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Optimization of Sensor Optics for Industrial Thermal Spray Sensors

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Abstract

For a decade now, industrial sensors have been commercially available to both academia and industry. In general, these sensors measure individual and/or bulk properties of the powders being sprayed. Experience has shown that normally, researchers will tend to favor sensors with high spatial resolution like the DPV 2000, because of the fundamental information they give about the plume structure. Such information is vital for proper gun design and spray parameter optimization. However, for process monitoring applications typically performed with a sensor like the AccuraSpray, it is often more convenient to measure global properties over a wider volume inside the plume. In this case, there is always a tradeoff to be made between spatial resolution and fundamental process understanding. This paper illustrates this point by comparing two optical configurations, one with high spatial resolution and another one with medium resolution. This latter configuration makes use of a cylindrical lens to expand the sensor field of view in a direction perpendicular to the spray direction. Results clearly show that with minor optical modifications such sensors can be tailored to precise industrial requirements.

Introduction

Optical thermal spray sensors have become over the last decade indispensable tools in the development and monitoring of thermal spray processes. Typically, they fall into two broad categories as described below.

High spatial resolution sensors such as the DPV 2000 (Tecnar Automation Ltée, St-Bruno, Canada) are in effect able, in real time, to isolate individual particles in a very small portion of the spray stream. Once isolated, all relevant information (size, speed, temperature and position inside the plume) can be extracted and analyzed [1]. This has proven to be an extremely useful tool for researchers and equipment manufacturers for better understanding the influence of spray parameters on particle state and for process optimization [2-7].

Lower spatial resolution sensors such as the PlumeSpector (Tecnar Automation Ltée, St-Bruno, Canada) are typically based on CCD cameras. These sensors give information about plume properties (brightness, shape, overall temperature) that are averaged over volumes of space that comprises a very large number of particles. These sensors have proven quite useful in many applications because of their ease of use and high sensitivity to small process disruptions (i.e. irregular powder feeding, nozzle clogs, etc) [8].

Industrial thermal spray coating applications are now so diverse that neither of these approaches are capable of completely satisfying all user needs. Indeed, it even seems that, from a commercial point of view, the most successful sensor (AccuraSpray [9,10]) somewhat falls in between these two spatial resolution extremes. Customers are always putting more stringent requirements on coating quality, process efficiency and cost. This requires that sensors be flexible enough to be custom tailored to specific applications [11].

In this paper, various optical modifications to the standard AccuraSpray sensor configuration are investigated. Results show that it is possible, simply by adding a cylindrical lens, to adjust the spatial resolution to fit various process requirements. The effect of such a modification of the sensor optics on the particle temperature and velocity measurements is examined.

Experimental Setup

A standard AccuraSpray sensor was used for this investigation. The sensor head optical axis was installed perpendicularly to the particle stream as shown in Figure 1. It was first used in its standard optical configuration which has a working distance of 90 mm and a measurement volume that is typically 3.4 mm (diameter) x 20 mm (depth of field).

Then the AccuraSpray optics was defocused along the Z axis by adding a cylindrical lens in front of the standard optics. The Z axis is parallel to the particle injection direction which is
perpendicular to the torch axis. Different focal lengths of the cylindrical lens were tested (50, 75 and 100 mm). The cylindrical lens was introduced to expand the volume of measurement of the instrument of the instrument, in effect, enabling us to investigate the possible benefits of increased spatial averaging for industrial monitoring.

In this paper, the X axis is aligned along the sprayed particle stream which is supposed horizontal, the Y axis corresponds to the optical axis of the AccuraSpray sensor (also horizontal, but perpendicular to the particle stream) and the Z axis points upwards. The plasma torch being used was a Miller SG 100 with an external injection port. The particles were injected downwards (parallel to the Z axis).

Two powders were used in this investigation. The first was a Zirconia powder (TSP 204NS) with a size cut of +10/-75 um. It was sprayed using a Ar/He plasma with a current of 700 amp. The carrier gas was Ar and powder feed rate was set to 14 gr/min. The second powder was a Ni-22Cr-10Al-1Y powder (Praxair NI 164-2) with a size cut of +44/-74um. It was sprayed using a Ar/He plasma with a current of 700 amp. The carrier gas was Ar and powder feed rate was set to 16.5 gr/min

Figure 1 illustrates the measurement principle of the AccuraSpray. A more detailed explanation of its working principles can be found in [1,2]. For the purpose of this article, we must simply recall that the instrument collects light from two adjacent spots within the spray plume, aligned along the X axis, by simple Gaussian imaging onto the polished extremities of two optical fibers mounted side by side. The Gaussian focus waist of these spots is referred to as the “measurement volume”. The mean particle velocity is obtained by measuring the mean transit time of the particles from the field of view of the first detector to the one of the second detector, the distance between the two fields of view being known. The mean transit time is calculated by computing the cross-correlation between the signals from the two detectors. The average particle temperature is obtained by two-color pyrometry from the ratio of the signal intensities collected by the two sensors filtered at two different wavelengths.

