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Process-Based Quality for Thermal Spray Via Feedback Control

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Quality control of a thermal spray system manufacturing process is difficult due to the many input variables that need to be controlled. Great care must be taken to ensure that the process remains constant to obtain a consistent quality of the parts. Control is greatly complicated by the fact that measurement of particle velocities and temperatures is a noisy stochastic process. This article illustrates the application of quality control concepts to a wire flame spray process. A central feature of the real-time control system is an automatic feedback control scheme that provides fine adjustments to ensure that uncontrolled variations are accommodated. It is shown how the control vectors can be constructed from simple process maps to independently control particle velocity and temperature. This control scheme is shown to perform well in a real production environment. We also demonstrate that slight variations in the feed wire curvature can greatly influence the process. Finally, the geometry of the spray system and sensor must remain constant for the best reproducibility.

Keywords diagnostics and control, flame spray synthesis, manufacturing, stability of processing, wire flame spray

1. Introduction

The objective of process-based quality is to greatly reduce or eliminate inspection and testing without sacrificing reliability. To achieve this objective, one must create and certify a manufacturing process that can never produce a bad product (Ref 1). The savings that can result are due to zero waste, no reworking, and low inspection costs.

Previously, process-based quality has not been achieved for thermal spray processes because the authors have never been able to monitor and control the process in such a manner that only an acceptable product is produced. State-of-the-art control systems for complex processes typically monitor and adjust selected process input variables, with the hope that holding several key variables within some tolerance range will result in a consistent product. For complex processes, the authors can never hope to achieve process-based quality with this input-based or "upstream" control methodology because there are always important variables that are impossible or impractical to monitor and control. In many cases, the factors responsible for causing production problems remain unknown. Component wear, drift in a not-normally-controlled parameter, incomplete knowledge of the process, environmental factors, and subtle variations in a process consumable are examples of these difficult-to-control and difficult-to-understand items. Nevertheless, these variables can have strong effects on final product quality.

To achieve process-based quality for thermal spray processes, a new methodology must be developed to build process control systems that monitor and control complex processes in real time based on process outputs rather than inputs. Considering the present state of technology, it is still unrealistic to propose developing a control system that would directly monitor and control actual final product properties in most cases. A different approach is required. By combining some key pieces of existing technology and adding new data analysis techniques, it is possible to collect and analyze downstream process sensor data on a real-time basis. Monitoring and controlling, in real time, critical downstream process observables that directly determine the microstructure, properties, and performance of the final product can yield improved results. Experience has shown that the concepts presented in this article have yielded coatings that are visibly superior in terms of consistent surface finish. This article demonstrates a simple control methodology that is practical enough to use on an everyday basis. Central to this effort is the use of an automatic feedback control system to adjust inputs for keeping particle temperature and velocity constant.

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2. Description of the Process

The typical thermal spray process consists of an energy source in the form of a flame or plasma jet, a feedstock wire or powder, and a substrate that is to be coated with the feedstock material. In the case of wire flame spraying, a feedstock metal wire is introduced into the center of an oxyfuel flame, where it is melted, and then atomized and accelerated by a powerful air jet that flows coaxially around the flame. The data presented in this article deal exclusively with 1.4 mm copper wire (0.0565 in.) that was fed into the center of an oxy-methane flame. Other materials have been tested and have performed well with the methods described herein. The molten droplets that are produced by the atomization process range in size from about 10 to 100 μm in diameter and reach velocities of several hundred meters per second. Typically, the molten droplets are heated to temperatures that are several hundred degrees above their melting point. In flight, these tiny particles can react with the surrounding atmo-

Fig. 1 Centered and off-centered wire positions within the spray hardware

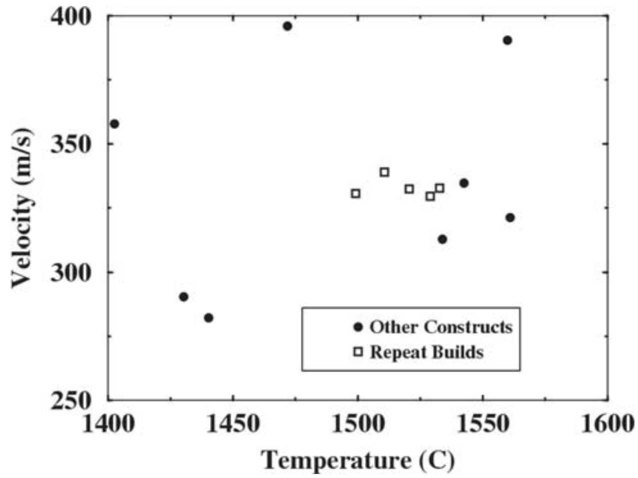

Fig. 2 Plot showing the range of particle temperature and velocity that result from swapping nozzles and air caps. Repeat builds with the same hardware resulted in less variation.

