Coating deposition in plasma spray process

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**COATING DEPOSITION IN PLASMA SPRAY
PROCESS**

**KANG CHANG WEI
SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING
2006**

Coating Deposition in Plasma Spray Proces

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ABSTRACT

Plasma spraying is widely used to produce coatings on complex engineering components because of its high deposition rate and wide range of materials that can be sprayed. Also, there are little limitations on the size of the parts and reasonably environmentally friendly as compared to the wet coating processes (e.g. electroplating). However, the three-dimensional shape of the components leads to the deficiency of the plasma spraying process since this process is prone to coating profiles' variations when spraying various surface topologies. Hitherto, the desired coating profiles are successfully optimized by costly and extensive trial and error testing, involving highly-trained manpower and part costs. A deposition model to predict the profiles for such parts is therefore desirable because in using this model, the cost and effort of the test spraying actual part will be reduced, if not eliminated, significantly shortening the process chain.

As the complex surfaces can be considered to comprise of multiple facets, each with individual inclination angle, a semi-empirical methodology of predicting the deposit formation on flat substrates at different inclination angles has been developed in this thesis. The methodology is referred as Substrate Cell Model (SCM) and requires three broad steps:

1. Splat measurement experiments to establish correlations for spread factor and aspect ratio with respect to angle of impact.
2. Computational Fluid Dynamics (CFD) analysis to solve the spatial distribution of size and impact sites on the substrate plane.
3. Modeling of deposit formation with 1 and 2 as the input data.

Abstract

In the splat measurement experiments, individual zirconia splats are captured by fast traversing the flat and inclined substrates in front of the plasma spray. Each substrate has a mean arithmetic surface roughness, R_a of 0.5 microns and is preheated to a temperature of 723 K. At each inclination angle, 50 splats are measured by high resolution WYKO NT-2000© optical surface profiler and quadratic equations are curve-fitted for the spread factor and aspect ratio. The spread factor, ξ , relates the diameter of a spreading circular splat to the diameter of an incoming droplet while the aspect ratio, ψ , defines the ellipticity of splat by the ratio of major to minor diameters. In addition, the effect of angle of impact on the splat final morphology has been examined by Scanning Electron Microscopy (SEM). From the analysis of the SEM photographs, oblique impact produces features such as fingering, ridging, splashing, overlapping and elliptical shaped splats. A study is conducted to find out the point of impact for the elliptical splat. It is found that the point of impact determined by means of backtracking the fingers radiating from the splat coincides well with one of the foci of the ellipse.

In the CFD analysis using FLUENT V6.02©, the spray process is modeled as a three-dimensional steady state plasma jet issuing from the torch exit by the volumetric heating of the arc gas within the torch. In the solution procedure, the plasma flow fields for temperature and velocity are firstly obtained. With the known plasma flow fields, multi-sized particles are introduced as solid entities which are heated and propelled by the plasma. The heat and momentum transport equations are solved to obtain the spatial distributions of the particle in-flight temperature, velocity and trajectory. In order to have an accurate modeling of the particle parameters, the effect of substrate is also being investigated. The simulations are performed for cases where flat substrates are either present or absent,

Abstract

for the former, the substrate is oriented perpendicularly or inclined to the torch axis. It is shown that although the presence of perpendicular or inclined substrate significantly influences the plasma flow fields in the vicinity of the substrate, the particle parameters remain relatively unaffected. The insignificant effect of the substrate on particle behavior is qualitatively verified by experimental observation using SprayWatch© imaging diagnostics equipment. Images captured by the equipment confirm that the particles travel through the plasma flame with high momentum and show no sudden change in their trajectories right before impacting the substrate. In addition, the quantitative measurements by the SprayWatch© system also conclude that the particle velocity is insensitive to the aerodynamic disturbances of the substrates. Both numerical and experimental findings show that the freestream model is sufficiently detailed in providing the particles parameters required in the SCM.

Having obtained the experimentally measured shapes and sizes of the splats as well as the numerically simulated particle parameters, the SCM predicts how incoming particles form splats at locations of the impact on the substrate and accumulates thicknesses of multiple splats formed on the substrate. The model is able to predict the deposit volumes and the three-dimensional profiles for different substrate inclination angles. The predictions have reasonable to good agreements with the experimentally sprayed deposits. For 60° substrate inclination angle, the percentage difference is less than 1% and it is 17% for 10°. Nevertheless, 17% which is the maximum percentage difference is tolerable in deposit formation. In future, this model can be further refined to predict deposition on continuously varying curved surfaces of realistic engineering components.

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NOMENCLATURE

A	Cross section area (m^2)
B	Empirical constant in wall functions (= 9.81)
C_D	Drag coefficient
C_p	Specific heat capacity (J/kgK)
C_μ	Empirical constant in standard κ - ε turbulence model (= 0.09)
$C_{I\varepsilon}$	Empirical constant in standard κ - ε turbulence model (= 1.44)
$C_{2\varepsilon}$	Empirical constant in standard κ - ε turbulence model (= 1.92)
c	Distance of the focus of ellipse from its center (m)
D_n	Diffusion coefficient (m^2/s)
D_{noz}	Nozzle diameter (m)
D_{nt}	Turbulent diffusion coefficient (m^2/s)
D_p	Particle diameter (m)
d	Splat diameter (m)
d_e	Equivalent splat diameter (m)
d_x	Minor splat diameter (m)
d_y	Major splat diameter (m)
E	Arc voltage (V)
E	Specific energy (J/kg)
e	Eccentricity of ellipse (m)
F_D	Drag force per unit mass (N/kg)
g	Gravity (m/s^2)
H_f	Latent heat of fusion (J/kg)

Nomenclature

h	Heat transfer coefficient (W/m ² K)
h	Specific enthalpy (J/kg)
I	Arc current (A)
J_n	Diffusion flux (kg/m ² s)
K	Dimensionless splashing parameter: $K = 0.5a^{1.25}We^{0.5}Re^{-0.05}$
K	von Kármán constant (= 0.42)
k	Thermal conductivity (W/mK)
k_{eff}	Effective thermal conductivity (W/mK)
l	Length (m)
m	Mass (kg)
N	Total number of interval counts
n_p	Number of particles
P_g	Vapor pressure (Pa)
P_{in}'''	Volume-averaged heat source (W/m ³)
p	Pressure (Pa)
Q	Volume flow rate (m ³ /s)
Q_{EVS}	Dimensionless equivolume skew: $Q_{EVS} = (V_{eq} - V)/V_{eq}$
$\dot{q}$	Heat flux (W/m ²)
R_a	Mean arithmetic surface roughness (m)
R_p	Particle radius (m)
r	Root locus of ellipse
S	Dimensionless solidification rate: $S = \tilde{s}/\sqrt{t}$
S_h	Source term
S_{ij}	Rate of strain tensor (s ⁻¹)
$\tilde{s}$	Dimensionless thickness of solidified layer

Nomenclature

T	Temperature (K)
ΔT	Temperature difference (K)
T_A	Plasma temperature at adjacent element to the substrate (K)
T_b	Boiling point (K)
T_i	Turbulence intensity (%)
T_m	Melting point (K)
T_p	Particle temperature (K)
T_w	Substrate temperature (K)
t	Time (s)
$\tilde{t}$	Dimensionless solidification time
t	Splat thickness (m)
t_D	Deposit thickness (m)
U	Velocity magnitude (m/s)
U_A	Plasma velocity at adjacent element to the substrate (m/s)
U_p	Particle velocity magnitude (m/s)
U_{pn}	Particle normal velocity component (m/s)
U_{pt}	Particle tangential velocity component (m/s)
U^*	Dimensionless mean velocity: $U^* = \frac{U_A C_\mu^{1/4} \kappa_A^{1/2}}{\tau_w / \rho}$
u	Velocity vector (m/s)
u_p	Particle velocity vector (m/s)
u'	Velocity vector fluctuation (m/s)
$\bar{u}$	Mean velocity vector (m/s)
V	Volume (m ³)
V_{eq}	Maximum volume of an equilateral cell (m ³)

Nomenclature

V_n	Volume fraction
V_p	Particle volume (m ³)
V_s	Splat volume (m ³)
W_D	Weight of powder deposited on the substrate (kg)
W_I	Weight of powder injected (kg)
W_x	Minor deposit diameter (m)
W_y	Major deposit diameter (m)
Y_n	Mass fraction
y	Distance from element to the substrate (m)
y_A	Distance from adjacent element to the substrate (m)
y^*	Dimensionless distance from element to the substrate: $y^* = \frac{\rho C_\mu^{1/4} \kappa_A^{1/2} y_A}{\mu}$
y^*_T	Dimensionless thermal sublayer thickness

Greek Symbols

α	Particle heading angle (°)
α	Thermal diffusivity (m ² /s)
χ	Dimensionless parameter of droplet mass loss
δ_{ij}	Kronecker-delta
ε	Turbulent kinetic energy dissipation rate (m ² /s ³)
η_t	Torch efficiency (%)
γ	Dimensionless roughness parameter: $\gamma = \lambda/R_p$
κ	Turbulent kinetic energy per unit mass (m ² /s ²)
ξ	Spread factor: $\xi = d_e D_p^{-1}$

Nomenclature

λ	Roughness height (m)
μ	Dynamic viscosity (kg/ms)
μ_t	Turbulent dynamic viscosity (kg/ms)
ν	Kinematic viscosity (m ² /s)
ω	Wetting angle (°)
ψ	Aspect ratio: $\psi = d_y/d_x$
ψ_D	Deposit aspect ratio: $\psi_D = W_y/W_x$
ρ	Density (kg/m ³)
σ	Surface tension (N/m)
τ_A	Particle aerodynamic response time (s)
τ_F	Time scale associated with the large scale eddies (s)
$(\tau_{ij})_{eff}$	Effective deviatoric stress tensor (N/m ²)
τ_w	Wall shear stress (Pa)
θ	Substrate inclination angle (°)
ς	Liquid fraction
$\mathcal{G}$	Normally distributed random number

Subscripts

f	Final state
l	Liquid state
max	Maximum state
n	Species
p	Particle
s	Solid state

Nomenclature

t	Turbulent state
w	Wall or Substrate
∞	Continuous phase (plasma)

Dimensionless Numbers

Bi Biot number: $Bi = \frac{k_{\infty}}{k_p}$

Gr Grashof number: $Gr = \frac{g\alpha\Delta T l^3}{\nu^2}$

Ja Jakob number: $Ja = \frac{C_p(T_m - T_w)}{H_f}$

Nu Nusselt number: $Nu = \frac{hD_p}{k}$

Pe Peclet number: $Pe = \frac{u_p D_p}{\alpha}$

Pr Prandtl number: $Pr = \frac{\nu}{\alpha}$

$Pr_{t,\kappa}$ Constant Prandtl number in standard κ - ϵ turbulence model (= 1.00)

$Pr_{t,\epsilon}$ Constant Prandtl number in standard κ - ϵ turbulence model (= 1.30)

Re Reynolds number: $Re = \frac{\rho_p u_p D_p}{\mu_p}$

Re_r Relative Reynolds number: $Re_r = \frac{\rho D_p (u - u_p)}{\mu}$

Sc_t Turbulent Schmidt number: $Sc_t = \frac{\mu_t}{\rho D_{nt}}$

Nomenclature

St Stokes number: $St = \frac{\rho_p D_p^2 / 18 \mu_p}{D_{noz} / U_\infty}$

Ste Stefan number: $Ste = \frac{C_p (T_m - T_w)}{H_f}$

We Weber number: $We = \frac{\rho_p u_p^2 D_p}{\sigma}$

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CHAPTER 1

INTRODUCTION

1.1 Background

Plasma spraying is a group of processes in which finely divided metallic and non-metallic materials are deposited in a molten or semi-molten state on a prepared substrate. These deposited coatings are capable of protecting the surfaces of thermal or mechanical components from the environmental attack, thermal shock, thermal fatigue, wear, erosion and corrosion. The coatings are also used to restore worn or poorly machined parts to their original dimensions and specifications. The wide applications of plasma-sprayed coatings are due to the following advantages:

- (i) a rapid process, i.e. the processes of melting, rapid solidification and consolidation are combined in a single step;
- (ii) the ability to spray purely metal or ceramic materials as well as a continuously varying mixture of metal and ceramic (functionally graded materials);
- (iii) high deposition rates and
- (iv) the capability of processing materials in vacuum environment to limit the oxidation of metallic spray particles.

The processes in plasma spraying are plasma generation, plasma and particle interaction and coating formation, as shown in **Figure 1.1**. They are separate but interrelated. In plasma generation, a high intensity electric arc is struck between the

cathode and anode to ionize the plasma forming gases and thus generate a heat source capable of melting any particulate materials. The materials are then fed into the high temperature and high velocity of plasma flame to be heated and accelerated via heat and momentum transfer. The droplets with high speeds are made to impact onto the part to be sprayed. On impact, the droplets form splats which rapidly solidify (up to 10^9 K/s at the very beginning of the cooling process) and adhere onto the surface thus forming a deposit after successive accumulation of multiple splats.

