INFRA-RED EMISSION OF AN ARC PLASMA JET IN AIR

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Abstract

The surface temperature of substrate and previously deposited layers during air plasma spraying (APS) governs many coating properties such as residual stresses.

A large spectral band pyrometer is used to achieve surface temperature monitoring, between ambient and 600°C, in the harsh environment of spray booths. However, such measurements are disturbed by:

- The evolution of the target emissivity due to change in the substrate roughness, the surface temperature and material of the target.
- The direct or reflected Infra-Red (IR) emission of the plasma.
- The thermal radiation emitted by particles that are introduced in the plasma jet to be accelerated and melted in order to form a deposit on a substrate.
- The absorption due to the dusts, water vapor and carbon dioxide present in the surrounding atmosphere.

These points have been studied to determine their influence upon pyrometric measurements in order to take them into account to achieve surface temperature measurements as exact as possible of the substrate or previously deposited layers during APS.

Experimental conditions have been carried out with an Ar-H₂ DC plasma jet and a monochromator equipped of a nitrogen-cooled detector made of HgCdTe able to work in the 2-15 µm spectral range.

Spectral bands where the disturbance is minimum have been deduced. And it has been possible to establish corrections to pyrometric signals.

1. Introduction

Nowadays air plasma spraying (APS) is a widely used process in industry (aeronautics, aircraft, automobile, etc...). It is used to realize heat, wear, erosion, corrosion resistant coatings in order to improve performance and/or service life of materials. But APS remains a complex process governed by many parameters as, for instance, plasma forming gas flow rate and composition, arc current, powder feed rate, relative torch / substrate movement and speed... [1]. Among all these parameters, the temperature of the substrate and that of previously deposited layers influence especially droplets flattening, interlamellar contacts and thus residual stresses [2,3]. This last property ensures a better resistance to the pulling off test if the coating is in compression instead of tension. Compressive residual stress could be reached by controlling the substrate surface temperature during the spraying stage for a given material/coating combination [4]. Figure 1 represents the evolution of residual stresses according to the substrate surface temperature. It shows that a compressive residual stress is obtained for a deposit temperature over 330 °C during spraying.

A large band pyrometer as been chosen in order to carry out surface target temperature measurements. Actually, the use of thermocouples is not possible in an industrial context and
the thermographic techniques remains expensive. The measurements were performed in the vicinity of the particle spray jet impact onto the target surface. The wavelength range of the pyrometer has been chosen to avoid both Infra-Red (IR) absorption due to carbon dioxide and water vapor contained in the atmosphere and also the IR emission of the plasma (Ar + H₂) and in-flight particles.

Figure 1 : Typical evolutions of mean quenching, thermal and residual stresses of a constant thickness coating X on a substrate Y according to the deposit temperature during air plasma spraying.

* Mean quenching stress  * Thermal stress  * Residual stress

First, will be presented the experimental set-up used to characterize the IR radiation environment of the APS in order to determine the wavelength range perturbed by the IR emission of both plasma and in-flight particles. In a second part, results will be described and discussed.

2. Experimental set-up

Figure 2 : Experimental set-up ; T : plasma torch, C: chopper, L : ZnSe lens (f = 100 mm), D : HgCdTe detector (2-15 μm), A : lock-in amplifier, I : electronic interface
The IR set-up is displayed in figure 2. It has been set in ambient air and consists of a Czerny-Turner monochromator, a ZnSe lens (f = 100 mm), a chopper (100 Hz), a lock-in amplifier, a HgCdTe detector with a wavelength range of 2-15 μm, and a computer for data acquisition and treatments. 2 gratings blazed respectively at 3 and 9 μm allows to observe the 2-15 μm spectral range. Both entrance and exit slit height are 20 mm. The exit slit width is 2 mm, that of the entrance slit varying according to the observed spectral range. Spectra are carried out in first order. A DC plasma torch is used. Its parameters are the following : Ar/H₂ at 32/8 slm, I = 480 A, U = 50 V, nozzle internal diameter = 7 mm, thermal efficiency ηₘ = 52 %. NiAl 5wt% powder (Metco 450NS), with clad particles and a size distribution 90+45 μm. These particles are self bonding and undergo an exothermic reaction during spraying. They are injected 3 mm downstream of the nozzle exit with a 1.8 mm internal diameter injector orthogonal to the jet axis. The powder feed rate is 1 kg/h and the carrier Ar flow rate is 3.7 slm.

3. Spectral emission of a plasma torch

![Figure 3: Calculated composition of a gas mixture of Ar/H₂ (32/12 slm) with 50% of air according to gas temperature.](image)

Typical composition calculations were performed for a mixture of 32 slm Ar with 12 slm H₂ with 4 to 400 slm of air entrained. The experimental data in moles/s result in the typical curve presented in figure 3 for 0.03 moles/s of air. It shows readily that below 3000 K the predominant species are N₂, H₂, H₂O and O₂. Over 4000 K the main species are H, O, At and N₂, N showing up only over 6000 K. The quantities of NO and OH are relatively small (less than one tenth in molar fraction). For the injected particles, Al and Ni atoms are excited over 6000 K.