sphere, forming oxides that later get incorporated into the coating. When the particles strike the substrate, they are splat-cooled at rates on the order 10^6 K/s and form a lamellar microstructure. Each droplet solidifies independently of one another. Not surprisingly, the thermal and kinetic energy distributions of the particles play a key role in determining the microstructure and properties of the sprayed deposit. The oxidation state of the particles and the substrate condition are also important parameters. In this program, the authors tried to institute procedures to ensure a repeatable substrate condition. Developing a methodology for dynamically controlling the in-flight characteristics of average particle temperature and average particle velocity was the focus of this program. Active control of the oxidation state of the particle was not possible at this point in time.

2.1 Sources of Variability in the Wire Flame Spray Process

Variability in the wire flame spray process can arise from a number of potential sources. Some of these are well understood, while others are difficult to pinpoint or to control. Arguably, the greatest single source for process variability is associated with the wire that is fed into the flame. Proper centering of the wire is essential due to the steep temperature and velocity gradients that are present in the flame. Figure 1 shows operation of the spray system with two different wire positions. In the top view, the wire is centered, and optimal performance is observed. In the lower view, the wire is off-center, resulting in a lower melting rate. It is not realistic for the feedback control scheme to compensate for such extreme problems, as shown in the photograph in Fig. 1. A video sequence of the wire in Fig. 1 would reveal that the wire tip actually oscillates in and out of the flame and melts very irregularly with time. The most common cause of centering difficulties is that the wire is not straight enough as it enters the flame. For this reason, considerable effort was expended to work with the wire manufacturer so that wires with reproducible curvature and stiffness could be procured on a long-term basis. In addition, wire straighteners were added behind the torch to provide improved straightness for the wire entering the flame. Finally, the drive wheels that pull the wire off of the reel and through the straighteners cannot have too high a grip pressure or else they will deform the wire and affect centering. Conversely, too low a grip pressure results in slippage and a nonuniform feed. Each material fed into the torch requires a separate grip pressure. The surface of the drive wheels was machined with a U-shaped groove that matches the wire diameter and properly locates the wire on the torch centerline. These improvements in the wire and in the wire-feeding hardware substantially improved the wire flame spray process; however, there will always be some small variability in the wire feedstock and its straightening, so the ability to dynamically fine tune the process is important for demanding applications.

Another major source of process instability is torch hardware. Several components are removed from the torch on a regular basis and are inspected by the operator. Hardware can be replaced due to wear or damage. In facilities where more than one torch is used, obtaining consistent performance from torch to torch is especially challenging because one necessarily has multiple sets of hardware to deal with. Figure 2 illustrates the kinds of variations in particle temperatures and velocities that can result by simply swapping out nominally identical sets of torch hardware. The data show the substantial changes in particle heating and acceleration that occurred when three different atomizing air caps and three different nozzles were put into the torch in various combinations.

Some of the data included in Fig. 2 compare particle temperatures and velocities taken from the repeated builds using the same hardware. The variability from the repeated data points was small; indicating that most of the variability observed in Fig. 2 was caused by changing out the nozzle and air cap hardware and not by irreproducibility in the sensor, the wire, or the gas control system. Ideally, one would hope that all of the hardware would give the same performance. In fact, simple dimensional measurements of such quantities as lengths and hole sizes failed to detect any noticeable differences between the various air caps and nozzles, yet substantial differences in performance were observed. It is also worth noting that even though the air cap and nozzle can be inserted at any angular orientation about the flame axis, the failure to fix the orientation every time the hardware gets assembled resulted in additional variability.

