JOURNAL OF MATERIALS SCIENCE 30 (1995) 1125–1138

Review
Sensors and techniques used to monitor processing parameters during spray atomization and deposition

D. E. LAWRYNOWICZ, E. J. LAVERNIA
Department of Chemical Engineering and Materials Science, University of California, Irvine, CA 92717-2575, USA

The emerging field of atomization and spray deposition is continually striving to improve the quality of its final products. A major obstacle to achieving consistently high-quality end products is the lack of ability to monitor the various operational parameters associated with spray processes. This paper will present a discussion of the diagnostic techniques that are currently available for monitoring processing parameters, such as droplet size, velocity, and concentration, as well as droplet temperatures and size distributions. To that effect, several methods for obtaining on-line feedback of these parameters are discussed and compared. Techniques such as high-speed cinematography, off-axis holographic cinematography and infrared thermal imaging, are compared and evaluated for their utility in providing information which will elucidate relevant atomization phenomena. In addition, the PCSV-P probe, phase Doppler particle analysis, EPMP monitor, and intelligent sensors are also reviewed and discerned for their usefulness, in making spray atomization and deposition a more controlled process.

Nomenclature

P_0	Gas jet stagnation pressure
P_e	Gas jet exit pressure
P_{dt}	Liquid delivery tube pressure
P_r	Reservoir pressure
D_{dt}	Outer diameter of liquid delivery tube = 9.91 mm
D_i	Inner diameter of liquid delivery tube = 3.00 mm
D_a	Inter-jet diameter = 10.69 mm
d_j	Individual jet diameter = 0.79 mm
f	Next state function
g	Output function
U_k	Control input at time k
X_k	State of the system at time k
X_{x+1}	State of the system at time $k + 1$
Y_k	Measurable output of the system at time k
Z_{dt}	Liquid delivery tube extent out of the jet exit plane = 2.54 mm
α_j	Individual jet angle = 22.5° with respect to the axis of symmetry of delivery tube

1. Introduction

Over the last few years, spray atomization and deposition has been a growing field of interest [1–3]. Many industrial and research facilities currently have sophisticated equipment that is used for material processing on the basis of these techniques. As a result, there has been a growing need for improved diagnostic equipment which can be used to monitor various critical parameters associated with these spray methods [4, 5]. During operation, a real need exists to be able to monitor and control the size and velocity of the powders and surface temperatures of the deposits. However, the atomization process is difficult to control: metallurgical properties are not always predictable, and consequently finished product rejection rates are high [6].

A review of process monitoring techniques and an assessment of current sensor technology, as it is related to spray atomization, has been reported recently in the literature [7, 8]. The purpose of this manuscript is to present a review of the most recent advancements in diagnostic technology and how they can be implemented to control the various parameters associated with spray atomization and deposition.

Some of the latest developments in this field have occurred primarily in four areas: laser light diffraction techniques, high-speed cinematography, thermal imaging, and expert systems. All of these techniques have their own advantages and shortcomings as related to monitoring on-line spray parameters. However, they all offer great potential towards making atomization a more reproducible and controlled

0022–2461

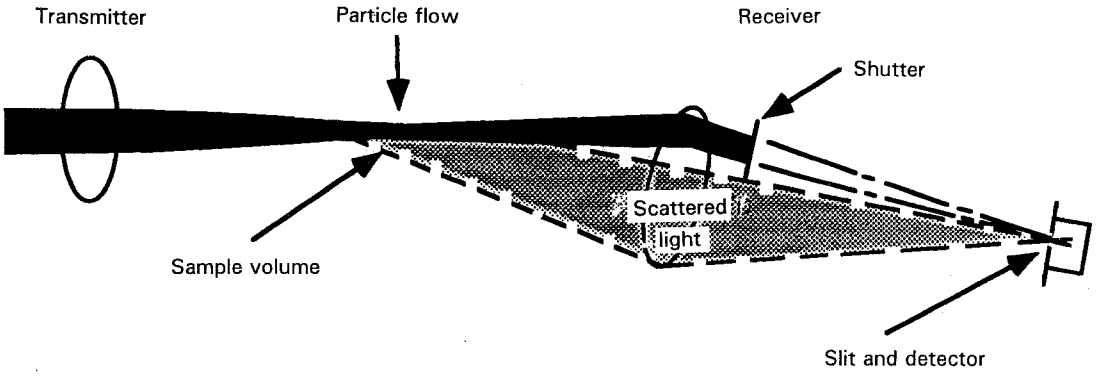


Figure 1 Schematic of PCSV-P optics [7].

science. In addition, using several of these methods simultaneously allows for some of today's most precisely monitored spray systems. In the sections that follow, the most widely used techniques are discussed in detail, paying particular attention to the associated advantages and shortcomings.

2. PCSV-P probe

The first of the laser light scattering techniques is the particle counting, sizing, and velocity measurement probe (PCSV-P), which can be used to obtain on-line measurements of particle size, velocity, and concentration [8, 9]. The system uses several pieces of hardware including a computer and an electronic probe. It can be used for large-scale industrial systems as well as small laboratory systems. The PCSV-P probe uses a fibre-optic based system within a water-cooled probe to allow remote measurements of the above-mentioned parameters.

This system uses well-understood light scattering techniques to obtain information from the atomized powder. A low-power laser is utilized to illuminate particles as they randomly pass through a sample volume (see Fig. 1). The sample volume is determined by the intersection of the laser beam and the receiver optics. A detector picks up the scattered light from the laser and transfers the signal to a photomultiplier, which converts the signal to a voltage pulse that can be interpreted by the signal processor. The PCSV-P probe technique utilizes an intensity deconvolution algorithm which relates the scattered light signals to measures of particle size and concentration. Because the technique uses a very small sample volume size, statistically there will be only one particle in that volume whose combination of diffraction intensity and duration in the volume can be correlated to give the size and velocity of the particle.

The probe is placed inside the spray chamber at a fixed distance below the nozzle. The exact placement is unique for each system and optimum placement has to be determined experimentally. The calibration of the instrument is accomplished by the use of a rotating disc (14 mm diameter). The disc consists of monodispersed clear "holes" which have been photoetched into an opaque substrate. These holes provide diffraction scattering centres which, in turn, provide data for calibration of the instrument. The calibration procedure is basic and rather simple, making the probe easy to set up and use.

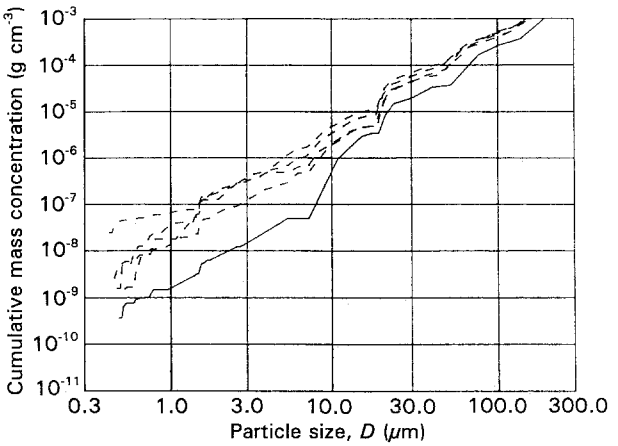


Figure 2 PCSV-P results for (——) 690 kPa (100 p.s.i.) and (– – –) 860 kPa (125 p.s.i.) showing reproducibility of measurements [7].

During operation the probe provided reasonably accurate data on particle size and velocity [10]. Fig. 2 shows the PCSV-P probe size measurements for two different atomization pressures (690 and 860 kPa). The resulting curves correlate well to theoretical values. It is expected in atomization, that higher gas nozzle pressure will yield finer powder and the values of the curves in Fig. 2 substantiate this premise. Velocity measurements were extrapolated from the sampling rate and time frequency of measurements, but no specific data were provided to check the associated accuracy.

After measurements of the particle size were made with the PCSV-P probe and atomization was complete, the powder was collected and again measured using a Micro-Trac instrument to see how well the two measurements would correlate. The results of the comparison can be seen in Fig. 3. Again it is evident that both techniques show general reduction in particle size with increasing pressure. Although the PCSV-P probe results predict a larger particle size than that measured with the Micro-Trac, the distribution shapes of the curves (see Figs 4 and 5) are similar at the smaller particle size, indicating consistency between the two methods.

