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A Particle Temperature Sensor for Monitoring and Control of the Thermal Spray Process

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Abstract

The temperature and velocity of thermally sprayed particles prior to their impact on the substrate are two of the predominant determinants of coating quality and characteristics. This paper describes an instrument developed for real time monitoring of in-flight particle temperature in an industrial environment. The instrument is designed to operate as a stand alone device for verifying that a desired particle temperature is attained or for developing process settings to yield a particular temperature. The device is also suitable for incorporation into a closed loop process controller. Data showing the relationship between torch parameters and average particle temperature are presented. There is good agreement between previous measurements using laboratory instrumentation and the simpler, industrially hardened technique described here. The assumption of gray body behavior is evaluated and for known emissivities corrections are developed.

IN THE THERMAL SPRAY PROCESS THE PARTICLE temperature at impact on the substrate surface is an important parameter which influences the quality and characteristics of the deposit formed. In order to ensure the repeatability of desired coating characteristics and to control the process, it is necessary to measure the temperature of the particles, in-flight before impact on the substrate. Since the particles are small (on the order of 10 to 100 microns in diameter) and moving at high velocity (up to 1000 m/s) and can have high temperature (as high as 4000 K) only non-intrusive optical techniques are applicable. These techniques deduce the temperature of an object by measuring the intensity of radiation emitted by the object in one or more spectral (wavelength or color) bands. A two-color pyrometer measures the temperature by calculating the ratio of the emitted radiation in two different spectral bands. By using the ratio, the measurement is insensitive to the absolutemagnitude of the radiation falling on the detector and the field of view need not be filled. The technique is however susceptible to errors caused by variations in emissivity with wavelength and special precautions must be observed to ensure that adequate signal strength is available to obtain an accurate measurement.

When attempting to measure the in-flight temperature of particles in the thermal spray process using conventional two-color pyrometers a number of problems unique to the process are encountered. These problems result from a wide range of conditions and materials used in thermal spray processes and is further complicated by the fact that the objects observed (particles in-flight) only partially fill the field of view. The materials sprayed range from pure metals, alloys, intermetallics, and refractories, to various ceramics, including special composite materials which can consist of oxides, carbides, or other compounds in a metal matrix. The temperatures to which these materials are heated for application varies over a wide range, hence the intensity of radiation emitted can vary by an order of magnitude or more. The spectral emissivity can also vary greatly from material to material, hence the intensity of radiation emitted by two different materials at the same temperature can vary by a factor as large as five. Since the objects observed do not fill the field of view, the intensity of radiation falling on the detector is also dependent on the particle feed rate or number of particles in the measurement volume at any instant and the extent and geometry of the spray field observed. In order to avoid these difficulties and to facilitate the use of a two-color optical pyrometry for the measurement of in-flight particle temperature a number of modifications and improvements have been engineered into the In-flight Particle Pyrometer (IPP) described here.

The IPP consists of three main components, the electronics, the optical measurement head, and the fiber cable which connects the two. The sensor head, figure 1, is compact and contains only passive optical components. The objective lens is interchangeable with a 200 mm focal length lens, standard. This lens forms a measurement volume which is pencil shaped, 5 mm in diameter and approximately 50 mm long. The temperature read by the IPP is then an average of all particles in this volume, however it is heavily weighted toward the high number density, "sweet spot", of the spray field. For

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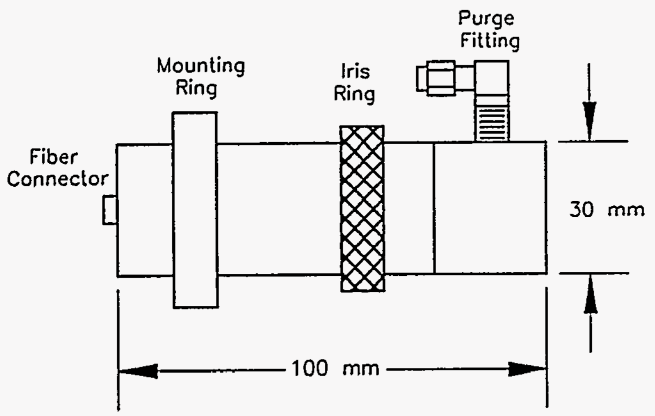