Some sources of variability in the sprayed coatings will not be addressed by the feedback control of the atomization process. For example, substrate preparation (i.e., grit blasting and solvent wash) and substrate temperature during spraying can have a profound effect on the quality of the interface between the substrate and the coating. Similarly, the geometrical aspects of the spray system (i.e., centering the torch to the part properly, setting the angle of the torch, and maintaining the standoff distance) can also strongly influence the microstructure, properties, and build rate of the deposit. Engineering and administrative procedures for controlling these potential sources of variability are important if one is to reap the full benefit of dynamically controlling particle temperature and velocity (Ref 2).

The acceptable amount of system variations will depend on the application. One would have to perform experiments with each product to determine the range of acceptable particle velocities and temperatures. In this study, the goal was to minimize drifts in the process over a spray run that last hours and on a product that is produced over years.

2.2 Measurement of Particle Temperature and Velocity

Over the past decade, a number of devices have been developed for measuring the temperature, size, and velocity of molten particles suspended in hot gas jets such as those existing in the wire flame spray process. Some of these techniques measure the characteristics of individual particles, while others measure the ensemble averages of properties. Particle temperatures are always measured using two-color pyrometry. Particle velocities are determined using either time-of-flight measurements or laser Doppler anemometry. Particle size is extracted from the intensity of the light emitted (or reflected, in the case of laser illumination) by individual particles. In the past, these sensors were very expensive and required specialized skills and careful attention to equipment operation to achieve reliable results.

For routine production usage of particle diagnostic technology, several requirements need to be met. The sensor must be simple to use, robust and reliable, easy to calibrate and align, and relatively inexpensive. If it is to be used for feedback control, it must provide updated data in a meaningful timeframe, and its output must be incorporated into the process control software on a real-time basis. Particles that are suspended in a thermal spray jet exhibit spatially and temporally varying characteristics. Particles in the periphery of the jet can be cooler and slower than those close to the centerline. The acceleration and heating of particles occur rapidly over the first several centimeters of travel toward the substrate and then tend to slowly decrease. It is generally not practical to locate the particle sensor near the substrate, so the measurement is typically made fairly close to the torch, where signal strengths are higher and interference of the sensor with the part being coated can be avoided.

A further complication is that the particle temperature and velocity are stochastic variables. Due to the distribution of particle sizes that form during atomization and the different particle trajectories through the plume, the particle temperature and velocity will vary. Molten drops are stripped from the wire feed at discrete times. So, the instantaneous output from the sensor is not necessarily representative of the process. Thus, time averages must be used as a control input. The averaging time must be significantly long to avoid significant temporal variations. Longer averaging times reduce the measurement noise but slow the response of the control system.

For this project, the authors used a sensor from Tecnar (Montreal, Canada). Other systems may be equally applicable (Ref 3). The Tecnar sensor was able to provide a local spatial average particle temperature and particle velocity data. Due to the low emissivity and low temperature of the copper in a wire flame spray torch, modifications to the optics in the form of larger lenses and broader bandpass filters for the detectors were used. Other changes to the software, to the calibration system, to the location of the sensor with respect to the plume, and to the sensor's alignment hardware were also made to make the Tecnar sensor a viable tool for feedback control of the wire flame spray process.

The authors' application used a 50 mm diameter lens to collect the infrared thermal emission from the atomized copper particles produced by the wire flame spray process. The light is focused onto the polished ends of two fiberoptic cables. Broad bandpass filters are placed in front of PIN photodetectors at the end of the fiberoptic cables to provide light intensity data at two different wavelengths for two-color pyrometry. The ratio of light intensity as recorded by the two detectors provides a measurement of average particle temperature. Average particle velocity is obtained by looking at the time-varying signal entering the two fibers. The fibers are arranged such that the signal entering them comes from two locations along the axis of the jet that are separated by approximately 2 mm. Thus, the signal collected by the first fiber from a packet of particles traveling across its field of view gets repeated a short time later in the second fiber when the particles arrive in its field of view. The time delay provides a measure of the average particle velocity. The velocity is determined by taking a cross correlation between the two signal traces and determining the time separation that provides the strongest correlation (Ref 4). The average temperature and velocity data from the sensor are both updated at approximately 10 Hz. This signal is further averaged over 10 s for use by the control system. A running average allowed automatic updating of the flow every 5 s.

3. Control Methodology

The basic approach to developing a process is to first identify the key sources of process variability and to address them as thoroughly as is practical. As a next step, it is necessary to identify potential process inputs that can be dynamically adjusted to stabilize the process. A sensor system is required that can monitor process outputs. Finally, an algorithm is needed to modify the process input settings in response to observed drifts in the process output.

