

VISION-AIDED MONITORING & CONTROL OF THERMAL SPRAY, SPRAY FORMING, AND WELDING PROCESSES

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ABSTRACT

Vision is one of the most powerful forms of non-contact sensing for monitoring and control of manufacturing processes. However, processes involving an arc plasma or flame such as welding or thermal spraying pose particularly challenging problems to conventional vision sensing and processing techniques. The arc or plasma is not typically limited to a single spectral region and thus cannot be easily filtered out optically. This paper presents an innovative vision sensing system that uses intense stroboscopic illumination to overpower the arc light and produce a video image that is free of arc light or glare and dedicated image processing and analysis schemes that can enhance the video images or extract features of interest and produce quantitative process measures which can be used for process monitoring and control. Results of two SBIR programs sponsored by NASA and DoE and focusing on the application of this innovative vision sensing and processing technology to thermal spraying and welding process monitoring and control are discussed.

INTRODUCTION

Thermal spray processes, electric arc welding, laser welding, and other energy-intensive high luminosity industrial processes are normally quite difficult to monitor with the human eye because the luminous volume of the plasma or flame obscures the details of the behavior of the solid or molten material in the heat affected area. Furthermore, when one attempts to use a photographic or video camera, the viewing is further degraded by the extreme brightness 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 — like the ones used in a welder's helmet — do not particularly help either. In the case of arc welding, one can expect to see a bright fireball at the center of the welding pool, but most of the detail at the edge of the welding pool and in the area of the welding seam and groove will be lost in relative darkness. With thermal spray processes, the injection and flow of particles within the plasma flame is almost totally concealed by the extreme brightness of the flame. In addition, the particles quickly accelerate to very high speeds, making their detection even more difficult.

Over the last six years, Control Vision has developed a unique viewing system capable of overcoming the extreme variation in scene brightness created by high luminosity phenomena such as flames, arcs, or plasmas and electronically producing a video image virtually free of arc glare. This patented 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 situation by viewing the process with a special-purpose video camera equipped with a CCD video sensor and a very high speed electronic shutter synchronized with the laser flash and the framing of the video sensor.

This innovative viewing system has already been used in a variety of applications in order to provide visual feedback to an operator for in-process monitoring during production or to allow observation of phenomena not otherwise visible during process research and development. In order to incorporate such a sensor in automated process monitoring or control applications, it is necessary to develop approaches for processing and analyzing the images produced by the sensor and extracting features that can be used for process control. Such customized image processing and analysis capabilities have been developed by Automatix on standard computer platform based machine vision systems. These developments are being pursued under two SBIR programs sponsored by NASA and DoE.

The DoE sponsored SBIR program focuses on welding process monitoring and control. Under this effort, Control Vision is developing a next-generation vision sensing system that is more compact and can be readily interfaced to a

robot or other automated welding equipment, whereas Automatix is developing vision processing techniques for image enhancement and image analysis for the detection of important weld features, such as the weld seam, molten metal puddle, or keyhole and the calculation of relevant dimensional measurements, such as seam-to-puddle offsets or puddle geometry.

The NASA sponsored SBIR program focuses on thermal spraying process monitoring and analysis. Special techniques are been developed to suppress the intense light of the flame or plasma and to allow the visualization of the powder particle flow carried by the flame or plasma with particular emphasis placed on low-pressure or vacuum spraying processes inside chambers. In conjunction to these sensing developments pursued by Control Vision, Automatix is developing image processing and analysis schemes for the automated extraction of quantitative process measures such as particle distribution, velocity, and flow rates from the video images produced by the sensor. Figure 1 schematically depicts the viewing system used in conjunction with the image processing and analysis system for computer-assisted visual monitoring of thermal spraying.