The differences between the two methods can be attributed to several reasons. First, larger particles (< 600 μm) were sieved from the collected powder prior to Micro-Trac measurements to remove coarse

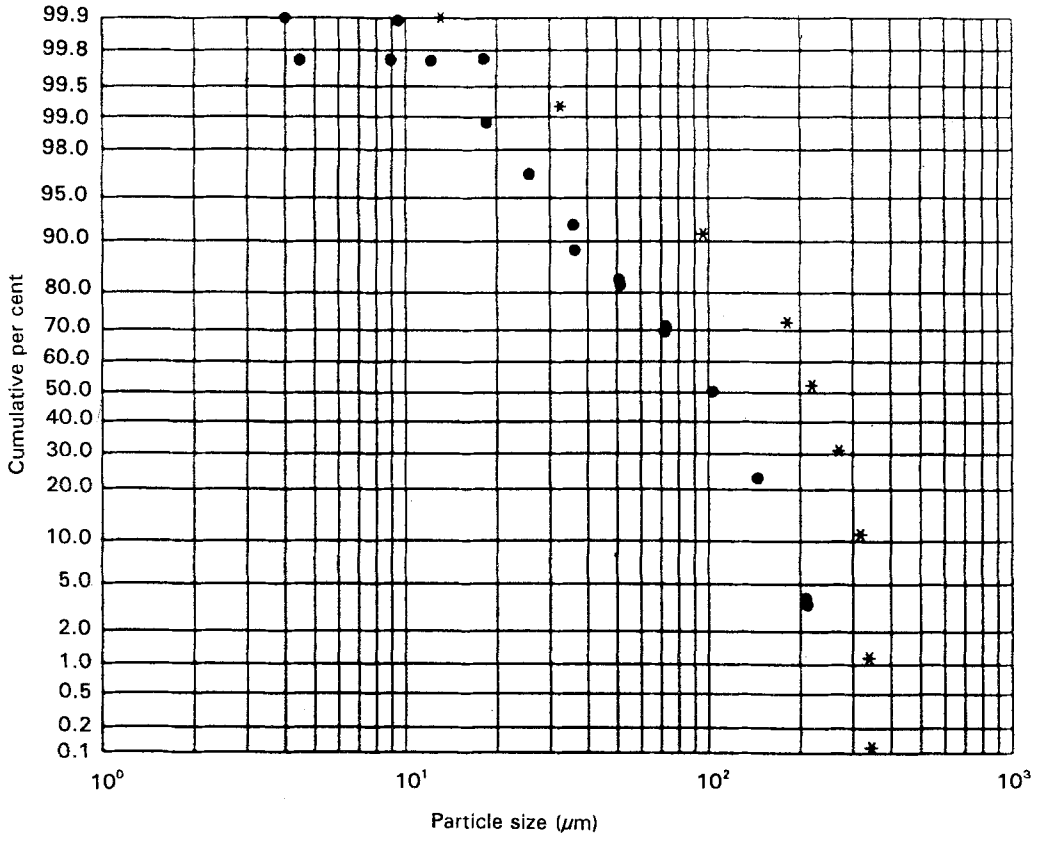


Figure 3 Log probability plot results comparing (●) Micro-Trac with (*) PCSV-P [7].

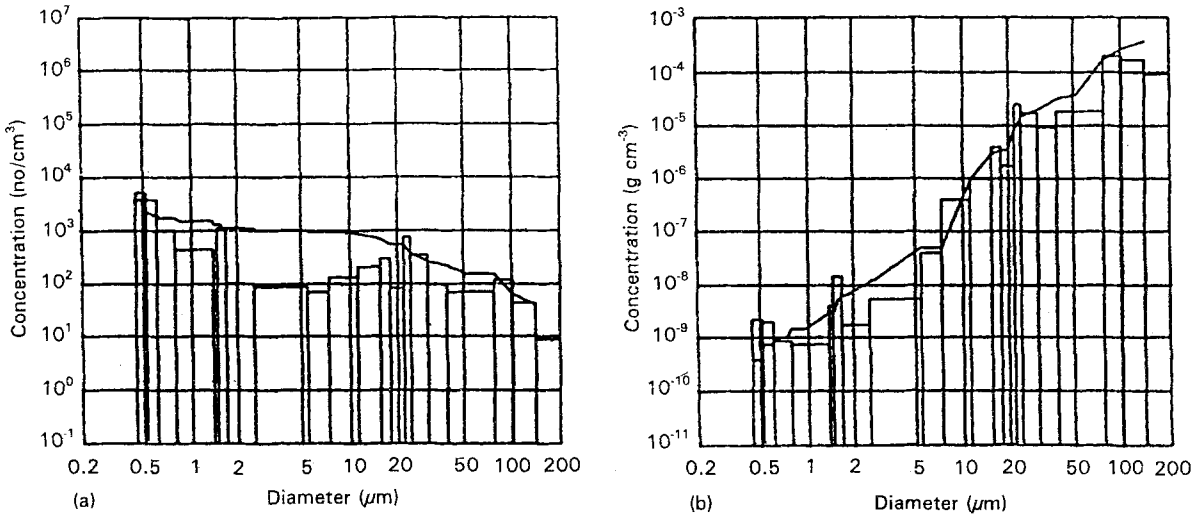


Figure 4 Micro-Trac distribution curves [7]. (a) Number concentration, (b) mass concentration: (——) cumulative, (□) $dN/d\ln d$.

metal fragments which inevitably accumulate during start up and shut down phases of the atomization process. This experimental bias would cause the results to be weighted towards the smaller particle sizes. Also, the Micro-Trac can measure particles in a larger size range (0.5–300 μm) than PCSV-P and therefore it is slightly more accurate.

In addition to the above evaluation based on comparison testing, several factors concerning the limitation of PCSV-P should be mentioned. First, for large particles (above 100 μm) the accuracy of the size measurements decreased rapidly due to the inconsistent diffraction data from the irregular shapes of the particles. In addition, when the technique was used for various powder types, it was determined that the size measurements were dependent to a significant extent on the absorption and diffraction characteristics of each individual material. These two factors account for some of the discrepancies associated with this monitoring method.

Overall this technique proved valuable and reliable, within certain experimental limits as previously mentioned. The instrument is well suited to perform reproducible and simultaneous measurements of velocity, size, and concentration. It is also very capable of producing data at high temperatures, which makes it

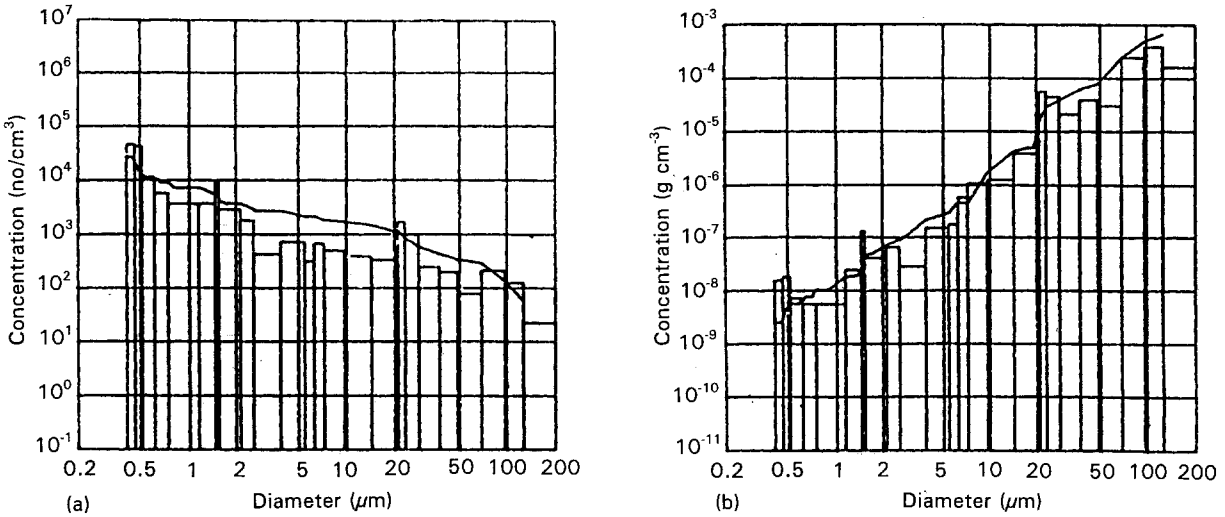


Figure 5 PCSV-P distribution curves [7]. (a) Number concentration, (b) mass concentration: (——) cumulative, (□) $dN/d\ln d$.

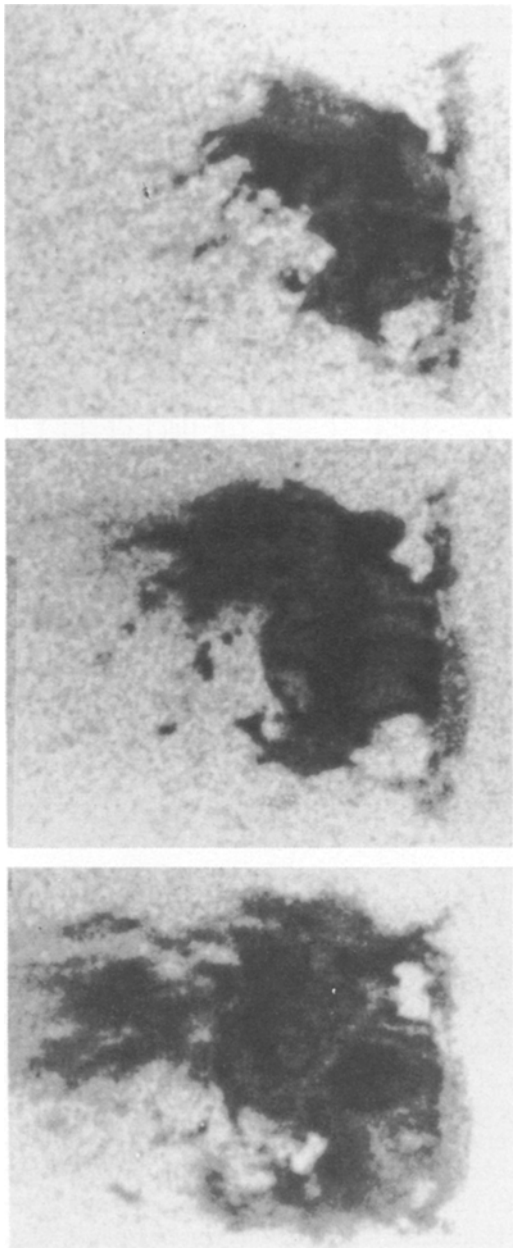


Figure 6 Images taken from a 10 000 frame/s movie [11].

useful when atomizing high-temperature alloys. In addition, the equipment associated with PCSV-P probes is flexible, allowing forward and backward scattering geometries; this renders the technique adaptable to numerous spray-chamber configurations. Furthermore, rapid signal processing (500 kHz) allows real-time information to be available on the quality of the atomized alloy. As a result, when the PCSV-P probe is properly implemented in a research or industrial setting it can serve to provide real-time monitoring of several above mentioned operational parameters during spray atomization.