Figure 1. Optical head

most applications this is the portion of the spray which forms the coating and is most indicative of gun performance. Depending on particle temperature, particle loading or feed rate, and the material being sprayed the brightness of the particle spray and hence the signal levels observed can change by an order of magnitude or more. This wide variation in brightness is accommodated by a continuously variable iris which is incorporated into the optical head. The iris manipulating ring is easily accessible for adjustment and is sealed to avoid admitting particulate material to the housing. Optimization of the iris setting is accomplished by observing the light bar indicator level and opening or closing the iris until the levels are consistently in the "green" area indicating an acceptable signal. The sensor head is coupled to the electronics via a fiber optic cable. Fiber optic coupling allows maximum flexibility of deployment while providing isolation of the electronics from electromagnetic interference and the hot, particulate laden environment of a typical spray booth. The fiber optic delivers light to the solid state detectors housed inside the electronics. Standard band centers for the two colors are $\lambda_{CH1} = 0.95$ µm and $\lambda_{CH2} = 1.35$ µm. Frequency response is limited to 10 Hz.

The preferred orientation of the optical head with respect to the spray device is approximately perpendicular to the gun axis, observing a region consistent with the stand off of the part to be sprayed, and slightly downstream of the bright plasma or combustion flame. The optical head is located in the plane defined by the powder injector and the torch axis. In this orientation changes in operation which result in changes in particle trajectory do not cause the spray pattern to move out of the IPP field of view. Alignment is facilitated by the ability to project a visible spot of light through the optical fiber and the imaging optics in the optical head. The visible projected spot coincides with the measurement volume extent as well as its location. The actual spray pattern produced may not, however, coincide exactly with the geometric centerline of the spray device. To overcome this problem the alignment of the measurement volume is optimized to coincide with the spray pattern "sweet spot" by maximizing the signal level meters on the front panel of the electronics. Once this alignment is accomplished the measurement is insensitive to minor variations in the spray pattern caused by changes in operating parameters and conditions. The digital display, figure 2, which provides a direct indication of temperature and has a "tare" feature which allows the operator to easily and unambiguously observe the changes in particle temperature caused by changes in operating parameters. For instance, if the baseline spray condition results in an average particle temperature of 1900 °C, and the "tare" feature is activated a "zero" is displayed. As the spray parameters are varied, the resulting change in particle temperature, represented as a delta temperature between the baseline condition and the new condition is displayed directly. Pushing the "tare reset" button returns the display to the actual particle temperature. If the signal levels drop below a minimum acceptable threshold the digital temperature display sets itself to "zero". When adjustments are made that raise the signal level above the minimum threshold the digital display automatically resets itself and resumes displaying the measured temperature. Along with a digital temperature display the device provides both single color and two-color ratio analog outputs which are suitable for input to control and data acquisition systems.

Calibration and Emissivity Correction

The basic premise behind all radiation thermometry is Plank's Law, which describes the emissive power of a radiating body as a function of wavelength, emissivity and temperature. Dual-wavelength (ratio or two color) pyrometry involves the measurement of the spectral energy in two different wavelength bands. Using Planck's law the ratio of radiant energy, R, in two different wavelength bands, λ_1 and λ_2, is given by:

$$R = \frac{\epsilon_{\lambda_1}}{\epsilon_{\lambda_2}} \left(\frac{\lambda_1}{\lambda_2}\right)^{-5} \exp\left[\frac{C_2}{T}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\right] \quad (1)$$

where T is the surface temperature of the radiating body, C_2 = 1.4388 (cm)(K) is a constant, and ϵ_λ is the spectral emissivity.