Figure 1.1: Three separate but interrelated processes involved in plasma spraying.

These processes have different parameters, which the operator can exercise some controls to achieve specific and optimized targets. They are listed below:

- (i) Plasma generation is linked to the primary gas flow rate, direct current, the plasma forming gas composition and composition of the enveloping environment.
- (ii) In particle dynamics and heat transfer, particle size distribution, particle morphology, carrier gas flow rate, powder feed rate, location of injection port and tilting angle should be considered to ensure that particle trajectories are within the core of the plasma jet. Particles therefore will be melted, yet not vaporized on reaching the substrate.

- (iii) Splat formation and layering depend on the resulting droplet parameters (velocity, temperature, diameter, number flux) at impact, substrate materials and characteristics, including roughness and preheating temperature.

Many papers have been published regarding these three stages of the plasma spraying giving impetus to the continuous development of this field (see review papers by Fauchais and Vardelle, 2000, Fauchais *et al.*, 2001a and Fauchais, 2004). The author finds that more efforts are directed towards the on-line measurements of plasma temperature and velocity, particle size, velocity and temperature, as well as modeling of plasma flow field and particle momentum and heat transfer. This is because the properties of the coatings depend strongly on the molten state and velocity of the particles upon impact. Through on-line measurements and modeling of the plasma and particle characteristics, the structure of the plasma sprayed coating, the reliability and reproducibility of the spraying process can be improved. However, studies about the formation of splats and their layering, i.e. coating formation, are still in their infancy and much is still to be done. Till now, investigations on the coating formation and material science are related to perpendicular impact of droplets onto the substrate and not many studies on oblique spraying have been carried out.

1.2 Application Needs for Plasma Spraying on Three-Dimensional Complex Surfaces

The importance of investigating coating formation under oblique impact has increased as the demands of spraying complex surfaces increase. This is because when spraying complex surfaces, thousands of particles propelled from the plasma torch will impact at multitude of angles. The following are the industries that have been using plasma spraying for coating on complex surfaces.

- (i) In chemical industry, inner coatings of water, oil or chemical pipelines are required to protect them against corrosion.
- (ii) In automotive industry, plasma-sprayed wear protection coatings are applied on brake discs of motorcycles and cylinder bores which are additionally exposed to temperature changes.
- (iii) In power generation industry, in order to increase the efficiency, there is certainly a need to increase the gas exit temperature as it is proportional to the power generated. As a result, the gas temperature has approached or exceeded the melting point of the substrate in localized regions and thermal barrier coatings are needed to insulate the turbine blades from the high gas temperature.

These industries currently spray based on “trial and error” basis due to the lack of understanding on coating formation under oblique impact. This technique has high capital costs (e.g. equipment, parts, powders, gases) and requires highly trained and expensive operators. The process becomes even more difficult and challenging when spraying turbine blades. This is because turbine blade has specific requirement on coating thickness i.e. thicker at the leading edge and reducing towards the trailing edge. **Figure 1.2** indicates the topological surfaces of

gas turbine blades. With this in mind, it is understood that a thorough investigation on oblique spraying is necessary.

Figure 1.2: Topological surfaces of gas turbine blades.

1.3 Objectives and Scope

In order to reduce the costs and efforts of the actual test spraying, a deposition model of predicting coating profiles at different inclination angles is being developed. This is because multi-curvature surfaces can be considered to comprise of multiple local flat facets, each with individual inclination. To successfully develop the deposition model for each individual inclined facet, the following three steps are needed:

- (i) experimental study on splat formation under oblique impact;
- (ii) numerical simulation on plasma flow field with injection of multi-sized particles, and
- (iii) combination of (i) and (ii) to build up deposits on substrates inclined at different angles.

It is apparent that after a droplet impacts perpendicularly on a substrate, a circular splat with its impact location at the geometric center of the circle is obtained. In the case of a droplet impacting on an inclined substrate, the splat elongates to an elliptical shape. However, a quantitative correlation between the splat elongation and angle of impact is not presented in most publications. The impact location for the elliptical splat also remains uncertain. Thus, it is decided that the main aim of this work is to conduct experiments to collect data to describe the degree of splat elongation under the influence of angle of impact and the impact location for elliptical splat. These information are important as they are the starting point for predicting coating profiles under oblique spraying. The experimental procedures to empirically derive the model are outlined in detail in **Chapter 3**. The predictions of the model will be compared with the existing data from literature

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search carried out in **Chapter 2**. The effect of oblique impact on the features within the splat such as fingering, spalling, ridge and cracking are discussed in **Chapter 3**.

The second step is to build up the data on the dispersion characteristics of particles and all their pertinent in-flight parameters, namely velocity, temperature and size. This is important because these parameters determine the first point the particle strike on the substrate and the final shape of the splat. Experimental measurements of all the individual parameters are not economic and impractical. The best method is by means of Computational Fluid Dynamics (CFD) analysis to simulate plasma heat generation and plasma-particle interaction. In order to accurately model the plasma flow, the effect of substrate is being considered. This is because the substrate obstructs and diverges the flow at the stagnation region. The blowback of the gas will affect the plasma flow at the upstream region and subsequently influence the entrained particle parameters and coating profiles. **Chapter 4** is devoted to the analysis of the three-dimensional CFD results on the effect of the substrate towards the plasma flow and particle behavior.

To verify the numerical results on the effect of the substrate on the particle behavior, experiments are conducted using imaging diagnostics equipment. The advantages of using this equipment are that it provides clear visual view on the in-flight particle flow, particularly right before impact on the substrate as well as measures the particle temperature, velocity and heading. The experimental results are related to the splat morphologies obtained in **Chapter 3**. The experimental procedures and the results of particle in-flight parameters under conditions with and without a substrate present are elaborated and discussed in **Chapter 5**.

Once the first and second steps are completed, it is necessary to develop a code to relate the database of likely shape and thickness of a splat with the

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incoming droplet distributions predicted by the CFD model to produce splat of known dimensions. As described in **Chapter 6**, this step involves integration and construction of deposits build-up of individual splats at different inclined substrates. The multiple process simulation steps coupled with intermediate steps of empirical calibrations can be described as a concept of “desktop manufacturing”. To confirm the accuracy of the code, experimental measurements under the same conditions as the numerical modeling are needed. The predicted deposit thicknesses are compared with the measured coating thicknesses, as well as shapes of the profiles.

The step by step procedures to achieve the objectives of this work are illustrated in **Figure 1.3**.

Figure 1.3: Flow chart for the PhD research project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Plasma spraying is a complicated process governed by numerous parameters. Three separate but interrelated processes as mentioned earlier are governed by independent parameters which need to be at the optimum level of performance, if possible. A literature review is carried out to understand the plasma generation, plasma-particle interaction and coating formation that are important in developing a more detailed picture of the plasma spray process.

The literature review is divided into four distinctive parts. In the first part, the atmospheric plasma spray (APS) system with its detailed parameters is described. Collections of the physical and thermal properties of the yttria-partially-stabilized zirconia (YSZ) are also tabulated in this part. This is important because zirconia is the powder used in this study and the list can provide reasonable values for the required properties of zirconia to be used in the author's simulation work. In the second part, modeling approaches for plasma heat generation and experimental measurements on the plasma temperature and velocity are given. The results gained will be utilized to verify or compare with the author's numerical results later. Appraisal of the particle in-flight characterization is reviewed in the third part. Research in this area has been carried out by simulation as well as experiments. Lastly, attention is focused on the work by previous researchers pertaining to

Chapter 2: Literature Review

theoretical, numerical and experimental investigations in coating formation. Compilation of spread factors measured under different process parameters and various factors affecting the deposition efficiency are included in this part.

2.2 Brief Review on Plasma Spraying Technology Relevant to This Thesis

The plasma spraying system involves a group of processes that deposit micro-sized materials onto a substrate to form a coating. The basic equipment as shown in **Figure 2.1** is required. This section describes the functions and importance of the equipment and the consumable. Review on the reports regarding the nozzle design and injection scheme to improve the particle velocity and temperature upon impact on the substrate are also included in this section.

Figure 2.1: Schematic diagram of a plasma spraying setup.

2.2.1 Equipment

Brief introduction of each component in the plasma spraying system is discussed.

(i) Plasma Torch

The plasma torch is one of the most important working unit in the whole spraying system. It consists of a circular copper anode, a cathode of thoriated tungsten, gas injector, nozzle and powder injector. The sectional view of the torch used in this study; SG-100© is shown in **Figure 2.2**.

Figure 2.2: Section of a SG-100© plasma torch (Praxair Surface Technologies Inc., 1998).

In this torch, the ionization of plasma gas in the electric arc between the cathode and anode induces a high energy state of plasma, in the form of a plasma jet, which leaves the nozzle at high velocity ($\approx 1000\text{-}2000$ m/s) and temperature ($\approx 10000\text{-}15000$ K). Due to the complicated movements of location of the anodic arc

root attachment, there are continuous time-dependent temperature and velocity variations of the plasma jet. These fluctuations subsequently result in the non-uniform transport and heating of the injected particles and thus affect the quality of the coating. Therefore, the ultimate goal is to control the arc root movements to distribute the heat load and thus prolong the anode life, while maintaining minimum arc fluctuations.

(ii) Control Console

The control console connects the plasma torch, power, gas and water systems and controls the plasma spraying process. It regulates the supply of electric current to electrodes in the torch to produce high intensity arc as well as the flow rates for plasma and carrier gases.

(iii) Powder Feeder

The powder feeder feeds an adjustable, uniform and reproducible amount of powder to the plasma jet. During the operation, slots in the powder wheel at the base of the canister are filled with powder. Rotation of the powder wheel, which determines powder feedrate, delivers the constant volume of powder to the hose exit. For different types of powder materials, the wheel speed can be set to the required powder feedrate based on **Figure 2.3**. An inert carrier gas provides gas pressure to mix the powder with the gas in the form of a dust cloud and forces the mixture through the hose exit to the plasma torch. The pressure of the carrier gas must be set in such a way that the powder is injected into the plasma jet at the optimum momentum.

Figure 2.3: Relation between the wheel speed of powder feeder to the powder feedrate for different types of materials (Praxair Surface Technologies Inc., 1997).

The powder feeder described above corresponds to the one used by the author. However, there are also powder feeders which are based on different working principles, such as fluidized beds. PF-700© and PF-730LF©, provided by Bay State Surface Technologies, Inc. (50, Howe Avenue, Building P, Millbury, MA, 01527 USA) and 9 MP© family of powder feeders, offered by Sulzer Metco Management AG (Zürcherstrasse 12, Building 211, CH-8401, Winterthur, Switzerland) are examples of powder feeders operating on the patented and proven fluidics principle.

(iv) Cooling System

Since the plasma torch is operating at high temperature, a cooling system is essential for ensuring a trouble free operation of the plasma torch and optimum life of the electrodes. In the cooling system, pressurized water which cools the torch

enters the cathode part and leaves the anode part circulating through the insulation tubes or channels. An enclosed cooling system using distilled water (clean and without mechanical impurities) is more advantageous. This is because city water leaves sediments of lime in the cooling channels, impairing heat transfer and thus the cooling efficiency.

(v) Exhaust System

The plasma spraying process generates gaseous residues of argon and hydrogen (plasma gases), vapors from the spray particles as well as powder remainders which do not adhere to the sprayed substrate. Amongst them, the metal oxide vapors are especially dangerous to the human health. As a safety precaution, an exhaust system is needed to filter all these waste products suspended in the atmosphere.

2.2.2 Consumable

The consumables such as working gases, electric power and powder that play significant roles in plasma spraying process are reviewed below.

(i) Arc Gas

The use of arc gas in the plasma spraying is not only for plasma generation, but also for the protection of the electrodes against oxidation and electrode cooling. Generally, the plasma generating gas can be categorized into two groups, monoatomic and diatomic gases (Matejka and Benko, 1989). The energy gained by the monoatomic gas in the plasma column is given by the specific heat and ionization energy, while in diatomic gas, in addition, the great volume of energy is obtained from the dissociation of molecules into atoms. For the first group, argon

and helium are usually used while the application of hydrogen and nitrogen belongs to the second group. The selection of plasma-forming gas is usually based on the desired temperature and velocity of the plasma jet and the characteristics of the sprayed material and the substrate. Different kinds of the plasma gas significantly affect the coating properties. For instance, Shimoizumi *et al.* (1987) have developed a new plasma system where the cathode and anode arc spot was fixed accurately and protected by a very small quantity of inert gas so that not only the inert gas, but also active gases (e.g. air and oxygen) could be applied as plasma gas. Spraying with this system, the α -Al₂O₃ composition in coating would increase when air and oxygen were used as plasma gas and the application of argon and nitrogen as plasma gas increased the β -Al₂O₃ composition.

In addition, the arc gas can also be grouped as primary gas that stabilizes the arc discharge and imparts momentum to the plasma jet and secondary gas that improves the flow behavior compared to those of pure arc gas. For example, addition of secondary gas, H₂ raises the thermal conductivity of Ar-H₂ plasma mixture (Roumilhac *et al.*, 1990). Viscosity of Ar-He mixture is higher than that of pure argon, which limits the turbulence mixing in the jet fringes and thus the convective cooling.