3. High-speed cinematography

High-speed cinematography has been utilized to monitor events occurring in atomization for a number of years [6]. This process is rather simple, involving a camera with the capabilities for high shutter speed and high speed film. It is usually set up at one of the windows of the spray chamber which allows a clear view of the spray cone. The procedure is capable of providing particle distribution, nozzle phenomena information, and velocity information from photographs. Consecutive frames, similar to those shown in Fig. 6, are used to track a single particle. Then by measuring how far the particle moves between frames and by knowing the time between frames, the velocity of the particle can be calculated. Fig. 7 shows how photographic measurements can be used to derive velocity information. Distribution of the particles and nozzle phenomena can also be directly observed from consecutive frames. High-speed cinematography, however, lacks fine detail due to the coarseness of high-speed film (see Fig. 6) and it also requires time to develop the film to obtain the results. Recently this process has been taken a step further by incorporating laser holography [8].

4. High-speed off-axis holographic cinematography

Another technique which improves on existing technology and can be used to extract real-time in-

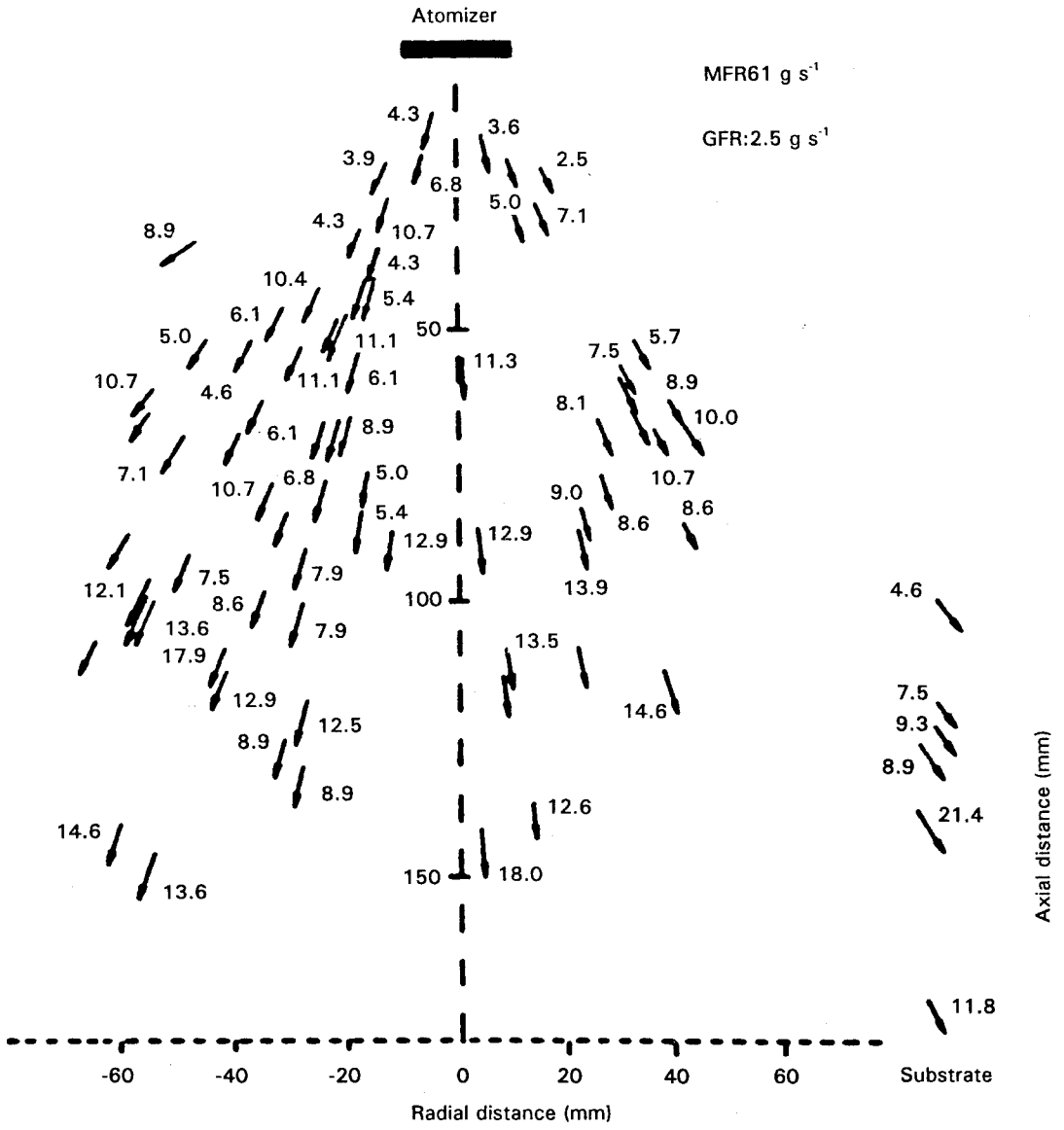


Figure 7 Droplet velocity vectors from photographic measurements [12].

formation from atomization is high-speed off-axis holographic cinematography. This new technique, originally developed by Lauterborn and Judt [8], has been utilized to access information on turbulent cavitation bubble clouds in fluid flow, but the experimental apparatus may be readily adopted to spray atomization. The basic premise of this method relies on high-speed strobe laser imaging which is capable of "freezing" atomization phenomena.

The system consists of a copper-vapour laser which emits a quasi-infinite series of short ($\sim$ 35 ns) light pulses with an energy of $\sim$ 1 MJ. The light comprises two spectral lines (yellow $\lambda = 578.2$ nm and green $\lambda = 510.6$ nm). The yellow light is used to expose the holographic images and the green light is used to pump a dye laser to improve the coherence and wavelength tuneability of the copper-vapour laser. (This is done because the coherence of the copper-vapour laser pulse is very low, making direct holographic recording severely limited.) A schematic diagram of the setup can be seen in Fig. 8. A computer-controlled shutter and laser combine to emit a fixed number of pulses which produce an equivalent number of holograms. The pulses leaving the dye laser are deflected by mirrors on to a beam splitter to provide two beams for off-axis holography; a reference beam and an object beam. The object beam traverses a delay line of prisms so that its path length to the holographic plate can be adjusted to approximately that of the reference beam. The light at this point serves to illuminate a given volume of the chaotic phenomena of interest (atomization) [6, 10]. The scene is then imaged by the use of two lenses in front of the holographic plate. The plate itself is placed on a rotating axle which permits it to rotate at $\sim$ 250 r.p.m. While it is rotating, the lenses focus each pulse and form a hologram roughly 1 cm^2 on a separate part of the plate (see Fig. 9). Each of the holograms is a successive image of a spatial event a fraction of a second apart (216 μs between frames).

The information from the separate holographic images can be used to obtain particle size and distribution information about atomization. The consecutive frames can also be used to track a single particle and measure its velocity based on movement through consecutive frames and time between frames. Fig. 10 shows a series of images from successive holograms revealing individual particles moving in space. Direct