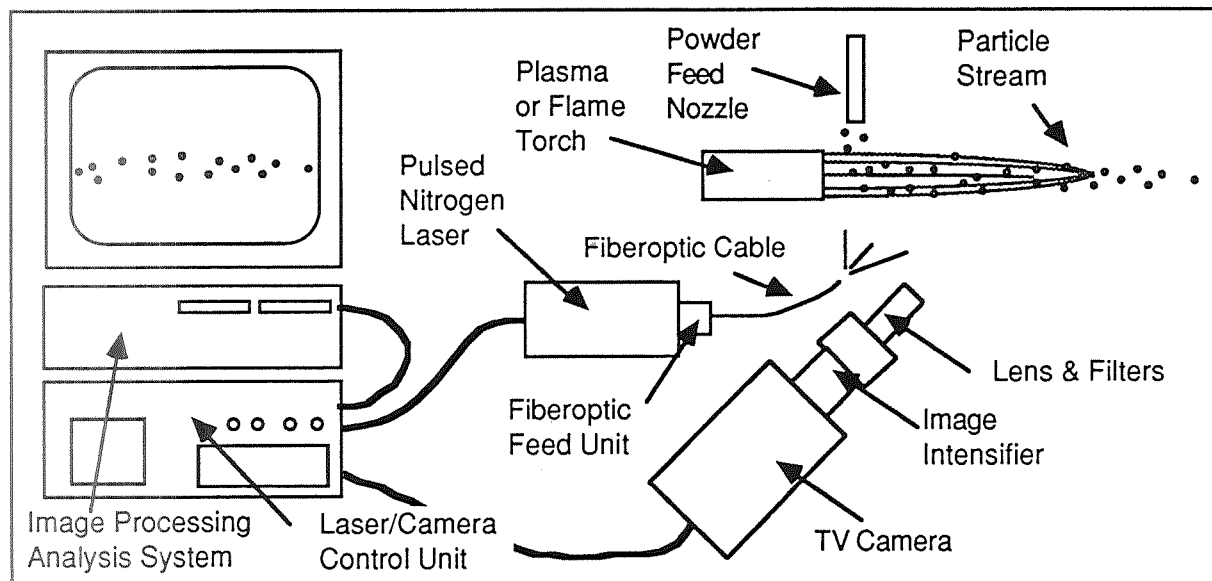


Figure 1 Typical experimental setup for thermal spraying process monitoring

In both welding and thermal spraying, the developed vision sensing and processing schemes can be used both during process development for parameter selection and process understanding or modeling as well as during production for real time process monitoring, process alarming, and ultimately process control (Figure 2).

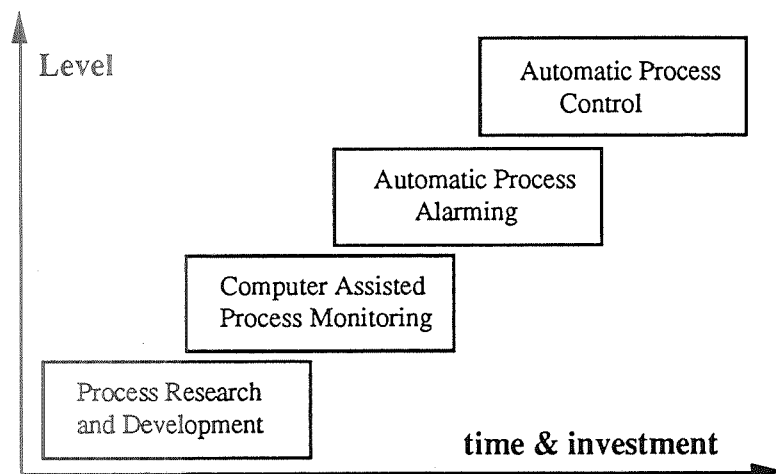


Figure 2 Different levels of application for the proposed monitoring systems

Specifically, such systems can be used during process research and development to evaluate the effect of different process parameters, explore alternative hardware designs, allow for better record keeping during process experimentation, and validate analytical process models. During actual production, these systems can be used for computer-assisted monitoring by computing different process measures and providing this information to an operator through graphical displays, for automatic alarming by comparing these computed measures to expected values and tolerances, and ultimately for real-time process control where the process parameters are automatically adjusted on the basis of the process feedback.

