Overview

Elements of Intelligent Process Control for Plasma Deposition

H.P. Wang, E.M. Perry, R.D. Lillquist and J.H. Taylor

Induction-coupled plasma deposition (ICPD) is currently a laboratory process relying on operator expertise rather than automated control. Intelligent process control for the ICPD process, which consists of integration of processing knowledge, process models, process sensors and control technology, offers the opportunity to provide closed-loop control as well as intelligent supervisory control to accelerate process development and bring the ICPD process to full-scale production. Intelligent process control for ICPD offers benefits such as higher material quality, control of the matrix microstructure, cost reduction, higher process yield, and shorter development and production cycle times.

INTRODUCTION

Induction-coupled plasma deposition (ICPD) is currently being explored to produce metal-matrix composite (MMC) materials for the aircraft engine and aerospace industries. MMCs combine the high modulus, strength and melting temperature of the nonmetallic reinforcing fibers with the ductility and conductivity of the metal matrix. The feasibility of manufacturing MMC monotapes by the ICPD process has already been demonstrated in the laboratory. The monotapes can be combined to form a multilayer panel or other component by either vacuum hot pressing or hot isostatic pressing for consolidation.

To meet the stringent quality constraints on the complex ICPD process and the resultant MMC material, an intelligent process control strategy must be developed to integrate processing knowledge, process models, process sensors and control technology. This integration is part of the intelligent processing of materials (IPM) initiative, unveiled by the Defense Advanced Research Projects Agency (DARPA) in 1985 for the orderly transfer of processing knowledge from the laboratory to production.[1]

Development of an intelligent process controller requires two key elements—a process simulator and process sensors. The major objectives of the simulator are to provide further understanding of and improvement in the ICPD manufacturing process, to provide a computer-aided tool for assisting in process optimization and to aid in designing the intelligent process controller. To meet these objectives, the simulator must be fast-acting. An innovative ICPD process simulator that maintains fidelity to the process physics and retains all of the control variables, yet operates in a responsive, interactive manner, has been developed.

The objectives of the process sensors are to provide measurements for real-time process control, as well as validation of the process simulator. An imaging radiometric process sensor system has been defined and demonstrated for observing the ICPD process, locating the deposition site (the "sweet spot") and measuring the deposit surface temperature distribution, which plays an important role in quality.

INDUCTION-COUPLED PLASMA DEPOSITION

The ICPD process is represented schematically in Figure 1. The apparatus consists of a reduced pressure chamber outfitted with a water-cooled quartz tube, an inductively coupled radio frequency (RF) plasma spray gun and a shaft that can rotate and translate the deposit target. The plasma gas is fed in upstream of the RF coil and is energized by the induced electromagnetic (EM) field. The feed powder is injected axially into the plasma stream using a water-cooled particle injection probe, which is inserted deep into the induction coil to prevent recirculation of the particles. The relatively large diameter of the quartz tube, coupled with the fairly slow speed of the plasma gas, provides good containment of the particles in the plasma stream, as well as a long enough dwell time to provide excellent particle melting. As the particles are melted by the plasma, they are propelled toward the cylindrical target, the outer surface of which has been wound with an orderly, continuous length of reinforcing fibers. Upon reaching the target, the molten droplets infiltrate the fiber bed and rapidly lose heat as they solidify to form an MMC monotape. Rotation and translation of the target is controlled to ensure uniform spray coverage.

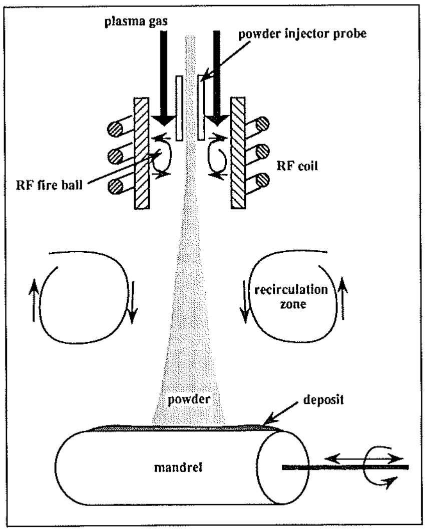

Figure 1. A schematic illustration of the ICPD process.

The quality of the microstructure produced by the ICPD process is a direct function of the processing history. There are several ways by which the properties of the composite can be degraded.[2] For example, volatile elements can evaporate from the molten droplets under extremely high-temperature environments. Temperature differences between the fiber and droplet can produce fiber thermal shock damage and spallation of the fiber coatings. Spray deposits often contain porosity in the fiber shadows. The generation of reaction products at the matrix-fiber interface, the phase of the solidified material and the production of residual stresses can result from thermal exposure during the spray and solidification processes. Residual stresses formed as a result of the thermal expansion mismatch between the fiber and matrix, and between the fiber and mandrel, can cause cracking in brittle-matrix alloys. Intelligent processing and control of this complex manufacturing process are needed to reduce these defects and meet stringent quality constraints.