(ii) Carrier Gas

The part played by carrier gas is to transport the suspended particles into the torch. The carrier gas flow rate determines the particle trajectory and dispersion of the spray particles during their flight in the plasma flame. This in turn influences the particle behavior and subsequently the deposition characteristics. For different densities and sizes of particles, different optimum carrier gas flow rates are required

to have them penetrate into the core of the plasma jet (Pfender, 1987 and Remesh *et al.*, 2003a and 2003b).

(iii) Power

High input current affects the length of the hot isotherms of the plasma plume (see **Figure 2.4**). The magnitude of isotherms depends on the surrounding atmosphere. By turbulent mixing, a plasma jet flowing in the surrounding air has the length of its isotherms reduced by a factor of 1.5 compared to that of flowing in a controlled atmosphere of argon, which has lower thermal conductivity (Fauchais *et al.*, 1987).

(a)

(b)

Figure 2.4: Ar (40 l/min)-H₂ (8 l/min) plasma jet temperature isocontours for (a) an arc current of 189 A (Voltage = 78 V) and (b) an arc current of 467 A (Voltage = 64 V) (Fauchais *et al.*, 1987).

(iv) Powder

Typically, powder consists of either metals (e.g. anticorrosion zinc, aluminium, steel, bronze), metallic alloys (e.g. Ni based alloys) or ceramics (e.g. zirconia, alumina). Usage of these powders depends on the engineering applications of the sprayed components. In this study, thermal barrier coating is of interest because it is commonly used as a protective coating against heat, erosion and corrosion of gas turbine blades. Thus, zirconia is one of the preferred materials

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since it has high melting point (≈ 2988 K), chemical inertness and low thermal conductivity (≈ 2.4 W/mK).

At room temperature, zirconia is in monoclinic form and at its transformation temperature (1100-1200 °C), it transforms to the denser tetragonal form (Lynch, 1989). This results in a disruptive volume change of about 9 %. Therefore, zirconia is usually stabilized with CaO, Y₂O₃ or MgO additions, which when fired, yields in a material having a cubic structure. The cubic form differs slightly from the monoclinic and tetragonal forms and is stable above and below the transformation temperature.

The zirconia powder is usually manufactured by arc fusing/crushing, hollow spherical particles (HOSP) plasma fusing and arc fusing/spray drying processes (Ott and Kushner, 1990). These processing methods have significant influence on the morphology of the produced powder. The first process produces particles that are irregular and non-uniform in size and shape. The fused and spray dried process produces spherical, hollow and with internal porosity particles. These different morphologies of the particles have been found to affect the plasma sprayed coating porosity and deposition efficiency. In terms of porosity of the coating, arc fused/spray dried offers highest porosity, followed by HOSP plasma fuse and arc fused/crushed. As for the deposition efficiency, the hollow sphere zirconia feedstock, for instance yields higher deposition efficiency than crushed zirconia because hollow sphere particle provides more uniform temperature distribution (Jewett *et al.*, 1997).

The zirconia powder is usually produced in a larger size range in a batch production. Different particle sizes are subjected to different rates of momentum and heat transfer. Smaller particles are accelerated and retarded faster than larger

particles due to their smaller inertia (Ng *et al.*, 2003 and Ma *et al.*, 2004) while for heat transfer, smaller particles, which have less mass with respect to their surface area are heated up and cooled down faster than the larger ones.

The properties such as density, thermal conductivity, specific heat capacity, latent heat of fusion, melting point, boiling point and vapor pressure are also important factors in the process of plasma and particle interaction. Collection of the properties for the zirconia powder is listed below. This list serves as guidance in choosing reasonable values of zirconia properties for the author’s numerical work of simulation in **Chapters 4 and 6**.

(a) **Density, ρ_p (kg/m³)**

Reference	ρ_p (kg/m ³)	Remarks
Lynch (1989)	5560	Monoclinic ZrO ₂
Joshi and Sivakumar (1992)	5400	Nil
Shackelford and Alexander (1994)	5890	Nil
Ahmed and Bergman (2000)	5700	Dense form ZrO ₂

(b) Thermal Conductivity, k_p (W/mK)

Reference	k_p (W/mK)	Remarks
Lynch (1989)	1.884 (400 °C) 2.052 (800 °C) 2.387 (1200 °C)	ZrO ₂ with 5-10% CaO
Joshi and Sivakumar (1992)	1.1	Nil
Shackelford and Alexander (1994)	2.4	Nil
Wan <i>et al.</i> (1999)	0.02-1.2	Nil
Ahmed and Bergman (2000)	2.4	Dense form ZrO ₂
Shackelford and Alexander (2001)	2.303 (at room temperature) 2.219 (800 °C)	Y ₂ O ₃ stabilized ZrO ₂

(c) Specific Heat Capacity, C_p (J/kgK)

Reference	C_p (J/kgK)	Remarks
Joshi and Sivakumar (1992)	604	Nil
Shackelford and Alexander (1994)	Refer to eq* below	Nil
Ahmed and Bergman (2000)	620	Dense form ZrO ₂

*For $273 < T_p < 873$ K
 $C_p = 1.06343 \times 10^{-6} T_p^3 - 2.188953 \times 10^{-3} T_p^2 + 1.709671 T_p + 1.466367 \times 10^2$
For $T_p > 873$ K
 $C_p = 678.5$

(d) Latent Heat of Fusion, H_f (J/kg)

Reference	H_f (J/kg)	Remarks
Joshi and Sivakumar (1992)	7.10×10^5	Nil
Shackelford and Alexander (1994)	7.10×10^5	Nil
Ahmed and Bergman (2000)	7.00×10^5	Dense form ZrO_2
Shackelford and Alexander (2001)	7.06×10^5	Nil

(e) Melting Point, T_m (K)

Reference	T_m (K)	Remarks
Lynch (1989)	2963	Monoclinic ZrO_2
Joshi and Sivakumar (1992)	2950	Nil
Shackelford and Alexander (1994)	2973	Nil
Ahmed and Bergman (2000)	2980	Dense form ZrO_2
Shackelford and Alexander (2001)	2988	Nil

(f) Boiling Point, T_b (K)

Reference	T_b (K)	Remarks
Lynch (1989)	4573	Monoclinic ZrO_2
Joshi and Sivakumar (1992)	4548	Nil
Shackelford and Alexander (1994)	5273	Nil
Wan <i>et al.</i> (1999)	5000	Nil

(g) Vapor Pressure, P_g (Pa)

Reference	P_g (Pa)	Remarks
Wan <i>et al.</i> (1999)	101325	Nil

2.2.3 Nozzle Designs and Particle Injection Schemes

(i) Nozzle Designs

Vardelle *et al.* (1993) presented an experimental study of the influences on particle temperature and velocity due to the changes in nozzle diameter. With the reduction of the nozzle diameter, the velocity of the plasma would increase but this was only experienced at the beginning of the plasma flame. At the end of the flame, turbulent entrainment and mixing took place, especially in the Atmospheric Plasma Spray (APS) to cause a decrease in velocity of the gas. Since the particle velocity was coupled to the velocity of the plasma gas, the particle also exhibited the same trend of velocity profile as the plasma, with respect to the changes of the nozzle diameter as indicated in the **Figure 2.5(a)**. As for the particle temperature, the changes of the nozzle diameter also exerted a significant effect. High velocity of

the particle (smaller nozzle diameter) would reduce its exposure time to the plasma flame, and thus displayed a lower value of temperature. This can be observed from Figure 2.5(b).

Figure 2.5: Radial distributions of (a) particle velocity and (b) particle surface temperature measured at 75 mm downstream of the nozzle exit for Al_2O_3 particles ($-45+22\ \mu\text{m}$) injected in Ar (45 l/min)- H_2 (15 l/min) plasma jet with an arc current of 600 A (Vardelle *et al.*, 1993).

(ii) Particle Injection Schemes**(a) One-Port Injection**

Conventionally, the powder is injected radially and perpendicularly into the plasma flame through one injection port. This injection port can be placed either inside the plasma torch (internal injection) or outside the torch (external injection). The different locations of injection port (either internal or external) depend on the types of powder being injected. Internal injection has the ability of retaining maximum powder at the point of highest energy, allowing more heat and momentum transfers and thus suitable for refractive materials. However, for metallic materials, external injection is usually preferable. In addition, the diameter of injector and carrier gas flow rate can be varied to inject the particles with a momentum similar to that of the plasma jet, so that the particles can penetrate to the hot core of the plasma jet. The latter is preferred because reducing the diameter of injector will increase the possibility of clogging within the injection port. Depending on the size distributions of sprayed particles, the range of injector diameter is between 1.2 mm to 2 mm.

The conventional method is reasonably efficient but some researchers have tried to further improve it by different injection schemes. This is because in the conventional one-port injection, the particle plume is always deflected towards the opposite side of the injection port. And with the large particle size distribution, it is very difficult to ensure the penetration of all the particles to the hot core of the plasma flame, even with the optimum carrier gas flow rate. Consequently, this leads to the skewed particle in-flight parameters across the plasma flame, which may not be favorable for forming a uniform coating. Three types of new injection methods were proposed to increase the particle residence time in the high

temperature core of the flame and thus receiving maximum heat and momentum transports from the flame. They were axial, two-port and tilting injections.

(b) Axial Injection

The idea proposed by Vardelle *et al.* (1990) was to inject the powder along the axis of the plasma jet. With this mode of injection, the particles directly entered into the core of the plasma flame and thus experienced higher velocity than the one obtained in a conventional method (see **Figure 2.6**). Another advantage of this approach was to spray the ceramic powders at a lower power level (i.e. at much lower arc current) than the conventional torch, to obtain ceramic coatings with comparable qualities. There is already commercial plasma torch with axial powder injection available in the market; i.e. Axial III©, provided by Norwest Mettech Corp. (120-1200 Valmont Way, Richmond, BC V6V 1Y4 Canada) and Thermico GmbH & Co. KG (Merklinderstrasse 10 D-44577 Castrop-Rauxel, Germany). However, at the present time, the powder mass flow rate is limited to 500 g/hr and the cathode erosion is more pronounced than with the conventional method.

Figure 2.6: Particle velocities measured for axial (given by points) and radial (given by lines) injections, using alumina powder (-45+22 μm) sprayed in Ar (40 l/min)-H₂ (3 l/min) plasma jet at an arc current of 108-175 A (Vardelle *et al.*, 1990).

(c) Two-Port Injection

A two-port injection scheme was investigated by Wang *et al.* (2003 and 2004) to obtain a more symmetrically distributed particle velocity about the centerline of the plasma gas. **Figures 2.7(a) and 2.7(b)** show the particle velocity distributions for one-port and two-port injections respectively, measured by the Phase Doppler Anemometer (PDA). The symmetrically distributed particle velocity using two-port injection was due to the interaction of two opposing powder-gas flows, and thus the particle trajectories were modified and tended to travel along the paths closer to the centerline of the plasma jet.

Figure 2.7: Radial distributions of particle velocity for (a) one-port and (b) two-port injections. Case 1-8 were studies conducted under different operating conditions: arc gas (Ar, 40-72 l/min), carrier gas (Ar, 3-7 l/min) and current (500-900 A) (Wang *et al.*, 2004).

(d) Tilting Injection

The powder injector could be tilted 60° counter to the flow to increase the particle retaining time in the plasma jet (Vardelle *et al.*, 1993). This change increased the particle mean velocity and its surface temperature as can be seen in **Figures 2.8(a) and 2.8(b)**, respectively. However, this resulted in a problem where

particles adhered and built up a deposit on the anode throat. Therefore, interest in this type of injection was reduced.

(a)

(b)

Figure 2.8: (a) Particle mean velocities and (b) surface temperatures in Ar (75 l/min)-H₂ (15 l/min) plasma jet with 400 A arc current, at two injection angles; i.e. 90° and 60° (Vardelle *et al.*, 1993).

2.3 Investigations in Plasma Flow Field

2.3.1 Numerical Modeling

The problem of practical importance that will be addressed in this section is the calculation of the velocity and temperature fields in the gas stream exiting the plasma torch for a given set of initial and boundary conditions. A notable pioneering work in this area was by McKelliget *et al.* (1982). Two-dimensional elliptic equations in conjunction with κ - ε turbulence model and energy transport equation were applied to predict the velocity and temperature fields of the plasma jet, issuing from a plasma torch. Solutions of the equations were then compared with the experimental measurements for velocity and temperature obtained from the Laser Doppler Velocimetry (LDV) and spectroscopic techniques respectively. Good agreement was obtained for the velocity profile but for the temperature field, the comparison was not as good. This was due to the assumptions of constant (temperature independent) specific heat and viscosity, which were unrealistic since the transport and thermodynamic properties of ionized gas were strongly dependent on temperature (Boulos *et al.*, 1993). One of the findings was that the contribution from gas radiation to particle heating was never greater than 0.5% of the contributions from that of conduction and convection. Thus, the assumption of optically thin plasma was reasonable and the radiation term could be ignored from the energy equation. In the further development, the temperature dependent transport and thermodynamic properties and three-dimensional modeling were applied by Dussoubs *et al.* (1997), Li and Chen (2002) and Xiong *et al.* (2003 and 2004) which were closer to reality. Similar to these methods of modeling will be adopted by the author to simulate the plasma flow field in **Chapter 4**.

