Real-Time Imaging for Thermal Spray Process Development and Control

J. Agapakis and T. Hoffman

Thermal spray and other high-temperature industrial processes are quite difficult to monitor with the human eye, because the luminous volume of the plasma or flame obscures the behavior of the solid or molten material in the heat-affected area. When a photographic or video camera is used, viewing is further degraded by the extreme contrast variation across the image area, making it impossible to achieve proper exposure throughout the image—except possibly for small areas of comparable brightness. Optical filtering with neutral density filters, such as those used in a welder's helmet, are of no practical benefit. With thermal spray processes, the injection and flow of particles within the plasma flame is almost totally concealed by the extreme brightness of the plasma, flame, or arc. In addition, the particles quickly accelerate to very high speeds, making their detection even more difficult. This article discusses the development of integrated thermal spray process monitoring and analysis techniques based on two principles. The first is a unique vision sensing system that suppresses the flame, plasma, arc, or other high-luminosity phenomena in the video image. A further improvement is the use of dedicated image and analysis processing to enhance the sensor images and extract features of interest or dimensional measurements. These experimental techniques can be used as feedback for automated process monitoring and control.

1. Introduction

FOR most of the last 25 to 30 years that thermal spray processes have been widely used, they have been considered more an art than a science.[1,2] In the past, thermal spray has been a completely manual process, whereby the operator directly manipulated the gun. The process parameters such as primary and secondary gas mass flow rates, thermal power application, work distance, spray impingement angle, relative surface travel rate, raw material feed rate, etc., were all set and adjusted manually. Significant part-to-part or operator-to-operator variation was possible because small variations in these parameters can adversely affect coating quality. Recently, because of increased military and commercial use of the process and requirements to meet more exacting specifications, significant emphasis has been placed on the areas of computerized process control and unmanned operation using robotics. Such developments not only result in increased process consistency and productivity, but also distance the operator from a hazardous work environment.

Such efforts include work sponsored by the U.S. Air Force,[3] as well as by thermal spray equipment manufacturers and users of the technology.[4-11] For example, a next-generation robotic plasma spray cell[12,13] has been developed that incorporates advanced robot and process programming and control capabilities.[14,15] However, these state-of-the-art automated systems only monitor and regulate the controllable process parameters. There is no in-process monitoring of the actual coating quality or its determinants. Thus, problems such as powder nozzle erosion, cable wear, or powder variation often result in improper powder feed and hence deficient coating quality. The monitored and controlled process parameters are selected, adjusted, and optimized iteratively and only on the basis of destructive, post-process evaluation of the coating quality. Conventional destructive testing of coated components involves coating of test coupons at the same time as the actual components in a batch. In addition to the test coupons, typically a certain number of components are also evaluated destructively. Failure of a test coupon or a part to meet the specifications may cause rejection of a large number of sprayed parts, even though the failure may be an isolated incident. Worst yet, a single defect or group of defects within a batch may escape detection.

The alternative to batch testing is to monitor and control, in real-time, important process parameters (such as particle flow pattern, velocity, mass flow rate, temperature, etc.) that relate to bond integrity and coating quality while the coating process is progressing. This requires direct observation and/or measure ment of these parameters. Examples of instrumentation techniques to determine certain measurable aspects of these parameters have included laser doppler velocimetry[16] and laser two-focus velocimetry.[17,18] These, however, are mainly laboratory techniques, providing only some of the required measurements, such as particle velocity, within a rather constrained observation volume.

An additional control application within thermal spray technology concerns the spray forming and atomization of materials. In this process, molten material is rapidly solidified into a semi-finished product, usually through an atomization or plasma process. This approach reduces the number of steps required to arrive at a finished product, compared to more traditional machining and powder metal processes. The resultant material also exhibits superior microstructures by eliminating macrosegregation and promoting finer microstructures.

Monitoring material deposition on the substrate, deflection in and around the molten stream, and material dispersion throughout the stream is required. As in other thermal spray ap-

Key Words: color temperature, diagnostic methods, imaging of particles, process control, process optimization, technical note, video image analysis

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plications, velocity, mass flow, pattern, and vector information is crucial to successful process development and control.