VISION SENSING

As mentioned above, the patented Control Vision viewing system incorporates external illumination in the form of intense pulsed laser light to overcome the extreme variation in scene brightness created by the flame or arc. The laser energy is transported to the welding site through a fiberoptic cable. A xenon flash lamp has also been used as a source of intense pulsed light. The system is also equipped with a narrow-band optical filter to match the laser wavelength and further suppress the arc lighting. The net combination of both temporal and spectral filtering results in a video image that is free of all of the adverse arc lighting effects.

Welding Applications

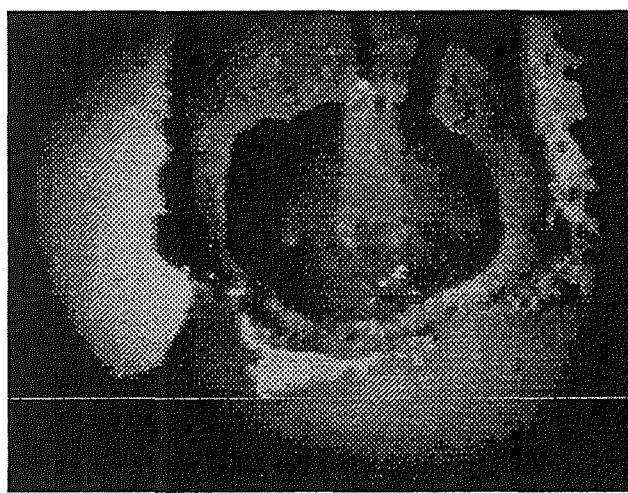


Figure 3. Gas Metal Arc welding viewed using the stroboscopic vision sensing approach



Figure 4 Gas Tungsten Arc welding viewed using the stroboscopic vision sensing approach

The viewing system has been applied to a variety of conventional welding processes including Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), Variable Polarity Arc Welding (VPPAW), Gas Metal Arc Welding (GMAW) as well as high energy welding processes such as Electron Beam Welding (EBW) and Laser Welding (LW). The VPPAW and GTAW processes are of particular interest to NASA since they are extensively used for the production of flight hardware such as the Space Shuttle External Tank and Main Engine.

Phenomena not easily seen through a conventional viewing system are readily visualized using the stroboscopic viewing approach making it a unique tool for welding process R&D. Figure 3 clearly shows metal droplet transfer, weld puddle depression, spatter formation, cathodic cleaning, and related phenomena observed during GMA welding of an Aluminum-Bronze alloy. The three frames of Figure 5 provide a clear back side view of the keyhole drilled by the plasma during VPPA welding. No evidence of the intense plasma remains in the image. The viewing system can be used for process monitoring and help a supervisory operator detect setup problems as in Figure 5(b) where the keyhole has moved away from the weld seam or process stability problems such as the unstable keyhole formation of Figure 5(c).