IPM CONTROL STRATEGY

There are four principal objectives of an intelligent controller for plasma deposition. The first is improved product uniformity of the manufactured MMC material, which can be gained through better process repeatability. The second objective is improved product quality, as measured, for example, by integrity of the reinforcing fibers, bonding between the fibers and metal matrix, thickness control and microstructure. This can be achieved through improved process instrumentation and appropriate control of process variables. The third goal is improved efficiency in the utilization of labor and ICPD facilities, as measured by system throughput. The fourth objective is to provide flexible science-based processing and planning to accommodate the evolution of materials, process technology and process requirements.

IPM provides a method for developing improved process control by combining process understanding and sensor information to devise an intelligent controller. Substantial process knowledge is gained through experimentation. Further understanding of the ICPD process can be achieved through exploration with the process simulator to identify key process control variables and to expand the limited process operating envelope determined through laboratory experiments. Such process knowledge and modeling is then used to synthesize control algorithms and logic, and to define the process constraints needed in the development of an intelligent control strategy. Real-time control will thus be based on sensor measurements and the parametric relationships and process dynamics derived from exercising the process simulator.

One difficulty in ICPD processing is the need to control material attributes that cannot be sensed in real time. To do this, there must exist process knowledge that enables the prediction of material attributes from the time-histories of variables that *can* be sensed and controlled in real time, and an IPM controller that implements this knowledge. For example, excessive fiber/droplet temperature difference (ΔT) leads to thermal shock and unacceptable fiber damage. To avoid this, suitable set-point schedules for fiber and droplet temperatures must be determined and real-time control must be designed to keep ΔT within bounds dictated by a given material attribute and the corresponding models. This requires an off-line planner, which generates set-point schedules for variables that can be controlled and control algorithms to achieve adequate process regulation. Model-based simulation and optimization are ways to achieve this.

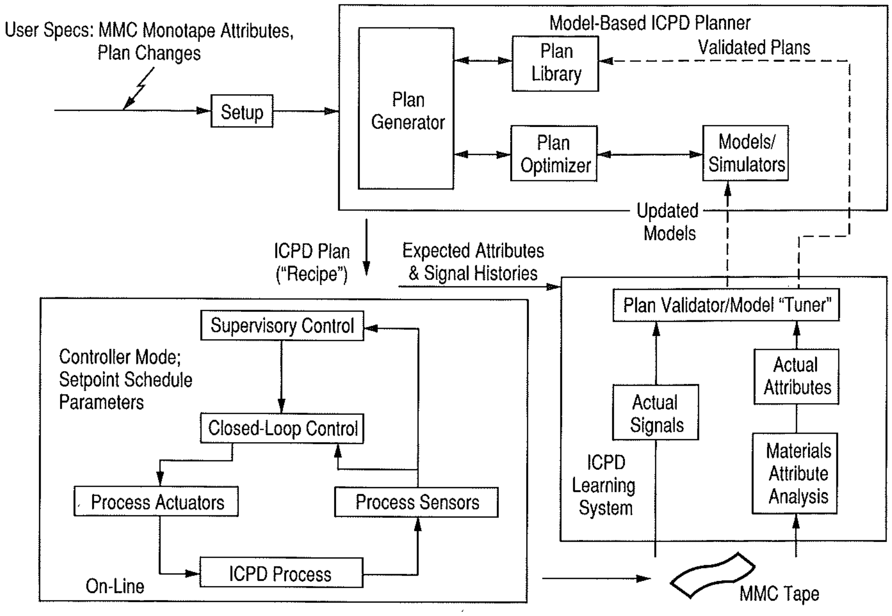

Figure 2. The architecture of intelligent control for ICPD.

Control Architecture

A schematic of the overall IPM control concept for ICPD is depicted in Figure 2. The lower left block represents conventional real-time process control. The ICPD equipment is instrumented with sensors that measure the process state. The controller compares the sensed and desired state and issues commands to the actuators to regulate the controllable parameters, including the plate current, valve positions for the plasma gas and manipulator settings for the target position. Thus, the nonlinear ICPD process is indirectly controlled to generate an MMC monotape with its associated material attributes.