2. Experimental Equipment

Direct observation of high-luminosity processes presents significant challenges. A solution is found in an electro-optical viewing system capable of overcoming the extreme variation in scene brightness created by high-luminosity phenomena. This system incorporates external illumination in the form of intense pulsed laser light. The laser light reflected from the site is, for an instant, much brighter than either the direct or reflected light of the process. The system exploits this temporary situation by viewing the process with a special-purpose video camera equipped with a very high speed electronic shutter that is synchronized with the laser flash.

The system is comprised of one or two strobe units, a camera unit, and a system controller, which are interconnected by both electrical and/or fiber optic cables. The standard strobe laser unit includes (1) a compact pulsed laser, (2) a small fiber optic feed module attached to the exit aperture of the laser, and (3) a fiber optic cable that transports the laser energy to the process, using a single large-core optical fiber. The camera unit is about 6 × 2 × 2 in. (about 16 × 5.5 × 5.5 cm). This camera unit provides the electronic shuttering capability and also amplifies the intensity of the image by a factor as great as 10,000 to 1. A separate system controller sends the appropriate trigger commands to fire the laser and initiate shuttering of the camera unit. The controller also serves as a power supply to the camera unit and provides a means to adjust the sensitivity, shutter speed, and frame rate of the camera. It includes a video frame storage capability that is programmed to repeat a video frame produced by the camera head until replaced by a new frame. The controller also includes a built-in monochrome video monitor unit with a 5-in. (12.7-cm) screen and a built-in video and audio recorder/playback unit incorporating a standard 8-mm tape cassette. Figure 1 shows a schematic diagram of this experimental arrangement and is quite common to all the examples in this article.

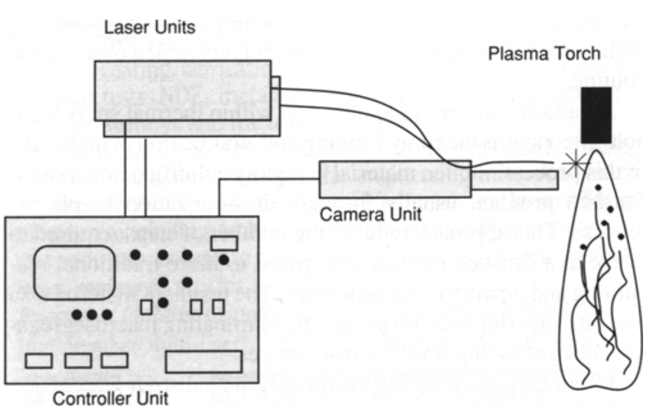


Figure 1 Plasma spray experiment.

3. Experimental Examples

This article presents work concerned with thermal spray coating processes and also with some new spray-forming and metal powder atomization processes. Coating systems that have been investigated include both internal and external injection plasma spray guns, twin wire arc spray systems, and high-velocity oxyfuel (HVOF) processes. Figure 2 is an example of a single video frame from a laser strobe system showing the operation of a plasma spray gun. The input power to the spray gun is about 20 kW, and this particular viewing angle is approximately perpendicular to the flow direction of the plasma stream so that the face of the plasma gun is situated to the left. The field of view covers the first 3 to 4 cm of the plasma flame, which is the most intense region of the flame. The injection of nickel-aluminum powder into the flame via the external injection nozzle is shown in the upper part of Fig. 2.

Individual particles of powder are observed, although some residual evidence of the plasma flame remains in the picture. Some of the highest temperature particles are clearly producing luminous vapor tails. Figure 3 shows the behavior of the particles a few centimeters further downstream. Note that some of the particles have been injected with too much momentum into the

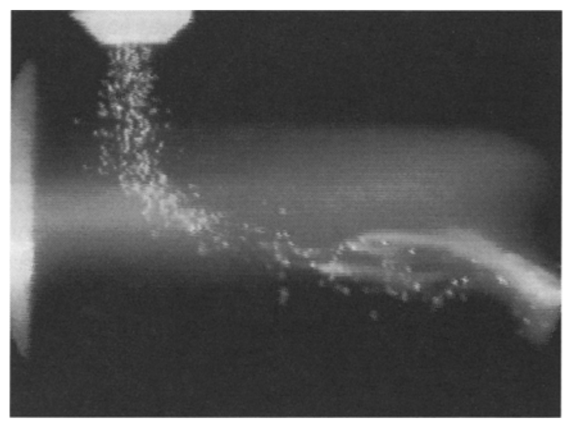


Figure 2 External injection dc plasma spray.

