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Technical Paper

Empirical modeling for processing parameters' effects on coating properties in plasma spraying process

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ABSTRACT

In order to model the effects of processing parameters (primary gas flow rate, stand-off distance, powder flow rate, and arc current) on the plasma spraying coating properties (thickness, porosity and micro-hardness), adaptive neural fuzzy inference system (ANFIS) and neural network (NN) based empirical models were proposed to estimate process parameters and understand the spraying process. To overcome the difficulty of the small size of sample data, and to balance the trade-off between model complexity and prediction accuracy, the bootstrap method was applied for the resampling technique, and cross validation was applied for the performance evaluation. The ANFIS and NN models were compared on the performance metrics of (1) mean square error (MSE), and (2) determination coefficient (R^2). With the limited size of experiment data, both models illustrated high accuracy. In the training stage: on the R^2, ANFIS has the value of 1, and NN has the minimum value of 0.84; on the MSE, ANFIS has the minimum value of 1.3e−5, and NN has the minimum value of 0.32. In the validation stage: on the R^2, ANFIS has the minimum mean value of 0.42, and NN has the minimum mean value of 0.512; on the MSE, ANFIS has the minimum mean value of 23.67, and NN has the minimum mean value of 89.50. The comparisons illustrated that ANFIS model showed significant superiority over the NN model. This may be due to the fact that ANFIS combines the strength of NN's learning capability and fuzzy logic's knowledge interpretation ability. With the obtained ANFIS model, the physical mechanisms – including (1) melting states of particles, (2) loading effect, and (3) oxidation – were interpreted as processing parameters' effects on the coating properties. The empirical models and that physical mechanism are viable to be effectively integrated with feedback control strategy to regulate the coating quality in plasma spraying process.

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1. Introduction

The plasma spraying process is typically used for producing thermal barrier coatings (TBCs) on turbine blades. The TBCs' complex structure is shown in Fig. 1. It is comprised of metal and/or ceramic multilayers which possess a very low thermal conductivity and a high melting point, so the turbine blades can be protected from the extremely hot working environment in aircraft and industrial gas-turbine engines, thus improving the durability and energy efficiency of the turbine machines [1].

The plasma spraying processes are described in [2]. The plasma spraying gun generates the heat by an electric arc. Feedstock material is heated and propelled as individual particles or droplets onto a substrate. When heated, the material phase is transformed to a plastic or melted state; the melted particles are then accelerated by a compressed gas stream and strike the substrate. As the sprayed particles hit the substrate, they flatten, cool, and build up layer-by-layer thin splats that conform and adhere to the irregularities of the prepared substrate and to each other.

In the spraying process, coating cracks, pores, and splats can significantly reduce thermal properties of the TBCs. The defected microstructure also causes nonlinear elastic modulus that weakens the strength of coating. Qualities on coating properties including thickness, hardness, and porosity rate should be controlled to maintain the quality of TBCs. This can be achieved through tuning the processing parameters including plasma gas choice, flow rates of plasma gases, nozzle size, injection type, feed rate of powder, feedstock powder particle size distribution, morphology of powder, and so on. However, process control with a large number of parameters is a formidable challenge due to two reasons: (1) the complicated interaction between the processing parameters and their joint effects on the quality of TBCs (the nature of plasma spraying is not yet fully understood); and (2) plasma spraying process has the characteristics of short run, which means smaller lot sizes,

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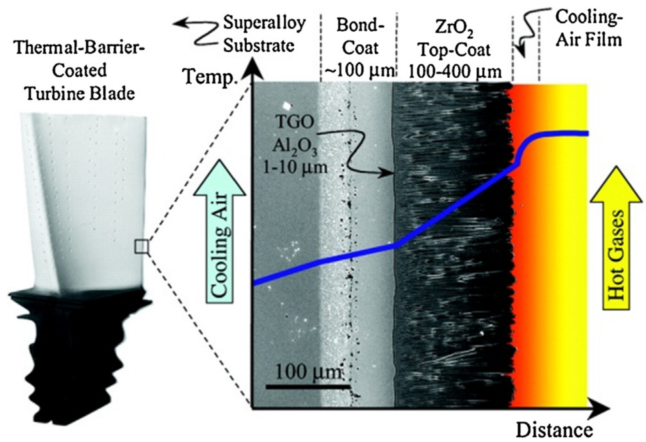

Fig. 1. Layers of thermal barrier coating on a turbine blade [1].

shorter lead times and less available process data to construct a control chart since most the gas-turbine engines are mass-customized. The repeatability of the coating process is the problem under investigation, but from state-of-the-art control of plasma spraying, a breakthrough has not been reported yet.