The model-based ICPD planner, which generates the set-point schedules and control modes (the "recipe") needed to manufacture MMCs, is also portrayed in Figure 2. This module accesses a library of previous plans to look for one appropriate to the current request which will serve as an initial guess. The planner also contains a process optimizer, which iteratively exercises the ICPD simulator to determine schedules needed to produce an MMC monotape meeting the given criteria. The planner is done when a recipe is found that meets the operator's specifications and constraints.

The problem of broadening the operating envelope of the ICPD process is also addressed in the architecture shown in Figure 2. The ICPD learning system serves to improve and extend the scope of the planner. Once a process recipe has been generated and used to manufacture the part with closed-loop control, the material attributes of the MMC monotape and the data-logs of the actual process variables are used either to validate the plan or to update the planner models, depending on the recipe's success. If an acceptable tape was produced, then this plan is added to the library for reuse. If the tape did not meet the desired specifications, then the models in the planner are revised. This process, along with planning, is conducted off-line.

The IPM system envisioned for ICPD thus incorporates two levels of control: a conventional controller that provides fast closed-loop control algorithms for the deposition process and supervisory control logic to accommodate mode changes, error conditions, etc.; and an intelligent control layer, that is, the planner and learning system governing the lower-level controller. It is the usage of an intelligent control layer which distinguishes this IPM system from conventional process control systems, as it performs many of the functions generally carried out by a process operator or engineer. Using sensor inputs and predictions of product quality based on process and material attribute models, the IPM control system checks the adequacy of the current process plan and corrects it if necessary to achieve processing goals.

PROCESS SENSORS

The metallurgical quality of materials produced by plasma spray processes depends, in part, on the deposit surface temperature at the time of deposition. One example of such a quality concern is preventing the MMC reinforcing fibers from exceeding their damage threshold. However, this key variable is among the most difficult to measure in production plasma spray facilities. Contact temperature sensors, such as thermocouples, cannot be used on the rapidly changing surface, and probes mounted in the mandrel reveal little about the surface conditions. (Contact sensors may also contaminate the deposit.) Optical temperature measurement techniques offer an attractive alternative to contact probes, but problems unique to the plasma spray environment must be solved to implement them. The intense, broad-band background radiation produced by the plasma effectively blinds conventional radiation pyrometers unless spectral transmission "windows" in the plasma can be found. The particulate spray and fumes generated during deposition can block a sensor's view of the surface as well as rapidly fog sight ports. Still, the advantages of using a remote deposit surface temperature sensor as part of the plasma spray process control strategy makes the efforts necessary to overcome these and other obstacles worthwhile.

The objective was to develop optical thermal sensing techniques—applicable to the ICPD process in particular and to plasma deposition processes in general—that would perform the following tasks:

- Monitor the progress of the plasma spray deposition process.
- Detect and locate the deposition site (the "sweet spot").
- Measure the deposit surface temperature distribution.
- Provide electrical signals for real-time process control.
- Provide the human operator with a more clear and informative view.

The hardware approach was to use an infrared imaging radiometric sensor system to measure the intensity of the thermal radiation passively emitted by the deposit and to provide some of the real-time measurement capability required by the control system. An approach using imaging radiometers rather than the more conventional "spot" radiation pyrometers was chosen to monitor the temperature distribution over the entire particle impact area and the surrounding heat-affected zone. Because optical access is generally extremely limited in vacuum plasma spray tanks, imaging radiometers offer an additional advantage over point sensors in providing operators with a superior visual monitoring capability, allowing them to "see" potential measurement problems. Interference from plasmas, haze, reflections and other sources may be readily identified on a display screen.

Certain barriers to the development of the imaging radiometric deposit temperature sensor had to be overcome before measurements could be made. In most plasma spraying processes, the plasma is an extended light source ten or more centimeters long which envelopes the part being sprayed.

Prior G.E. sensor development work[3,4] indicated that for argon, helium and some other noble gases, an abrupt decrease in plasma brightness occurs in the mid-infrared wavelengths longer than ~3.5 μm. To efficiently identify spectral transmission window regions for the various plasma gas mixtures in the laboratory, the radiant emissions from a gas tungsten arc welding torch were measured over the range of 0.4 to 14 μm. Once promising wavelength regions were identified, a near-infrared imaging radiometer[5] and a mid-infrared imaging radiometer[6] were fitted with narrow-band filters and used to monitor the aperture of a 500°C blackbody furnace viewed through an ICPD plasma spray plume. Using the mid-infrared sensor system, the presence of the plasma plume and particulate spray resulted in measurement errors of less than 10°C relative to the known blackbody furnace temperature.