In a wire flame spray, the major sources of process variability are associated with the characteristics of the feedstock wire, the torch hardware, and the gas flows. By adjusting the gas flows via feedback control, variations in the other inputs can be accommodated. There are three adjustable parameters associated with the gas flows: the flow rates of methane, oxygen, and air. These flow rates can easily be dynamically adjusted by using an electronic regulator to vary the supply pressures of the gases. In this system, gas flows are determined using critical orifices. As long as the supply pressure is above the choke point pressure, and the gas temperature is constant, the flow rate of the gas is linearly related to supply pressure. Software can be written to account for changes in the gas temperature. The amount of time from when a change in gas flow is requested until it appears at the torch needs to be faster than the averaging time for best results. Gas flow response times are typically from about 0.5 to 1.0 s, which is a much shorter time than the averaging times used (typically 10 s). It is important to note that this control process runs continuously throughout deposition to automatically correct process drifts.

Experience has shown that the most useful method for working with the oxygen and methane flow rates is to express them instead as total combustion flow (TCF) and oxyfuel ratio (OFR). The TCF is simply the sum of the oxygen and methane flow rates, and it represents the total amount of combustion energy that is available to the process. The OFR has a strong effect on flame temperature and the oxidation state of the product gases. For methane, the maximum temperature is obtained near the stoichiometric point, but the maximum velocity is obtained at a slightly higher OFR value. The airflow (AF) rate plays an important role in atomizing the molten droplets as they stream off the wire tip. Using the gas flows of TCF, AF, and OFR, it will be shown that it is possible to dynamically control the average particle temperature and particle velocity.

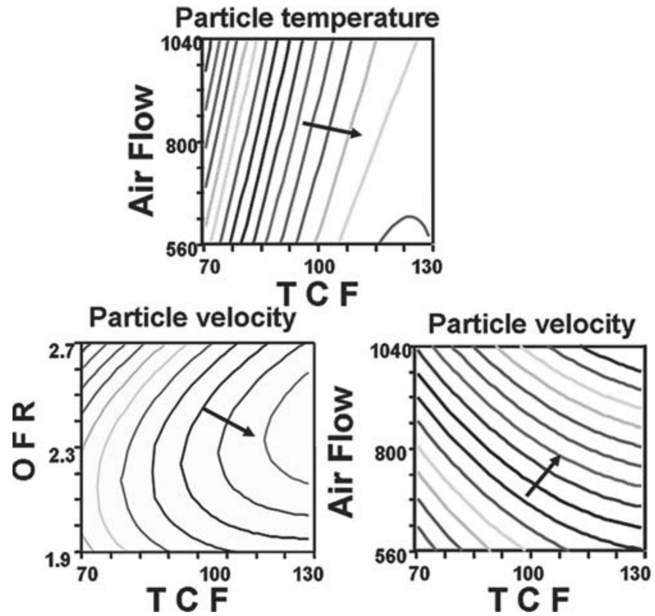

Fig. 3 Contour maps of particle velocity and temperature as a function of the three inputs. The arrows indicate direction of increasing contours.

3.1 Process Maps

The wire flame spray process is well behaved in the sense that changes in gas flows result in predictable changes in particle temperature and velocity. For example, increasing the AF to the torch typically results in faster particles. While the precise extent of the changes in particle temperature and velocity that are caused by perturbing the gas flows may vary somewhat from day to day or from system to system, the trends are predictable. This predictability makes it worthwhile to construct steady-state maps that link process inputs and outputs. Process maps are often the first step in creating a control system (Ref 5–7). It is generally accepted that the time constant for process changes is on the order of the particle travel time through the plume, so the use of a steady-state map for process control is sufficient. However, one should still examine system stability issues.