Over the range of temperatures for which the IPP is applied (1000 to 4000 K) and because of the way in which the spectral bandwidths and band centers are chosen, the temperature as a function of the ratio of radiant energy can be approximated by a linear function of the measured voltage ratio, V_{CH1}/V_{CH2}. The expression for the observed ratio temperature, T, is given by:

$$T = A + B\left(\frac{V_{ch1}}{V_{ch2}}\right) \quad (2)$$

where A and B are calibration constants and V is the voltage out of the individual detector amplifiers. Using this approximation

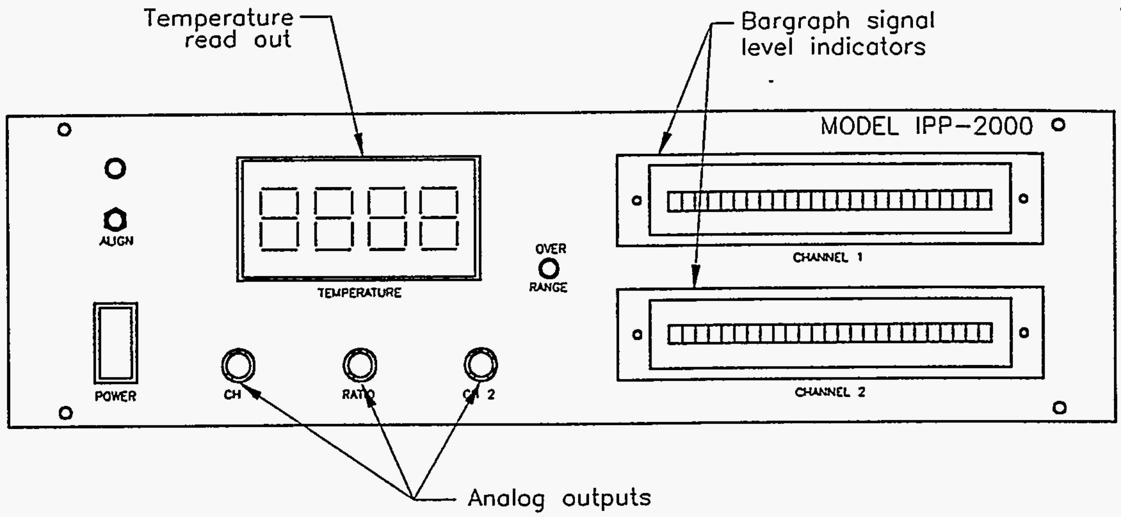

Figure 2. Front panel

the IPP is calibrated against a tungsten ribbon standard. The square of the residuals for this linear calibration is > 0.995. This end to end calibration takes into account responsivities, area, and amplifier differences in the detectors and when calibrated on a tungsten lamp, includes the spectral emissivity variation of tungsten. For materials with a spectral emissivity ratio similar to tungsten (1.29)[1] the uncertainty in the absolute temperature read by the IPP is on the order of ± 5%.

For applications where the absolute measurement of temperature is not required, such as controlling about a set point, or determining relative changes about a known condition, an emissivity correction may not be necessary. The temperature indicated will be single valued for a given spray condition. That is, even if the spectral emissivity relationship is not known, and is not accounted for, the desired condition can be repeated by "setting" the spray device to produce particles which yield the same temperature reading. For example, an increase in particle feed rate may require an increase in operating power to produce a particle stream at the desired temperature condition. Since the IPP is insensitive to particle loading, the same average particle temperature at the new feed rate is assured by adjusting the input power to yield the same IPP temperature reading. Another application would consist of maintaining the particle temperature within a quality control operating window. In this case the absolute measurement of temperature may not be necessary. The major concerns are the ability to repeat a condition and compensate for drift from that condition. If a quality control set point has already been determined then the IPP can be used without emissivity compensation to ensure that this set point is maintained.

For applications where the absolute measurement of temperature is desirable, such as process development or scientific investigations, emissivity correction factors should be considered. The problem is basically one of how to infer the true temperature from the radiant energy sensed by the IPP. If the relationship between emissivity and wavelength is known it is possible to estimate a correction from the tungsten calibration. The difference between the temperature read by the IPP, T_w, and the true temperature, T_x of a material who's spectral emissivity ratio differs from that of tungsten, is found from setting the ratio of emissive powers for material x equal to that of tungsten, w, to arrive at:

$$\frac{1}{T_x} = \frac{1}{T_w} + \frac{\ln\left(\frac{\epsilon_{\lambda_1}}{\epsilon_{\lambda_2}}\right)_w \left(\frac{\epsilon_{\lambda_2}}{\epsilon_{\lambda_1}}\right)_x}{C_2\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)} \qquad (3)$$

Shown in figure 3 is the true temperature as a function of the temperature read by the IPP as described by equation 3 for different spectral emissivity ratios. Many metallic materials such as nickel, stainless steel, and inconel have spectral emissivity ratios between 1.20 and that of tungsten, 1.29[1,2].

