PARTICLE TEMPERATURE AND RESIDENCE TIME CONTROL FOR REACTIVE SPRAYING

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ABSTRACT

Reactive plasma spraying is a viable method for the in situ production of a variety of composites and nitrogen-strengthened materials. The process utilizes the high thermal energies in thermal plasmas to produce reactive chemical species from precursor gases in the presence of high temperature solid or liquid particles. The kinetics of the reactions and the ultimate degree of reaction is governed by the temperature of the particles and their residence time in the reactive environment. In practice, this is controlled by the particle temperature and velocity as well as the characteristics of the reactive environment. This paper describes the practical implementation of particle temperature and velocity control via the direct, real-time monitoring of particle temperature and velocity and the taking of corrective actions rather than the traditional approach of simply setting process variables.

INTRODUCTION

The motivation for the development of real-time closed-loop feedback control of the thermal spray process is to improve final product quality and increase the repeatability of the spray process by lowering the sensitivity of the process to inherent variations in spray parameters. As performance and quality requirements increase, the need for real-time process control becomes more necessary. For reactive plasma spraying the kinetics of the reactions and the ultimate degree of reaction is governed by the temperature of the particles, their residence time, and the characteristics of the reactive environment. Other applications, such as the spraying of graded materials can also benefit from active control. As the composition of the feed stock changes, real-time control allows the precise setting of particle temperatures and velocities. Closed-loop control requires the direct, real-time monitoring of process performance, via real-time sensing of particle spray parameters and the taking of corrective actions, rather than the traditional approach of setting process variables and post process examination. The primary parameters to be controlled are the particle temperature,particle molten state or fraction, and particle velocity. The particle molten state is not directly measurable in a real-time manner, hence the particle temperature must be used as an indicator.

Controllers for the thermal spray process may be required to act as regulators, whose purpose is to maintain conditions at an infrequently changed set point, and as servo or follow-up systems, where the controlled variables may be "ramped" through a sequence. The applications of the regulator mode are obvious. The servo mode has application in advanced processes, such as the spraying of graded materials where it is desired to vary particle temperature and velocity over the thickness of the coating or even over different regions of the part as the composition of the coating is varied. The ability of simple, first generation, controllers to perform in the servo mode will be examined.

FEEDBACK CONTROL

A simple closed-loop control system is shown in Figure 1. For thermal spraying the output that we wish to set and automatically maintain are particle temperature and/or particle velocity. Suitable sensors directly monitor the particle temperature and velocity. The process consists of the spray gun, control console, power supply, and powder feeder. The inputs to the process are electrical signals that alter the process settings; gun current, primary and secondary gas flow rates, etc. The process and sensors are connected in a closed loop with a third element referred to as a compensator, controller or filter.

The system input(s) or set point is a reference signal. The desired outcome is that the system output is equal to the system input. If a different output (particle temperature or velocity) is desired the system input is changed. The output value measured is compared with (subtracted from) the input resulting in a difference or error signal. If the output equals the input, the difference is zero, and no error signal is generated to modify the process. If the error is non-zero, in a properly designed system, the error signal causes a response to the process such that the magnitude of the error is reduced. The compensator is a filter for the error signal. Modification of the error signal is generally required to ensure satisfactory process performance. As a minimum, performance requirements include stability, disturbance rejection, adequate response, steady-state accuracy, and robustness. Robustness means that the closed-loop system characteristics tend to be insensitive to small inaccuracies in the system model. This characteristic is very important because real systems generally have significant nonlinearities and are only approximately represented by linear system models.

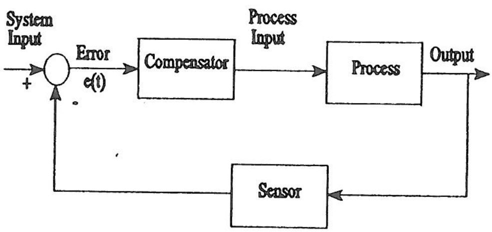

Figure 1. Closed-loop controller schematic.