Experimentation with the authors' flame spray torch revealed the range of gas flow conditions over which it would operate in a stable fashion. Using these flow ranges, a statistically designed set of experiments was performed in which the gas flows were adjusted to numerous settings while the particle temperatures and velocities were measured. The input conditions are transformed into coded variables that each range from −1 to +1. This coding is used because it allows one to examine the magnitude of the fit coefficients to determine the relative importance of each variable. The particle temperature and velocity data can be empirically fit to quadratic equations that link them to the gas flows. These equations are of the form:

$$T_p = C_0 + \sum C_i * F_i + \sum C_{ij} * F_i * F_j$$

$$V_p = D_0 + \sum D_i * F_i + \sum D_{ij} * F_i * F_j$$

where the C and D terms are the fit coefficients of a least-squares regression, and F_i is the input factors. The coefficients of the fit are used in the feedback control algorithm. It is worth noting that collecting the data and determining the fit coefficients do not require a lot of time and are readily automated. Process maps are obtained from the coefficients to display the trends of the two outputs with the three inputs. These can be reconstructed whenever the operator suspects that a substantial change in system performance has occurred, for example, when a new set of torch hardware or a new reel of wire is introduced. The vectors shown in Fig. 3 display the direction of increasing magnitudes of the output contours.

The diagram in Fig. 4 shows the envelope of particle temperatures and velocities that the authors' torch could attain over the range of operating conditions that were examined. These were obtained from the fit coefficients and thus do not require any additional experimental evaluations. Because the quadratic fits of temperature and velocity to the gas flows are of good quality, it is possible to accurately interpolate temperature and velocity at conditions that are not experimentally determined.

It is necessary that the desired particle temperature and velocity lie within the envelope of the attainable conditions shown in Fig. 4. The specific values to choose for temperature and velocity need to be selected so that the microstructure and properties of the resulting coating meet the requirements of the specific application. In practice, temperature and velocity should not be located near the edge of the envelope where it may be difficult to stay within the range of acceptable torch-operating conditions as the controller works to hold particle temperature and velocity constant.

3.2 Control Vectors

Once a particle temperature and velocity have been selected for the application, it is necessary to have a feedback control algorithm that holds them constant during the spray process. When the process starts to drift, adjustments will have to be made to the control signals that are sent out to the electronic regulators that control the gas flows to the torch. These correc-

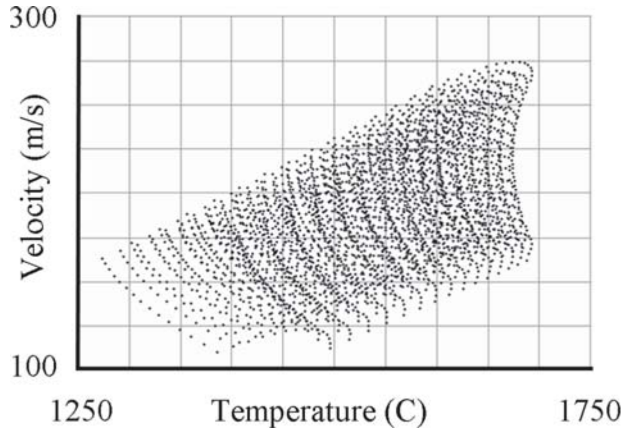

Fig. 4 Plot of particle temperatures and velocities that can be obtained over the range of the inputs

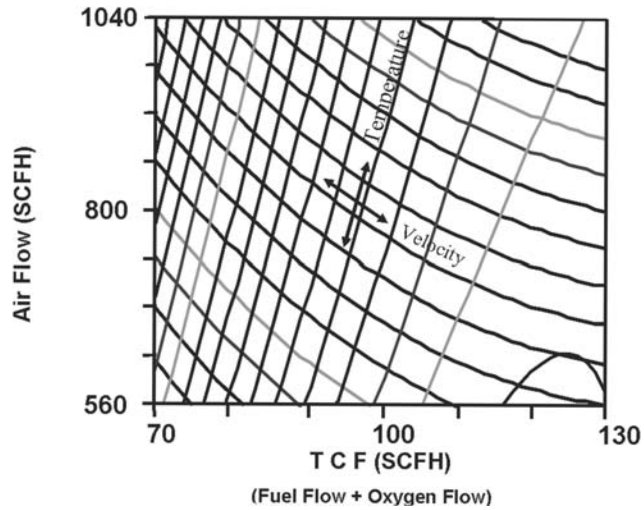

Fig. 5 Contour plots of constant particle temperature and velocity as a function of AF and TF (OFR = 2.0). One control vector is parallel to the isotherm and the other is parallel to a constant velocity.

tion terms may be represented as vectors in the input parameter space. Typically, these control vectors involve combinations of inputs being adjusted simultaneously. Another important consideration is, of course, the rate at which these corrections are applied. Unless it is done correctly, the response can be too sluggish, can overshoot, or can become unstable.

