Applied Surface Science 288 (2014) 26–33

Contents lists available at ScienceDirect

Applied Surface Science

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

Experimental and numerical study of residual stress evolution in cold spray coating

R. Ghelichi [a,b,*], S. Bagherifard [a,b], D. MacDonald [c], I. Fernandez-Pariente [d], B. Jodoin [c], M. Guagliano [a]

[a] Politecnico di Milano, Via G. la Masa, 1, 20156 Milan, Italy
[b] Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, United States
[c] University of Ottawa, 770 King Edward, Ottawa, ON, Canada K1N 6N5
[d] University of Oviedo, Department of Materials and Metallurgy Engineering, Campus de Viesques, 33203 Gijón, Spain

ARTICLE INFO

Article history:
Received 30 July 2013
Received in revised form
11 September 2013
Accepted 12 September 2013
Available online 3 October 2013

Keywords:
Cold spray
Residual stress
Annealing
Finite element

ABSTRACT

Residual stresses are among the most important factors affecting the properties and service lifetime of materials and components. In the cold spray coating process there are two contradictory factors that influence the final residual stress state of the coated material; the impact of the high velocity micron-size particles induces compressive residual stresses, whereas the gas temperature can have an opposing annealing effect on the induced stresses. These two simultaneous phenomena can in turn change the residual stress profile, thus complicate the assessment of the final residual stress state.

In this paper the residual stress evolution during cold spray coating process has been studied through experimental measurements and numerical simulations performed on several series of samples coated using different spray process parameters. A detailed finite element (FE) analysis of the process has been developed to calculate the stresses induced through impacts and then the annealing effect has been taken into account through an analytical model. The results of the experiments and numerical–analytical approach confirm the considerable effect of annealing on the eventual stress distribution in the coated samples.

1. Introduction

Residual stresses are present in materials that are produced by nearly every mechanical, chemical, and thermal process, including coatings [1]. As a result, most metallic and ceramic coatings are in a state of internal residual stress. The residual stress can be either compressive or tensile. It is generally recognized that compressive stresses in coatings are more favorable due to their positive effect on the fatigue life and strength of the materials, components and structures [1,2]. A number of factors influence the residual stress level in thermal spray coatings, including quenching the sprayed material due to high cooling rate, peening effect due to the plastic deformation of non-molten or semi-molten particles impacting the substrate, thermal mismatch between the coating and substrate materials and temperature gradient in multi-pass deposition processes. Constant bombardment of particles on the substrate and coating area is known as a major feature that results in increasing the residual stresses [3]. Cold spray process, is principally different from other types of thermal spray coating process, in terms of its lower process temperature and higher particle impact velocity, both of which affect directly the resulting residual stress distribution. Experimental studies have been performed on residual stresses distribution generated during the cold spray coating process and similar impact based processes. McCune et al. [4] have measured residual stresses for copper coatings and Bagherifard et al. [5] performed X-ray diffraction (XRD) measurements on stresses induced in aluminum coatings. Ghelichi et al. [2] measured the residual stress of different Al alloy coated samples and studied their effect on fatigue behavior. An interesting common observation in almost all studies is the relaxation of the compressive residual stresses at the interface of the coating and the substrate; conversely, the major difference is the reported stress in the substrate that is almost zero in [4] whereas considerable values with respect to that of the deposited material are observed in other studies [2,5]. There are very few studies which follow empirical approaches for residual stress measurement in cold spray coated samples. Luzin et al. [6] studied the residual stress in Cu and Al coated samples by neutron powder diffraction stress measurement. They used the Tsui and Clyne's progressive model [7] that is

* Corresponding author. Tel.: +39 0223998206.
E-mail addresses: ghelichi@mit.edu (R. Ghelichi), sbagheri@mit.edu (S. Bagherifard), daniel.macdonald@uottawa.ca (D. MacDonald), inesfp@uniovi.es (I. Fernandez-Pariente), Bertrand.Jodoin@uottawa.ca (B. Jodoin), mario.guagliano@polimi.it (M. Guagliano).