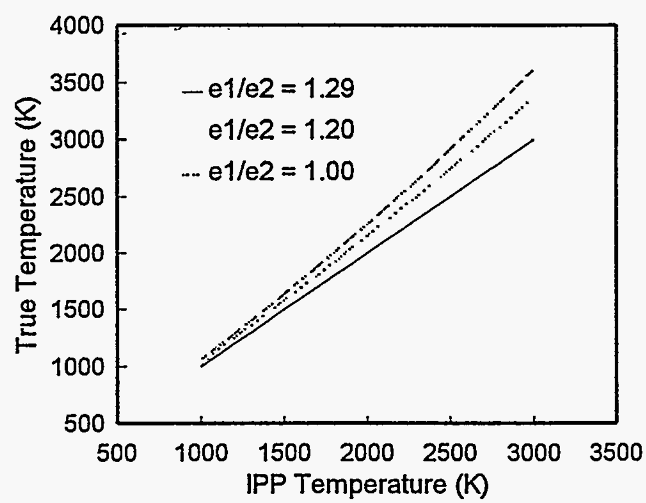

Figure 3. Correction for the IPP calibrated on a tungsten lamp standard.

For an IPP reading of 2000 K, the true temperature, T_x, for a material with an emissivity of 1.20 would be 2066 K. Many metal oxides and ceramics behave more like gray bodies, i.e. their emissivity ratio is unity[3]. In this case the actual temperature, T_x, of the particles is 2256 K while the IPP reads 2000 K. This gray body correction represents the worst case. Although the difference between the gray body temperature and the tungsten calibration is significant, the linearity of this correction over the useful temperature range makes it relatively simple to program the temperature display to read the correct temperature.

The procedure described above should be considered only a first order correction. The development of more precise corrections is possible, however it depends heavily on the materials, temperature ranges, formation of oxide layers or other chemical reactions, etc. Unfortunately it is not possible to provide a simple general correction for all situations which may be encountered.

Results

In order to investigate the validity of the temperature correction described above, the IPP was set up on a black body source. The temperature of the black body source was measured with a type S thermocouple. This data is shown in figure 4 along with the IPP data. The temperature read by the IPP is displayed as a function of the ratio of emissive powers or the ratio of output voltages at the two different colors. Applying the correction discussed above with an emissivity ratio of 1.0 brings the IPP reading in line with the black body temperatures measured by the thermocouple.

For all the sprayed particle data described here, the Miller SG-100 plasma torch was used with a 165/129 anode/cathode combination. Nominal torch operating conditions are 800 A at 35 V, for a total power input of 28 kW. The inlet plasma gas flow rate is 2830 liters/hr of argon and 1330 liters/hr of helium. The particle carrier gas flow rate is 368 liters/hr, also argon. All results were obtained in air at an atmospheric pressure of 85.5 kPa. Figures 5 and 6 compare the multi particle data taken by the IPP to data taken on single particles[4,5]. Figure 5 is a radial scan of average alumina particle temperature at a standoff of 100 mm from the torch face. The single particle data represents a time average of approximately 200 individual particles at discreet measurement locations. The multi-particle data was taken by traversing the IPP across the spray, continuously taking data at 10 Hz. Due the relatively large measurement volume this data is not only time averaged but spatially (line of sight) averaged. Spectral emissivity data on alumina indicate gray body behavior, i.e. the ratio of emissivities at the wavelengths used by the IPP is unity. With this the IPP temperatures were corrected using the above procedure. Considering that these two sets of data were taken at different times, the agreement from the spacial and time average of the IPP to the time average of the single particle data is reasonable and well within the uncertainties. The fact that the single particle temperature is slightly lower than the corrected multi particle data may indicate that the gray body assumption for alumina is not completely accurate. Figure 6 is a radial scan