The form of the controller used is the proportional-plus-integral-plus-derivative (PID) type with e(t) the compensator input and m(t) the output. The PID compensator[1] is defined by the equation:

$$m(t) = K_P e(t) + K_I \int_0^t e(\tau)\,d\tau + K_D \frac{de(t)}{dt} \quad (1).$$

The proportional gain K_P, the integral gain K_I and the derivative gain K_D are parameters which must be determine in the design process. For a particular design one or more of the controller gains may be set to zero.

The PID controller is second order, with a phase-lag (integral term) element and a phase-lead (derivative term) element. The PID controller offers a wide range of adaptability to desired system characteristics. It is the most commonly employed controller in closed-loop control systems and is used almost exclusively in industrial control. The controller is implemented digitally, using a computer. The interface with the process is via digital-to-analog conversion (D/A) of calculated numerical values. Digital implementation has the advantage that system modification, simulation, and implementation are easily and quickly accomplished.

The effect of K_P is pure gain or proportional control. Pure gain compensation is used in situations in which satisfactory transient and steady state response can be obtained by simply setting system gain, when dynamic compensation is not required for stability. The effect of adding compensation with a gain value less than unity is to shift (downward) the frequency response characteristic with no change in shape. The phase relationship remains unchanged. This has the effect of increasing the stability phase margin at the expense of reducing the system bandwidth. The system rise time typically increases but the overshoot in the transient response is less.

The integral or phase-lag term is used to improve the accuracy of the steady-state response of the system. The effect is to reduce the overall gain at higher frequencies, at the same time it introduces phase lag which can affect the system stability phase margin. The phase-lag is in effect a low-pass filter; the high frequencies are attenuated relative to the low frequencies. In general, reduced gain tends to stabilize a system while phase-lag tends to destabilize a system. The phase-lag must be placed in a frequency range such that stability is not adversely affected.

The derivative or phase-lead element improves the system transient response. The gain of the phase-lead element increases as frequency increases. If a signal is changing rapidly in time the derivative of the signal is large. High frequency noise will be amplified by a phase-lead element and the higher the frequency the greater the amplification. To prevent problems with high frequency noise the phase-lead element is sometimes modified by adding a pole to the transfer function to limit high frequency gain. Because the phase-lead element is capable of generating large signals (large gain), its output should be limited to avoid system damage.

SENSORS

The two sensor systems used to obtain measurements of particle temperature and velocity are described in detail elsewhere[2,3] and will be only briefly described here. Particle velocity is obtained from laser Doppler velocimeter (LDV). Because of the shallow beam crossing angle used the device averages over several millimeters of the region of highest particle concentration. The velocity data is time averaged, hence the velocity obtained represents both a time and space averaged value which is heavily weighted toward the spray pattern centroid. Particle temperature is obtained from an in-flight particle pyrometer (IPP)[3]. This device derives particle temperature by measuring the radiation emitted by the particles in two narrow wavelength bands. The temperature derived is averaged over the IPP field-of-view and line-of-sight. The temperature data is also time averaged, hence the temperature value used is both time and space averaged and is also heavily weighted toward the spray pattern centroid.

RESULTS AND DISCUSSION

The system chosen for demonstration of closed-loop feedback control of the thermal spray process is the subsonic plasma spray deposition of NiAl powder. The gun used was a Miller SG-100 with a standard 165/129 anode/cathode combination. The nominal operating conditions were primary and secondary gas flow rates of 47 slm argon, 22 slm helium, the current was 800 Amps and the carrier gas flow rate was 0.6 slm of argon. The powder feed rate was held constant at 10 kg/hr. MKS mass flow controllers were used to set and regulate all gas flows. The gun efficiency was continuously monitored by measuring the coolant water mass flow rate and the gun inlet and outlet temperatures.