Previous studies have been published for the feedback control of thermal spray systems. Li et al. (Ref 8) have investigated a control system but have only used numerical modeling to illustrate their concepts. This avoids all of the problems that experimental noise generates. All sources of noise cause problems in thermal spray process control. This noise can be generated by the sensor inaccuracies and process variations. Process variations can also be due to the rate of droplet stripping from the wire feed. All sources of noise are perturbations that are faster than can be controlled by the current system. It is only the time averages that can be controlled, not the individual particle (or small group) velocity and temperature. These averages are calculated within a finite sampling time and space.

Moreau and Leblanc (Ref 9) used a sensor to monitor particle velocity and temperature in the plume. However, they proposed open-loop control systems or system monitoring with manual adjustments. They did not use an automatic feedback control system to maintain stable operation.

Fincke et al. (Ref 10) have experimentally demonstrated their control scheme. However, they chose to tie together single-input and single-output control schemes to control velocity and temperature separately. This may not yield the optimum control system. In the feedback system presented here, we used vectors of inputs to independently control both particle temperature and velocity. This should result in a more stable system.

In this particular example of the wire flame spray process, there are three inputs that are to be varied (OFR, TCF, and AF) and two output quantities to control (particle temperature and velocity). The extra degree of freedom afforded by the fact that there are more inputs than outputs can be put to use in several different fashions. For example, one could use it to select that control vector that has the shortest length from the infinite set of possible vectors. That is to say, the control vector that requires the smallest change in input conditions could be selected. This would result in smaller perturbations to the system, and possibly in less change in the coating properties.

However, a decision to keep the control algorithm as simple as is reasonably possible was made. This choice resulted in a follow-on decision to use only TCF and AF to dynamically control temperature and velocity. It should be recognized that numerous other control options could be constructed beside the one discussed here.

Although OFR is an important variable, the OFR-TCF contour map of particle velocity seen in Fig. 3 demonstrates that OFR is a complex quantity to use in a control scheme. If one considers the effect that OFR has on particle velocity at a TCF of 100, the problem becomes apparent. At low OFRs, note that increasing OFR results in faster particles. At high OFRs, the opposite behavior occurs: decreasing OFR results in faster particles. Of course, at intermediate OFRs (near the stoichiometric ratio), particle velocity is essentially unchanged by variations in OFR. By contrast, it can be seen that both of the AF-TCF contour maps of temperature and velocity show much simpler, monotonic behavior. Only at very high TCF and low AF does the particle temperature contour map reveal troubling curvature behavior. The process maps describe the performance of the system at the time they are constructed. The inevitable shifts and changes in the details of the maps that occur during actual production make the use of a control variable that undergoes a sign reversal less reliable. Keeping the OCR constant offers another advantage. This may keep the oxidation state of the particles more constant and may help to keep the coating properties constant.

If one overlays the AF-TCF contour maps from Fig. 3 for temperature and velocity, a reasonable approach for selecting control vectors becomes apparent (Fig. 5). One arrow indicates a direction parallel to the constant velocity contours (isovels). The other arrow indicates a direction that is parallel to the isotherms marked on the plot. Adjustments to AF and TCF along an isovel will change particle temperature while keeping velocity constant. Adjustments along an isotherm will change only particle velocity. These control vector directions work well except in the lower right corner of the plot where the 1500 °C isotherm rolls over. If the temperature and velocity selected for the process were 1500 °C and 140 m/s, then a more careful consideration of the control vectors would have to be made.

To obtain the best performance, it is recommended that the contours be regenerated periodically, resulting in the control vectors shown in Fig. 5, whenever significant changes occur to the system. For example, the changing of hardware often changes the system response. The control vectors typically only change slightly. An automated procedure has been developed to regenerate the data required and the new control vectors.

3.3 Process Dynamics

The control vectors identified in Fig. 5 allow the independent adjustment of particle temperature and velocity. These vectors require the simultaneous adjustment of all three of the gas flows to the torch: methane, oxygen, and air. The rate of adjustment of the flows needs to be consistent with the rate that the slowest of the controllers can accommodate. The desire is to have the system respond as quickly as possible with minimal overshoot and minimal ringing. A variety of dynamic control algorithms were considered for this application. Eventually, it was decided that a traditional proportional-integral (PI) control methodology approach was adequate. The inclusion of a derivative term was found to make the controller less stable, so it was not used.