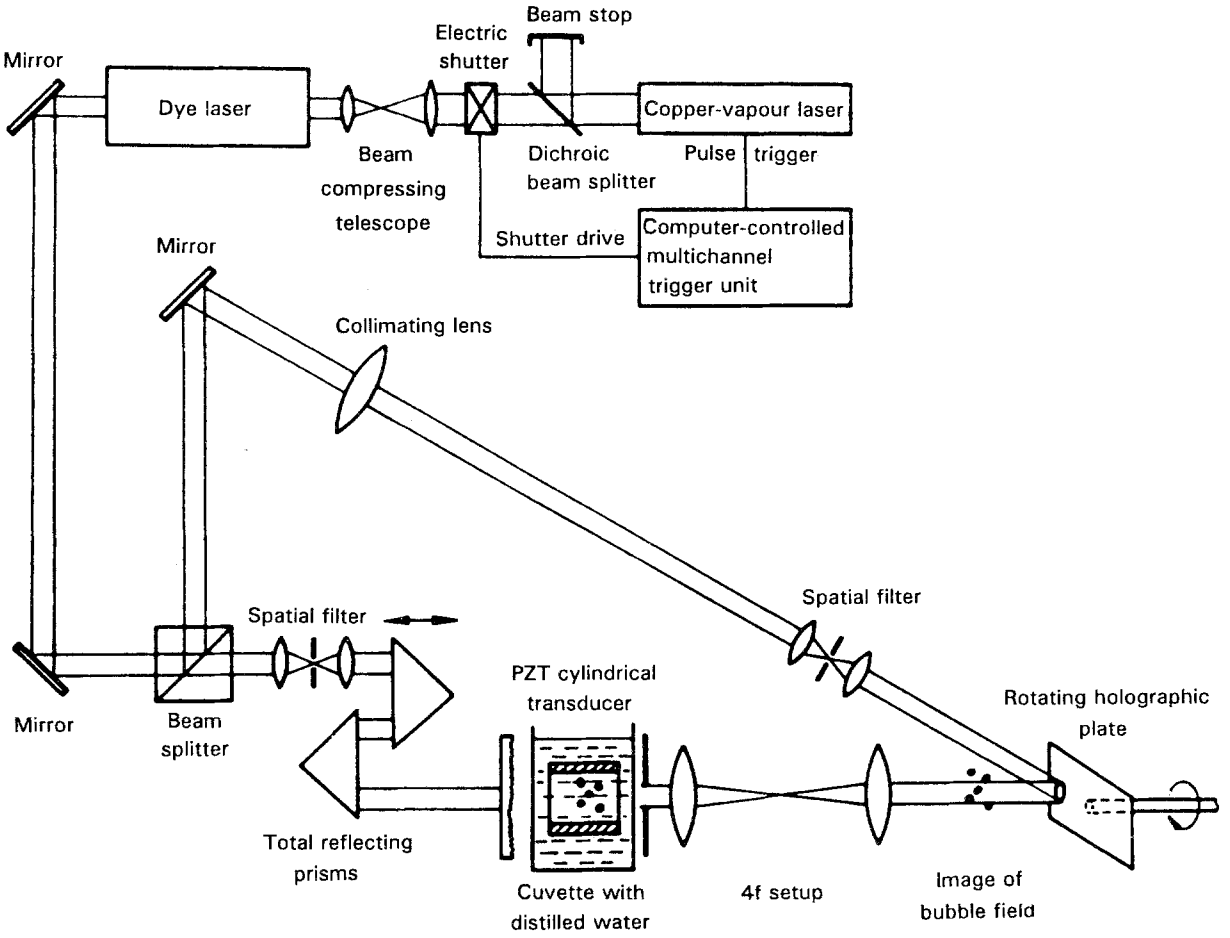


Figure 8 Schematic illustration of high-speed off-axis holographic cinematography [8].

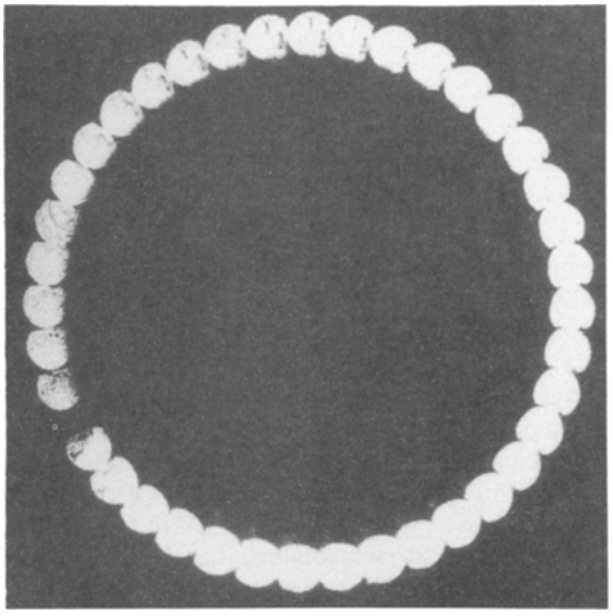


Figure 9 Example of a series of holograms on the rotating holographic plate [8].

measurements made from these images can yield the above-mentioned results.

In summary, the off-axis holographic cinematography can be successfully adapted to obtaining diagnostic information about spray processing. The system has the advantage of providing three-dimensional information about particle characterization and offers basically an infinite field of depth in selecting a sample volume. The very short pulse and high light energy of the laser system coupled with the pumped dye is capable of "freezing" atomization events. In addition, the system can be combined with a digital image processing unit which could provide slow-motion three-dimensional pictures of the atomization process.

The shortcomings of this system include the limited resolution which is possible when dealing with very small particles and holographic plates. Also, limited velocity information can be gathered from the consecutive frames. However, the system already has improved over the last two years and continued improvement in this technology will make this process an important tool for monitoring atomization events.

5. Infrared thermal imaging

Another process which has been used to monitor deposit surface temperatures and droplet cooling characteristics during spray forming is infrared thermal imaging [12, 13]. The system basically consists of a thermal camera positioned at a spray chamber window and a computer for image analysis procedures. The system operates on the premise that the intensity of infrared radiation falling on the detector (camera) is proportional to temperature to the fourth power. This is assuming that radiation emitted by the surrounding atmosphere and other background sources are taken into account and compensated for. In

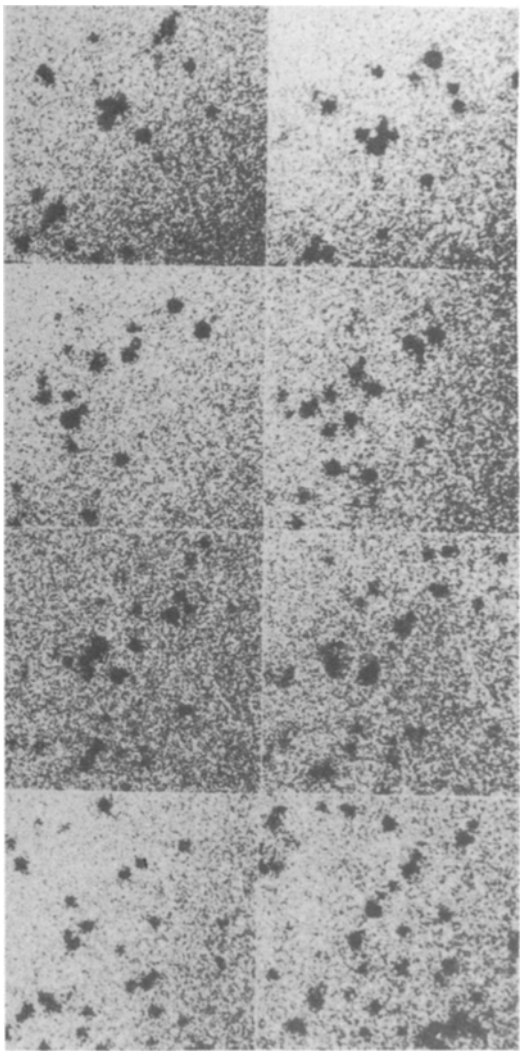


Figure 10 Series of images from successive holograms. The time between frames is 216 μs. Time proceeds from left to right and from top to bottom [8].

addition, it is necessary to calibrate each individual camera with each specific chamber in an effort to compensate for variations in background absorption and emitting characteristics of each unique experimental apparatus.

Once the equipment is properly calibrated and in place, it can provide interesting insight of atomization phenomena as well as monitor the process. A series of infrared thermographs are taken at various time intervals. The thermographs are then examined with the aid of a computer in order to obtain specific information about the nature of the spray and the deposited material. The instant feedback available on video screens is a desirable on-line diagnostic feature of this system. The temperature resolution of existing systems is on the order of 0.1 °C/shade. Experiments reported by Cantor and Bewlay [12] of deposition by atomization of an alloy resulted in the thermographs of Fig. 11. From the thermographs it can be concluded that the deposit surface temperature of the material takes ~ 15 s to reach an approximate steady state level. This supports the premise that droplets deposited at the onset of spraying, directly on to the substrate, are more efficiently quenched by the substrate than droplets deposited later on to a warmer material. Thermographs can also reveal information about the distribution of particles and cooling characteristics of the spray. The shape and colour of the spray cone can be correlated to the size distribution of the droplets. It can also be deduced from the thermal data that larger droplets within the spray tend to reside in central regions of the gas flow because of their larger inertia, whereas smaller droplets are more likely to be swept towards outer regions of the diverging spray cone. Information such as this can be used to better understand the events occurring during atomization.

This technique has demonstrated that useful information about atomization parameters can be obtained using thermal imaging; however, several problems are still associated with this type of system. First, infrared thermal imaging systems tend to be expensive and cumbersome due to the need for cryogenic operation of the camera. Also, sophisticated computer algorithms are required to decipher the shades of the thermal maps for transient systems such as atomization. In addition, the presence of both liquid and solid phases within the impinging droplets makes accurate calibration of the system very difficult.

More recently, developments in advanced pyroelectric ceramics for thermal infrared detection and imaging by Whatmore [9] have decreased the price of the equipment and raised the maximum temperature of efficient operation. These developments will allow greater resolution and increased ease of operation. General Electric also has made progress on intelligent algorithms for deciphering the thermal maps in transient systems [14]. Together, these two advancements may bring this technology to the forefront of diagnostic techniques for atomization and deposition processes.

