Expert Systems with Applications 38 (2011) 260–271

Contents lists available at ScienceDirect

Expert Systems with Applications

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

Intelligent system for prediction and control: Application in plasma spray process

A.-F. Kanta [a,*], G. Montavon [b], C.C. Berndt [c], M.-P. Planche [a], C. Coddet [a]

[a] LERMPS, Université de Technologie de Belfort-Montbéliard (UTBM), Site de Sévenans, 90010 Belfort Cedex, France
[b] SPCTS – UMR CNRS 6638, Université de Limoges, 123 Avenue Albert Thomas, 87030 Limoges Cedex, France
[c] School of Engineering, James Cook University, Townsville 4811, Australia

ARTICLE INFO

Keywords:
Expert system
APS
Diagnostics
Control

ABSTRACT

Parametric drifts and fluctuations occur during plasma spraying. These drifts and fluctuations originate primarily from electrode wear and intrinsic plasma jet instabilities. One challenge is to control the manufacturing process by identifying the parameter interdependencies, correlations and individual effects on the in-flight particle characteristics. Such control is needed through methods that (i) consider the interdependencies that influence process variability and that also (ii) quantify the processing parameter-process response relationships. Due to the large amplitudes of the drifts and fluctuations, the strategy to adopt would depend on the required corrections to apply to the in-flight particle characteristics. Artificial intelligence is a pertinent tool to reach this objective. The system is flexible in order to permit a full control based on pre-defined rules aiming at maintaining at constant values in-flight particle characteristics (average surface temperature and velocity) by adjusting in real time the arc current intensity, the total plasma gas flow and the hydrogen content whatever the fluctuations.

1. Introduction

The performance of the industrial equipments and the production rate depend on the capability of some parts to resist wear. Thus, to improve these performances and to confer specific characteristics to the part, the surface treatment methods such as atmospheric plasma spraying (APS) are used. This process permits to create a coating on a surface in order to confer singular characteristics to protect it from phenomena such as wear, corrosion, erosion, etc. (Normand, Fervel, Coddet, & Nikitine, 2000). APS consists in injecting in a viscous enthalpy plasma jet (animated by a momentum) powder particles whose average size ranges from 10 to 100 μm. These particles are melted and simultaneously accelerated towards the surface of the part to be covered. They form, after impact, spreading and solidification, lamellae of a few tens to hundreds micrometers in diameter and a few micrometers thick. The coating results from the stacking of these lamellae (Fauchais & Vardelle, 2000). Fig. 1 summarizes the principle. APS process is characterized by several parametric drifts and fluctuations at different characteristic times (100–500 μs). These phenomena originate especially from the electrode wear (in tens of hours) and intrinsic plasma jet instabilities.

The objective of this work was to develop an expert system which can adjust the operating process parameters as a function of the measured in-flight particle characteristics to elaborate a coating. Due to the large amplitudes of these drifts and fluctuations, the strategy to adopt would depend on the required corrections to apply to the in-flight particle characteristics. Artificial intelligence (AI) based on artificial neural networks (ANN) concerning the prediction of the parameters to be reached (which adjustment must be proceeded to tend towards the target value?) and on fuzzy logic (FL) concerning the strategy to adopt to control the process parameters (on which parameters to act and with which amplitude?) (Kanta, Montavon, & Coddet, 2006; Kanta et al., 2008). The system is flexible in order to permit a full control based on pre-defined rules aiming at maintaining at constant values in-flight particle characteristics (surface temperature T and velocity V) by adjusting arc current intensity (I), total plasma gas flow (H_2 + Ar) and hydrogen content (H_2/Ar) whatever the fluctuations. The methodology and the key steps of the process were validated experimentally in the specific case of alumina–titania coating.

2. APS process

2.1. Process parameters

APS constitutes a special process in the sense that the result (coating with given in-service properties) does not directly depend on extrinsic variables (i.e. operating parameters) but on intrinsic

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[*] Corresponding author. Address: Service de Science des Matériaux, Université de Mons, Rue de l'Epargne 56, 7000 Mons, Belgique. Tel.: +32 65 37 44 37; fax: +32 65 37 44 00.

E-mail address: Abdoul.Kanta@umons.ac.be (A.-F. Kanta).

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doi:10.1016/j.eswa.2010.06.056