Figure 4 presents the plasma jet isotherms obtained with the used working conditions. The collected light along a sight of view at a given axial position integrates the emission resulting from a broad range of temperatures: in the plasma core from 12000 K to 2000 K at z = 14 mm and from 4000 to 2000 K at z = 80 mm. According to these temperatures:

- atomic lines emitting over 6000 to 8000 K are mainly in the visible as shown in table 1.
- molecular spectra (see table 2) cover a wider spectral range. The most intense emission over 1.8 μm being that of water which, according to figure 3, occurs below 3000 K.
Besides the emission, the surrounding air containing H$_2$O, CO$_2$, NO and NO$_2$ may also absorb the plasma emission with again a strong effect of H$_2$O and CO$_2$ in the Infra-Red, see table 3.

The results presented in figure 5, for $2 < \lambda < 6$ μm, were obtained at $z = 14$ mm respectively with and without powder. The spectra have been carried out with a 0.5 mm entrance slit and corrected to account for the spectral response of the filter (which was placed in front of the entrance slit), grating and HgCdTe detector. It can be seen that the main spectra is that of water. This is probably due to the fast diffusion of hydrogen in the jet fringes where the temperature gradients are very high ($> 5000$ K/mm at $z = 14$ mm) and its recombination with the dissociated oxygen from air the zone where $3000 < T < 5000$ K. No molecular spectra or lines from the plasma at $T > 8000$ K shows up. The effect of the powder is quite negligible, probably because at that distance the particle temperature is below 1800 K.

Figure 6 represents the results obtained at $z = 80$ mm also with and without powder in the same wavelength range. In this case the entrance slit width was 2 mm and spectra were corrected to account for the spectral response of the grating and IR detector. The spectra are very weak (about two orders of magnitude less than in the preceding case). The H$_2$O spectra can be identified within the noise (the signal is very weak). The weakness compared to the previous case can be explained by the dilution of the water with the plasma jet expansion. When powder is injected, the emitted signal increases due to the thermal radiations of the hot particles in the spray jet. It can be observed some areas where signal seems to be absorbed. It
could be due to water vapor surrounding the spray jet and/or to a change in emissivity of the molten particles.

Figure 5: IR spectra of Ar/H₂ (32/8 slm) APS (I=480 A, U = 50 V) without and with (1 kg/h) NiAl5wt% recorded 14 mm downstream the nozzle exit along a cross section.

Figure 6: IR spectra of Ar/H₂ (32/8) APS (I = 480 A, U = 50 V) without and with (1 kg/h) NiAl5wt% recorded 80 mm downstream the nozzle exit along a cross section.

Figure 7: IR spectra of Ar/H₂ (32/8) APS (I = 480 A, U = 50 V) without (1 kg/h) NiAl5wt% recorded 14 mm downstream the nozzle exit along a cross section.

Figure 7 presents the spectrum obtained at 14 mm downstream of the nozzle exit with a 2 x 20 mm² entrance slit. Spectra were corrected to account for the spectral response of the grating and IR detector and also the filter placed in front of the entrance slit to avoid recovery from second order spectra. The main emission is again due to water vapor emission and self
absorption. According to figures 3 and 4 the emission is due to the water surrounding the spray jet in the area where T < 3500 K. Then these radiations are self absorbed by the water vapor contained in the atmosphere, at about 298 K, along the optical path. No change occurs with the particles which are below 1800 K at z = 14 mm with their maximum emission around 1.6 μm. At z = 80 mm without particles the spectrum is almost inobservable and with particles no change is noticed with particles at T = 2500 K.

Conclusion

The Infra-Red environment of the plasma spray process has been studied in order to justify the choice of a large band pyrometer over 6 μm. It allows to determine an appropriate spectral range to measure the target surface temperature during the spraying process. The 8-14 μm wavelength range has been selected. In this spectral area the influence of the absorption due the carbon dioxide and the water vapor contained in the atmosphere, along the optical path, is avoided. The IR emission is due to the plasma forming gas and that of the surrounding air entrained into the plasma core. Finally, in the 8-14 μm wavelength range, the thermal radiations emitted by the in-flight particles in the plasma spray jet are negligible.

The pyrometer in the 8-14 μm range will allow to measure temperatures from ambient to 600 °C. But this choice does not mean that measurements of the spray spot temperature across the plasma plume are straightforward. It just means that with a pyrometer in this wavelength range the plasma perturbation will be minimized.

To reach a good precision in measurements, target surface emissivities have to be determined as well as the temperature perturbation range which seems to be about ± 25 °C. Work is in progress to measure emissivities according to the coating, its roughness and temperature.

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References