0169-4332/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.apsusc.2013.09.074

Nomenclature

D	diameter
D_{rr}, Q	Rosin–Rammler distribution parameters
V	velocity
ρ	density
M	Mach number
A	area
T	temperature
μ	viscosity
Pr	Prandtl number
Re	Reynolds number
C_p	heat capacity
B_1, B_2, n, C, m	Johnson-Cook material model constants
$\epsilon_p(\epsilon_{p0})$	equivalent plastic strain
$\dot{\epsilon}_p(\dot{\epsilon}_{p0})$	equivalent plastic strain rate
$T\,(T_{init})$	temperature
T_{melt}	melting temperature
σ_{eq}	equivalent normal plastic stress
t	time
S, S_1	Zenner-Wer-Avrami constants
K	Boltzman constant
ΔH	activation enthalpy for the relaxation process

Suffixes

*	throat
e	exit of the nozzle
0	initial condition
a	annealing
C_D	drag coefficient

originally developed to model the residual stress accumulation in thermal spray coatings, to interpret the results empirically. Luzin et al. [6] concluded that the residual stress is determined almost entirely by the plastic deformation process of the spray material due to the high velocity impact of the particles and that the thermal effects do not play a notable role in changing the distribution of the induced stresses. The Tsui and Clyne's approach [7] considers the effect of temperature as a parameter to introduce the residual stress due to the mismatch of the thermal expansions.

Spencer et al. [8] also followed the same approach using Tsui and Clyne's progressive model [7] to interpret the residual stress distribution obtained by using neutron diffraction with high spatial resolution on Al and Al alloy cold spray coatings deposited on Mg substrates. They concluded that the residual stress profiles depend more on the alloy content, i.e. intrinsic resistance to plastic deformation, than on the spray processing conditions. However, they also reported that in cases where the spray temperature was high, the thermal mismatch effect was more notable and affected the obtained residual stress profile [8]. It is to be mentioned that Tsui and Clyne's model [7] considers the effect of temperature as the main reason of curvature change due to the thermal mismatch; whereas the annealing effect of the temperature has not been taken into account.

In fact, one peculiar factor in the cold spray coating process with respect to other impact based peening treatments, such as shot peening, is the gas temperature; the bombardment of the particles induces residual stress in the substrate while the gas temperature can have a simultaneous annealing effect on the residual stress induced by those impacts. Thus, the favorable compressive residual stress induced intrinsically by the continuous peening of the surface can be partially relieved by the process temperature itself. Although the previous studies show the importance of the temperature in the coated samples [9], it is assumed that this parameter can have a negative side effect in this regard.

Previous study of the authors revealed notable difference in residual stress distribution for samples of the same substrate coated with different powders [2]. It was postulated that rather than other parameters, the gas temperature that is adopted for each powder type can play an in situ annealing role and consequently partially relax the residual stresses induced by the high velocity impacts. To the best of authors' knowledge, the conflicting effects of these two parameters on the residual stresses induced in the substrate have not been reported in the literature.

The present study has been performed to investigate the effect of the spray process parameters including particle impact and gas temperature on the residual stress distribution during the cold spray coating process and to evaluate their role in the evolution of residual stresses in the substrate. Residual stress state has been studied experimentally and numerically considering the peening effect of the impacts as well as the annealing phenomenon as results of the coating temperature and exposure time.

There is a general agreement that grit blasting can increase the deposition efficiency of the coating material by increasing the roughness of the substrate and thus enhancing mechanical anchoring [10–13]; thus grit blasting is frequently used as a preliminary treatment before cold spray coating. Also here all the substrates were grit blasted prior to the coating process.

In this study, the cold spray process has been numerically simulated for different combinations of substrate-coating materials using adopted coating parameters. Several aspects of the process have been implemented in the steps of the numerical simulation. A random distribution has been considered for the particles' diameter, corresponding to the powders used in the experiments; the velocity and temperature of the particles have been calculated individually as a function of their diameter and other process parameters have been approximated through an analytical approach. The residual stress induced through the preliminary grit blasting process has been experimentally measured and considered as initial stress distribution in the substrate model. The preliminary numerical studies show that particle diameter, impact velocity, and temperature have considerable effects on the residual stress induced in the substrate. Then, the effect of annealing on the residual stress is introduced analytically to survey the influence of gas stagnation temperature on the final results. The annealing parameters, presented in Zenner-Wer-Avrami function [14], are derived experimentally by measuring the residual stress in the samples under different exposure coating times and temperatures.

The results of numerical simulation have been verified through experimental in-depth XRD stress measurements. In this regard different combinations of aluminum alloys have been coated and the residual stress on the samples has been experimentally measured and numerically calculated. In order to account for the annealing effect of the process gas temperature in the experimental measurements, a series of grit blasted samples were put through the coating process condition without spraying any powder. The residual stresses were measured on these samples prior to and after the replicated coating process, thus allowing studying the effect of the process temperature solely.

2. Experimental tests

Al5052 and Al6061 aluminum alloys have been considered as substrate materials and coated with Al7075 and pure Al powders. All samples have been grit blasted before coating to provide an increased surface roughness for enhanced mechanical bonding of the coatings to the substrates. The grit blasting parameters are presented in Table 1. The residual stresses have been measured