2.3.1.1 Heat Generation Modeling

The high intensity of electric current in the plasma torch plays an important role in ionizing the arc gas and thus generates heat required for particle heating and acceleration. The modeling of the heat generation can be summarized into three methodologies. They are:

- (i) Magnetohydrodynamic (MHD) model
- (ii) Inlet profiles for temperature and velocity
- (iii) Constant heat source model

In the first technique, the electromagnetic equation together with heat and flow equations were solved by Westhoff and Szekely (1991 and 1992) and Szekely and Westhoff (1992). In the development of the model, allowances were made for the conservation of mass, momentum, thermal energy and the continuity of current. The important feature of this model was that it could predict both the temperature contours and the electromagnetic forces within the torch as well as externally. Another advantage was that this approach did not rely on any arbitrary assumptions or adjustable parameters. The results are shown in **Figure 2.9**. It seemed that the electromagnetic force was important since the curves shown indicated that the calculated exit velocity was four times higher with the existence of electromagnetic force than without. However, no experiment results were provided in the plot to verify the model.

Figure 2.9: Effect of electromagnetic force on the radial profiles of (a) plasma temperature and (b) plasma velocity at torch exit (operating conditions: 750 A, 0.59 scmh argon and $S_w = 0$) (Westhoff and Szekely, 1991).

The second technique was utilized by Ramshaw and Chang (1992) and Chang and Ramshaw (1993). In this technique, the complex plasma generation phase was avoided and the focus was on the external flow into the ambient atmosphere. These studies assumed power law profiles of plasma velocity and

temperature at the torch exit as the starting condition for modeling the external plasma flow characteristics. The power law profile is generally written as:

$$\frac{\phi(r) - \phi_w}{\phi_c - \phi_w} = \left[1 - \left(\frac{r}{R} \right)^n \right] \quad (2.1)$$

where $\phi(r)$ represents the variable (temperature, velocity or enthalpy) at the distance r , ϕ_c the value of the variable at the torch axis, which is usually based on experimental measurement and ϕ_w the value at the wall, R the torch radius and n an exponent which can be chosen. However, the author finds that by using the power law profile, the modeling may be restricted to the application of external powder injection because the two experiment dependent values, ϕ_c and n measured at the exit of the torch.

As another option to the above two techniques of modeling, Eichert *et al.* (1998) and Remesh *et al.* (2003a and 2003b) assumed a volume-averaged heat source calculated from the torch electric power reduced by a reduction factor, to account for torch inefficiency. The torch efficiency η_t , was measured based on the difference of temperatures in the cooling water. It was usually in the range of 60%-70% which implied that approximately 30% of the energy was lost in the cooling process. **Equation 2.2** represents a uniform power generation in a given volume V inside the torch and was included as a source in the energy equation:

$$P_{in}''' = \frac{\eta_t E(t) I}{V} \quad (2.2)$$

where P_{in}''' is the volume-averaged heat source, $E(t)$ the fluctuating arc voltage and I the arc current. By applying the imposed voltage fluctuations, $E(t)$, the time-dependent plasma conditions could be directly computed. However, Park *et al.* (1999) found that the time-averaged plasma conditions averaging over the axial

fluctuations were very close to the steady-state conditions. The average particle velocity and temperature profiles were also similar to the steady-state profiles.

From the above three techniques, the author selects the third technique with constant voltage for the plasma heat generation, which will be further described in **Chapter 4, section 4.2.4.4**. The main reason is that the local arc phenomenon is complicated and the research is still ongoing. The second technique is restricted to only external injection and there are two arbitrary constants that must be determined from experiment. In addition, the third approach has the advantage of being flexible as it can be easily modeled for different operating conditions.

2.3.1.2 Turbulence Modeling

It is well known that plasma flow is a highly turbulent jet flow as it can reach the velocity of 1000-2000 m/s and Reynolds number of approximately 15,000. The turbulent phenomenon does not only result in rapid decay in plasma temperature and velocity away from the nozzle exit, but also influences heat and momentum transfer rates to particles traveling through the jet, which subsequently affect the particle behavior (temperature, velocity and trajectory). Appropriate turbulence model is, therefore required to obtain accurate particle behavior as well as impact sites of particles on the substrate.

Bauchire *et al.* (1997) developed a 2D mathematical model, considering heat, fluid as well as magnetic hydrodynamic flow to describe the effect of different turbulence models towards temperature and velocity profiles of the plasma flame. Two types of Prandtl's mixing length model and a standard κ - ϵ model were used. It was found that all the turbulence models gave very similar results for temperature and axial velocity. However, they proposed the usage of κ - ϵ model since more

information on turbulence were provided. The detailed information might be useful for other purposes, such as the local value of turbulence intensity or kinetic energy necessary for determining turbulent dispersion of particles.

As to reveal the influence of different types of κ - ε model on plasma temperature and velocity, Liu *et al.* (2000) utilized the linear (standard), non-linear and RNG (Re-Normalization Group) κ - ε models in their simulation. The results as shown in **Figure 2.10(a)** did not indicate much discrepancy between all the models for temperature. But for velocity, the non-linear model predictions were closest to experimentally measured data (see **Figure 2.10(b)**).

However, the author finds that despite at the distance of 30 mm from the nozzle exit (as encircled in **Figure 2.10 (b)**), the standard κ - ε model agrees well with the experimental measurements. Most of the previous studies by Lee and Pfender (1987), Chang and Ramshaw (1996), Chen *et al.* (1997), Bolot *et al.* (1997) and Zhang *et al.* (2001b) also successfully simulated the plasma flow fields using the standard κ - ε model. This implies that the standard κ - ε model is satisfactory to represent the turbulence phenomenon in the plasma spraying process. Thus, the standard κ - ε model will be utilized in **Chapter 4** to describe the turbulent effect in plasma flow.

Figure 2.10: Influence of different κ - ϵ turbulence models on the computed flow (a) temperatures and (b) velocities in the axial direction along the torch axis (operating conditions: 17.7 kW, 85 l/min Ar-H₂) (Liu *et al.*, 2000).

2.3.2 Experimental Measurements

In the plasma flow characteristics measurement, Brossa and Pfender (1988) used the enthalpy probe to measure flame temperature, velocity and chemical composition simultaneously.

Figure 2.11: (a) Argon concentration and (b) plasma temperature axial profiles under different arc currents and mass flow rates (Brossa and Pfender, 1988).

From **Figure 2.11(a)**, one could observe that the highest concentration of argon gas occurred at the highest arc current and the lowest mass flow rate. At the lowest mass flow rate, argon gas had more opportunity to receive energy from the electric arc and subsequently reached higher temperature. This increase of temperature would ensure high viscosity, causing less entrainment of surrounding air into the plasma flame. A similar explanation was given to the effect of highest arc current on the existence of highest concentration of argon gas. Due to the fact that air had higher specific heat than argon gas, when more surrounding air

entrained into argon gas, the temperature within the plasma flame would subsequently be reduced. This was the main reason for elucidating the trend in **Figure 2.11(b)**.

The application of enthalpy probe was also presented by Fincke *et al.* (1993a and 1994). In the experiment, the entrainment and demixing effects were studied by measuring both the plasma temperature and velocity at the jet centerline. The results showed that a sharp decay in both velocity and temperature occurred at approximately 15 mm, corresponding to the point at which the mixing layers reached the centerline and the concentration of the air in the core region became significant. The entrainment and mixing processes were complete at about 50 mm away from the nozzle exit.

Both the experimental results discussed by Brossa and Pfender (1988) and Fincke *et al.* (1993a and 1994) are of great interest to this study. The discussion provides a much better understanding on the variations of plasma temperature and velocity due to the changes of operating conditions and the interaction with the surrounding environment. The comprehensive understanding can help the author to strengthen the knowledge and analyze the results in **Chapter 4** in a more detailed manner. However, radial distributions of temperature and velocity which the author required for verifying the numerical work are not presented.

By applying the laser scattering technique, Murphy and Kovitya (1993) measured both the axial and radial distributions of plasma temperature for different power inputs and primary gas flow rates. The plasma flow field was also simulated using the Magnetohydrodynamic (MHD) model which initially developed by Scott *et al.* (1989). As clearly shown in **Figure 2.12**, good agreements between the predicted temperature distributions of the flame with those measured by laser

scattering technique were obtained. Hence, the results are potentially useful for comparison with the author's numerical work. For the case where arc current of 400 A, arc voltage of 27 V and argon flow rate of 40 l/min, the radial distributions of the plasma temperature at different axial distances away from the nozzle exit are shown in **Figure 2.13**. These results will be compared with the author's numerical results in **Chapter 4**, section 4.2.8.3.

Figure 2.12: The measured (given by points) and simulated (given by lines) flame temperatures for different operating conditions along the axis of the torch (Murphy and Kovitya, 1993).

Figure 2.13: The measured (given by points) and calculated (given by lines) temperatures along the radial directions at different axial distances away from nozzle exit, under the same operating conditions defined in Figure 2.12 (Murphy and Kovitya, 1993).

As for the effects of arc current and mass flow rate on plasma velocity, the results presented by Singh *et al.* (2000) are shown in **Figures 2.14** and **2.15**. In this experimental measurement, a method based on the application of Fast Fourier Transform (FFT) in the form of a long time series of multi-channel records of the plasma jet optical emission along and across the jet was adopted. The plasma velocity U was derived from **Equation 2.3**.

$$U = 2\pi d \frac{\Delta f}{\Delta \phi} \quad (2.3)$$

where d is the distance between sampling points, Δf the frequency increment and $\Delta \phi$ the difference of phase angles from the two sampling points.

From **Figures 2.14** and **2.15**, the increase in arc current and mass flow rate clearly resulted in the increase of plasma velocity. When progressing further downstream, it was noticeable that plasma velocity was decreased. This was because the entrainment and mixing of the atmospheric air into plasma jet retarded the flow of the plasma gas.

Figure 2.14: The influence of arc currents on argon plasma jet velocities for arc gas flow rate of 20 slm, at 5 mm and 10 mm away from nozzle exit (Singh *et al.*, 2000).

Figure 2.15: The influence of arc gas flow rates on argon plasma jet velocities for current of 200 A, nozzle diameter of 6mm, at 5 mm away from nozzle exit (Singh *et al.*, 2000).

2.4 Investigations of Particle Behavior

2.4.1 Modeling of Plasma to Particle Heat and Momentum Transfers

In modeling the plasma to particle heat and momentum transfers, basically, the Newton second law of motion is applied for momentum transfer and energy balance for heat transfer. These techniques will be adopted as a basis for the particle dynamics and heat transfer formulation in **Chapter 4**. Others addressed effects such as particle loading, turbulence, particle internal conduction, variations of plasma temperature and velocity, particle size, properties and injection velocity to make the process more realistic.

In the work reported by Lee and Pfender (1987), a two-way coupling effect between the continuous phase (plasma) and discrete phase (particle) was considered. The two-way coupling implied that the processes of heating or cooling and acceleration or retardation took place from the plasma to particle as well as in reverse. However, other researchers (Crowe, 1982, Swank *et al.*, 1993 and Sobolev *et al.*, 1999) have suggested that the coupling effect would not be significant when the particle loading ratio which defined as the ratio of particle mass flow rate to plasma mass flow rate was less than 0.3. In this study, the particle loading ratio is 0.08 and the modeling of plasma and particle interaction in **Chapter 4** may be considered as one-way.

Huang *et al.* (1995) studied the influence of turbulence transport on particle behavior via a two-fluid turbulence model. One of the interesting work was the introduction of the Stokes number (St) which defined as the ratio of the particle aerodynamic response time (τ_A) to the time scale associated with the large-scale eddies (τ_F). **Equation 2.4** shows the formula for Stokes number (St).

$$\text{St} = \frac{\tau_A}{\tau_F} = \frac{\rho_p D_p^2 / 18 \mu_p}{D_{noz} / U_\infty} \quad (2.4)$$

where ρ_p , D_p and μ_p are the particle density, diameter and viscosity respectively and D_{noz} and U_∞ are the nozzle diameter and bulk velocity respectively. For large Stokes numbers ($\text{St} \gg 1$), the particles would not have sufficient time to respond to the motion of the large-scale eddies and would move in nearly rectilinear paths. For small Stokes numbers ($\text{St} \ll 1$), the particles would have enough time to respond to the changing velocity fields of large-scale eddies and would be subjected to the motion of the fluid parcels. For intermediate Stokes numbers ($\text{St} \approx 1$), the particles might be entrapped in vortices and centrifuged beyond them.