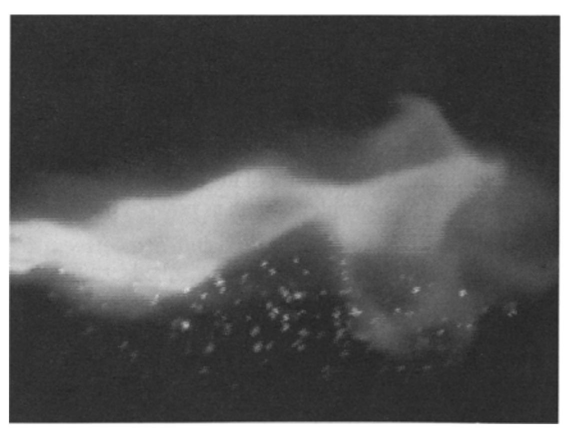


Figure 3 External injection dc plasma spray.

plasma stream such that they have passed through the highest temperature core of the plasma. In addition, at this point, the particles have accelerated to a very high speed, between 80 to 120 m/sec, but their motion is easily frozen by the very fast laser pulse.

Some processes do not require intense laser illumination to defeat process-related light. One such process is HVOF. Figure 4 shows laser illuminated HVOF. A large amount of water vapor exiting the nozzle obscures some of the powder material. Because the HVOF process temperatures are significantly lower than those experienced with plasma spraying, an alternate lighting scheme, such as a xenon strobe, could be used to image the particles.

In spray forming and atomization, imaging work has included inert gas atomization, RF plasma spray forming in a vacuum chamber, and some very recent work with spray casting. Figures 5 and 6 show examples of the primary breakup in an annular atomization process where molten metal is rapidly solidified by high-velocity helium gas. In the first case, pulsed laser light was used, and the second frame shows the process filmed in a passive mode, that is without laser illumination. In both cases, the dynamic interaction of the gas and molten stream is apparent. It was discovered, however, that the reflected glint from the intense laser light tends to conceal the geometry and pattern information of the molten globules of material. Significant loss of image contrast caused by very fine metal powder circulating throughout the chamber was noted. Using passive viewing, as in Fig. 6, clearer images of the geometry during primary breakup were obtained. Due to the lack of external illumination, the exposure time was increased to 5 µsec to obtain acceptable sensitivity.

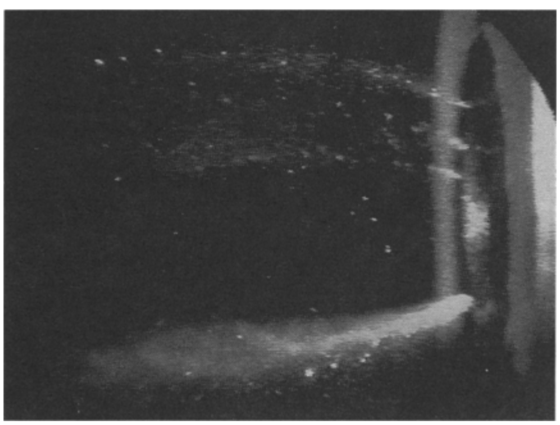


Figure 4 High-velocity oxyfuel spraying.

4. Imaging Approaches

Several imaging approaches that may be used to measure some of the process parameters that are important to the plasma spray community are discussed below.

4.1 *Particle Flow Pattern and Powder Mass Flow Rate*

The laser strobe sensing approach may be used to obtain meaningful video data for controlling particle flow pattern and powder mass flow rate. Figure 7 shows video images taken from a plasma spray process as carrier gas parameters are being changed. In Fig. 7(a), the powder flow pattern is not optimal, as particles can be observed being injected through the plasma stream. In the second frame (Fig. 7b), the gas flow rate is reduced and the powder appears to be floating on the surface of the plasma. Finally, in Fig. 7(c), a much more optimal pattern is observed, with the particles being injected into the center of the plasma.

4.2 *Plasma/Flame Geometry*

The system is designed to eliminate or at least minimize the appearance of a plasma or flame in the video picture. However, the sensitivity of the system to the flame can be increased by increasing the duration of the electronic shutter and adjusting the sensitivity of the camera. A laser strobe system is being used to assist in the development of more stable plasmas with this approach.

