PLASMA WATER INTERACTIONS IN UNDERWATER PLASMA SPRAYING

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ABSTRACT

Potential mechanisms responsible for the lower stand-off distance needed in underwater plasma spraying are analysed. Entrainment of water into the jet appears likely to be a major mechanism. Comparison of the plasma velocity head pressure with local hydrostatic head pressures suggests that a pressure balance criterion would not account for the short stand off needed in practice.

1. INTRODUCTION

Early studies of underwater plasma spraying [1,2] showed that the stand-off distance between torch-nozzle and substrate has to be substantially lower than for plasma spraying air or other gaseous medium. The shorter distances reported, have been used in subsequent studies [3,4]. The reason proposed [1] for the lower stand off requirement was entrainment of water into the plasma stream. This would reduce the mean stream temperature to such a low level that deposition would not occur due to slowing and cooling of the plasma and particles and formation of a water layer on the substrate. Entrainment when spraying in air or other gas is less problematic as the gas has a lower heat absorption capacity and obviously cannot wet the substrate. Recently, Verstak et al [4] have proposed that entrainment of water into an underwater plasma spray jet is negligible. Here mechanisms potentially capable of causing the reduced stand off requirement underwater are examined in more detail.

2. EXPERIMENTAL

Equipment and procedures have been described previously [1,2]. A d.c. torch sprays downwards onto a rotating substrate at a water immersion depth of about 150mm with a carefully controlled stand-off distance between nozzle and substrate. An example of the influence of stand-off in spraying aluminium underwater is shown in Figure 1. At 20mm stand-off an even adherent deposit is produced some 6-7mm wide. Increasing the stand-off to 25mm gives an uneven deposit with significant bare spots and about 50% of the coverage at 20mm. Three potential causes of the loss of deposition on increasing the standoff by only 5mm are assessed in the following sections.

3. POTENTIAL CAUSES OF LOSS OF DEPOSITION AT INCREASED STAND-OFF DISTANCE

3.1 Presence of a liquid water layer

If a layer of water were present on the substrate surface then formation of an adherent deposit would seem most unlikely. To check this intuitive judgement the relative effects of air and water on particle dynamics and heat loss from particles have been modelled. This analysis is also relevant to the behaviour of molten particles in the outer fringes of a plasma jet. Individual molten aluminium particles of specified diameter, temperature and initial velocity are assumed to enter a stagnant fluid, either air or water at 300°K. Particle diameters from 25 - 100μm, initial temperatures from 1000 - 2750°K and initial velocities 50 to 250 m/s were studied. Any entry effects such as splashing or distortion are neglected. Trajectories of the particles are calculated incrementally using standard equations [5] for drag coefficients as a function of Re_p.

The heat transfer modelling takes account of heat loss by conduction convection and radiation. As the Biot number is low, internal particle temperature gradients are small and neglected. Boundary layers are assumed to be established instantaneously. For the water medium, a steam film is assumed around the particle. Variation in transport properties is taken into account by integration over the boundary layer. Particle trajectory and heat transfer equations are solved simultaneously

The onset of solidification of a particle in flight is taken as the absolute limit for successful deposition, (mp = 933°k). For a 50 μm drop distances to onset of solidification in air range from about 20mm to over 400mm depending on initial temperature and velocity (Fig 2). Particle velocities there range from about 10 to 200m/s. The same drops entering water start solidifying within less than about 2mm and have been slowed in most cases to about 2mm/sec. Clearly a water layer could not be tolerated unless very much thinner than 2mm and even then its effect on wetting behaviour needs to be considered.

3.2 Temperature and Velocity Reduction by Entrainment

Any water entrained into the plasma stream would reduce plasma velocity and effective mean temperature. Rapid entrainment of surrounding fluid is a characteristic of turbulent jets. Entrainment of air into a plasma spraying jet was measured by Hasui et al [6] . The mass of air entrained was about 5 times the argon flow within only 75mm from the nozzle. Entrainment of water and consequent cooling was proposed previously [1] as the most likely reason for the reduced stand off requirement underwater. The effect of water vaporisation on mean temperature over a wider range of conditions is shown in Figure 3. For 5kW power in the argon plasma the limiting water/argon mass ratio that could be tolerated before reaching the solidification temperature of the particle ranges from about 0.4 for zirconia to about 2 for aluminium. The limiting ratio decreases with increasing argon flow rate. Verstak et al [4] suggest that a plasma would only have sufficient power to vaporise up to a mass ratio of 0.05. This at variance with Fig 3.

Water entrained but not evaporated could have a worse effect by wetting the substrate. A high velocity jet in a liquid can generate liquid drops [7] which could then be entrained. Correlations for mean drop size are not directly applicable to the present situation but depending on assumptions suggest sizes from 10 to several hundred microns. Calculated time requirements (Fig 4) for evaporation of such drops were obtained by applying a correlation of Chen and Pfender [8] for evaporation of water drops in a plasma. Figure 4 is approximate because the simplest correlation for NU = 2 was used and drop concentrations could be higher than in the model. Particle residence times of the order of 1m.sec. have been reported for plasma spraying [10] of particles around 20μm, admittedly under different conditions to those used here. Drops of say 20μm may therefore evaporate depending on entry conditions. Those with diameters of several hundred microns are unlikely to evaporate completely even in the maximum axial length available of about 25mm. Entrained liquid water reaching the substrate may still evaporate there.