**Results**

When a sheet of paper is placed in front of the AccuraSpray sensor head at the instrument’s working distance, two red spots come into focus allowing the user to visualize its measurement volume size and position (Figure 2). These spots are produced by the alignment optical fibers located on the X Axis, on each side of the light collecting fibers and imaged through the same optics. Therefore, the measurement volume can be imagined as two similar spots located in between the red ones.

In Fig. 3, a 75 mm focal length cylindrical lens has been added to the imaging optics. We can see that the alignment spots and, therefore, the measurement spots as well, have been elongated along the Z axis, perpendicularly to the spraying direction (X axis). The 6-mm blue squares on the sheet of paper give a rough estimate of the elongation (approximately 35 mm).

When a cylindrical lens is added to the optics, it expands the sensor field of view making it possible to collect the thermal radiation emitted by particles traveling in a larger range of trajectories. The use of the cylindrical lens leads also to a sharp reduction in the collected signal intensity emitted by each particles traveling in the sensor filed of view. This is
expected because the particles are then “out of focus” in one direction, which understandably means that a sizable proportion of the light entering the AccuraSpray optics is no longer imaged onto the fiber ends.

This effect is shown in Fig. 4 for various cylindrical lenses. The data was collected at 100 mm from the torch exit when spraying the zirconia powder. Obviously, the defocusing effect increases with shorter focal lengths (f) as illustrated by the monotonous reduction of the signal as a function of the focal length inverse, $1/f$. So, larger measurement volumes actually reduce overall signal strength.

It is important to mention that an alternative solution would have been to design a true anamorphic lens (similar to what is used in wide screen cinema). Such a lens will focus a rectangular object plane onto a square image plane, resulting in elongated measurement spots without significant loss of signal. However, the cost, complexity and size of such a device make it impractical for this purpose, especially if “retrofit” capability is required on the current sensor optics. In addition, for many applications where insensitivity to plume movement relative to the sensor position is important such as with flame and plasma spray processes, the signal intensity collected from the spray particles is generally high (Fig. 5). Consequently, the reduced signal intensity does not significantly affect the precision of the temperature and velocity measurements. The graphs clearly illustrate that the desired spatial averaging effect is achieved, evening out the sharp signal intensity variations normally observed across the plume. For example, at the extreme + or – 10 mm positions, the light intensity collected by the normal AccuraSpray spot has decreased by 80% whereas the defocused optics still collect comparable amounts of light.

The most important point, of course, is to investigate how the temperature and velocity measurements are affected by the cylindrical lens. This is the object of Fig. 6 where these values are plotted as a function of vertical displacement (Z) when using cylindrical lenses of various focal lengths.

The standard AccuraSpray results show the expected plume structure that has been well documented before for this top injection configuration under these parameters; lighter (i.e. smaller) particles tend to not penetrate well into the plasma. Even tough they are heated and accelerated more, they tend to reside mostly in the upper portion of the plume. Large (heavy)
Figure 6: Particle temperature and velocity measured as a function of vertical displacement (Z axis) captured using no cylindrical lens, as well as with 50-mm, 75-mm and 100-mm focal length ones. Measurements were carried out with the zirconia powder at a 100-mm stand-off distance.

particles, because of their larger momentum, tend to end up at the bottom of the plume. These spatial variations are strongly attenuated when a cylindrical lens is added and, as expected, more so for shorter focal lengths. The central “wiggle” in the standard AccuraSpray data is unexplained.

Figure 7 presents similar measurements, but for the NiCrAlY powder using the spray parameters given in the previous section. In this case, results with the 75-mm lens are compared with those obtained with the standard configuration. Again, the same spatial averaging effect is observed.

A common feature of both Fig. 6 and 7 is that the measured values are lower using the cylindrical lens when the sensor’s bull’s-eye is centered on the plume (Z = 0). This is expected because the spatial averaging effect of the cylindrical lens is skewed by the larger, thus brighter particles that are known to be also cooler and slower.

Finally, the sensitivity to motion of the plume in the horizontal plane was also examined. Figure 8 shows comparative temperature and velocity measurements as the sensor is moved closer or farther from the spray plume (Y axis). The expected result is less sensitivity to working distance variations because the defocusing should increase the instrument’s depth of field. This is somewhat evident in the temperature data. The velocity data does not exhibit any significant difference. Both curves show the anticipated, small linear decrease in apparent velocity due to simple geometrical increase in effective magnification as the sensor moves away from the light source.

**Conclusion**

In conclusion, it has been shown that the addition of a cylindrical lens to the AccuraSpray’s optics defocuses its measurement volume in the vertical direction. This achieves the desired effect of spatial averaging, therefore significantly reducing the instrument’s sensitivity to vertical movements of the spray plume.
Figure 8: Comparative temperature and velocity measurements as a function of displacement of the sensor head in the Y direction. Measurements carried out with the zirconia powder at a 100-mm stand-off distance.

As expected, a significant reduction in the amount of light collected by the sensor was also observed. This “side effect” is inconsequential for applications where this modification may be useful, mainly plasma spraying, because of the process’s intense brightness. The instrument’s sensitivity to working distance is not significantly affected by this modification.

For general process monitoring and quality control under production conditions, this method therefore gives a quick and easy way to optimize sensor response to the actual industrial needs.

References