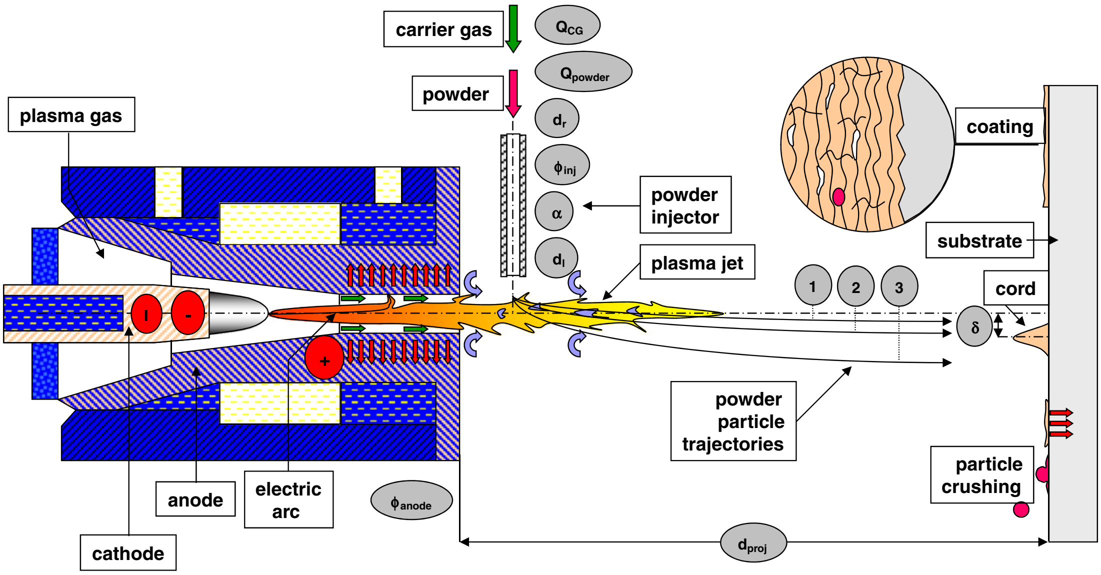

Fig. 1. APS principle.

variables, that is to say the in-flight particle characteristics upon impact and their flattening mechanism. Spray processing parameters can be divided into many categories (Fisher, 1972): feedstock material parameters, power parameters, feedstock injection parameters, kinematic parameters and substrate/coating parameters. These parameters are intimately interrelated *via* complex – non-linear – relationships, Fig. 2.

The coating properties derive from the molten particle characteristics upon impact (momentum and viscosity); the molten particle characteristics upon impact derive from the plasma jet thermodynamic characteristics and these latest rises from the process parameter adjustment.

These parameters are closely interrelated (i.e. adjusting power parameters imposes to adjust feedstock injection parameters and to optimize geometric and kinematics parameters) and have hence interrelated effects on the in-flight particle characteristics and on the coating structure and properties (Guipont, Mollins, Jeandin, & Barbezat, 2002; Tului et al., 2002). Some phenomena which intervene in APS process deserve still to understand their interaction with the plasma jet and to look further into their incidences on the coating. In particular, the dynamic behaviours of the electric arc and its relation with the electrodes are of prime interest since they result in arc tension fluctuations. These fluctuations generate the energy variations provide to the plasma gas and thus, introduce finally a strongly random character into the process. These phenomena, which have consequences on the result reproducibility, relate to the electrode wear and plasma jet intrinsic instabilities: the jet power changes by modifying the plasma properties significantly and the thermodynamic coefficients, consequently the momentum and the thermal transfers to the particles.

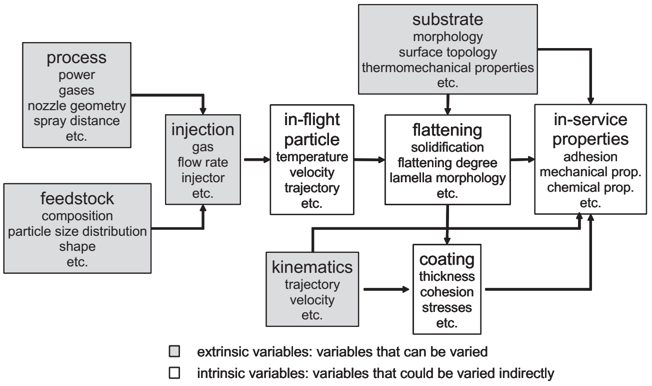

Fig. 2. Process parameters.

2.2. Drifts and fluctuations

The plasma torch operating principle consists in transferring energy from an electric arc, created between cathode and anode, with a mixture gas to form plasma. Plasma is sensitive to various instabilities whose characteristic times differ from several orders of magnitude, Table 1.

The injection conditions (angle, position and diameter of the injector, carrier gas flow), fixed according to the powder nature and its morphology, have an influence on the in-flight particles in order to give them a momentum adapted to that of plasma at the injection point and thus, to ensure a good penetration in the jet. The plasma gas composition affects directly the torch (Pateyron, Elchinger, Delluc, & Fauchais, 1992). The jet instability is characterized by (i) the deviation and the dispersion of the particle trajectories because of the jet momentum variation, (ii) the widening of the particle velocity and temperature local distributions. Indeed, the continuous variation of the enthalpy provided to gas can be interpreted by fluctuations in the jet dimensions and its characteristics (velocity, temperature, composition).

The electric arc is composed of a principal column of arc, fixed at the cathode (source of electrons) extremity, and of a connection column which ends in the arc root on the anode surface. The arc root moves in a permanent way on the anode surface in a back and forth pass with a lengthening phase of the arc downstream from the anode, stopped by the arc breakdown which is restarted upstream or downstream from the preceding arc root. These arc root fluctuations result in fluctuations of the electrode voltage.

The tension measured between the electrodes is the sum of the cathode, the anode and the arc tensions. It is impossible, by the measurement of the tension to dissociate these three components. Generally the sum of the cathode and the anode tensions is supposed to be constant, so that only the variation of the arc tension