4.3 *Particle Velocity*

The laser strobe system presently has the capability of firing two lasers in rapid sequence (and in synchronism with double

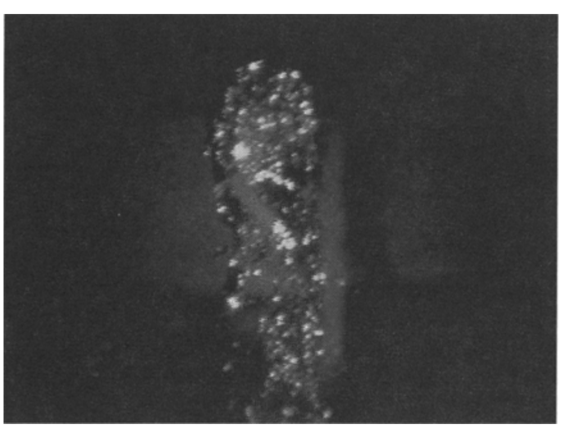


Figure 5 Laser illuminated gas atomization.

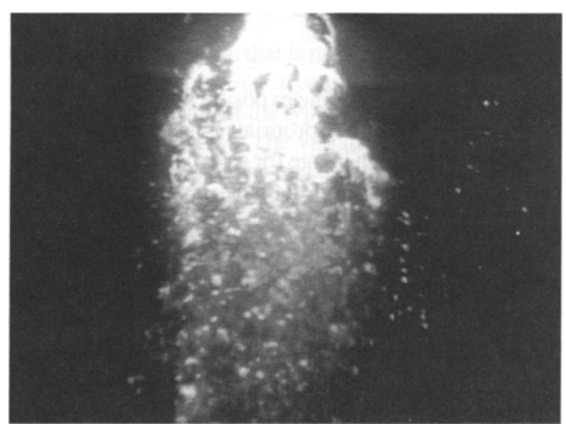
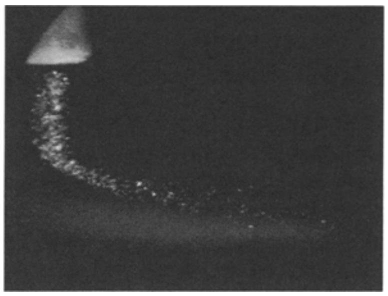
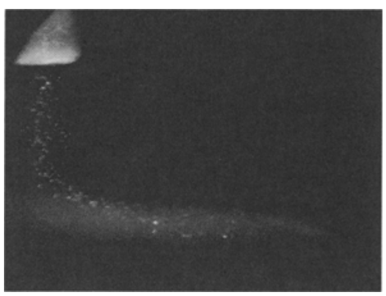


Figure 6 Passive viewing of gas atomization.

(a)



(b)



(c)

Figure 7 (a) Particles through plasma. (b) Particles atop plasma. (c) Optimal injection.

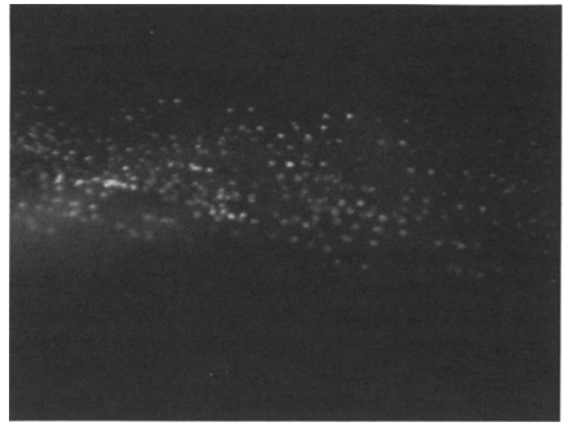


Figure 8 DC plasma spray twin images.

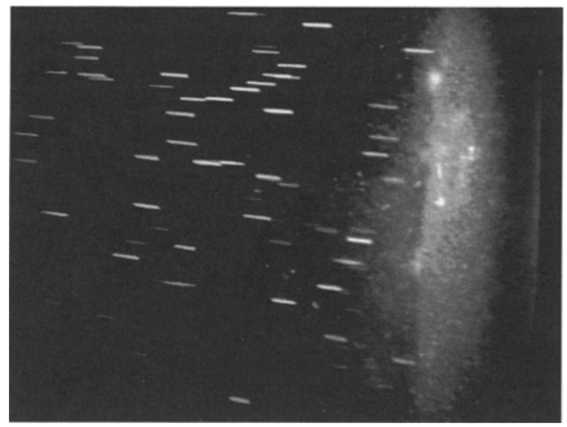


Figure 9 Passive viewing plasma spray impact.

shuttering) to produce a double exposure of the particle field, as shown here in Fig. 8. With appropriate adjustment of the double shuttering interval, a twin image for each particle in the field can be obtained. Particle velocity vector can be determined by measurement of the displacement between these twins. The twin images in the video frame are easily recognized when the particle population is low, but for higher population levels, adjacent twins will become intermixed, and more sophisticated interpretation of the image is required.