6. Phase/Doppler particle analysis (P/DPA)

An already established technique, termed phase/Doppler particle analysis (P/DPA), has been implemented in many existing diagnostic systems [4]. The P/DPA technique is basically a single particle counting technique that can provide information about particle size, velocity distribution, and particle concentration for a small given volume. The hardware consists of a transmitter, receiver, and a signal processor. A schematic illustration of the phase Doppler interferometer can be seen in Fig. 12. The entire system operates on the simple premise of measuring the phase shift of light diffracted from particles in the path of the optics [15]. The optics are comprised of a continuous gas laser such as helium–neon (He–Ne) or argon ion used for illumination of the particles. A beam splitter is utilized to divide the highly collimated light into two parallel beams of equal power. A high-quality lens then focuses the two beams to the same point. This region where the two beams converge is the sample volume space where particle measurements are made. In this volume, interference between the two beams results in spatial modulation of the light intensity which can be thought of as a grating of light and

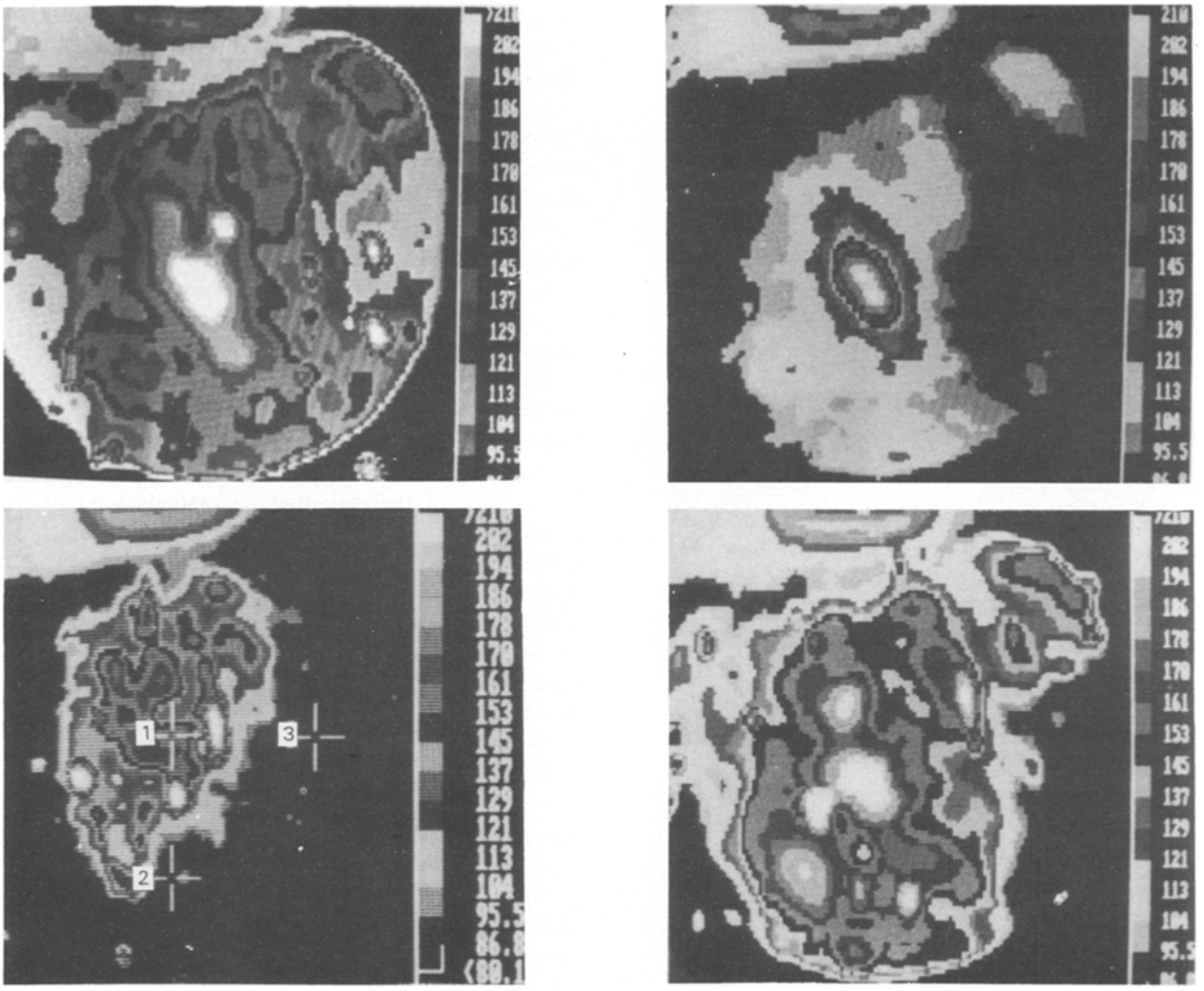
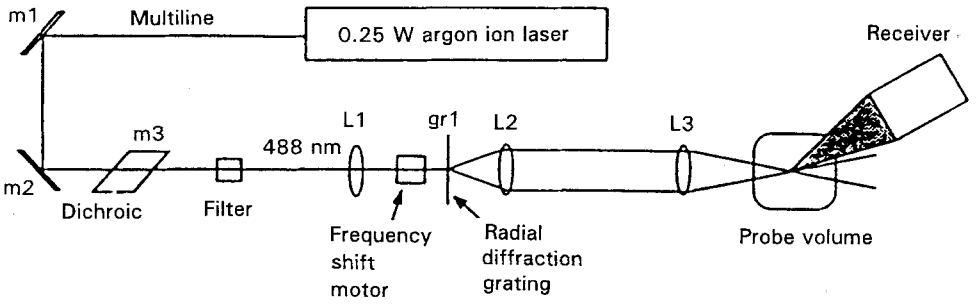


Figure 11 Example of thermo-graphs at various time intervals; numbers refer to temperature [13].



L1 120 mm
L2 200 mm
L3 300 mm

Detail of receiver

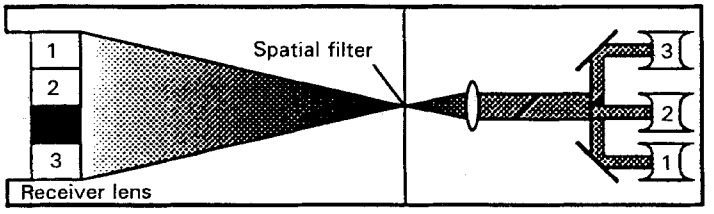


Figure 12 Schematic illustration of the phase Doppler interferometer [5].

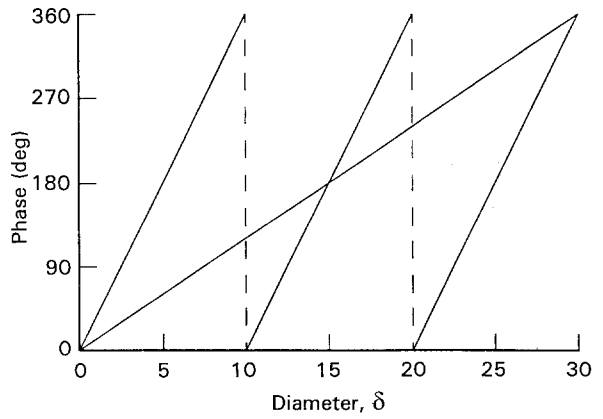


Figure 13 Relationship between phase shift and particle size [5].

dark stripes on a macroscopic scale. A particle passing through this region scatters the light whose temporal intensity pattern corresponds to the gratings spatial intensity pattern. The correlation or differences of the patterns is related to the particle velocity. The scattered light from the two beams is collected by the receiver lens and focused through an aperture on to photodetectors. The scattered light waves produce a Doppler shift signal which can be analysed and correlated to the particle velocity. The magnitude of the Doppler shift on the detector can be related to the size of the particle. It should be noted that the system assumes a spherical particle when it produces size information and this is not always an accurate premise. For the most accurate results, three detectors should be used to record the Doppler shift. Then, by knowing the relationship between phase shift and powder size (see Fig. 13), the size and velocity of the particle can be quantified.

The system can be calibrated from velocity and turbulence data which can be inferred from seed particle measurements. Calibration is not necessary for velocity measurements; however, in order to withdraw any other relevant information, the system should be normalized for all unique particles and atomization conditions. Once the system is fully set up and calibrated, it is capable of measuring particle sizes from 1–3000 μm.

The phase Doppler monitoring technique offers several advantages over some of the other methods already reviewed. This method relies on the measurement of frequency modulations and time intervals which make it independent of signal attenuations and environmental effects. The linear relationship between the Doppler shift and particle size allows for accurate size measurements. It is worth noting, however, that P/DPA does have some limitations. The particle shape and optical absorption characteristics of the powders can skew the accuracy of the measurements. New versions of this technique are concentrating on overcoming these obstacles and future systems should provide even more accurate data. Overall P/DPA is a well established monitoring technique which is currently being utilized by many facilities employing atomization units. With continued improvements, this technique has the potential of becoming the dominant monitoring tool for diagnostic systems.

7. Electric principle-based monitor for particulates (EPMP)

Up to this point, only techniques that are based on optical principles have been discussed. These systems all appear to have similar disadvantages, specifically complex alignment of optics and potential contamination of the lenses. Another method exists for obtaining information from atomization, based on an electric principle which does not have these shortcomings.