The software that controls the torch uses two PI algorithms simultaneously: one for particle temperature and one for particle velocity. The PI coefficients are determined for each algorithm using the Ziegler-Nichols (Ref 11) critical-gain approach. Turning the integral term off, the proportionality gain is increased until the system begins to oscillate. Then, this critical gain value is noted along with the period of the oscillation. The optimum gain is set to 45% of the critical gain, and the integral parameter is set at 80% of the measured period. It was found that in the application, the authors had to further reduce the gain by a factor of 2 to obtain the best performance. Once the PI parameters have been determined, they do not generally need to be adjusted further.

As the PI algorithm runs, it generates adjustment factors for AF and TCF to control the particle temperature. These correction perturbations are converted to adjustments in methane flow, oxygen flow, and AF. Simultaneously, the PI algorithm for velocity is generating its own correction perturbations. The resulting adjustments are simply the addition of the two perturbations, and these are sent out to the electronic gas regulators.

Other more modern control schemes are available; however, the thought was that the Ziegler-Nichols (Ref 11) approach was a logical starting point due to its simplicity.

3.4 System Performance

This approach to feedback control works well. Figure 6 shows the typical results that are obtained by the system. In the two graphs, the gray line shows what the operator requested, while the black line shows how the system performed. The pair of graphs shows an example in which a step change and a ramp in the particle velocity were requested while holding temperature constant. Similar results were obtained for changes in particle temperature. This plot is shown to illustrate the control performance and does not represent typical operations. The typical application is to maintain a constant set point.

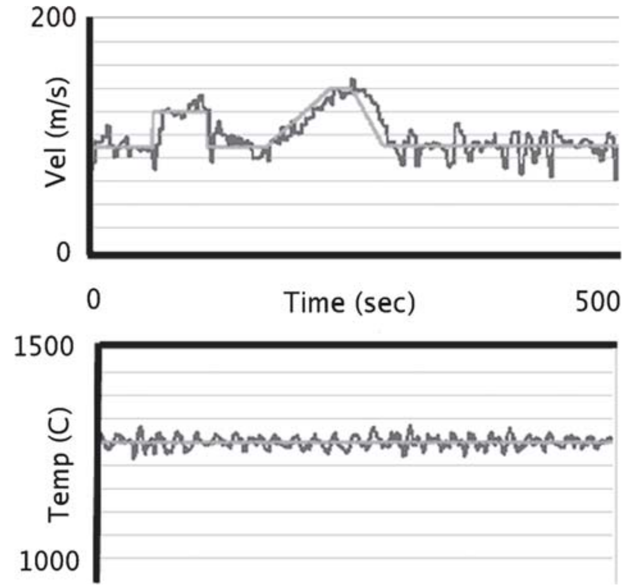

Fig. 6 Typical results of the feedback control algorithm. Gray is the requested transient; black is the actual system response.

There are several important considerations to keep in mind when relying on this type of feedback control approach. The performance of the sensors becomes a critical factor. Proper calibration and alignment to the plume are vital to determining the success of the approach. Techniques and tools that ensure that the sensor is functioning as expected are required. Because the goal is the repeatable manufacture of parts, the absolute accuracy of the calibration is not as important as the consistency of its operation. It was realized that good parts are created when the sensor reads a certain particle temperature and velocity. There is no real need to ensure that those absolute temperature and velocity values are accurate.

A calibration unit is supplied with the Tecnar sensor. It has a special tungsten lamp and integrating sphere assembly that is used to check the calibration of the temperatures recorded by the sensor. The integrating sphere homogenizes the signal from the lamp, making the calibration insensitive to the exact position of the sensor in the mounting fixture of the calibrator. An electronic pulse generator is used to verify the accuracy of particle velocity measurements.

An accurate physical alignment of the sensor with respect to the hot particle jet is very important. A carefully machined fixture for holding the sensor, an alignment rod with scribed lines, and alignment beams emitted from a pair of fiberoptic cables in the sensor head ensure that the sensor is correctly positioned with respect to the jet. With this custom hardware, it is possible to repeatedly achieve an alignment that is accurate to within a small fraction of a millimeter.