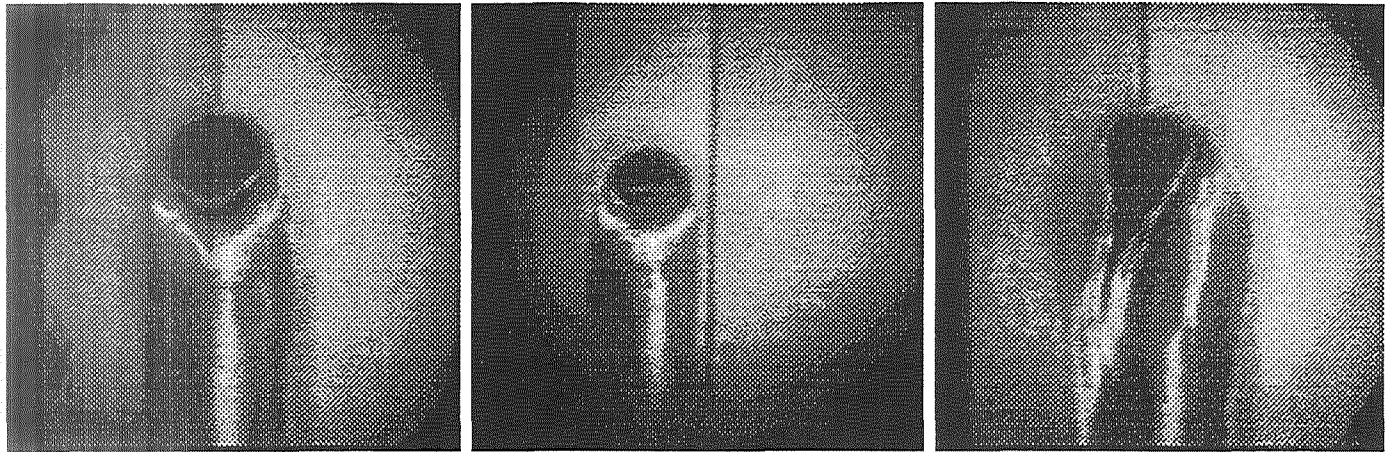


Figure 5 Backside view of the keyhole drilled by the plasma during VPPA welding

Thermal Spraying Applications

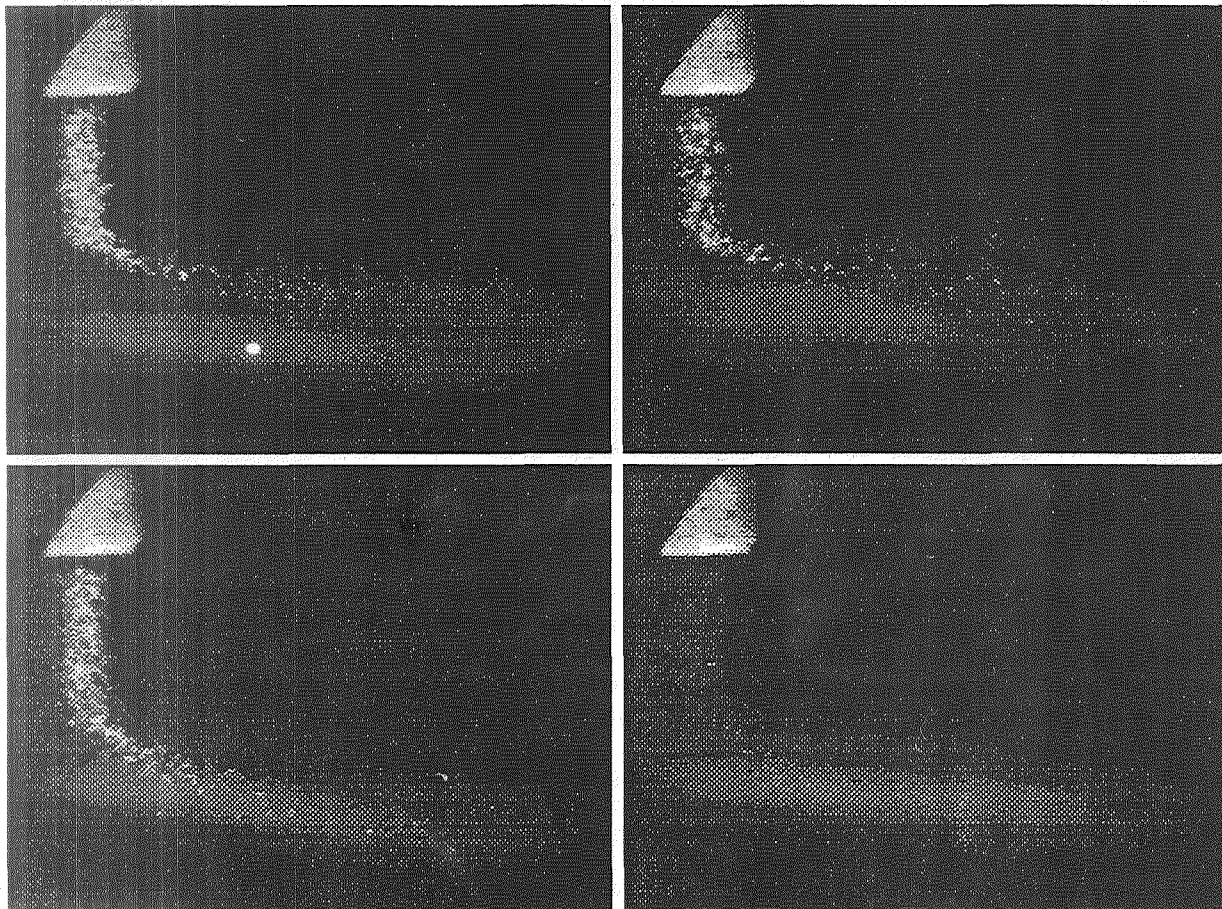


Figure 6. DC plasma spraying showing the effect of varying powder feed parameters in the particle distribution within the plasma plume. As the process parameters are changed the particles ride on the plasma plume (top left and right), overshoot (bottom left), and are optimally carried by the plasma (bottom right).

The vision sensing technology presented in this paper has been used in other manufacturing processes involving a plasma, arc or flame. A family of such processes of particular interest to NASA and the aerospace industry is

thermal spraying which is widely used today for spray coatings and spray forming applications. Thermal coating processes (flame powder, flame wire, wire arc, plasma, etc) utilizing a heat source (chemical combustion or electric arc) to generate an intense flame, arc, or plasma which in turn is used to heat to a molten or elevated temperature solid state, accelerate them to a high speed, and carry and deposit them on a workpiece. Such coatings can minimize or impede environmental effects, improve wear resistance, develop abradable seals or thermal barriers, allow worn-part build-up, or control tolerances. Thermal spraying is also used in forming applications whereby molten material is sprayed layered and rapidly solidified onto a semi-finished product. This approach reduces the number of steps required to arrive at a finished product, compared to more traditional processes. The resultant material also exhibits superior micro-structures by eliminating macro-segregation and promoting finer micro-structures.