A relatively new instrument, called the SIMP (surface ionization for monitoring particles) [12] relies on interpreting the electronic information that is discharged by atomized particles [5, 16]. When an atom or molecule whose ionization potential is comparable with the work function of a metal comes into contact with a heated metal surface, an atom or molecule may leave the surface as a positive ion. The SIMP instrument collects ions produced by this process using a special electrode. The burst of ions accompanying the impact of a particle containing surface ionizable impurities produces a sizable electrical pulse. Many atoms, such as sodium, potassium, barium, calcium, thorium, and uranium, have this characteristic. The instrument utilizes a resistance-heated tungsten wire placed in the path of the falling droplets. Current is run through the wire and, due to infrared heating from its intrinsic resistance, it is maintained at a constant temperature. The potential difference between the filament and the collection electrode is monitored. The electrical signals that are produced can be correlated with particle size. The technique relies on the detection of the impurity ions which are common in most alloys, and is capable of detecting particles as small as 100 μm. The diameter of the wire is small, making it a non-intrusive technique. The system only responds to detecting alkali and other surface ionizable constituents [6, 17]. Other particles, such as combustion products, water mist, and photochemical smog, do not affect the detection capabilities of the system.

This method of monitoring particle size is effective, simple and inexpensive, but it does hold some disadvantages. The relationship between electrical pulse height and particle diameter is non-linear and depends on material characteristics. This makes it rather difficult to calibrate the instrument. Also, the range of particle-size detection is limited, making the system inapplicable to some atomization units. However, it still offers an economical alternative to other optical diagnostic units for certain specific applications.

8. Intelligent sensors

The final diagnostic tool which will be reviewed here encompasses several of the methods already mentioned and adds an intelligent process control system. Several different research groups have made great progress towards achieving automated process control of atomization and spray deposition [18–24]. However, the dynamic nature of the atomization process makes it difficult to achieve reproducible results and gain full control over the properties and microstructure of the final product. Understanding and quantifying some of the critical atomization para-

meters such as nozzle size, gas pressure, metal flow rate, etc., will allow spray deposition and atomization to become a more predictable fabricating methodology.

Typifying some of the pioneering work being done on intelligent sensors, Ridder *et al.* [11] in a recent publication have been able to correlate nozzle geometry to spray cone shape and particle size [11, 25]. Then by using this information as a data base and utilizing other diagnostic tools such as infrared and laser diffraction sensors, they have been able to set up a primitive intelligent control system for atomization [18, 19]. For their study, Ridder *et al.* utilized the Supersonic Inert Gas Metal Atomization (SIGMA) system located at the National Institute of Standards and Technology (NIST).

Through the use of high-speed cinematography and laser holography, Ridder *et al.* were able to isolate the turbulent phenomena at the nozzle [11]. The atomizing nozzle assembly used by SIGMA is shown schematically in Fig. 14. The actual assembly is comprised of 18 gas nozzles arranged in a circle around a liquid delivery tube. The specific dimensions and identification of the nozzle features are provided in the Nomenclature. For the purpose of this manuscript, we will address only three of the features shown in Fig. 14. P_0, gas jet stagnation pressure, P_r, the reservoir pressure, and P_{dt}, liquid delivery tube pressure are the three quantities which ultimately dictate the characteristics of the gas flow field and consequently the properties of the atomized droplets. By modelling of these parameters, together with schlieren photography and laser pulsed holography, Ridder *et al.* proposed that the wave patterns of the gases at the nozzle resembled those in Fig. 15. Gas-pressure measurements for three different gases (nitrogen, argon, and helium) were made at the important locations of the nozzle (P_0, P_r, P_{dt}). The results were compiled and plotted in Figs 16 and 17. With computer analysis and modelling, Ridder *et al.* were able to correlate the peaks of the aspiration curves to specific points of the wave pattern in Fig. 15. Finally, using the information derived from the nozzle analysis, Ridder *et al.* [11, 25]

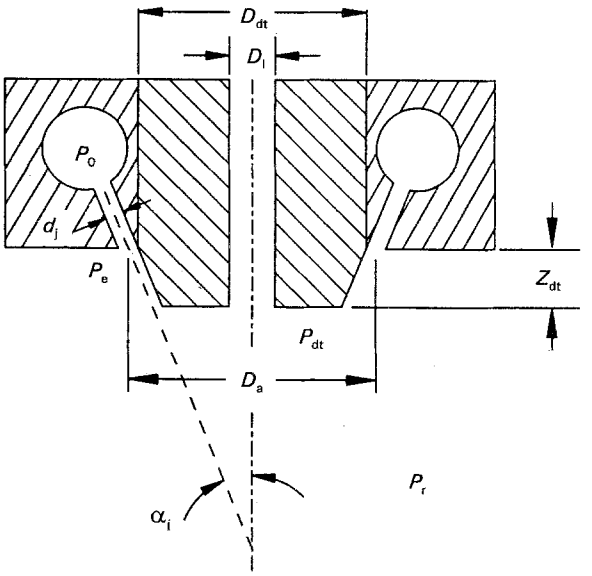


Figure 14 Schematic cross-section of the nozzle [11].

were able to formulate primitive mathematical equations to model the behaviour of the gases. In turn, these equations were used to formulate input–output relationships for the computer control of dynamic systems such as atomization. The form of these equations is as follows

$$X_{x+1} = f(X_k, U_k) \quad (1)$$

$$Y_k = g(X_k, U_k) \quad (2)$$

where X_k is the state of the system at time k, U_k is the control input at time k, Y_k is the measurable output of the system at time k, X_{x+1} is the state of the system at time $k + 1$, and the functions f and g are the next-state and output functions, respectively [11, 18]. They were then able to use those equations to write basic if – then algorithms to predict particle size and distribution. By using laser diffraction techniques they were able to correlate their predicted and experimental results as shown in Fig. 18. As is evident from Fig. 18 their initial results look very promising.

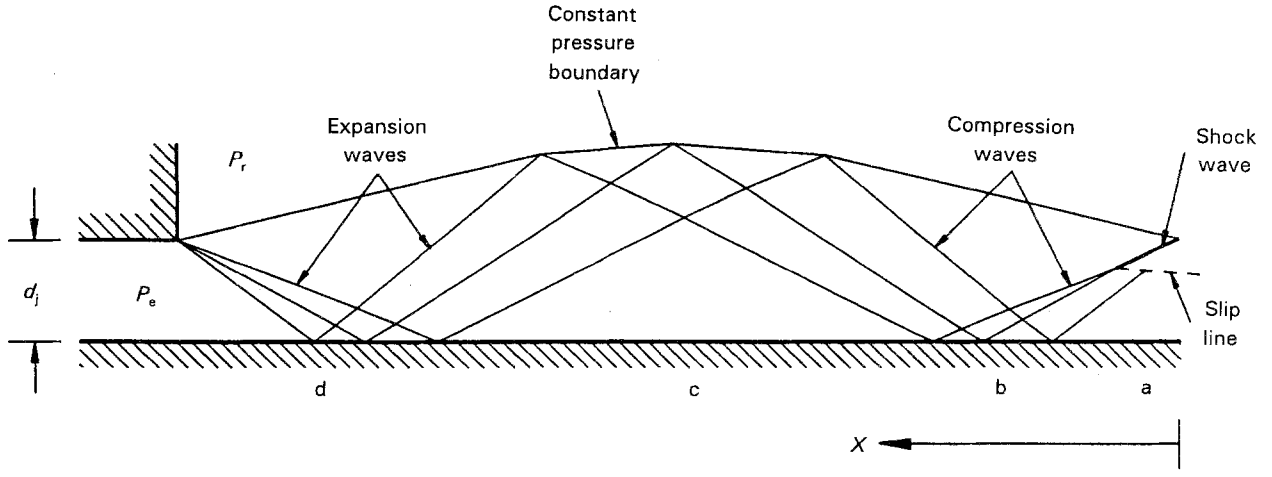


Figure 15 Schematic illustration of the wave pattern at the nozzle. (a–d) Positions of the liquid delivery tube relative to the jet at conditions a, b, c, and d in Fig. 17 [11].

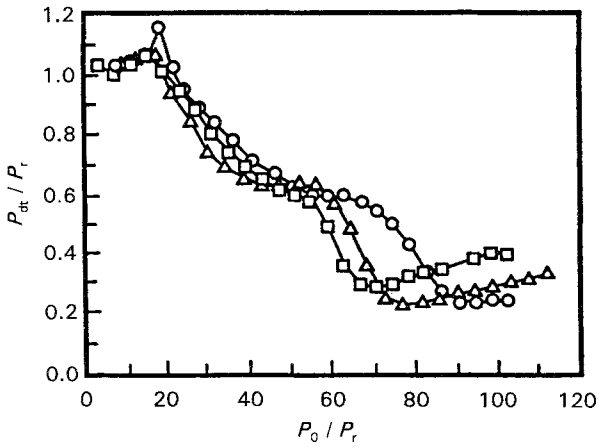


Figure 16 Aspiration curves for (△) nitrogen, (□) argon, and (○) helium [19].