In plasma spraying, the particle may be vaporized during its transit through the plasma flame. In addition, the particle may also experience other phase changes like melting and resolidification. To provide a clearer view on these phase changes, Wan *et al.* (1999) developed a model as shown in **Figure 2.16** to consider the heat conduction within a particle. The relative importance of this model could be made based on the value of the Biot number, $\text{Bi} = \frac{k_\infty}{k_p}$ with k_∞ and k_p the integrated mean value of gas and particle thermal conductivity, respectively. When the Biot number was larger than 0.3, substantial difference could exist between the temperature at the surface of the particle and that at its center (Bourdin *et al.*, 1983).

Figure 2.16: Schematic of the particle geometry and heating model (Wan *et al.*, 1999).

No melting followed by resolidification phenomenon was shown for the particles with size below 80 μm . However, it occurred for a 100 μm particle at about 6.6 ms (see **Figure 2.17**). The main reason for this was that the larger particle flew quickly to the peripheral region and had shorter residence time in the hot core region. In addition, 80 μm particle showed some interesting trend. At about 6 ms, the surface temperature indicated decreasing trend when the temperature at the particle center reached the melting point (as encircled in **Figure 2.18**).

Figure 2.17: Movement of the phase-change interfaces of a 100 μm zirconia particle sprayed under the operating conditions of 600 A current, 70 V voltage and Ar (40 l/min)-H₂ (12 l/min) plasma gas (Wan *et al.*, 1999).

Figure 2.18: Temperatures at the particle center and particle surface for different particle sizes of zirconia, under the same conditions given in Figure 2.17. Surface and center temperatures were represented by solid and dotted lines, respectively (Wan *et al.*, 1999).

A computer code was developed by Zhang *et al.* (2000) to investigate the effects on particle velocity and its surface temperature due to variations of plasma

velocity and temperature. For the purpose of this analysis, the particle size was fixed at $36\text{ }\mu\text{m}$. **Figures 2.19(a) and 2.19(b)** show that at higher plasma velocity or temperature, the particle was pulled closer to the central axis, resulting in higher axial velocity of particle. This subsequently increased the heat transfer coefficient and the efficiency of heat transfer from the flame to the particle surface, irrespective its shorter residence time in the flame. Hence, the particle experienced higher surface temperature.

Figure 2.19: Influences of (a) plasma velocity and (b) temperature on the axial velocity of a $36\text{ }\mu\text{m}$ particle (Zhang *et al.*, 2000).

Ahmed and Bergman (2000) investigated the effect of particle size on particle surface temperature. From the results presented in **Figure 2.20**, a $30\text{ }\mu\text{m}$ particle was noted to melt early and remained in the molten stage along the rest of the flight, whereas, particle of $70\text{ }\mu\text{m}$ never melted. This was because the dissimilarity of particles size caused the difference in particles trajectories, leading to the different lengths time of exposure in the core of the plasma flame. Larger and heavier particles penetrated through the core region rapidly and thus have shorter exposure time for heat transfer.

Figure 2.20: The evolution of the surface temperatures for 30, 50 (solid and hollow) and 70 μm particles along their axial locations through the Ar-H₂ (80:20 by volume) plasma jet (Ahmed and Bergman, 2000).

In another work reported in 2001 by Ahmed and Bergman, the effects of various carrier gas flow rates on the injected particles were investigated. It was shown that the carrier gas flow rate played an important role in determining the particle trajectories and the dispersion of the spray particles. However, the influences of the carrier gas flow rate on the molten fraction and the retained nanostructured fraction of the particles were found to be minor compared to the sensitivity of the particle size.

Recently, the work by Williamson *et al.* (2002) had examined all the parameters that may influence the particle in-flight behavior. These parameters were: turbulent dispersion, injection velocity, injection direction angle, particle size and density. Introduction of “one phenomenon at a time” was practiced in order to distinguish and characterize those effects and then all phenomena were considered simultaneously. From this numerical simulation, there were 3 interesting conclusions;

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- (i) Regarding particle dispersion in the injection direction, particle size, injection velocity, turbulence, injection direction or particle density distributions (in the order of decreasing importance) were significant effects.
- (ii) Particle density distribution and turbulence played important roles in dispersion in normal-to-injection direction.
- (iii) Particle size was the main effect for determining particle velocity and temperature.

In this study, in order to reflect the influence of oblique impact, the same operating conditions (arc current, primary and carrier gas flow rates) are maintained. Amongst all the effects discussed earlier, the factors that affect the particle velocity and temperature are the turbulence, particle size and properties. In view of this, the author will utilize the standard κ - ε turbulence model to predict the dispersion of particles due to turbulence. The actual particle size distribution as specified by the manufacturer and accurate particle properties will be included in the modeling of plasma to particle heat and momentum transfers in **Chapter 4**.

2.4.2 Particle In-Flight Characteristics Measurements

Considerable efforts have been devoted in the fields of particle size, velocity and temperature measurements. Due to the hostile nature of the plasma jet, in-situ measurements of particles traveling within the plasma jet have become a challenging one. Various diagnostic techniques have been developed to achieve accurate measurements of those parameters.

Fincke *et al.* (1990 and 1993b) utilized a combination of Laser Particle Sizing system, Laser Doppler Velocimetry (LDV) as well as two-color pyrometer to achieve measurements of size, velocity and temperature. The simultaneous measurement was aimed to identify the existence of cold particles (<1600 K) since these data were useful in understanding the plasma to particle interaction and provided the necessary link with the coating characteristics. The results presented in **Figure 2.21** indicated that at the upper edges, hot particles were in small sizes because small particles were unable to penetrate through the high velocity of plasma jet. These small particles have smaller heat capacity and could therefore be heated up easily. However, at this location, some cold and small particles existed. This was because these particles were entrained by the cold eddies. Towards the centerline, the size of the hot particles increased. The existence of cold eddies resulted in the presence of cold and small particles at the centerline. At the lower edges, size of the hot particles remained nearly the same as those in the centerline but the size of the cold particles was increasing till nearly the same size of hot particles. This was because more large particles were accumulated at the lower edges and their thermal masses were so large that they did not reach the melting point.

Figure 2.21: Radial distributions of particle size for hot (□) and cold (+) particles at the axial location of 76.2 mm (operating conditions: 800 A, 35 V, Ar (2830 l/hr)-He (1330 l/hr) plasma gas and Ar carrier gas (368 l/hr)) (Fincke *et al.*, 1993b).

The problem with simultaneous measurement of particle surface temperature and velocity using two-color pyrometer and Laser Doppler Anemometry respectively was based on different measuring principles, therefore, the measured particle parameters were not from the same particle. To overcome this, Coulombe *et al.* (1995) proposed a method based on direct measurement of thermal radiation at two wavelengths when the particles passed through a well-defined measurement volume. The technique to determine the particle surface temperature was the same

as that of used in two-color pyrometer. The particle velocity, U_p was estimated based on **Equation 2.5**.

$$U_p = \frac{H}{\tau R} \quad (2.5)$$

where H is the height of the measurement volume, τ the time interval and R the image ratio determined by the optical setup used. Results of particle velocity measurement were compared to that obtained by Laser Doppler Anemometry with a difference of less than 5 %.

Further simultaneous measurement of particle parameters was reported by Cetegen and Yu (1999). An experimental rig was designed, consisting of Phase Doppler Anemometer (PDA) for particle velocity and size measurements and a two-color pyrometer to determine particle temperature. The results showed that in the early part of the plasma jet (at smaller Z), there was an increase of mean particle velocity, followed by a decay at further downstream (at larger Z). This was due to the entrainment of ambient air into the plasma jet. This turbulent entrainment provided obstruction towards plasma flow, resulting in alleviation of plasma flame velocity and subsequently particle velocity was reduced. Other than that, the result from the study of the effect of a substrate on particle velocity was also presented. In the experiment, particle mean velocity was measured at $Z = 7.62$ cm by PDA with and without a substrate, which was located 5 mm downstream of the measurement location ($Z = 8.12$ cm). Radial distributions of particle mean velocity in **Figure 2.22** indicated that the existence of a substrate would slow and diverge the flow near the stagnation region but this gave minimum effect of less than 5% reduction of the particle velocity.

Figure 2.22: Impact of the presence of a substrate on particle axial velocities measured under the torch operating conditions of 600 A, 60 V, Ar ($2.27 \text{ m}^3/\text{hr}$)-H₂ ($0.59 \text{ m}^3/\text{hr}$) plasma gas and N₂ carrier gas ($0.31 \text{ m}^3/\text{hr}$) (Cetegen and Yu, 1999).

Several studies as mentioned earlier have shown the usefulness of laser based optical methods in studying the particle characteristics in plasma flow. However, these diagnostic methods are technically very demanding and also expensive, and therefore not very suitable to be used in industrial environment. Recently, a fast and non-intensified CCD camera has been marketed as another promising option to measure particle trajectory, velocity and temperature. This is an imaging diagnostic equipment; the SprayWatch© system developed by Oseir Ltd. (Hermiankatu, 6A, 33720 Tampere, Finland). It is based on a digital fast shutter CCD camera and spectrally resolving optics for monitoring and diagnostics of various thermal spraying processes.

Figure 2.23 shows the measurement principles of the SprayWatch© system. Array A is used for visual imaging, particle count and particle velocity

measurement while array B is for particle temperature measurement (Vuoristo *et al.*, 2001). Time of flight basis is applied for calculating particle velocity in array A. Array B is covered by two optical filter stripes for the measurement of the radiation intensity of the particle in two narrow wavelength ranges centered at 680 and 870 nm. Temperature of the particle can thus be determined using two-color pyrometry.

Figure 2.23: Measurement principles of the particle parameters in the SprayWatch© system (Vuoristo *et al.*, 2001).

Vuoristo *et al.* (2001) had successfully utilized SprayWatch© system to measure the particle in-flight parameters under three different levels of oxygen flow rate in High Velocity Oxygen Fuel (HVOF) process. The results as in **Figures 2.24(a)** and **2.24(b)** showed that the highest average temperature and velocity of particles were obtained at the highest oxygen flow rate, respectively. In addition, over-oxidized structures were not obtained. Thus, they concluded that the highest oxygen flow rate gave the best coating structure.

Figure 2.24: Influence of the oxygen flow rates on the average (a) temperature and (b) velocity of the in-flight particles in HVOF spraying of NiCoCrAlY powder (Vuoristo *et al.*, 2001).

Hämäläinen *et al.* (2003) also employed the SprayWatch© system to monitor and measure particle parameters during the coating of cylinder bore using the plasma spraying. The results showed that the SprayWatch© system was a promising tool for both the development and production monitoring of cylinder bore coating process as well as for realizing a closed-loop spray control system.

The above two published papers have demonstrated the capabilities of SprayWatch© system in monitoring and measuring particle in-flight parameters in plasma and HVOF processes. In addition, the reasonable cost and yet sufficient sensitivity and time resolution have made the system very attractive for laboratory and industrial use. In this study, the SprayWatch© system will also be utilized in **Chapter 5** to monitor the particle trajectories right before hitting the substrate. Also, the particle in-flight parameters measurements will be carried out for cases where the substrate is either present or absent.

2.5 Investigations in Coating Formation

Plasma sprayed coating consists of microstructural unit called splats, which formed from the spreading of particles with high temperature and velocity on the substrate. The shapes of the splats and how they bond with each other and the substrate strongly affect the coating properties such porosity, adhesion strength and roughness. In order to control the quality of the coating and its reproducibility, it is certainly a need to understand the coating formation and material science. It is, however, a very complex process because it is governed by various parameters; i.e. particle in-flight parameters, dynamics of spreading, degree of solidification as well as the conditions of the prepared substrate. Thus, considerable efforts have been devoted via theoretical, numerical and experimental investigations to improve the understanding.

A first and simplified model to predict the final splat size and thickness was provided by Madejski (1976). The model included inertia and viscous effects and based on the assumption that the solidification occurred subsequent to deformation. **Equation 2.6** represents the Madejski's model for the spread factor of a circular splat.

$$\xi = aRe^b \quad (2.6)$$

where ξ is the spread factor which defined as the ratio of splat diameter to droplet diameter; i.e. $\xi = d/D_p$ (see **Figure 2.25**), $a = 1.2941$ and $b = 0.2$, $Re = \frac{\rho_p u_p D_p}{\mu_p}$

where ρ_p , u_p , D_p and μ_p are density, velocity, diameter and viscosity respectively of a spray particle. Analytical and numerical investigations by other groups are tabulated in **Table 2.1** wherein each proposed various values for constants a and b .

Figure 2.25: Perfect formation of disk-shaped splat from a spherical molten droplet.

Table 2.1: A collection of spread factor models obtained from the literature. The analytical solutions were based on first principles and numerical methodology solutions required computing assistance to solve the complex equations.

a	b	Author	Methodology
1.2941	0.20	Madejski (1976)	Analytical
1.0000	0.20	Trapaga and Szekely (1991)	Numerical
0.8200	0.20	Watanabe <i>et al.</i> (1992)	Numerical
0.8300	0.21	Yoshida <i>et al.</i> (1992)	Numerical
1.0400	0.20	Liu <i>et al.</i> (1993)	Numerical
1.0600	0.17	Fukanuma (1994)	Analytical
1.1626	0.20	Delplanque and Rangel (1997)	Analytical

However, the experimental investigation by Vardelle *et al.* (1994) on zirconia particles sprayed perpendicularly on stainless steel substrate largely supported the Madejski’s spread factor model. Other experimental measurements of spread factor are summarized in **Table 2.2** which will be utilized for comparison with the author’s spread factor measurement in **Chapter 3, section 3.6.2.1**.