Figure 7. Active viewing of twin-wire arc spray in the immediate area of the gun nozzle

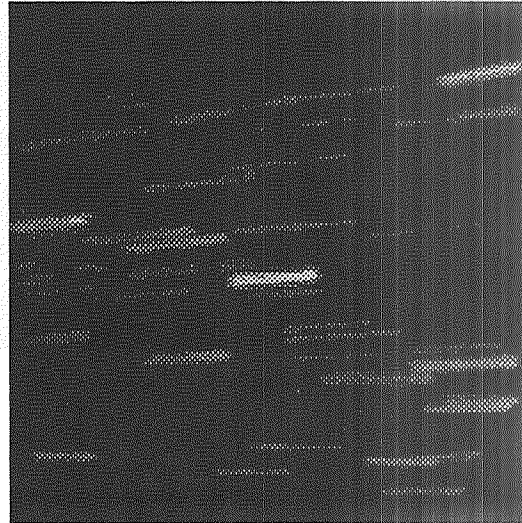


Figure 8 Passive viewing of wire arc spray downstream from the gun nozzle

The strobing parameters can be adjusted so that the plasma can be completely removed from the image. This is demonstrated in Figure 7 showing twin wire arc spray process in the immediate region of the gun. At the opposite end, the laser strobing can also be removed for completely passive viewing. This is only meaningful in the region away from the gun where no evidence of the flame exists. Passive viewing of the plasma is shown in Figure 8. Note that the particles now are shown as light streaks corresponding to the short path they traverse during the sensor integration time. The length of the streaks is thus proportional to the velocity of the particles.



Figure 9 Twin images obtained using two lasers fired sequentially.

Another approach for visualizing the velocity field that has been explored is the use of two lasers or strobes fired in rapid succession. This results in two particle images shifted with respect to one another by an amount that is proportional to the local direction and size of the velocity vector. This is depicted in Figure 9.

Other thermal spraying processes that can benefit from the unique capabilities of the sensor include single wire arc spraying, PTA hardfacing, and gas atomization. Figure 10 shows two digitized images from a videotaped single wire arc sequence.