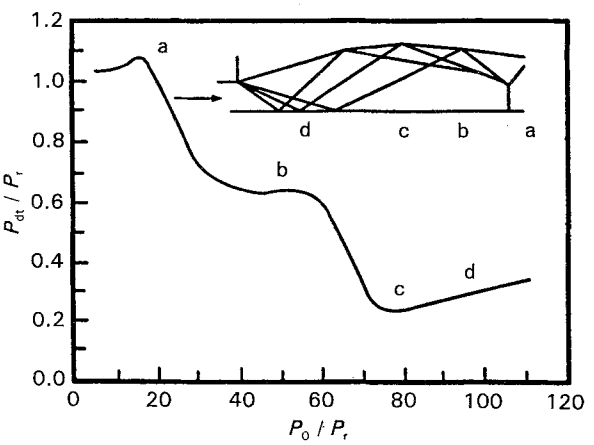


Figure 17 Generalized aspiration curve showing the predominant features of the curves in Fig. 16. (a–d) The nozzle locations shown in Fig. 15 [19].

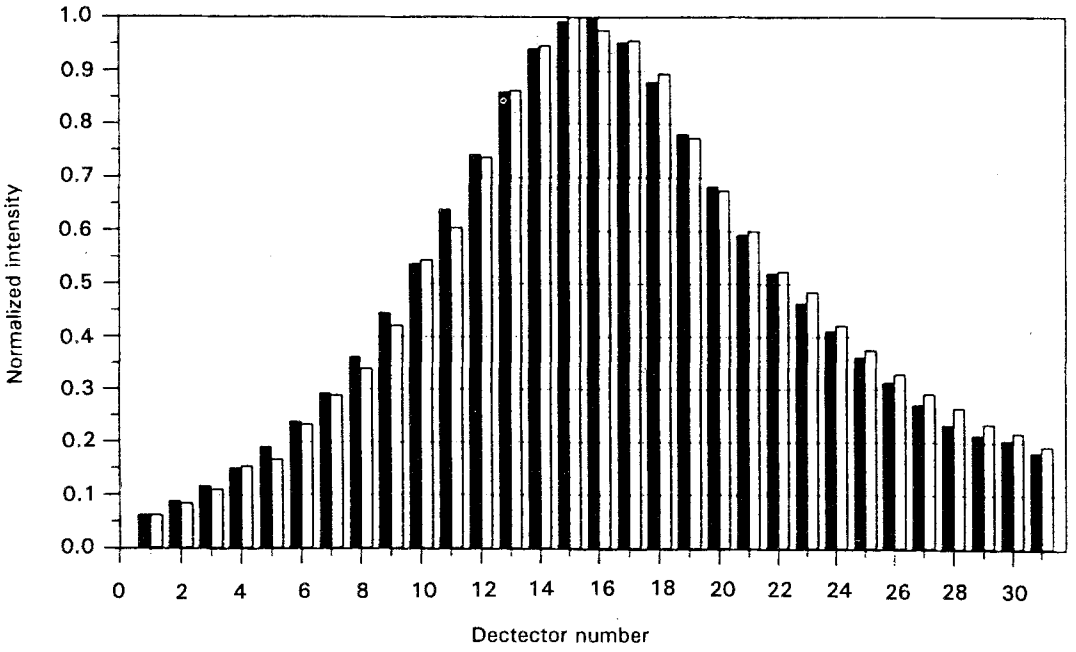


Figure 18 Comparison of (■) modelled and (□) measured light intensity [11].

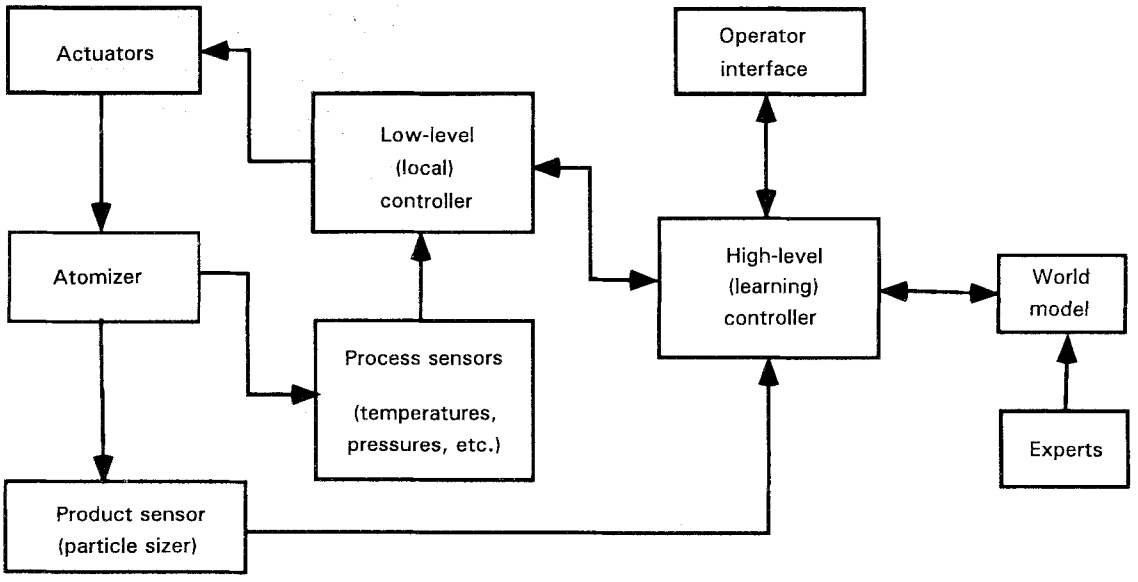


Figure 19 Logic loop for intelligent sensors [11].

Eventually, Ridder *et al.* envision a system where, by monitoring gas pressures, nozzle geometry, viscosity of atomization liquid, gas type, chamber pressure, etc., they will be able accurately to control particle size and distribution which will, in turn, dictate the materials mechanical performance [20, 21]. Currently they have a system which is able to monitor some of these parameters and react based on if – then statements. Their system follows the logic of Fig. 19. The high-level controllers decision-making strategy is based on the principle of Hierarchical Control. In this approach, the strategy is considered to be goal-direc-

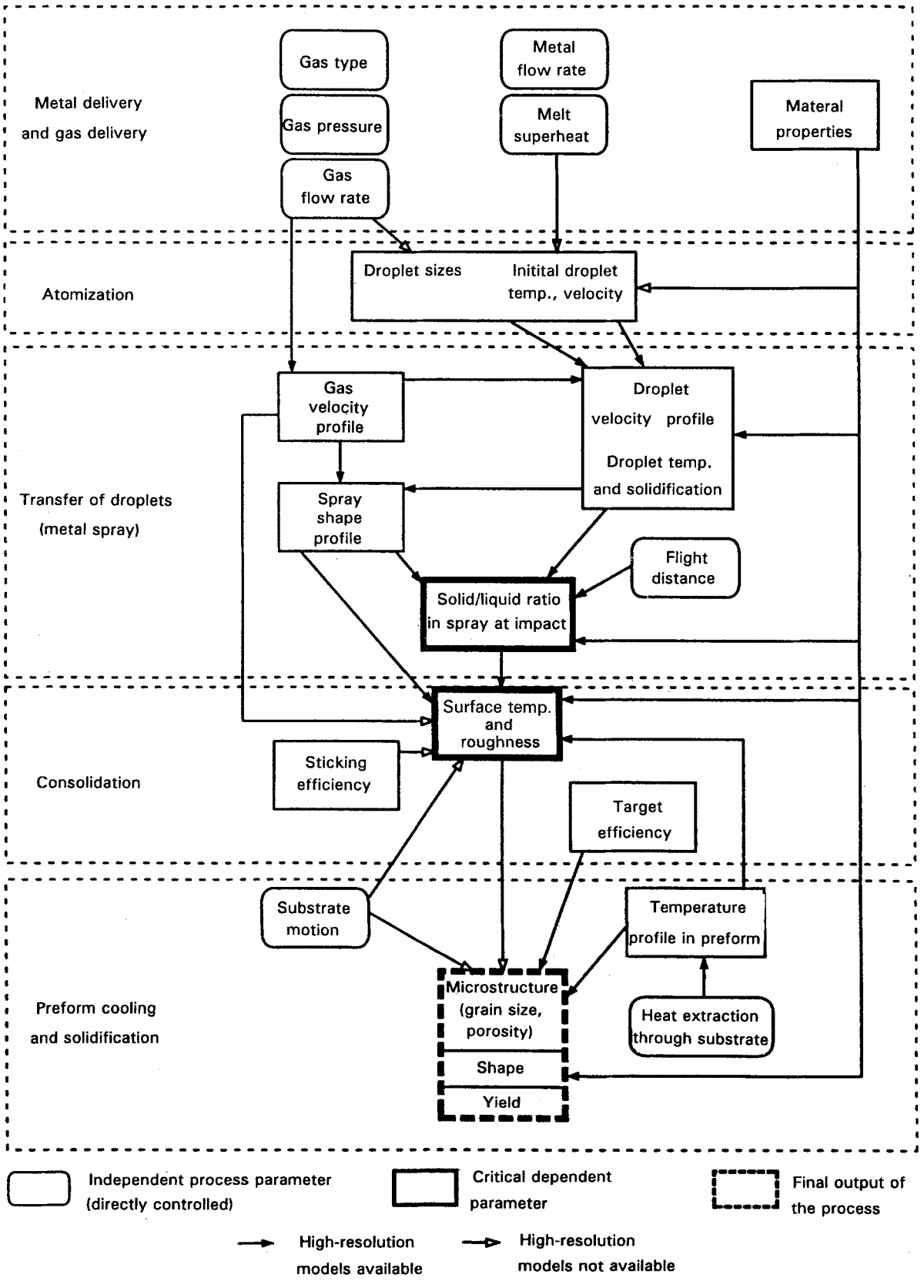


Figure 20 Flow chart depicting the interlinking of independent and dependent process parameters to the various stages of Osprey processing [22].

ted. For the controllers highest level goal, the objective is decomposed into a number of more elementary sub-goals. All of the sub-goals have to be achieved in order to accomplish the objective. To date, all of the preliminary work and models done to support this method appear very encouraging [11, 19].