Figure 3 shows a block diagram of the imaging radiometer sensor system. The imaging radiometer in its most general form is comprised of the components on the left portion of this figure, which together output a composite monochrome video signal. The interface between the radiometer and external control devices is a Colorado Video model 321 video analyzer. This instrument produces d.c. output signals related to the composite video signal amplitude at the intersection of two operator- or computer-directed cursors and the cursors' addresses. The correspondence between absolute spectral band radiant intensity and video analyzer output voltage level is established when the radiometer system components are matched and calibrated using a blackbody furnace. The video analyzer has certain advantages over digital frame-grabber interface techniques, including cost, robustness in electrically noisy environments, signal update at full video framing rates and ease of connection with virtually any control device. Several video analyzers may be used together or in conjunction with digital frame grabbers to monitor several points simultaneously.

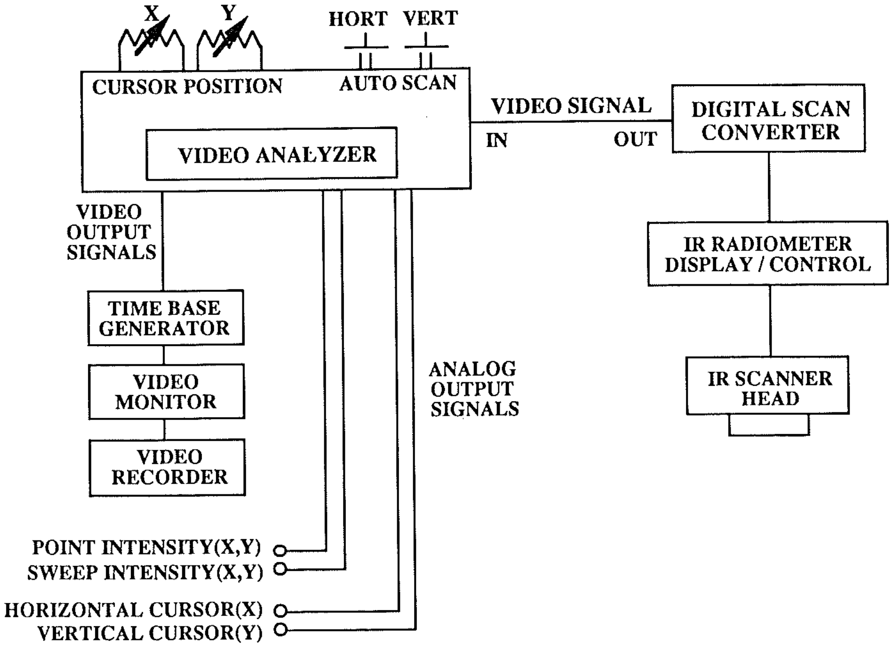

Figure 3. A block diagram of the imaging radiometer sensor system.

Figure 4 shows a typical mid-infrared image of an MMC monotape during spray deposition experiments to test the sensor system and define unacceptable limits for the ICPD process. Bright areas indicate thermal excursions where the deposit is separating from the substrate. Note that the plasma and particulate spray are "invisible" to the sensor.

Additional work on other process sensor systems is also needed. Microstructural sensors for measuring porosity and phase transformations within the deposit must be developed, and a sensor that can measure the deposit thickness as it builds up is needed. Also, in addition to deposit temperatures, the temperature distribution of the particles prior to impact at the target is a key factor in the ICPD process, and an optical indication of the temperature of particles in flight is an important goal of future sensor development.

PROCESS SIMULATOR

Process models have been developed for the various phases of the ICPD process, and have been combined into an integrated, fast-acting process simulator, which runs in a responsive, interactive manner.[7] For the control of mechanical systems, the classical simulator dealt with ordinary differential equations for the spring-mass-damper representing the physical system. However, the ICPD process simulator must deal with partial differential equations involving spatial as well as time dependence, making the numerical procedure for solving the problem much more demanding.

Figure 5 schematically illustrates the ICPD process and associated models. The simulator controls communication among the models, allows user interruption to change the processing parameters, and provides graphical display of the simulation results.

Models

The gas mixtures model computes the thermal and transport properties of the multi-component plasma gas mixtures, including the density, heat capacity, thermal and electrical conductivities, and viscosity. These properties are computed as a function of temperature, assuming local thermodynamic equilibrium (LTE).