It can be expected that a small group of particles in a localized area of the image will all be traveling at the same velocity. Because this group will exhibit a unique pattern, the double exposure process will result in a duplication of that same pattern at a displaced position, and the displacement will then be indicative of the group velocity. Of course, the duplication of these patterns will be concealed by spatial noise created by other background or foreground particles. A large body of image processing technology is now available that can deal with this type of problem.

If the velocity measurement is to be made further downstream, where the particles have exited the flame, then the camera system is operated in a passive mode, *i.e.*, such that the particles are detected by means of their own luminosity, rather than with the laser. The particles are then seen on the video screen as short streaks, with the length of the streaks proportional to a predetermined shutter speed and the particle velocity. Furthermore, when operating in the double shuttering mode, a single particle produces a streak with two segments interrupted by a dark segment representing the time interval between the two shutter pulses. The length of the three segments provides additional information on particle acceleration.

Figure 9 is an example of imagery obtained with passive viewing of a plasma spray. The shutter speed was approximately 10 μsec. The viewing angle is perpendicular to the spray direction, and the location is a few centimeters downstream from the nozzle of the gun. The spray can be seen impacting the substrate.

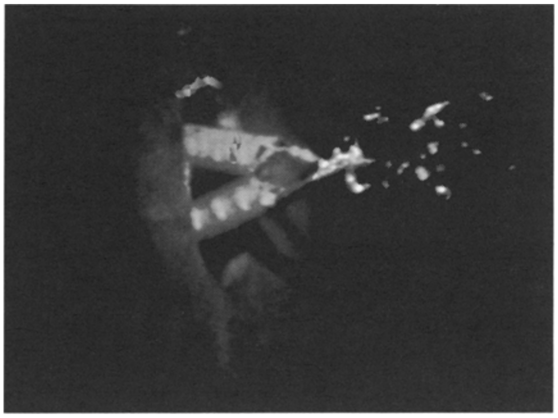


Figure 10 Twin wire arc spray.

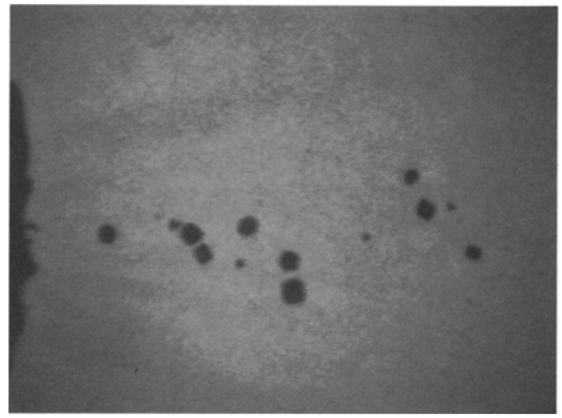


Figure 11 Backlit salt particle tests.

Here, the brightness of a streak is related to particle temperature. Frame by frame analysis of this sequence shows that the hotter particles splat on the substrate, whereas the cooler particles, toward the bottom of the frame, bounce off the surface. Figure 10 is another video image taken with a twin wire arc spray process, using the same laser strobe camera system operating in the active, pulsed laser mode. This shows the formation of the metal droplets in the immediate area of the gun nozzle and provides some idea of the variation in size of these droplets. The formation of much larger globules of molten metal can be observed in the recorded video from which this frame was taken. This wide variation in droplet size can produce a corresponding variation in the width and intensity of streaks seen further down the spray stream. The streak pattern for a powder spray process is expected to be much more uniform because the particle size is generally much more uniform.