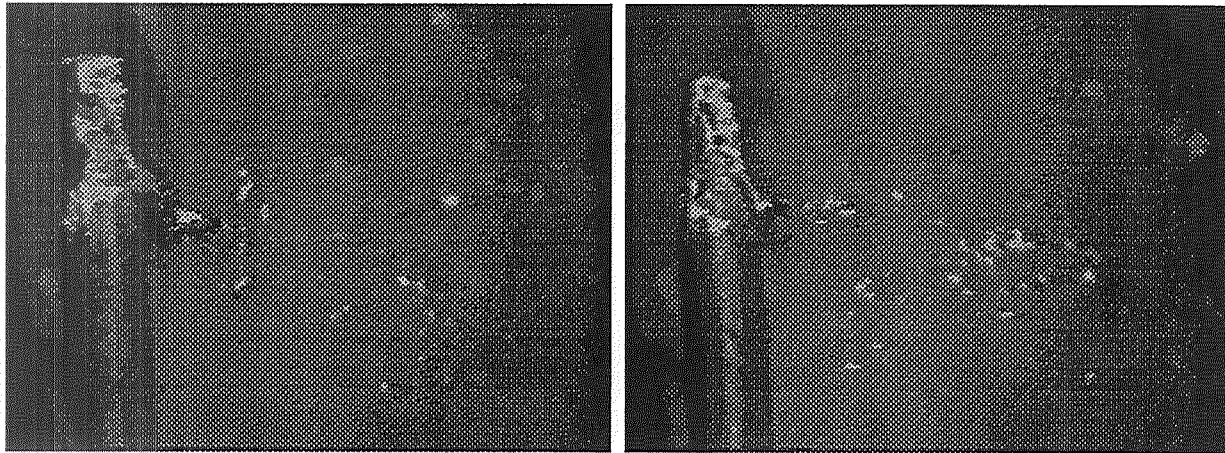


Figure 10 Single wire spraying images

VISION PROCESSING

Under the previously mentioned research programs, Automatix is developing image processing and analysis approaches for processing and analyzing the video images produced by the sensor. These capabilities are developed on commercial machine vision systems implemented on industrially hardened standard computer platforms using the vision application development environment highlighted in [Schurr 1991].

Image Processing for Image Enhancement

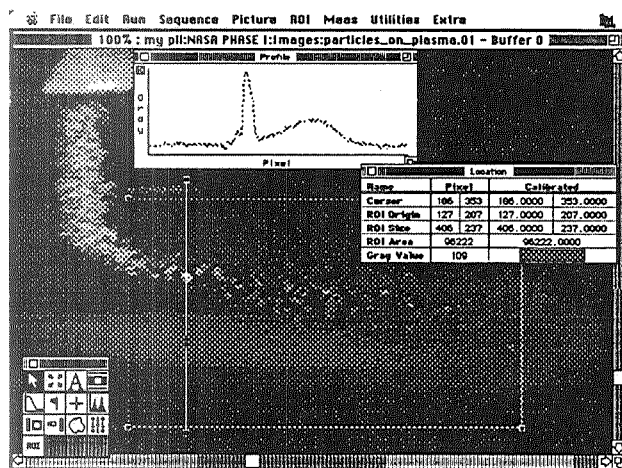


Figure 11 Unprocessed image showing remaining evidence of the plasma plume

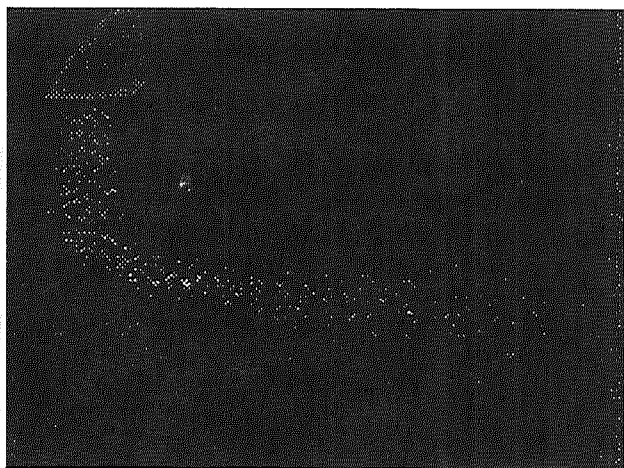


Figure 12 Sample image processing operation to remove the plasma plume

Image processing refers to operations that produce a new image from an original image so as to enhance the subjective image quality, reduce noise, accentuate features of interest, or eliminate image formation problems. Such processing may be useful to make it easier for a human operator to interpret the image or as a preprocessing step prior to any subsequent image analysis. Image enhancement or restoration may also be necessary when analyzing a

recorded sequence of weld images. In such a case, it is no longer possible to change the viewing or picture taking parameters.