From **Table 2.2**, it is noted that there is no obvious difference in spread factors for substrate materials of steel and steel pre-coated with zirconia. This implies at least from the limited experimentation that the spreading behavior of the

splat on the bare substrate or on previously coated zirconia substrate is indifferent. In addition, the splat is observed to spread wider on smoother substrate (glass microscope slide with surface roughness of 0.02 μm). This is because with smoother substrate, less viscous dissipation occurs during spreading which leaves more kinetic energy to contribute to spreading.

Table 2.2: Spread factors, ξ obtained by atmospheric plasma-sprayed zirconia on various substrates based upon published data.

Author	Substrate Material	Surface Roughness, Ra (μm)	Substrate Temperature, T (K)	Spread Factor, ξ
Leger <i>et al.</i> (1995)	Steel	0.05, 0.40 or 9.00	573 - 773	4.90*
Leger <i>et al.</i> (1995)	Steel coated with Zirconia	0.20 or 4.00	573 - 773	4.70*
Vardelle <i>et al.</i> (1997)	Polished Stainless Steel	0.10	473 - 573	(3.50-5.50)
Kucuk <i>et al.</i> (2001)	Glass Microscope Slide	0.02	Not Reported	5.50* (4.80-6.20)

*Note: Average spread factors, ξ from experiments. Bracketed data indicates ranges.

Another simple analytical model was developed by Pasandideh-Fard *et al.* (1998) to predict the maximum spread factor. This model was based on equating droplet energy before and after impact, accounting for energy losses because of viscous dissipation and solidification. The model is given in **Equation 2.7**.

$$\xi_{\max} = \sqrt{\frac{We + 12}{3(1 - \cos \omega) + We \sqrt{\frac{3Ste}{4Pe}} + \frac{4We}{\sqrt{Re}}}} \quad (2.7)$$

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where ω is the wetting angle, We the Weber number: $We = \frac{\rho_p u_p^2 D_p}{\sigma}$, Re the Reynolds number: $Re = \frac{\rho_p u_p D_p}{\mu_p}$, Ste the Stefan number: $Ste = \frac{C_p (T_m - T_w)}{H_f}$ and Pe the Peclet number: $Pe = \frac{u_p D_p}{\alpha}$.

In **Equation 2.7**, the influence of solidification on the droplet spreading was characterized by the term $We \sqrt{\frac{3Ste}{4Pe}}$. The term $3(1-\cos \omega)$ was the adhesion tension of splat on substrate and $\frac{4We}{\sqrt{Re}}$ represented the work done in deforming the droplet against viscosity. If $\sqrt{\frac{Ste}{Pr}} \ll 1$ where $Pr = \frac{Pe}{Re} = \frac{\nu_l}{\alpha_l}$, the kinetic energy loss due to solidification would be too small to affect the extent of droplet deformation.

In addition, Delplanque and Rangel (1998) addressed the effect of solidification in the numerical analysis of the transient behavior of the deformation of metal droplet impacting on a flat surface. The solidification rate was obtained by solving the thermal energy equation in the liquid and solid and the mechanical energy equation governing the motion of the liquid disk is shown in **Equation 2.8**.

$$\frac{d}{dt}(E_k + E_p) = -\frac{dE_d}{dt} \quad (2.8)$$

where E_k and E_p represent the kinetic energy and surface-tension potential energy, respectively, and the right hand side represents the rate of viscous dissipation. Good agreement was achieved between the predictions and the experimental observations. However, the author finds that the models by Pasandideh-Fard *et al.* (1998) and Delplanque and Rangel (1998) are for lower particle velocity (≈ 2 -50 m/s) and larger particle size (≈ 2 -5 mm) and cannot be directly applied to high

velocity and micro-sized droplets in plasma spraying. This is because by comparing the potential energy per unit volume, $E_p \approx \sigma/D_p$ (σ is the surface tension and D_p is the droplet diameter) and the energy dissipated per unit volume, $E_d \approx \mu u_p/D_p$ (μ is the viscosity and u_p is the droplet velocity), the ratio of the potential energy to the energy dissipated by viscous effect can be expressed as:

$$\frac{E_p}{E_d} \approx \frac{\sigma}{\mu u_p} \approx \frac{Re}{We} \quad (2.9)$$

If Re/We is large (i.e. for larger particle and lower velocity), the spreading process is surface-tension-dominated, while for small values of Re/We , most of the impacting particles' kinetic energy are dissipated by viscous forces.

There are more suitable models to be used in plasma spraying to predict the spread factor. The following subsections describe the models considering the effects of surface roughness, substrate temperature and solidification. In addition, the effects of surface tension, wettability and oblique impact on the coating formation and material science are addressed.

2.5.1 Effect of Surface Roughness

Two types of surface roughness have been distinguished: low values, corresponding to $Ra < 0.2 \mu\text{m}$ and large values (Fauchais *et al.*, 2004). The low roughness could be related to the formation of oxide layer at the surface of a metallic substrate. The oxide thickness, composition, morphology and roughness depended on the substrate material, polishing procedure, and the thermal treatment to preheat the substrate over the transition temperature. This type of roughness promoted adhesion because when the oxide layer was thin (a few tens of nm), it could be melted by the impacting droplet and if a chemical reaction took place

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between the melted oxide layer and droplet, adhesion could be promoted. For example, Chraska and King (2002) showed that partially stabilized zirconia was strongly bonded to the 20-30 nm thick thermally grown oxide layer formed at the surface of a 316L stainless steel substrate preheated at 723 K.

As for the second type, i.e. large surface roughness ($R_a > 0.2 \mu\text{m}$), the spreading behavior of a droplet was completely different. In this case, the surface roughness increased the friction between a spreading droplet and the surface and thus retarding the spreading process. As a result, the contact between splat and substrate was poorer as well as exhibiting splashing behavior. Hitherto, to the author's best knowledge, there are only models available in describing the splat spreading under the effect of second type surface roughness.

Sobolev *et al.* (1996) and Sobolev and Guilemany (1999) developed a model as in **Equation 2.10** to elucidate the effect of surface roughness on splat spreading.

$$\xi_f = 0.8546 \chi^{1/2} \text{Re}^{1/4} (1 - 0.06 \gamma^{1/2} \text{Re}^{1/2}) \quad (2.10)$$

where χ is the dimensionless parameter of droplet mass loss and γ the dimensionless roughness parameter, which defined as the ratio of the roughness height, λ to the particle radius, R_p ; i.e. $\gamma = \lambda/R_p$. From **Equation 2.10**, it followed that an increase of the surface roughness decreased the spread factor, ξ . Note that, in the ideal case, where the surface is smooth ($\gamma = 0$) and without mass loss ($\chi=1$), **Equation 2.10** can be simplified to Reynolds number based model as in **Equation 2.6**, only with different value of constants; i.e. $a = 0.8546$ and $b = 0.25$.

The effect of surface roughness towards the splat spreading was also presented by Feng *et al.* (1998). A frictional resistance condition at the substrate-coating interface was introduced to include the effect of surface roughness. From

Figure 2.26, it was clear that frictional dissipation energy increased with the surface roughness. Subsequently, spreading velocity and spread factor were decreased.

Figure 2.26: Evolution of kinetic energy versus time (Feng *et al.*, 1998).

2.5.2 Effect of Substrate Temperature

The substrate temperature is another essential factor to the splat morphology and properties of the coating. By marginally increasing substrate temperature above its transition temperature, splat morphology can be significantly modified from fragmented or “splashed” morphology to a more disk-shaped morphology with limited or no splashing. The adhesion strength of the coating to the substrate can also be improved correspondingly.

The transition temperature is the temperature at which the splat pattern changes from splashed shape to a well-formed disk shape. It has shown that different substrate materials have different transition temperatures. Fukumoto *et al.* (1998) provided a relation between thermal conductivity of various substrates and transition temperatures as shown in **Figure 2.27**. The figure indicated that substrate with larger thermal conductivity tended to have higher transition temperature.

Figure 2.27: Relationship between thermal conductivity of substrates and transition temperatures (Fukumoto *et al.*, 1998).

The dramatic effect of substrate temperature in modifying the morphologies of splat was strongly supported by Sampath and Jiang (2001). They concluded that substrate temperature affected splat morphologies through the changes in interface nature, surface chemistry, solidification behavior, wettability and contact of molten droplet with substrate as well as droplet and substrate mechanical interaction. At higher substrate temperature, the existence of adsorption of gases on the surface was lower. This was clear that the wettability and contact of droplet with substrate were improved and thus reduced splashing.

Besides the substrate transition temperature, particle behavior of size, velocity and temperature were also significant in determining the occurrence of splashing (Lugscheider *et al.*, 2001 and Planche *et al.*, 2001). A splashing parameter, K as in **Equation 2.11** was proposed by Fukumoto *et al.* (2001) to incorporate the particle parameters.

$$K = 0.5a^{1.25}We^{0.5}Re^{-0.05} \tag{2.11}$$

By using the relation between substrate temperature, T_s and splashing parameter, K , splat morphology could be judged. From **Figure 2.28**, it was observed that at point 1 where substrate temperature, T_s was high and splashing parameter, K was low, good wettability and low thermal contact resistance existed, resulting in high heat transfer rate. Therefore, driving energy of the droplet for the spreading transferred to viscous energy effectively and disk splat formed. At point 2 where K increased, impact velocity of droplet increased, causing the driving energy for spreading to increase. Subsequently, rapid spreading and splashing occurred. When both T_s and K were relatively small (see point 3), poor wettability resulted ineffective energy transfer. Rapid spreading with low viscosity occurred although the original driving energy was small, resulting in splashing. Lastly, for the case where T_s was low and K was high (at point 4), existence of poor wettability and high impact velocity caused the splashing to occur most easily.

Figure 2.28: Physical meaning of transition phenomenon of splat morphology (Fukumoto *et al.*, 2001).

The above discussion highlights the significant effect of substrate temperature on the splat pattern. Therefore, in this study, in order to obtain splats with clear boundaries and thicknesses for accurate surface profile measurements, the substrate will be preheated to increase the substrate temperature (see **Chapter 3, section 3.3.2**).

2.5.3 Effects of Surface Tension, Wettability and Solidification

Wan *et al.* (2001) performed analysis to reveal the effects of surface tension and wettability on the splat spreading. **Figure 2.29** shows two criteria where above the lines representing the criteria were the viscous dissipation dominant region. Also the typical process values of droplet diameter and velocity ranges for molybdenum (Mo) and zirconia (PSZ) were indicated with a shadowed area. It was noted that all the zirconia droplets were in the viscous dissipation dominant region, implying that the surface tension and wetting angle effects could be ignored in the case of zirconia. But, for many sizes of Mo droplet, the effect of surface tension might be comparable to the effect of viscous dissipation. Nevertheless, the influence of wettability on spread factor was not as significant as that of the viscous dissipation. Generally, the spreading of droplet with lower velocity is more dependent on droplet surface tension and wetting angle. This is because a particle with lower velocity has a higher value of Re to We number ($\frac{Re}{We} = \frac{\sigma}{u_p \mu}$, where σ , μ and u_p are droplet surface tension, viscosity and velocity, respectively). A higher value of Re/We number implies that the effect of surface tension is more significant than viscous dissipation in splat spreading.

As for the effect of solidification, the study showed that it had a significant influence on the final splat thickness, only if the spreading time was lesser than the

solidification time. Conversely, the splat spreading would be in solidification insensitive region.

Figure 2.29: Viscous dissipation dominating region was above the lines representing the criteria for different materials. The shadowed area represented the typical conditions in plasma spraying (Wan *et al.*, 2001).

Based on the above results, they neglected the effects of surface tension and wettability to consider only the effects of inertia, viscous dissipation and solidification in the theoretical correlation. **Equation 2.12** shows the explicit relationship for spread factor and Reynolds number.

$$\xi = \left[\sqrt{1 + \left(\frac{S}{2} \sqrt{\text{Re}} \right)^2} - \frac{S}{2} \sqrt{\text{Re}} \right]^{0.4} (1.18 \text{Re}^{0.2}) \quad (2.12)$$

where S is the dimensionless solidification rate: $S = \tilde{s} / \sqrt{\tilde{t}}$ with $\tilde{s}$ the dimensionless thickness of solidified layer and $\tilde{t}$ the dimensionless solidification time.