4.4 *Particle Temperature*

With regard to measurement of spray temperature, the luminosity of a particle is related to its temperature, and it therefore appears that the camera and image processing system might be used in the passive mode to monitor this temperature. In organizing a strategy for this measurement, it is first necessary to recognize that particle brightness is not only related to temperature, but is also proportional to the radiant emissivity of the particle, a parameter that can be quite variable and difficult to measure. The standard method for dealing with an unknown emissivity factor is to utilize two-color pyrometry. A reasonably accurate assumption with this method is that the radiant emissivity of the particle is constant for the two different spectral bands.

An alternative to implementing a two-color pyrometry scheme, which would be among the simplest temperature monitoring approaches to implement, would be to measure the average brightness (using only one color filter) of all particle streaks in the stream. The computer system would then automatically compare this average brightness with reference brightness data taken from an earlier spray sequence established as a standard of known quality. Adjustments to the process could then be made to match brightness (as well as matching velocity and other parameters) without any attempt at making an absolute measurement of temperature.

5. Vision Processing Approaches

Different image processing and analysis schemes are necessary to determine the quantitative measures discussed previously. Some of these schemes are discussed below.

5.1 *Particle Flow Pattern*

Flow patterns can be analyzed using the computer to detect and measure particle density as a function of the x and y coordinates of the video image. These numerical data would then be compared with earlier reference data taken under preferred spray conditions, using the same camera viewing coordinates. To provide cleaner, more distinct images for processing, work is currently underway to develop an alternative backlighting approach to imaging particles entrained within the plasma. Figure 11 is an example of a backlighting scheme showing the flow of salt particles within a bright oxyacetylene flame. More information regarding particle geometry can be obtained by observing the particles in silhouette against a uniformly illuminated background.

5.2 *Plasma/Flame Geometry*

A great deal of variation that is not seen with the naked eye or with standard video techniques can be distinguished when the distribution and intensity of the typical plasma flame is observed on a frame-by-frame basis. The variation may be due to turbulence in the flow produced by misalignment or erosion of internal components of the spray gun, by fluctuation in the electrical or chemical power of the flame, or other factors. A statistical analysis of a sequence of video frames using the computer would provide a means for detection of off-normal conditions.

5.3 *Powder Mass Flow Rate*

As the powder flow rate and particle velocity are increased or reduced, it is expected that the total population of particles within a particular video frame (a frame that includes the entire

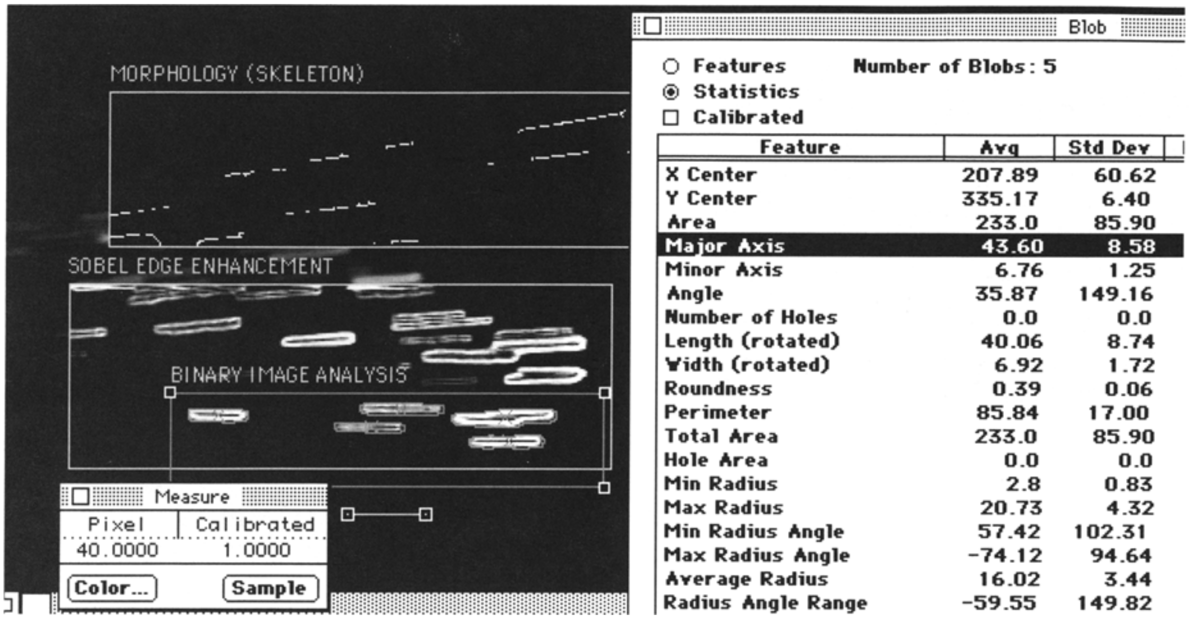


Figure 12 Sample image analysis results for particle detection and velocity estimation (passive viewing).

