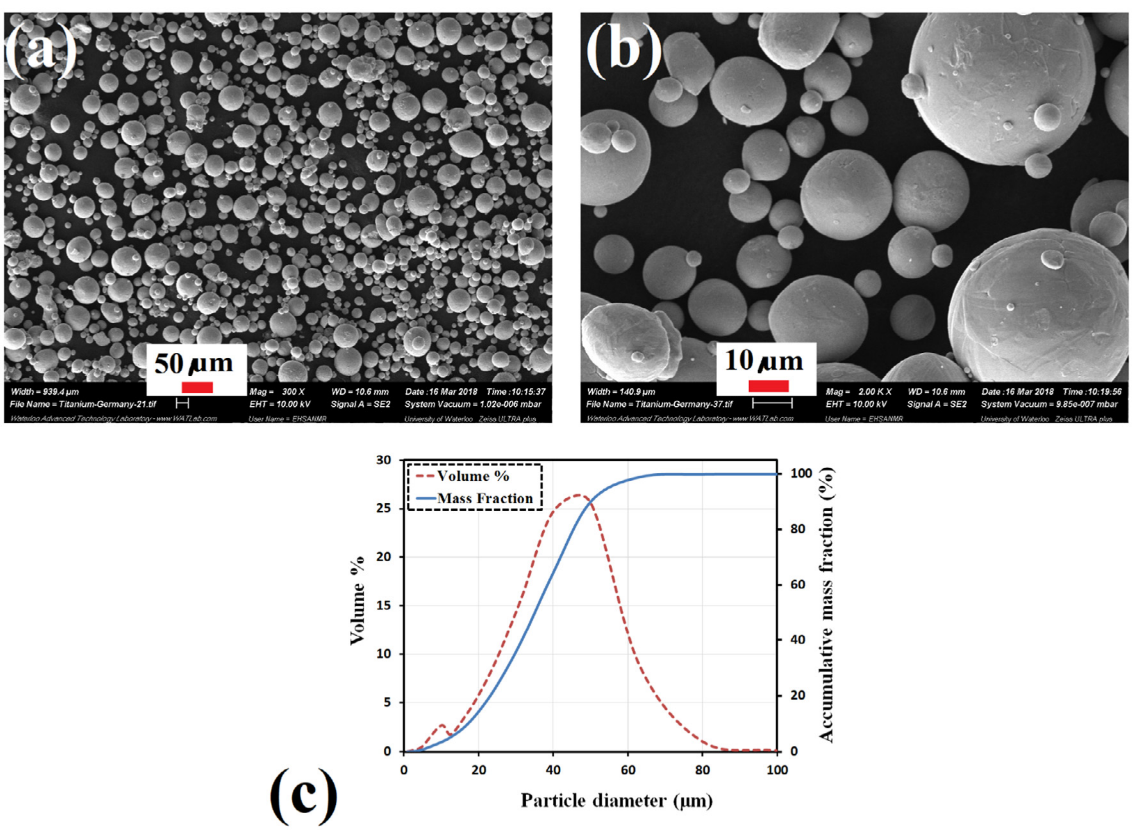

Fig. 1. (a, b) FE-SEM images from the titanium particles and (c) powder size distribution.