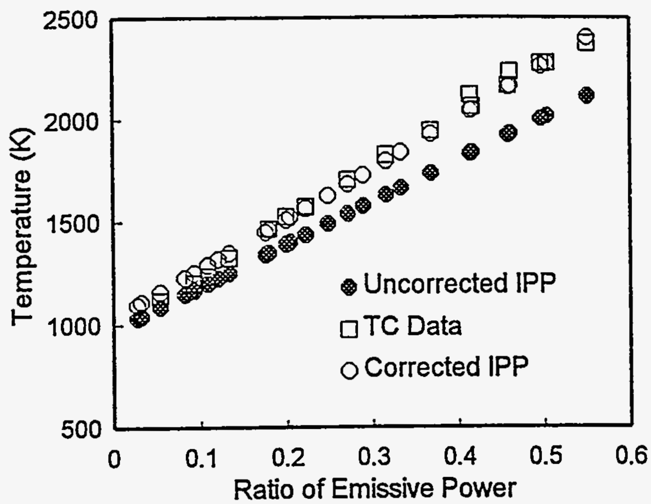

Figure 4. Temperature of a black body source measured with a type S thermocouple and the IPP

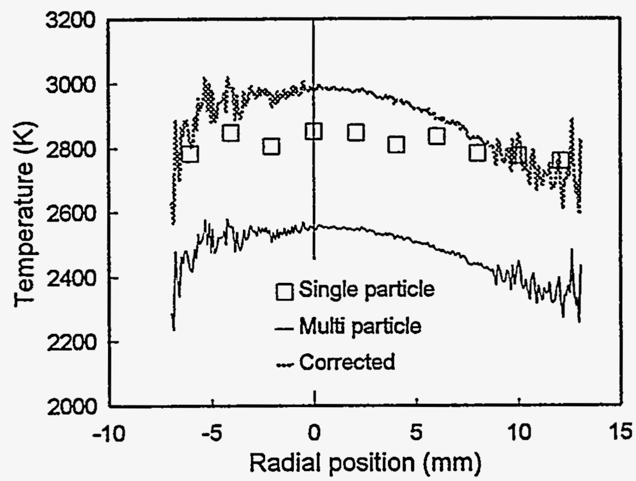

Figure 5. Comparison of single particle and multi particle average temperatures for alumina.

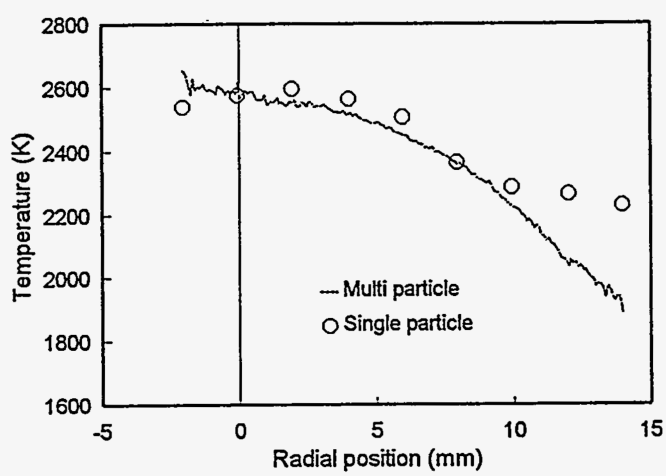

Figure 6. Comparison of single particle and multi-particle average particle temperature for NiAl.

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of average temperature for NiAl particles at a standoff of 63 mm from the torch face, sprayed at the nominal torch operating conditions. In this case the ratio of emissivities for NiAl is assumed to be similar to that of tungsten and no correction was made. Again, the agreement between a single particle average and a multi-particle average is good.

Figure 7 and 8 are examples of how the IPP can be used to monitor and correlate particle temperature to torch operating conditions. For both plots the pyrometer was aligned to produce the highest signal level at a standoff of 100 mm from the torch face. The particle velocity was obtained from a laser Doppler velocimeter (LDV) which is described elsewhere[5]. The enthalpy available in the plasma also shown in figure 7 and 8, was calculated based on the difference between the power input to the torch and the heat lost to the cooling water. Figure 7 shows nearly a 200 degree increase in average particle temperature for a ± 20% random change in torch operating current. Figure 8 shows a 50 degree decrease in average particle temperature for a ± 20 % random change in the primary gas flow rate. Changes in particle velocity for both the variations in torch current and primary gas flow rate are approximately 10 m/s. Assuming that the plasma volume remains relatively constant, the particle temperature change can not be attributed to changes in residence time. However figure 7 shows an increase in the plasma enthalpy, ultimately increasing the particle temperature and figure 8 shows a slight decrease in the available enthalpy which accounts for the small decrease in particle temperature.