Regarding the extent of water entrainment, direct measurement of entrainment into gas jets from underwater plasma torches [9] shows that for an 8mm nozzle water/gas mass ratios greater than 1 can be reached within 12mm from the nozzle. For smaller diameter nozzles much higher entrainment occurs, to mass ratios over 20. Even a small fraction of the entrainment measured in gas jets would influence the plasma and spraying performance. Verstak et al [4] used velocity head measurements to deduce temperature and velocity profiles in an underwater plasma. By integration over the cross section a total mass flow rate was obtained which implied that no water had been entrained.

3.3 Water ingress at the substrate level

Whether or not water is entrained, another potential way for water to reach the substrate is for the local hydrostatic pressure to exceed the velocity head pressure in the plasma stream. Verstak et al [4] suggest that a plasma can only exist underwater if $\rho v^2/2 \geq \rho_w g h_w$ where h_w is the depth of the torch underwater, and $\rho v^2/2$ the velocity head of the torch operating normally in air. This however does not appear to be a useful criterion because when a torch is immersed the internal torch pressure rises to overcome the hydrostatic pressure at the nozzle exit. Non transferred plasma jets have been operated underwater at equivalent water depths of several hundred metres in this laboratory. Water depths of hundreds of mm used in underwater plasma spraying [1,2,3,4] impose a negligible increase in total pressure at the nozzle exit.

A more important parameter in downward spraying would seem to be the differential hydrostatic pressure $\rho_w gs$ corresponding to the stand off distances. The velocity head pressure of the plasma at the substrate needs to exceed $\rho_w gs$ to avoid the potential for water ingress. Estimates of the velocity head pressures in the plasma/substrate impingement region has been obtained from data on measured plasma temperature profiles and studies on impinging gas jets. For gas jets impinging on a flat plate Hrycak et al [11] found negligible decrease in velocity along the axis until very close to the plate for $s/d_o = 4$. S/d_o has not exceeded 4 in reports on underwater plasma spraying [1,2,3,4] and so it is reasonable to assume $\rho v^2/2$ near the substrate to be similar to that at the nozzle, at least near the axis. To estimate $\rho v^2/2$ for a plasma jet, temperature distribution data measured by Gravelle et al [12] for a 7.1mm diameter nozzle have been used. A corresponding velocity distribution was obtained by applying the relationship

$$V/V_o = T\text{-}T_a/T_o\text{-}T_a \quad .... (1)$$

proposed by Gravelle et al [12]. Integration then gives the total thrust, F where

$$F = \int_0^R 2\pi r.\, dr\, \rho v^2 \quad .... (2)$$

This allows calculation of a mean velocity head pressure averaged over the stream cross section. The velocity head pressure averaged over 8mm diam is equivalent to 147mm water. For a central region of 6mm diam the mean is 190mm water. This was for a 300amp argon plasma, with 3.45 Kw thermal power, both towards the lower levels used in underwater spraying. These equivalent heads are significantly greater than the stand-off head of 25mm water. Thus the velocity head pressure acting in a horizontal direction just after impingement should be sufficient to repel the surrounding water from at least the central part of the impingement region. The stand-off limit for this mechanism would therefore appear to be several times the limit of about 25mm found in practice. The velocity head pressure on the axis of an underwater plasma measured by Verstak et al [4] was about 120mm water, similar in magnitutde to present calculated values. There the velocity head pressure was compared with the local hydrodynamic pressure at the nozzle rather than with the differential head resulting from stand off.

Further information on the validity of a velocity head criterion is provided by measurements of the length of underwater gas jets [9]. The value of $\rho v^2/2$ can be obtained much more reliably for such jets. These jets terminate in distances which are orders of magnitude lower than would be predicted by taking the limiting total hydrostatic head as equal to $\rho v^2/2$. Termination in such shorter distances is attributed to entrainment. [9]

4. CONCLUSIONS

Analysis of the dynamics and cooling of particles confirms that a water layer could not be tolerated at the impaction region in underwater plasma spraying. Consideration of the entrainment characteristics of jets and the influence of water on plasma stream temperature suggests that water entrainment is likely to be a major factor governing the experimentally observed stand off restriction. Comparison of the plasma velocity head pressure with the differential hydrostatic pressure resulting from stand off shows that taking equality of these as the limiting case substantially overestimates the maximum permissible stand-off.

SYMBOLS

d_o	Nozzle diameter
F	Thrust force
h_w	Water depth
Nu	Nusselt No
r	Radial position
Re_p	Particle Reynolds No
R	Radius
T	Plasma temperature
T_o	Plasma temperature on axis at nozzle exit
T_a	Ambient temperature
s	Stand off distance
v	Velocity
v_o	Plasma velocity on axis at nozzle exit
ρ	Density of plasma or gas
ρ_w	Density of water

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