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# THE MEASUREMENT OF SINGLE PARTICLE TEMPERATURE IN PLASMA SPRAYS

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## ABSTRACT

A measurement technique for simultaneously obtaining the size, velocity, temperature, and relative number density of particles entrained in high temperature flow fields is described. In determining the particle temperature from a two-color pyrometery technique, assumptions about the relative spectral emissivity of the particle are required. For situations in which the particle surface undergoes chemical reactions the assumption of grey body behavior is shown to introduce large Temperature measurement uncertainties. Results from isolated, laser heated, single particle measurements and in-flight data from the plasma spraying of WC-Co are presented.

## INTRODUCTION

The behavior of a particle and the interactions between a particle and the plasma surrounding it are important in the understanding, development and optimization of plasma spray coating processes that involve fine powders. To fully characterize the particle flow field, it is necessary to measure the particle size, velocity, temperature and number density. In this paper we will describe a measurement technique for simultaneously obtaining these parameters in high temperature flow fields and will concentrate on the difficulties associated with the in-flight measurement of temperature. In the determination of temperature assumptions about the relative spectral emissivity of the particles are required. For non-reacting materials the assumption of grey body behavior does not generally introduce large uncertainties. In reactive systems, however, the plasma spray process is complicated by complex chemical reactions which occur on the particle surface. In particular, the formation of oxides can lead to large deviations from grey body behavior. An example is the spraying of tungsten carbide-cobalt, a commonly used wear coating. In this system, 5μm tungsten carbide particles are bound together by Cobalt into nominally 20 μm diameter particles. Tungsten carbide, when sprayed in oxygen containing environments, is known to decompose via oxidation of the carbides, leading to inferior, carbon deficient coatings [1,2]. The temperatures characteristic of the WC-Co spray material are summarized in Table I. Results from isolated, laser heated, single particle experiments and in-flight data from the plasma spraying of WC-Co are presented in the following sections.

## IN-CELL SINGLE PARTICLE MEASUREMENTS

Measurements of the time-temperature profiles of single particles of cobalt and tungsten, simulating thermal histories encountered in the plasma spray were conducted by suspending particles in a quadrupole electrodynamic balance, heating the particles with a $CO_2$ laser beam, and observing the radiation emitted. The objective is to evaluate the validity of the assumption of grey body behavior. This evaluation is important in the interpretation of in-flight results obtained in the plasma spray environment.

The quadrupole electrodynamic balance was originally developed by Wuerker [3]. Since the cell has been described in detail elsewhere [4,5] only a brief description will be given here. A hyperboloid electrode configuration (two DC end electrodes and an AC ring electrode) is used to create a saddle point in the electric field at the center of the cell where a particle with the proper ratio of surface charge to mass can be suspended. When the suspended particle is heated to high temperatures ($T>1000$ K) thermionic emission causes a loss of charge from the surface and leads to the destabilization and ejection from the focus of the heating laser beam. It has been found experimentally that for particles in the 10-50 μm size range, heated to temperatures above 2000 K, retention times on the order of 10-50 ms can be attained. These times are comparable with the particle residence times in a plasma spray.

Table I. Characteristic Temperatures, in degrees Kelvin, of the WC-Co plasma spray system.

| Material | Melting Point | Boiling Point | Decomposition |
|---|---|---|---|
| WC | ---- | ---- | 2873 |
| $W_2C$ | 3133 | ---- | ---- |
| W | 3683 | 5933 | ---- |
| Co | 1768 | 3173 | ---- |

Particles were injected by means of a syringe inserted through one of the asymptotic ports of the quadrupole cell. In this process the particles acquire triboelectric charge and and those with a charge-to-mass ratio of approximately the value required for suspension are captured near the center of the field. By manipulating the applied AC and DC fields all but one of the particles are ejected. A 20W pulsed $CO_2$ laser beam is divided by a beam splitter and focused onto the particle from opposite sides of the cell. The radiation emitted by the particles is detected by photomultiplier tubes. The particle surface heating rates range between $10^3$ and $10^6$ K/s, and surface cooling rates in the range of $10^4$ to $10^5$ K/s were observed.