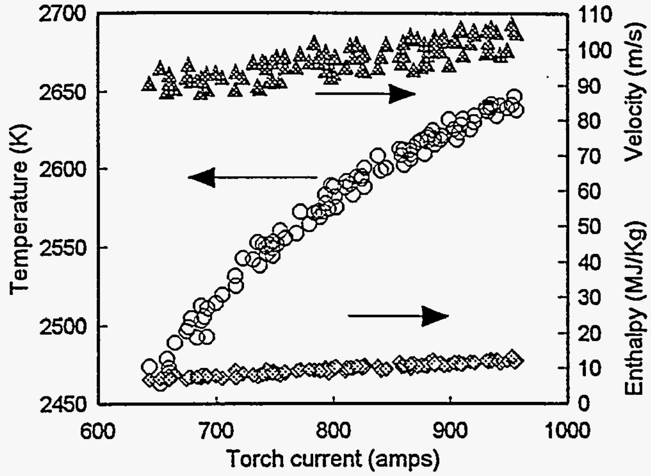

Figure 7. Average NiAl particle temperature as a function of torch current.

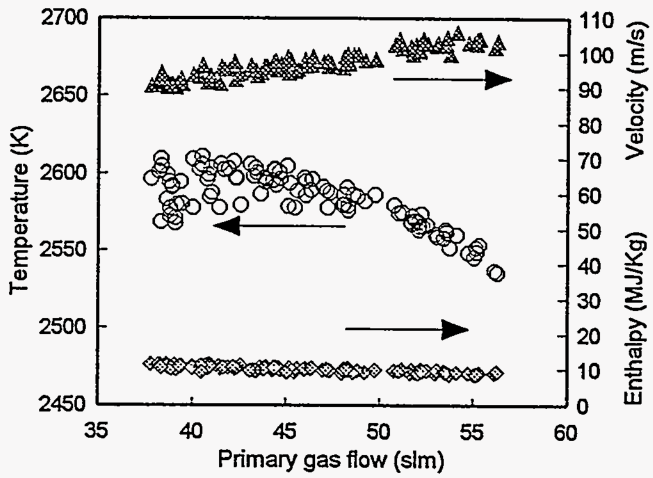

Figure 8. Average particle temperature as a function of primary gas flow rate.

Conclusions

Due to inconsistencies in spray booth equivalency, powder quality, wear, human error and a variety of other reasons, coatings produced by thermal spray are not always consistent. One of the more significant parameters which determine the characteristics of a coating is the particle temperature just before it impacts the substrate. Providing a measure of this parameter, the IPP is applicable to thermal spray processes in several ways. As a simple monitor of particle temperature in daily spray operations, the IPP can ensure proper spray equipment performance and equivalency between spray systems, thus improving coating quality consistency. The IPP is also a valuable tool for process parameter development. Correlations between torch parameters, particle temperature and coating characteristics makes it possible to produce coatings with the desired characteristics. A limited investigation of the dependence of particle temperature on torch parameters shows that the particle temperature is a strong function of the input power and that the primary gas flow rate has less of an effect.

As the application of thermal spray processes expands into automated manufacturing it is becoming evident that feed back control of the process is necessary. The IPP is an instrument which is both durable and simple enough to be used as a sensor for feed back control in an industrial environment. For set point control or monitoring applications, deviations in the particle temperature are important while the absolute value is not so significant. In the case of research and process development application, it may be desirable to know the absolute particle temperature. The correction described above allows the user of the IPP to correct the IPP reading for different materials. The accuracy of this correction is only limited by how well the spectral emissivity is known for the material. Assuming alumina behaves as a gray body the corrected IPP temperature readings, which are both spatially and temporally averaged, are brought within the uncertainty of the single particle data which is only temporally averaged.

Acknowledgments

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