For example in thermal spraying applications, the main objective of image enhancement is to process captured images and clean up any remaining evidence of the plasma and/or isolate the particles or the plasma plume. This separation of the particles from the plasma can be based on the fact that the plume has a lower spatial frequency content than that of the particles. This difference is clearly demonstrated by looking at the intensity distribution through the particles and the plasma (Figure 11). Figures 12 and 13 show examples of successful image processing to isolate the powder particles.

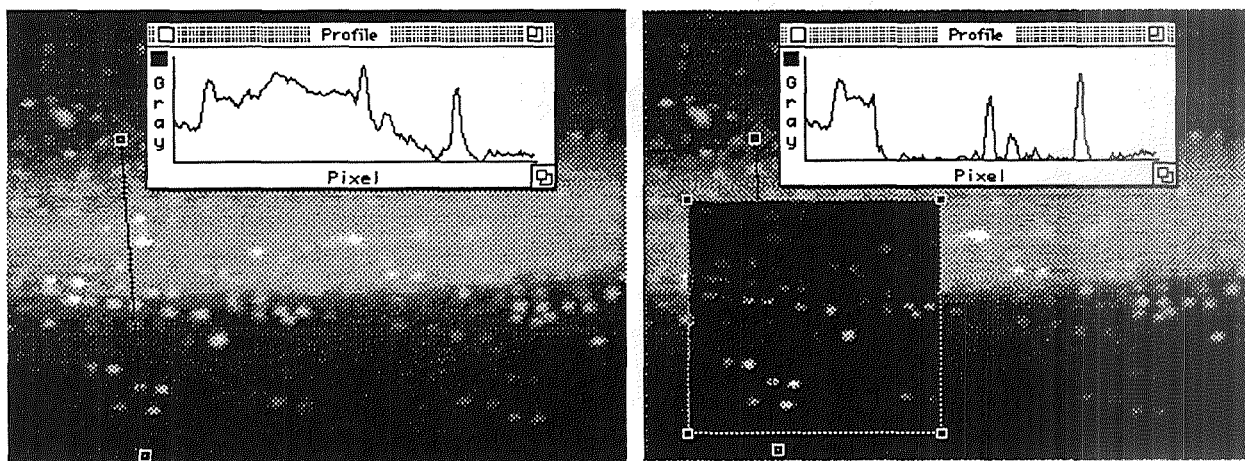


Figure 13 Another example of image processing to remove the plasma plume from the image.

Image Analysis

The main objective of image analysis is to extract features of interest and other quantitative measurements from an image. In the context of welding applications, image analysis is used to:

- to detect the weld joint ahead of the welding torch (its location and size can be used for real-time torch guidance, pre-weld joint inspection, and real-time welding process parameter adjustment) [Agapakis 1990];
- to detect the molten metal puddle or keyhole under the arc (its shape and size can be used for process monitoring and real-time process control);
- to detect the solidified weld bead behind the arc and puddle (its shape and dimensions may be used for post-weld inspection or process control);
- to detect other features of potential interest such as the welding torch, electrode, filler metal wire, molten metal droplets, or the welding arc and plasma.

In thermal spraying applications, image analysis is used:

- to detect the particle detection through image segmentation
- to compute particle area and other particle characteristics
- to compute measures of particle spatial distribution
- to determine the mean particle path
- to compute the particle velocity distribution
- to extract the geometry of the plasma plume or flame

Examples of results of such image analysis for welding applications are shown in Figure 14, where both the centroid of the detected keyhole or puddle and the centerline of the detected joint seam are shown graphically. The distance between the puddle/keyhole centroid and of the seam centerline can be computed during the process and used for seam tracking.