## RESULTS OF SINGLE PARTICLE MEASUREMENTS

Results obtained on cobalt and tungsten particles are presented here. Figure 1a shows typical traces of the photomultiplier signal from a cobalt particle heated to a temperature above its melting point, cooled below its normal melting point and solidified by recalescence. The single color temperatures, calculated by using the melting point as a reference temperature are compared to the two color temperature based on the assumption of a grey body are shown in Figure 1b. The two color temperatures calculated with experimentally measured emissivities at 650 and 550 nm reported by Jain et al [6] are shown in Figure 1c. This result indicates that, for the case of cobalt the grey body assumption leads to an error of about 100 K in the measured temperature.

Similiar experiments were conducted on tungsten particles in air. The possible effect of surface reactions and transformations of the emissivity and, consequently, the effect on the measured temperatures of single particles in the plasma spray is of particular interest. From the measured radiation signal intensities at the melting point it is possible to calculate the apparent emissivity ratios of the particle. Using the emissivity at 650 nm as the reference value, the emissivity ratios obtained from signals at other wavelengths (450, 550, 750, and 850 nm) for different tungsten particles are shown in Figure 2, and compared to emissivity ratios for tungsten reported in the literature [7]. The emissivity ratios resulting from this calculation are indicative of an absorption edge within the visible range of the optical spectrum. Such and edge has not been found, nor would be expected, for tungsten or any other metal. However, absorption edges are characteristic of tungsten and other metal oxides. Figure 3 shows approximate absorption spectra for three tungsten oxides derived from data reported by Porter et al [8]. The absorption edges of $WO_2$ and $W_{18}O_{49}$ are blue shifted relative to the emissivities ratios of Figure 2. The absorption edge of $W_{20}O_{58}$ more nearly matches the experimentally measured emissivity ratios although it is also somewhat blue shifted. Tungsten forms oxides in diverse stoichiometric ratios, and the tungsten-oxygen phase diagram is well known only up to about 1800 K. Thus an oxide phase formed at the particle surface at temperatures near the melting point of tungsten may be one possible explanation of the abnormal grey body temperatures of tungsten particles inside the plasma spray.

## IN-FLIGHT PARTICLE MEASUREMENTS

The measurement system developed for the simultaneous measurement of particle size, velocity and temperature integrates a laser Doppler velocimeter (LDV) system with a scattered light particle size measurement and a high speed two-color pyrometer. Since the measurement system has been described in detail elsewhere [9], only a brief description will appear here. The particle size is determined from the absolute magnitude of scattered laser light, particle velocity is determined by a dual crossed-beam LDV, and temperature is determined from a measurement of light emitted by the individual incandescent particles at two wavelengths. A multi-line 6 W Ar ion laser is used as the light source for velocity and sizing. The LDV measurement volume, consisting of the intersection of two 514 nm laser beams, is situated in the center of the larger diameter 488 nm beam. The intersection of the LDV measurement volume and the second beam constitutes the particle size measurement volume. Simultaneously, the light emitted by the hot, incandescent particles passing through this same region is observed. The particle temperature is derived from the ratio of the signals at each of the two wavelengths observed (600 and 700 nm). The spatial resolution of $<1$ $mm^3$ is such that the distribution of particle size, velocity and temperature can be mapped over typical flow fields. The estimated measurement uncertainties are 125 K at 2500 K for particle temperature (assuming grey body behavior), 4.9 $\mu m$ for particle size and better than 5 m/s for particle velocity.

## RESULTS OF PLASMA EXPERIMENTS

The commercial plasma torch used in this study has a nozzle exit diameter of 8 mm. Particles are injected radially into the flow, on the nozzle diameter, at a single axial location, 18mm upstream of the torch exit. Typical torch operating conditions are 900 A at 38 V, for a total power input of 34 kW. Approximately 68% of the total torch power is deposited in the gas. 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.