The circuitry model determines the efficiency of the plasma torch by consid-

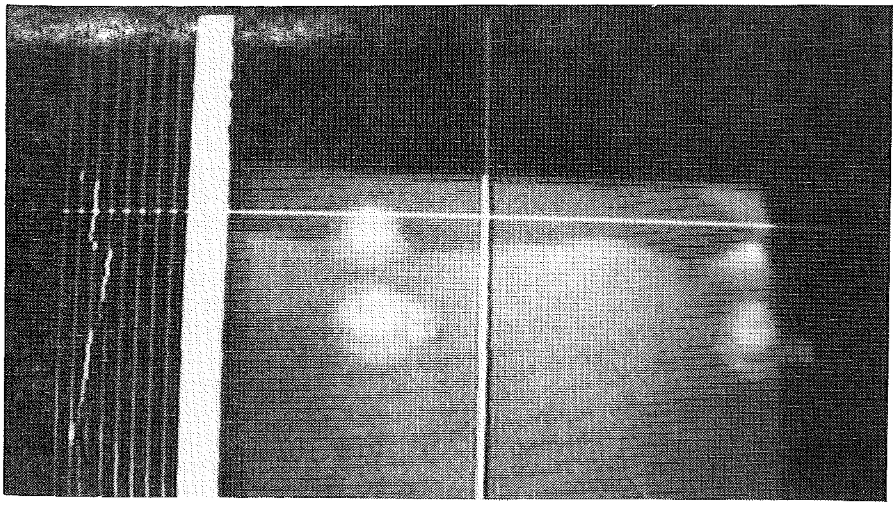

Figure 4. A mid-infrared image of a mandrel-mounted MMC monotape during plasma spraying.

ering the total system circuit, including the power oscillator, tank coil, gun coil, and the plasma plume itself. The model determines the coil current as a function of input plate current and other operating parameters. The result will provide necessary input data to the free stream model.

The free stream model[8] solves the full Navier-Stokes equations for the multiphase- (gases and particles), multidimensional-, multifield- (EM, flow and thermal) coupled system to model the plasma torch and predict the heat losses through the injector and torch enclosure. The high degree of coupling between the EM, momentum and thermal fields, as well as the complexity of the resulting equations, make the direct numerical solution of this problem computationally intensive, requiring extensive computer processing time. Precalculation with this model was required to provide boundary conditions for the central core model for various sets of processing conditions to achieve a fast-acting process simulator.

The central core model[9] handles the coupling between the plasma jet and the particles, factoring in the effect of the particles on the temperature and velocity fields of both the plasma and particles at the time of impact on the target. The core model uses a boundary layer technique to model the plasma torch, accessing a database of precalculated results from the free stream model for the thermal and flow fields in the absence of particle injection. Through the use of precalculation and this reduced order model, the calculation time was reduced significantly.

The mandrel boundary layer model calculates the convective heat transfer between the plasma plume and the rotating mandrel by simulating the fluid flow characteristics of the plasma jet impinging on the mandrel. The heat transfer coefficient as a function of angular position, gas composition, and incoming plasma velocity and temperature from the core model will be used as input to the deposit dimensional and thermal model.

The deposit dimensional and thermal model[10] performs a transient calculation of the deposit build-up and predicts changes in the deposit, fiber and target/mandrel temperatures. Values for the temperature within the mandrel allow assessment of how rapidly the powder solidifies after striking the mandrel and whether or not the damage threshold of any of the reinforcing fibers is exceeded.

The MMC quality model predicts the mechanical and metallurgical state of the deposit, determining the fiber thermal shock and deposit residual stress as a function of the processing conditions. The microstructure of the deposit is directly correlated to the local temperature history through the solidification rate and temperature gradient.

The Simulator

The fast-acting ICPD process simulator was developed based on two concepts: a reduced order model that maintains fidelity to the physics of the process, and precalculation of key thermal and fluid flow fields beyond the scope of real-time computation. The simulator can be used both in the design of the real-time controller and as an integral part of the process planner for intelligent control, as it is able to predict the effect of a process schedule on deposited material quality. By quickly providing numerical simulations, it will reduce the number of experiments required to define control relationships and limits and will thus serve as an extremely valuable tool in accelerating the development of ICPD as a manufacturing process.

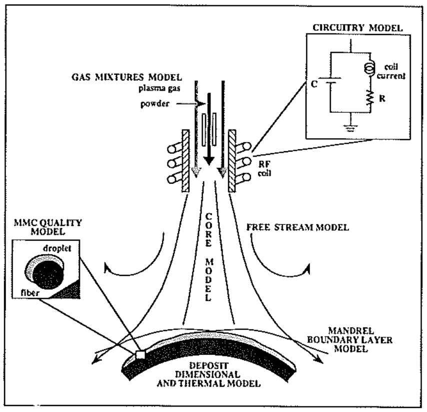

Figure 5. The architecture of the ICPD process simulator.

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