The controller consists of two serial PID controllers, one for temperature and one for velocity. In this configuration, temperature is first manipulated by adjusting current, then velocity is manipulated by adjusting primary gas flow. This control scheme is a particularly simple one and will serve to illustrate controller performance. It should not, however, be considered "optimal". It is certain that better configurations exist with gain values which are better tuned for overall system performance.

The ability of the controller to follow a temperature and a velocity ramp is shown in Figures 2 and 3. The initial transients are a result of the controller seeking the set point from the initial system condition when the controller is engaged. In Figure 2 the velocity is held constant and the temperature is varied over a 600 K range. The high-end response is limited by the system imposed maximum gun current. Noise in the low end response is due to the fact that these conditions are somewhat outside the optimum operating range of the plasma gun. In Figure 3 the temperature is held constant and the velocity set point is varied between 80 and 125 m/s. The maximum velocity attained is limited to 120 m/s. This limit is imposed by the maximum gun current and primary gas flow rates. While the controller is somewhat noisy, the response, overshoot, and steady-state accuracy are acceptable.

CONCLUSIONS

A stable particle velocity and temperature controller for the plasma thermal spray process has been demonstrated. The controller was designed using an accepted discrete

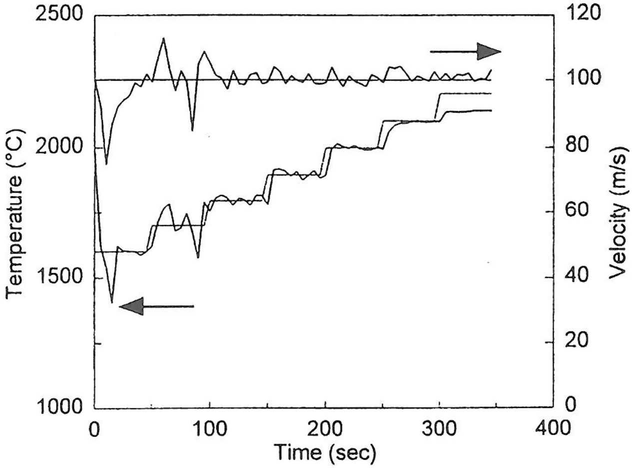

Figure 2. Temperature ramp response.

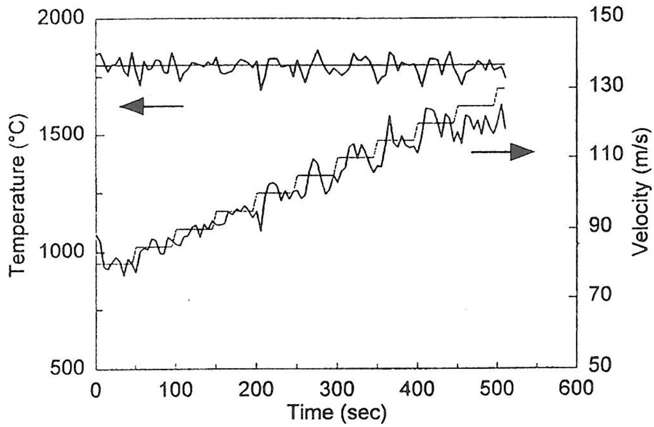

Figure 3. Velocity ramp response.

digital control approach. While the control of only one plasma spray system has been illustrated the methodology used is general. The serial controllers used are by no means the only approach to control. Other control methodologies may have superior performance and are under investigation.

The particle injection velocity was not included in the model. Its importance should, however, not be ignored. The particle injection velocity controls the position of the spray relative to the centerline of the gun and has a significant effect on the spread of the spray. Because particles in the periphery of the spray may not have optimum temperature and velocity they may be detrimental to the coatings produced. Additional instrumentation, whose purpose is the sensing of spray position and spread of the spray are required to achieve complete control .

ACKNOWLEDGMENTS

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