The average centerline values of particle size and temperature, assuming grey body behavior, appear in Figures 5 and 6. The particle size data indicate a gradual decrease in particle size out to an axial location of approximately 80 mm. This decrease in particle size is consistent with the observation that half of the cobalt initially present is lost through vaporization in the spray process [1]. The measured particle temperatures, assuming grey body behavior, however, do not indicate vaporization. In fact the measured particle temperatures, except for locations very near the nozzle exit are almost 1000 K below the boiling point of cobalt. A possible explanation is that near the nozzle exit little oxygen is present and the grey body assumption is justified. In torches of this type the surrounding atmosphere is rapidly entrained into the core flow [10], resulting in an ample supply of oxygen and the formation of tungsten oxides and oxi-carbides with potentially large changes in relative emissivities. Also shown in Figure 6 is the same data assuming a relative emissivity ratio of 1.3. This adjustment to the data yields temperatures that are consistent with the particle size data (temperatures near the boiling point of cobalt) and observations in Reference [1].

## CONCLUSIONS

The measurement of particle size, velocity, temperature and relative particle number density in plasma torches and other high temperature processes is essential to the understanding of process parameters and of the transformations that define the structure of the final product. A major difficulty in such measurements is the accurate determination of temperature by radiation pyrometry. This is complicated by the fact that the intensity of the radiation signal is a function of the emissivity, hence composition and structure, of a reacting particle. This paper illustrates how additional measurements conducted on isolated particles can assist in the interpretation of in-flight measurements in a plasma torch.

## ACKNOWLEDGEMENT

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FIGURE NOT AVAILABLE AT THIS TIME

Figure 1a. Photomultiplier output at 550, 650 and 850 nm from pulse heating of 47 $\mu$m particle.

NOT AVAILABLE AT THIS TIME

Figure 1b. Single color (550 and 650 nm) temperatures compared to grey body two color temperature (650/550 nm), for pulse heated 47 $\mu$m particle

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Figure 1c. Single color (550 and 650 nm) temperatures compared to emissivity-corrected two color temperature, for pulse-heated, 47$\mu$m particle.

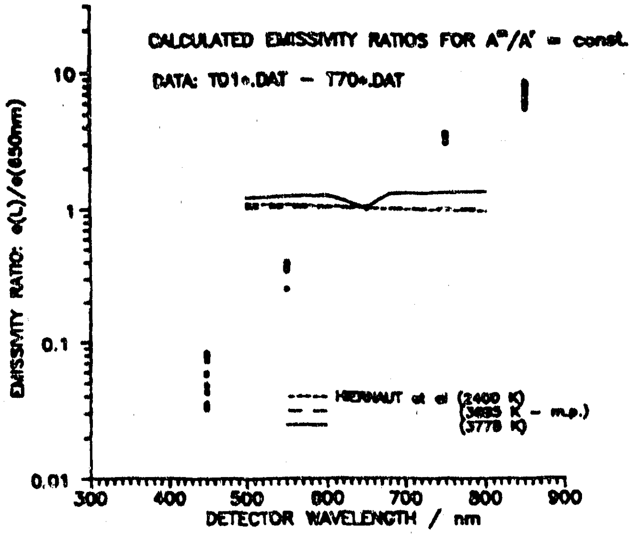


Figure 2. Emissivity ratios at the melting point calculated from radiation signals from pulse-heated tungsten particles.

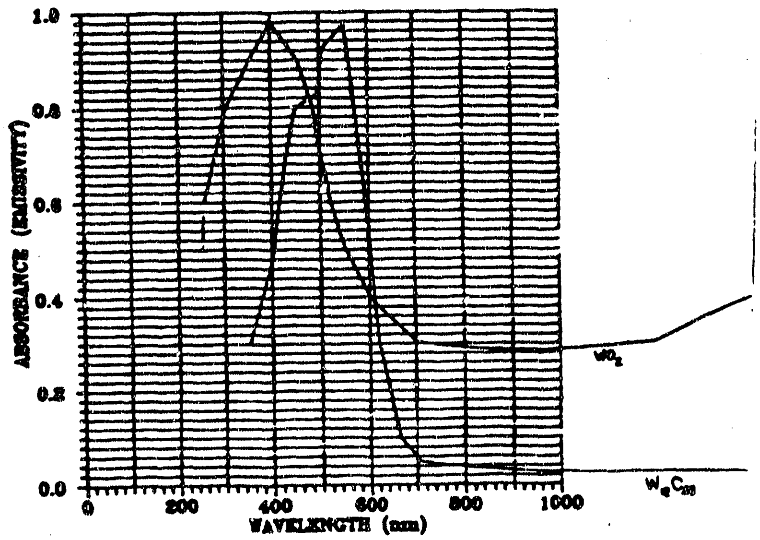


Figure 3. Absorption spectra of intermediate oxides of tungsten (after data from Reference 9).