In this application, the sensor is mounted at a position 70 mm downstream of the torch exit plane. The authors examined the effects of traversing the sensor across the plume both axially and radially by mounting the sensor on micrometer-driven optical stages. Not surprisingly, the average temperature and velocity of the particles fall off when the sensor is translated radially. In the axial direction, this rapid fall off is not observed. Note that the depth of field of the sensor is greater than the diameter of the

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particle stream at these standoff distances. Thus, significant averaging in the radial direction is always present. It was found that it was not difficult to reproducibly position the sensor to minimize errors due to positioning.

Another consideration is that the wire be well centered in the flame. The center of the particle stream should be coincident with the center of the flame where the sensor is pointed. Periodically verifying that the wire is being properly straightened is important. The curvature of the wire (after straightening) is measured as the displacement of the center of the piece of wire away from the line connecting the end points. Testing has shown that as long as the curvature of a 300 mm wire is <5 mm, it is possible for the feedback control approach to compensate and hold particle temperature and velocity constant at their set points. If the curvature gets too large, ~10 mm or more, the wire tip position is not stable and the controller is unable to function correctly; adjustments to the straightening hardware would then be required to bring the wire back within the 5 mm limit.

The controller should be able to correct for the variations that result when swapping out hardware. Figure 2 showed that substantial variations in temperature and velocity result when torch hardware is changed. The same nine combinations of hardware were rerun on the torch, but this time feedback control for temperature and velocity was used. The results showed that the feedback control technique was able to bring the particle temperature and velocity to the same set point in most cases. However, in two cases where the temperature and velocity were substantially displaced from their target values the feedback control approach was unable to obtain stable operation. Clearly, hardware that cannot produce the desired temperature and velocity values should not be used.

In actual production, the target values for particle temperature and velocity need to be held constant from run to run for many months or years. It is interesting to note that the use of a feedback control scheme for temperature and velocity, combined with an automated spray booth that is deliberately designed to minimize operator exposure to the thermal spray environment, can result in a situation in which the operator relaxes somewhat and may not monitor the spray process as carefully as in the past. An additional level of monitoring that has proven useful is to limit the extent to which the gas flows can be adjusted away from the values predicted by the process maps to bring particle temperature and velocity to their target values. In practice, allowing the flows to vary by ±15% allows the system an adequate range of adjustment. If the controller requires more than a 15% adjustment, something is probably wrong with the system, and it needs to be checked out by the operator before more parts are sprayed. By limiting the extent that gas flows can be adjusted, one may prevent uncontrolled perturbations (such as particle oxidation) from ruining the coatings.

Figure 6 provides a graphic display of the noise level that is inherent with this system. The velocity varies over a range of 30 m/s, and the temperature varies over a range of 50 °C during periods when constant values are requested. Some of this noise is due to averaging measurements over a finite time, and some are due to actual system variations (i.e., wire tip position) over time. Sensor inaccuracy is on the same order as the variations in Fig. 6.

Due to the averaging time period of 10 s, the response time is on this order. Thus, it is too long to take out the high-frequency variations shown in Fig. 6. The control system was intended to account for variations in hardware and long-term drifts in the process. These are difficult to illustrate because it requires the presentation of data over hours of operation to capture changes that are associated with part wear.

An oscillation was observed in the measured average velocity and temperature with a period equal to the wire feed system rotational period (10 s). Thus, a time period was chosen for the signal averaging that was equal to the wire feed rotational period. This helped to stabilize the control system.

4. Summary and Conclusions

Attaining precise control of the wire flame spray process requires a complete understanding of process fundamentals. The gas jet provides heating and acceleration of the particles and must be both stable and reproducible. The wire must be well centered in the flame. Additional care must be taken to control the mechanical performance and alignment of the numerous components that comprise the spray system. The control system should be designed to incorporate the stochastic noise inherent in measuring particle temperatures and velocities. It is important to recognize that the feedback control technique can only be used to make fine adjustments to the system. It does not absolve the user from performing the solid engineering work that is required to field any high-quality process. The feedback control approach adjusts the gas flows to the torch to tune the particle temperature and velocity. The approach is generally able to correct for the two main sources of process variability: hardware swapping and wire curvature. The process corrects other sources of drift that are not well known or understood, as long as they do not become too large. Using feedback control, mean particle temperatures are typically controlled to within ~30 °C (Tecnar engineers state that this value is essentially at the performance limit of the detector) and mean particle velocities to within ~30 m/s, which is a major improvement over past performance. The process is simple enough to use on a daily basis in a production environment and does not require specialized training or expertise to operate.

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