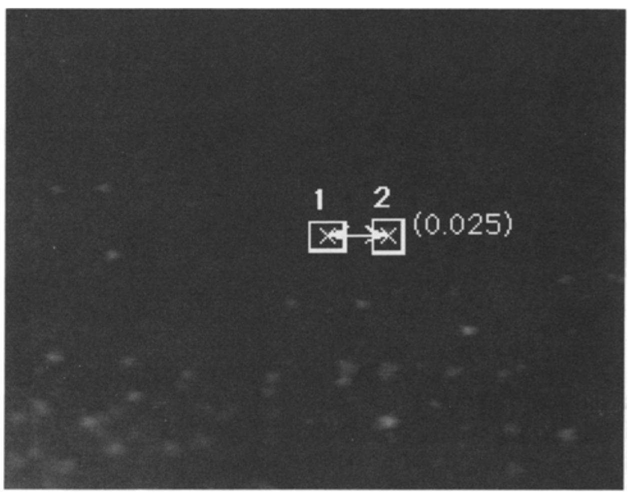


Figure 13 Twin imaged particles measured in plasma.

cross section of the particle stream) will change correspondingly. Conversely, it is possible to calculate the instantaneous flow rate by using the computer to count all of the particles in a given frame (or to measure the total fractional image area occupied by the particles), assuming there is the capability for simultaneous measurement of average particle velocity. The goal would not be to measure flow rate absolutely, but to monitor fluctuation of the powder flow, while continuing to use the present methods to monitor the absolute average rates.

5.4 *Particle Velocity*

In the passive viewing system configuration, discussed above, image analysis schemes can be used to determine the length of each particle streak or the average particle streak and therefore infer the individual or average particle velocity. Figure 12 demonstrates several processing options for the passively viewed images. Specifically, the top region of interest (in the left half of the image) has been processed using mathematical morphology to detect skeletons of particle streaks. The middle region of interest was processed using the Sobel Edge enhancement operator, which highlights all edges while suppressing regions of uniform intensity. Finally, the bottom region of interest is analyzed using binary image analysis where the bright particles are detected by thresholding as continuous regions of connected pixels in the dark background. Five contiguous bright regions ("blobs") were bound by thresholding. The feature analysis techniques allow the determination of more than 50 geometric and topological features for each blob in the image. The most relevant are the minor and major axis of each blob and the computation of the length and width of each blob along these directions. The window on the right shows statistics for the features calculated on each blob. These results are only indicative of the options available with image processing and analysis systems. More elaborate processing sequences must be investigated and developed to deal with overlapping particle trajectories, differences in luminosity, and foreshortening effects introduced because of perspective (because trajectories are not in the same two-dimensional plane).

When active viewing is used, two translated particle images are superimposed on one another. Because the direction of translation between particle pairs is generally along the stream direction, techniques are available to detect the most dominant translation direction. The image in Fig. 13 has been obtained using two lasers fired sequentially. For demonstration purposes, two small regions of interest have been manually placed by the operator over two corresponding particles (also selected manually by the operator). Image analysis was used simply to detect the particle centroids and calculate the distance between them.

Speed of image processing and analysis is of great importance for the use of the proposed schemes in real-time process monitoring and control. An advanced vision processing system incorporating a high-performance vision processing board that allows pipelined hardware implementation of a wide variety of image processing and image analysis algorithms is in the final stages of development.[21]

Acknowledgments

Several of the images and image processing approaches presented in this article were obtained in collaboration with Dr. Christopher Berndt, State University of New York, Stony Brook; Dr. Ronald Smith, Drexel University, Philadelphia; Dr. Tom Eddy, Mr. Gary Wilson, Mr. Joe Burch, and Dr. John Flynn, Idaho National Engineering Laboratory, Idaho Falls; and Mr. Zbigniew Zurecki, Air Products and Chemicals Incorporated, Allentown, Pennsylvania.

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