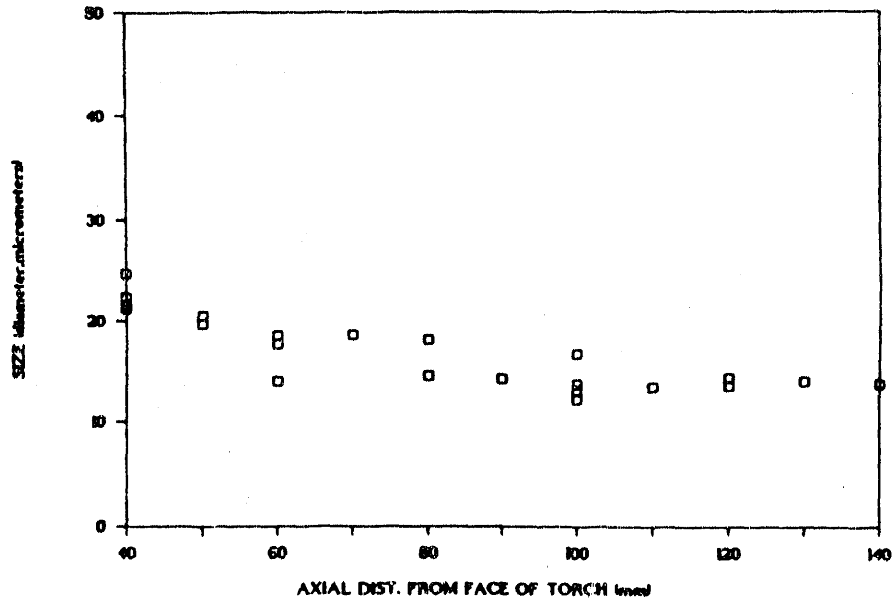


Fig. 4. Average centerline particle size data.

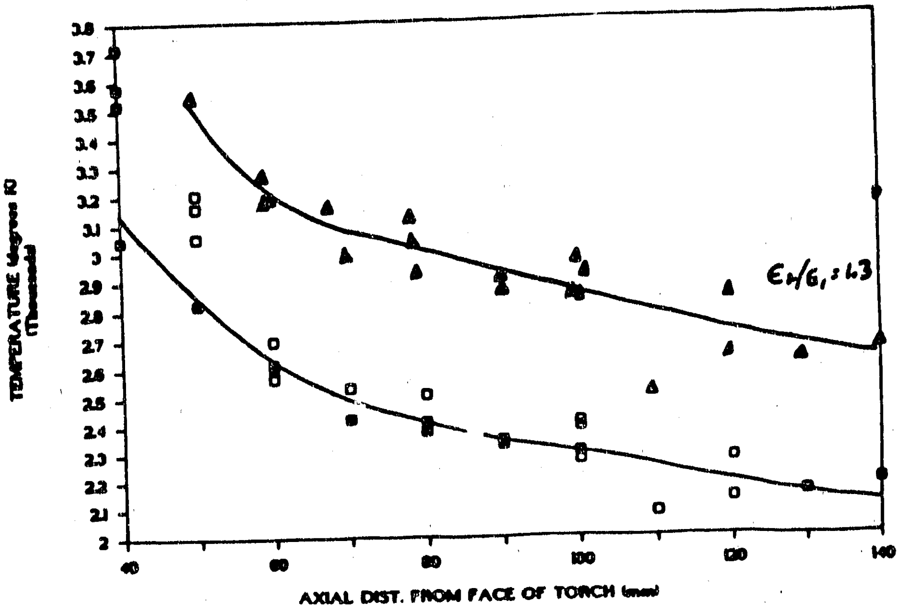


Fig. 5. Average centerline particle temperature data.

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