Based on the following simplifying assumptions:

1. The substrate temperature was constant,

2. The solidified layer had a linear temperature distribution and
3. The surface contact was perfect.

The non-dimensional solidification rate, S can be expressed as in **Equation 2.13**.

$$S = \sqrt{\frac{2Ja}{\text{Re Pr}} \frac{k_s}{k_l}} \quad (2.13)$$

where Ja is the Jakob number: $Ja = \frac{C_p(T_m - T_w)}{H_f}$, Pr the Prandtl number: $\text{Pr} = \frac{\nu_l}{\alpha_l}$

and k the thermal conductivity with the subscript l represents the liquid state while s for the solid state.

Substituting **Equation 2.13** into **Equation 2.12** gave

$$\xi = \left[\sqrt{\frac{Ja}{2 \text{Pr}} \frac{k_s}{k_l}} + 1 - \sqrt{\frac{Ja}{2 \text{Pr}} \frac{k_s}{k_l}} \right]^{0.4} (1.18 \text{Re}^{0.2}) \quad (2.14)$$

It is noted that **Equation 2.14** is analogous to the well-known spread factor formulation as in **Equation 2.6**, where a is in the functions of Jakob number, Prandtl number and thermal conductivity and b equals to 0.2.

To further improve the accuracy, **Equation 2.14** was modified by Zhang *et al.* (2001a) to include the temperature distribution in the substrate by redefining the Jakob number based on the temperature difference between the equilibrium freezing temperature, T_m and the bottom temperature of the splat, T_B , as can be seen in **Equation 2.15**. Definition of the bottom temperature of the splat is given as in **Equation 2.16**.

$$Ja = \frac{C_p(T_m - T_B)}{H_f} \quad (2.15)$$

$$T_B = \frac{k_l T_l / \sqrt{\alpha_l} + k_w T_w / \sqrt{\alpha_w}}{k_l / \sqrt{\alpha_l} + k_w / \sqrt{\alpha_w}} \quad (2.16)$$

where k is the thermal conductivity, α the thermal diffusivity and the subscript l represents the liquid state while subscript w for the substrate.

All the above analytical spread factor models are quite useful in relating the splat diameter to the impact variables and substrate conditions. Because of many simplifications in their derivations, their usefulness is, however, limited. To better understand the dynamics, spreading and solidification, Mostaghimi *et al.* (2002) and Pasandideh-Fard *et al.* (2002) studied the heat transfer and fluid flow of an impacting droplet on a substrate via three-dimensional numerical analysis. The numerical results as in **Figure 2.30** showed that for splashing to diminish, solidification should be delayed and therefore the fluid flow would not be disturbed as much by a thinner frozen layer. This could be achieved by increasing the initial substrate temperature. Raising the substrate temperature would reduce the temperature gradient between splat and the substrate. Subsequently, this would slow down the rate of heat transfer from the splat to substrate and delay the solidification phenomenon.

However, recent work by Vardelle *et al.* (2000) have shown that the predictions of the model of Mostaghimi *et al.* (2002) did not match the experimental results as it was observed that the highest cooling rate was obtained on hot substrate and not cold substrate. In Vardelle *et al.* (2000) work, they found that by using substrate with temperature greater than transition temperature, the thermal contact resistance between the spreading particle and substrate (SP-S) or the previously deposited layer was small ($\approx 10^{-8} \text{ m}^2\text{K/W}$), implying a good SP-S contact. A good contact could result in better surface heating, higher cooling rate (4 to 10 times than that using substrate with temperature below transition temperature), and melting of

a thin layer of substrate or oxide layer at the substrate surface and thus promote the adhesion between the molten layer and the spreading particle without any splashing.

Figure 2.30: (a) Computer images of the impact of a molten nickel particle on a substrate initially at 290°C and **(b)** shape of the nickel splat at 10 μs on substrate initially at 400°C (Mostaghimi *et al.*, 2002).

2.5.4 Effect of Oblique Impact

The above discussion concentrates on the coating formation and material science under perpendicular impact. The realistic engineering components, however, require the torch to differ from normal due to their three-dimensional complex surfaces. This kind of spraying is known as oblique spraying or off-normal spraying. The problem encountered in oblique spraying is the difficulties in obtaining the desired thickness profiles. Hitherto, a successful set of spray parameters has been obtained by costly and extensive trial and error testing. To the author's best knowledge, the modeling of the coating formation under oblique spraying which can significantly reduce the cost and effort of the actual part spraying is not available. At the present time, much of the work is found to focus on the variations of coating properties due to off-normal spraying.

Experiments conducted by Montavon *et al.* (1997) and Leigh and Berndt (1997) highlighted significant effects of oblique spraying on geometric characteristics and properties of sprayed deposits, respectively. In their studies, the spray angle was defined as the angle between the axis of the plasma torch and the surface of the substrate. From the findings reported by Montavon *et al.* (1997), the splat was elongated from circular to elliptical shape when the spray angle changed from 90° to 30°. The prediction of splat elongation due to oblique impact was also carried out numerically by Bussmann *et al.* (1999). In the model, they only concerned the flow of material without taking the effects of surface roughness and solidification into consideration and the results are shown in **Figure 2.31**.

Figure 2.31: Comparison of splat elongation resulted from a 25 μm Ni particle at 500 m/s impacted onto a solid smooth substrate at spray angle of 45° (left) and 30° (right) (Bussmann *et al.*, 1999).

The experimental results by Leigh and Berndt (1997) revealed an increase in porosity and decrease in mechanical properties (such as microhardness, tensile adhesion strength and interfacial fracture toughness) of coating at lower spray angle.

It was seen in **Figure 2.32**, the coating porosity increased from 2.1 to 4.5% for $\text{Cr}_3\text{C}_2\text{-NiCr}$ and from 2.5 to 4.2% for NiAl when the spray angle varied from 90° to 50° .

Figure 2.32: Variation of porosities with spray angles (Leigh and Berndt, 1997).

The changes of porosity with spray angles were partly due to the changes of particle impacting momentum. At a spray angle of 90° , the particles have the highest normal velocity, i.e. at the highest impacting momentum. When the particles impacted on the substrate at smaller spray angles, their perpendicular impacting momentum was reduced in exchange to their tangential component. This resulted in ineffective coverage over the roughened surface of the substrate or previously deposited layer. Theoretical investigation by Sobolev and Guilemany (1998) also showed that the coating porosity was at a minimum when spraying was carried out at normal angle and the porosity increased as the spray angle decreased. **Figure 2.33** shows the analytical means for relative porosity prediction, which in reasonable agreement with the experimental observation.

Figure 2.33: Variation of relative porosities with respect to spray angles (Sobolev and Guilemany, 1998).

2.5.5 Deposition Efficiency Measurement

Typically, deposition efficiency (DE) is calculated from **Equation 2.17** and in the range of 40-60%, depending on the process parameters used.

$$DE (\%) = \frac{W_D}{W_I} \times 100 \quad (2.17)$$

where W_D is the weight of the powder deposited on the substrate and W_I is the weight of the powder injected.

Quantitative measurements for deposition efficiency obtained from the work conducted at different process parameters are compiled in **Table 2.3**. The DE values will be utilized in **Chapter 6, section 6.5.1** for comparison with the author's experimental result.

Table 2.3: Collection of deposition efficiencies from the reported literature.

	Operating Condition	Powder Material	Substrate Material	Deposition Efficiency (%)
Fincke and Swank (1992)	900 A, 34 V, Ar (47 l/min)-He (22.2 l/min)	Zirconia (AI-1075)	-	40-65
Leblanc <i>et al.</i> (1997)	800 A, 34-42 V, Ar (50 l/min)-H ₂ (2 l/min)	Fused YSZ	Grit-blasted Mild Steel	55
Jewett <i>et al.</i> (1997)	500-600 A, Ar (40 l/min)-H ₂ (7-12 l/min)	Crushed YSZ	Grit-blasted Steel	48-51
	500-600 A, Ar (40 l/min)-H ₂ (7-12 l/min)	Hollow Sphere YSZ	Grit-blasted Steel	51-60
Kucuk <i>et al.</i> (2001)	600 A, 70 V, Ar (40-50 l/min)-H ₂ (12 l/min)	YSZ	Glass Slide	7-25

As shown in **Table 2.3**, the lowest deposition efficiency occurs for spraying on a glass substrate, which is relatively smooth. This is because a smoother surface weakens the mechanical adhesion between splats and substrate and thus reduces the deposition efficiency. There are various other factors influencing the deposition efficiency. A summary was given by Kucuk *et al.* (2001), stating that the deposition efficiency was lower for the deposits sprayed (i) with lower torch power, (ii) at larger standoff distance, (iii) with a worn torch electrode, (iv) with higher powder feed rate and (v) with irregular powder morphology.

2.6 Conclusions

This chapter reported on the valuable insights due to analytical, numerical and experimental efforts by many researchers in plasma spraying technology. Some of the modeling techniques will be utilized in the author's numerical work; for instance, the volumetric heating in heat generation modeling and the standard κ - ϵ turbulence model in calculating plasma temperature and velocity. Plasma temperature measured experimentally by Murphy and Kovitya (1993), given in **Figure 2.13** will be used to verify the author's numerical plasma temperature prediction. Spread factors and deposition efficiencies collected as shown in **Tables 2.2** and **2.3**, respectively will be compared with the author's experimental measurements. Besides, zirconia properties required for the author's simulation work can be selected from the collection of properties of zirconia presented in **section 2.2.2**. Basically, the properties provided by Shackelford and Alexander (1994 and 2001) are utilized.

In addition, to the author's best knowledge, there is lack of published data on the spreading behavior due to oblique impact (only references listed in **section 2.5.4**). Much of the reported work has been associated with perpendicular impact. Quantitative correlation between spread factor and angle of impact is not presented in most publications. Therefore, in the absence of comprehensive data, the author develops techniques to investigate the spreading and shaping behavior (**Chapter 3**) which are useful for predicting coating formation in **Chapter 6**.

The author also finds that most of the research groups have neglected the influence of substrate, either in their experimental setup or numerical model. As the substrate provides significant obstruction to the flow field, it may affect the particle behavior. Therefore, the author devotes **Chapters 4** and **5** to the investigation of

Chapter 2: Literature Review

the influence of substrate on particle behavior by means of numerical and experimental approaches, respectively. Conclusions from both chapters will determine the particle behavior from the appropriate model (either model with or without a substrate) to be applied in the modeling of deposit formation at different inclination angles in **Chapter 6**.

CHAPTER 3

EXPERIMENT ON INDIVIDUAL SPLATS GEOMETRIC CHARACTERIZATION

3.1 Introduction

A FORTRAN© program has been written for calculating the formation of the deposit on flat substrate based upon a Substrate Cell Model (**Chapter 6**), subjected to perpendicular impact of particles of a stationary torch to substrate. In the case of perpendicularly sprayed flat substrate, the spray particles are assumed to impact normally on the substrate resulting in circular shaped splats. A deposit can be simulated as an accumulation of many such circular splats. In order for the Substrate Cell Model to simulate deposit formation at different inclined substrates, the program requires the spread factors (ξ) and aspect ratios (ψ) for the elliptical splats that are formed when the droplets impact at oblique angles. With the difficulty of finding suitable test data for the prediction of deposit topology, the author has found it necessary to perform experiments to obtain the quantitative correlations for the spread factors (ξ) and aspect ratios (ψ) with angles of impact.

This chapter describes the experimental techniques for the extraction of empirical spread factors, ξ and aspect ratios, ψ for zirconia particles on mild steel substrates under oblique impacts. The experimental procedures as can be seen in **Figure 3.1** involve: substrate preparation, spraying on specially designed rig and substrate examination by means of Scanning Electron Microscopy (SEM) and high

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resolution surface profilometry. Discussion on the morphologies of the splats and the results of spread factors, ξ and aspect ratios, ψ under the influence of substrate inclination angles are presented.

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Figure 3.1: Flow chart of the procedures for single splat experiment.

3.2 Substrate Preparation

15 x 10 x 3 mm thick mild steel substrates were cut from 3 mm thick sheet stock using a Struers Discotom-5© universal cut-off machine (Struers Inc., 24766 Detroit Road, Westlake, OH.). The small size of the substrate is required for the ease of polishing as well as subsequent access to the test chambers of the SEM and the optical surface profiler equipment. In order to provide reliable measurement of splat volume, the substrates have to be polished to remove surface roughness. The substrates were polished with progressively finer grades of grit paper, in ascending order of grit numbers: 180, 400, 800 and finally 1000. After polishing, the roughness of the substrates was measured by the Surftest 301© surface roughness profiler (Mitutoyo, Japan). All the substrates exhibit the mean arithmetic surface roughness, Ra of 0.5 microns. This is important as they provide consistent surface conditions for spraying experiment. The substrates before and after polishing are shown in **Figure 3.2**. The substrates were protected from oxidation by immediate drying and storing in a desiccant chamber until they were required for spraying experiments.

Figure 3.2: 15 x 10 x 3 mm thick substrates (a) in the raw state and (b) after polishing.