Sample results of image analysis for thermal spraying applications are shown in Figures 15 and 16.

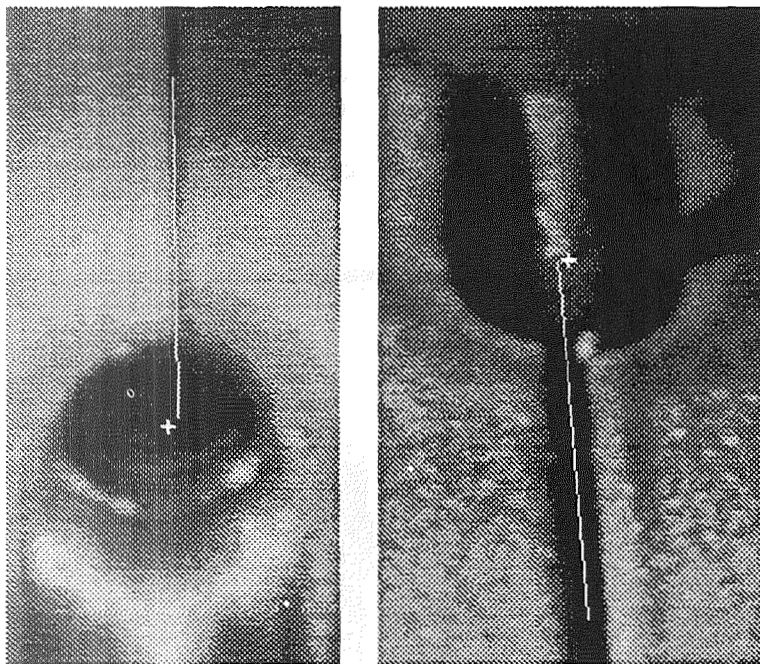


Figure 14 Results of image analysis during VPPA and GTA welding demonstrating the detection of the seam centerline and of the keyhole or puddle centroid.

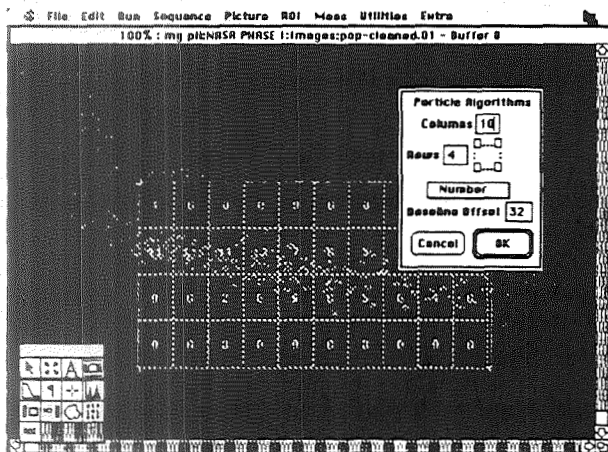


Figure 15 Determination of particle spatial distribution

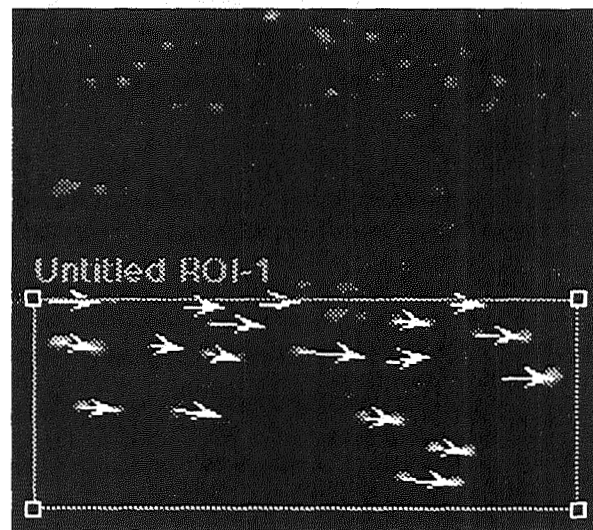


Figure 16 Determination of local velocity vector field

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