Mathur *et al.* have also made some very significant contributions to intelligent sensors [22–24]. His group, working on optimizing the Osprey™ process, has developed a computer-controlled spray-casting apparatus. Mathur *et al.* have focused their research on optimizing control of eight independent process parameters such as super heat, gas flow rate, substrate to nozzle distance, etc. (see Fig. 20) which will enable them in turn to control the dependent parameters such as solid/liquid ratio in spray at impact, surface temperature, grain size, etc., (see Fig. 20). By trial and error, Mathur *et al.* have compiled a data base of optimum independent process parameters settings. This information, together with mathematical equations which relate all the parameters to final material properties, have allowed them to program a computer-controlled spray-casting apparatus which is capable of monitoring itself and producing desired end-products with specified material characteristics [22]. The flow chart of Fig. 20 depicts the interlinking of the process parameters. Coupling the optimum independent process parameter settings with appropriate sensor and control technology has enabled Mathur *et al.* to achieve remarkable process control and near automation of atomization and spray deposition [22, 23].

Intelligent control of atomization is not yet a reality. The atomization phenomena is not yet fully described by mathematical representations. The complex stages of atomization ranging from sheet, ligament and primary droplet formation to secondary droplet formation to coalescence and solidification are extremely difficult to quantify (see Fig. 21); however, more of the gas flow and nozzle events can now be represented by equations [11, 23]. This, together with some of the other diagnostic techniques, is bringing the industry one step closer to full diagnostic control.

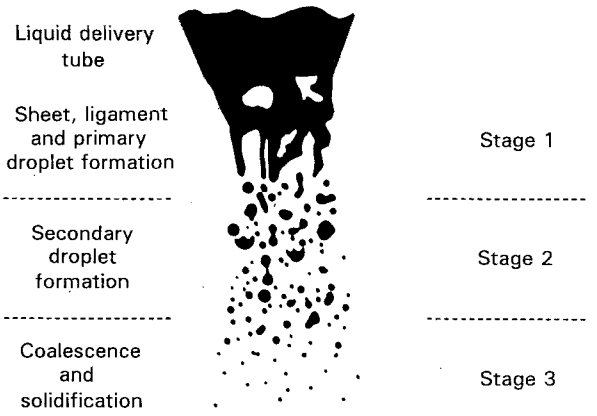


Figure 21 Schematic diagram showing the three stages of gas atomization [18].

9. Conclusion

All of the sensors and diagnostic techniques reviewed here are aimed at controlling atomization events which will, in turn, allow control of the particle size and distribution. Most of the methods mentioned are fundamentally unique. Some utilize optical measurements to obtain powder characterization information while others use electrical signals or geometrical features. Each of these methods offers its own advantages

TABLE I Summary of diagnostic methods

Method	Advantages	Disadvantages
Particle counting, sizing and velocity measurement (PCSV-P) probe Fibre-optic based system	Simultaneous measurements of velocity, size, and concentration. High-temperature operation. Backward and forward scattering geometry	Inaccurate for particles larger than 100 μm diameter. Measurements sensitive to material characteristics
High-speed cinematography	Simple Inexpensive	Poor resolution. Takes time to develop film
High-speed off-axis holographic cinematography	Provides three-dimensional information about particle characterization. Infinite field of depth. Provides particle size and distribution information	Complex set up. Limited resolution. Limited velocity information
Infrared thermal imaging Intensity proportional to T to the 4th power	Provides droplet cooling data and size-distribution information, instant feedback	Needs complicated computer algorithm to decipher thermo-graphs. Complex calibration
Phase Doppler particle analysing (P/DPA)	Measures size, velocity, and concentration. Unaffected by signal attenuations or environmental effects	Based on spherical geometry of droplets. Optical absorption of droplets may affect results
SIMP monitor Electrical signal correlated with particle size	Simple. Non-intrusive. Inexpensive	Dependent on material impurities. Limited particle-size detection. Complex calibration
Intelligent sensors Correlate operational parameters to properties of final material	Automated operation. Reproducible results. Full diagnostic control	Limited mathematical models currently available. Complicated computer algorithms

for each particular application. In addition, each sensor also exhibits some type of shortcoming inherent to its methodology, (see Table I for a comparison of all the reviewed methods). Evaluating each method and its potential diagnostic application will yield the sensor which is best suited to a particular users need. There is no single best or worst diagnostic tool for atomization, but rather a best-suited application. Continued research and integration of the available diagnostic methods will advance atomization science and help yield more reproducible results with custom powder characteristics.

Acknowledgement

The authors acknowledge support of the work on sensors and techniques for atomization and spray deposition from the United States Air Force Office of Scientific Research (grant AASERT F49620-92-J-0262).

References

1. X. LIANG, J. C. EARTHMAN and E. J. LAVERNIA, *Acta Metall. Mater.* **40** (1992) 2923.
2. Y. WU and E. J. LAVERNIA, *Metall. Trans.* **23A** (1992) 2937.
3. X. ZENG, H. LIU, M. CHU and E. J. LAVERNIA, *ibid.* **23A** (1993) 3394.
4. R. PEREZ, J. ZHANG, M. GUNGOR and E. J. LAVERNIA, *ibid.* **24A** (1993) 701.
5. G. JIANG, G. HENEIN and M. W. SIEGEL, *J. Powder Metall.* **26** (1990) 253.
6. M. W. SIEGEL, and H. HENEIN, in "Synthesis and Analysis in Materials Processing: Characterization and Diagnostics of Ceramic and Metal Particulate Processing", edited by E. J. Lavernia, H. Henein and I. Anderson (TMS, Warrendale, PA, 1989) p. 1.
7. H. HENEIN and P. L. MEYER, *J. Powder Metall.* **28** (1992) 149.
8. W. LAUTERBORN and A. JUDT, *Optics Lett.* **18** (1993) 4.
9. R. W. WHATMORE, *Ferroelectrics* **118** (1991) 241.
10. S. D. RIDDER, F. S. BIANCANIELLO, P. I. ESPINA and S. A. MILLER, in "Synthesis and Analysis in Materials Processing: Characterization and Diagnostics of Ceramic and Metal Particulate Processing", edited by E. J. Lavernia, H. Henein and I. Anderson (TMS, Warrendale, PA, 1989) p. 73.
11. S. D. RIDDER, S. A. OSELLA, P. I. ESPINA and F. S. BIANCANIELLO, *J. Powder Metall.* **28** (1992) 133.
12. B. CANTOR and B. P. BEWLAY, *Metall. Trans.* **21B** (1990) 899.
13. B. CANTOR and P. S. GRANT, *Scripta Metall.* **23** (1989) 1651.
14. F. GATASKA, General Electric Corp.-Lynn, MA, private communication (1990).
15. V. G. MCDONELL, E. J. LAVERNIA and G. S. SAMUELSEN, in "Synthesis and Analysis in Materials Processing: Characterization and Diagnostics of Ceramic and Metal Particulate Processing", edited by E. J. Lavernia, H. Henein and I. Anderson (TMS, Warrendale, PA, 1989) p.13.
16. M. KUMAR, T. V. BALASUBRAMANIAN and R. D. K. MISRA, *Sci. Lett.* **9** (1990) 147.
17. L. SALGADO, and F. A. FILHO, *Mater. Sci. Eng. A Struct. Mater. Prop. Microstuct. Process.* **133** (1991) 692.
18. F. S. BIANCANIELLO, J. J. CONWAY, P. I. ESPINA, G. E. MATTINGLY and S. D. RIDDER, *Mater. Sci. Eng.* **A124** (1990) 9.
19. S. A. OSELLA, S. D. RIDDER, F. S. BIANCANIELLO and P. I. ESPINA, *J. Mater.* **43** (1991) 18.
20. F. S. BIANCANIELLO, P. I. ESPINA, G. E. MATTINGLY and S. D. RIDDER, *Mater. Sci. Eng.* **A119** (1989) 161.
21. F. S. BIANCANIELLO, C. PRESSER and S. D. RIDDER, *ibid.* **A124** (1990) 21.
22. P. MATHUR, S. ANNAVARAPU, D. APELIAN and A. LAWLEY, *J. Mater.* **41** (1989) 23.
23. *Idem, Mater. Sci. Eng.* **A142** (1991) 261.
24. S. ANNAVARAPU, D. APELIAN and A. LAWLEY, *Metall. Trans.* **21A** (1990) 3237.

Received 16 November 1993
and accepted 8 June 1994