To understand the processing parameters' effects on the coating properties is the very first step to effectively control the process. Initiated by these, this article aims at modeling the plasma spraying process with empirical models, since it is too difficult to model plasma spraying using classic control theory such as state space approaches. The study started from data collection with design of experiment (DOE) techniques. With the collected data, ANFIS or NN based models are applied to recognize the pattern between the processing parameters and desired output properties. Finally, the process knowledge will be physically interpreted between processing parameters and coating properties based on the empirical models.

The rest of this paper is organized as follows. Section 2 reviews related research work on modeling and control of plasma spraying process. A research gap is summarized at the end of this section. Section 3 discusses the details of the proposed methodologies including data collection with DOE techniques, then ANFIS and NN based models, and further bootstrap and *k*-fold cross validation (KCV) as the model assessment approaches. Section 4 describes the case study and modeling results to illustrate the proposed approach. Section 5 presents the discussions on modeling results, and illustrates the physical mechanism of processing parameters' effect on coating formation. Section 6 concludes the research and outlines future direction.

2. Literature review

The modeling on plasma spraying can be conducted on (1) the relationship between processing parameters and in-flight particle states (temperature, velocity and melting states), or (2) the relationship between processing parameters and final coating properties. The first kind of models is mainly for the purpose of real time control of thermal spraying, since the in-flight particle states can be measured in an in-situ way with diagnostics sensors such as DPV 2000® [3] and Accuraspray® [3]. However, there still a gap and uncertainty on the relationship between particle states and coating deposition structure/properties. On the second kind of models, it is difficult to conduct on-line measurement of coating properties when spraying with the current technology. Thus, these models cannot be directly applied on the process since they are involved with measurement delay. Current applications with the second kind of models have been conducted on regular regression analysis [4], stepwise regression analysis [5], neural network [6,7], and/or fuzzy logic [7].

Datta et al. designed his experiments using central composite design (CCD) method and then analyzed the experiment with regular regression analysis [4]. With the data collected on processing parameters (recipe) (primary gas flow rate, stand-off distance, powder flow rate, and arc current) on three outputs responses (thickness, porosity, and micro-hardness of coatings), nonlinear regression analysis was conducted. Surface response equations and plots were deducted from the analysis. From the analysis and the plots, the researchers found that the above four processing parameters have varying influences on different responses. However, all the above three responses were found to be significantly dependent on primary gas flow rate.

Li et al. studied plasma spraying processing parameters' effect on deposition efficiency, porosity and micro-hardness using a uniform design of experiments and stepwise regression analysis [5]. The processing parameters were arc current, argon flow rate, hydrogen flow rate, spray distance, and powder feed rate. The measured deposition efficiency, porosity and micro-hardness of the coatings were regressed as the first- to third-order polynomial equations of processing parameters using stepwise regression analysis. They identified that the third-order regressed equations were the most appropriate to identify the influences of the investigated process parameters on the deposition efficiency, porosity and micro-hardness. Within the range of the uniform design of experiments, argon flow rate and hydrogen flow rate were the most significant two parameters affecting the deposition efficiency, porosity and micro-hardness among the five process parameters. Consequently, despite the fact that the regression equations were different in terms of elements of the five investigated process parameters, the porosity decreased and micro-hardness increased with an increase in the deposition efficiency.

Montavon et al. investigated neural network [6] or fuzzy logic [7] based artificial intelligence methodologies for quality control of plasma spraying coating processes. They monitored the inflight particles' state including average velocity, temperature, and diameter before impinging the work piece and forming a deposit. These particle characteristics represent the most pertinent indicators of the coating properties and characteristics reproducibility. In [6], the particle states were the output of a neural network. The model was built considering the system input with the plasma and particle powder injection-processing parameters. In [7], fuzzy logic based models were implemented to predict in-flight particles characteristics as a function of process parameters. The spray parameters were also predicted as a function of achieving a specified hardness or a required porosity level. The predicted results were compared to the results of experimental data resulting from a non-intrusive sensor conventionally used by industries to control the coating quality. Good consistencies were found between these results.

From the literature, it is identified that in control of plasma spraying processes, the current literatures lack enough consideration on these issues; yet, how can we involve uncertainty of the control parameters in the modeling of thermal spraying? Based on the statistics models deducted from the experiment data, can we physically interpret the process knowledge between processing parameters and coating properties? These research questions will be addressed in the following sections.

3. Methodologies

3.1. Data collection based on design of experiment

The study started from data collection with design of experiment (DOE) techniques. DOE permits researchers to study

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