3.3 Single Splat Capture Experiment

3.3.1 Feedstock Powder

The feedstock powder was a commercially available powder; yttria-partially-stabilized (8%) zirconia (YSZ), product code: 204 NS (Saint-Gobain Norton K.K., Singapore). The particle size distribution as specified by the manufacturer was in the range of 22-125 microns (Saint-Gobain, 2004). As measured by the Analysette 22 Compact© laser particle sizer (Fritsch GmbH, Industriestrasse 8, D-55743, Idar-Oberstein, Germany), the size distribution as shown in **Figure 3.3** was found to be between 10 to 120 microns in diameter with a mode of 37 microns. The range of particle diameters was based on 0.5% of differential number particles, because below which the number of particles is too small to give a reliable measurement. The powder was characterized by near-perfect spherical particles, as shown by the SEM photograph in **Figure 3.4**.

Figure 3.3: Particle size distribution of yttria-partially-stabilized (8%) zirconia (YSZ) powder as measured by Analysette 22 Compact© laser particle sizer.

Figure 3.4: SEM photograph of yttria-partially-stabilized (8%) zirconia (YSZ) powder showing near-perfect spherical particles.

3.3.2 Experiment Equipment

The investigation was carried out using a model SG-100© plasma torch (Praxair Surface Technologies Inc., N670 Communication Drive, Appleton, Wisconsin 54915, USA) with 2 mm internal diameter powder injector. A roto-feed powder hopper (Miller) model 1264© (also from the above supplier) was used to introduce the powder at the rate of 9.6 g/min into the plasma torch and sprayed atmospherically onto the substrate. The plasma-forming gas and carrier gas used in this study were argon. Details of the spray conditions are listed in **Table 3.1**. The spray parameters were chosen from the optimum case of the earlier study conducted by Remesh (2002).

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Table 3.1: Experimental spraying conditions.

Parameter / Unit	Magnitude
Nozzle Diameter / mm	15.5
Torch Diameter / mm	8
Injector Diameter / mm	2
Injector Location	Internal
Current / A	900
Voltage / V	35
Primary Gas Flow Rate (Argon) / psi (slm)	80 (72)
Carrier Gas Flow Rate (Argon) / psi (slm)	30 (4.2)
Powder Feedrate / g/min	9.6
Powder Size / μm	22-125
Standoff Distance / mm	80

The substrate inclination angle is defined as the angle between the vertical plane (Y-axis) and the substrate surface. Note that the substrate inclination angle is different from the spray angle used in the literature (e.g. Leigh and Berndt, 1997 and Bussmann *et al.*, 1999) reported in **Chapter 2**. In fact, the substrate inclination angle equals 90° minus the spray angle. To avoid confusion, substrate inclination angle will be adopted in the rest of the thesis.

The substrate inclination was obtained by means of the tilting mechanism behind the backing plate. The angle of inclination was measured with the aid of

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spirit level and protractor as can be seen in **Figure 3.5(a)**. The experimental rig as shown in **Figure 3.5(b)** consisted of a traverse rig that carried a backing plate onto which was attached the substrate.

Figure 3.5: (a) Changing of substrate inclination to 10° by the tilting mechanism with the assistance of spirit level and protractor, (b) single splat capture experimental rig for 30° substrate inclination angle and (c) $15 \times 10 \times 3$ mm thick of gold-coated substrate with visible specks of zirconia splats.

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The splats were captured by traversing the substrate in front of the stationary spray at a fairly rapid speed such that individual splats were segregated from each other. From trial and error, the best traverse speed was found to be in the range from 40 to 60 mm/s. When compared with the impact velocity of the arriving particles which are in the magnitude of 100-200 m/s, the traversing speed has a negligible influence on the overall direction of the incoming particles. Also, the number of passes in front of the torch was limited in order to avoid overlapping the splats. Each substrate was sprayed once at a standoff distance of 80 mm from the nozzle front face of the plasma torch. The substrate with visible specks of splats is shown in **Figure 3.5(c)**. Before spraying, the substrate was preheated to an estimated temperature of 723 K by traversing it for 20 passes in front of the torch without powder supply (from previous experimental study by Gan, 2002). This is important because a preheated substrate is required to obtain well-formed splats (with regular shapes).

In the series of experiments, inclination angles ranging from 0° to 60° at intervals of 10° were investigated, as schematically illustrated in **Figure 3.6**. Three substrates were sprayed for each substrate inclination angle, resulting in a total of 21 substrates being sprayed at 7 different angles.

Figure 3.6: Schematic diagram for 7 substrate inclination angles conducted in the experiments.

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3.4 Characterization of Individual Splats

3.4.1 Scanning Electron Microscopy of Individual Splats

In order to observe the morphologies of the splats, the substrates were subjected to Scanning Electron Microscopy (SEM) examination. As zirconia is a non-conducting material, prior to the SEM analysis, the substrates with zirconia splats on them were gold-coated using a Polaron SC7640© sputter coater (Quorum Technologies, Unit 15A, Euro Business Park, New Road, Newhaven, East Sussex, BN9 0DQ, England). 20 random images were collected from substrates at each inclination angle. A discussion on the various features in the SEM images is presented in the **sections 3.6.1.1 and 3.6.1.2.**

3.4.2 Microscopic Measurement on Individual Splats Geometry

The splat profiles were measured by the WYKO NT-2000© optical surface profiler (Veeco Tucson Inc., 2650 East Elvira Road, Tucson, AZ 85706 USA). The WYKO© surface profiler system, as seen in **Figure 3.7** is a laser based non-contact 3D measurement system that uses two modes i.e. phase-shifting interferometry (PSI) or vertical-scanning interferometry (VSI) to measure surface heights from 0.1 to 500 micrometers resolution, respectively (Veeco Tucson Inc., 1996). The former mode is suited to smooth surfaces while the latter for rough surfaces. For this study, analysis was carried out in the VSI mode which was best suited to the micro-sized surface features of the splats.

In vertical-scanning interferometry (VSI), a white-light beam passes through a microscope objective to the sample surface. A beam splitter reflects half of the incident beam to the reference surface. The beams reflected from the sample and

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the reference surface recombine at the beam splitter to form interference fringes. During measurement, the reference arm containing the interferometric objectives is moved vertically by a linearized piezoelectric transducer to scan the surface at varying heights. Fringe contrast at a single sample point reaches a peak as the sample is translated through the focus. The vertical position corresponding to the peak of the interference signal is extracted for each point on the surface and grouping of all vertical positions provides a three-dimensional profile for the measured splat (Veeco Tucson Inc., 1996).

Figure 3.7: WYKO© surface profiler for individual splats geometry microscopic measurement.

Fifty splats for each inclination angle were selected randomly for their well-formed shapes that were free from overlapping, overlaying and lesser degree of splashing for scanning by the WYKO© surface profiler. Typical scans are shown in **Figures 3.8(a) to 3.8(g)**, respectively which provide three-dimensional data for heights and side elevations of the splats. The XYZ data was then post-processed by

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Mountains Map© software (Digital Surf, 16, Rue Lavoisier, F-25000 Besançon, France). Mountains Map© is a software package dedicated to the high definition microtopography analysis of surfaces. It offers useful tools such as volume integration and distance measurement which are required in this study. For the volume integration, a boundary was firstly defined by carefully digitizing the points along the perimeter of the splat. Ridges and fingers were included whilst defining the boundary to obtain an accurate volume measurement. As for the case of distance measurement, endpoints of the splat in respective directions of X and Y were selected. Distances between the selected endpoints gave the length and width of the splat.

Figure 3.8: (a) (i) 3D view and (ii) 2D contours showing the thickness (μm) of the splat in magnified scale for the case of 0° substrate inclination angle scanned by the WYKO© surface profiler. The impacting particle diameter is calculated as $13\ \mu\text{m}$. Volume, V_s and length dimensions were extracted from these plots. The striations seen in the background are the grinding scores left by the polishing process.

(i)

(ii)

(b)

Figure 3.8: (b) As in Figure 3.8(a), but the calculated diameter of the impacting particle is 14 μm and at 10° substrate inclination angle.

Figure 3.8: (c) As in Figure 3.8(a), but the calculated diameter of the impacting particle is 13 μm and at 20° substrate inclination angle.

Figure 3.8: (d) As in Figure 3.8(a), but the calculated diameter of the impacting particle is 13 μm and at 30° substrate inclination angle.

Figure 3.8: (e) As in Figure 3.8(a), but the calculated diameter of the impacting particle is 12 μm and at 40° substrate inclination angle.

(i)

(ii)

(f)

Figure 3.8: (f) As in Figure 3.8(a), but the calculated diameter of the impacting particle is 19 μm and at 50° substrate inclination angle.

Figure 3.8: (g) As in Figure 3.8(a), but the calculated diameter of the impacting particle is 17 μm and at 60° substrate inclination angle.

3.5 Spread Factor, ξ and Aspect Ratio, ψ

This section describes the parameters for characterizing the splat in geometric terms. In the case of a droplet with diameter D_p impacting normally on the substrate, see **Figure 3.9(a)**, the splat takes up a circular shape defined by the diameter d and thickness t . The spread factor, ξ is defined as the ratio of splat diameter to droplet diameter, i.e.

$$\xi = \frac{d_e}{D_p} \quad (3.1)$$

Because, the spread factor relates the circular splat diameter to droplet diameter, it does not relate well to the elliptical shaped splat. For this, the elliptical splat area obtained under oblique impact is converted to an equivalent splat of circular shape so that its equivalent diameter, d_e can be derived (see **Figure 3.9(b)**). This is carried out by conservation of volume, whereby

$$\text{Volume of circular splat} = \text{Volume of elliptical splat}$$

For the same thickness, the areas are equivalent, that is;

$$\text{Area of circle} = \text{Area of ellipse}$$

$$\frac{\pi d_e^2}{4} = \pi \frac{d_x}{2} \frac{d_y}{2}$$

where d_e is the equivalent diameter, which defined as the diameter of a circular splat with the same area as the elongated splat. Therefore,

$$d_e = \sqrt{d_x d_y} \quad (3.2)$$

where d_x and d_y were measured and post-processed by WYKO® surface profiler and Mountains Map®, respectively.

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Figure 3.9: Idealized illustration of (a) perpendicular impact of molten particle resulting in circular splat with diameter, d and (b) oblique impact of molten particle resulting in elongated splat with its aspect ratio, ψ of d_y/d_x and its equivalent diameter, d_e .

The volume of the droplet which causes each splat is uncertain because the individual droplet before impact cannot be observed much less measured in the extreme environments. By an inverse calculation procedure, the volume of the droplet can be deduced from the volume of the splat it created. Hence, the diameter of the droplet is as follows:

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$$\text{Volume of the droplet, } V_p = \frac{\pi D_p^3}{6} = V_s$$

where V_s is the volume of the splat formed.

Therefore,

$$\text{Impacting droplet diameter, } D_p = \left(\frac{6V_s}{\pi} \right)^{\frac{1}{3}} \quad (3.3)$$

where the volume of the splat, V_s was measured by WYKO© surface profiler and post-processed by Mountains Map©. It is therefore important that the splat volume V_s must be measured with utmost precision for this deduction of the diameter to be effective.

From **Equation 3.1**, the spread factor is finally obtained. In terms of the fundamental measurements, it is given in **Equation 3.4**.

$$\xi = \frac{\sqrt{d_x d_y}}{\sqrt[3]{\frac{6V_s}{\pi}}} \quad (3.4)$$

Concerning the aspect ratio, it is defined as the ratio of major to minor diameters,

$$\psi = \frac{d_y}{d_x} \quad (3.5)$$

For the case of impact on an inclined substrate, as illustrated in **Figure 3.9(b)**, the elliptical splat is obtained which is defined by the aspect ratio of greater than unity.

3.6 Results and Discussion

Images from SEM examination and data from WYKO® surface profiler are carefully processed and analyzed. In the SEM image analysis, features of well-formed splats including fingering, ridging, cracking and spalling as well as splashing, overlapping and overlaying of malformed splats have been observed and examples are shown in **Figures 3.10** and **3.11**. The deposition simulation program (**Chapter 6**) being developed by the author requires the following input data: the impact location, aspect ratio and spread factor as well as the inclination angle. Impact locations of the splats produced at higher substrate inclinations ($\theta \geq 20^\circ$) are determined from SEM photos (**Figure 3.12**). Subsequently, the influence of substrate inclinations on spread factors and aspect ratios are discussed.

3.6.1 Image Analysis

3.6.1.1 Feature Analysis for SEM Images of Well-Formed Splats

A well-formed splat is formed from an individual impacting droplet free from any destructive defects such as cavitation, spalling, overlaying of smaller splat or bursting. **Figures 3.10(a)** to **3.10(g)** show the SEM images of well-formed splats for the complete range of substrate inclination angles from 0° to 60° . The splat shown in **Figure 3.10(a)** for 0° perpendicular impact is almost a perfect circle, while other, seen in **Figures 3.10(b)** to **3.10(g)**, depicts a progressive elongation of the splats as substrate inclination angle increases.

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Figure 3.10: (a) SEM examination of splat morphologies obtained from impacting droplets at substrate inclination of 0°.

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Figure 3.10: (b) SEM examination of splat morphologies obtained from impacting droplets at substrate inclination of 10° .

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Figure 3.10: (c) SEM examination of splat morphologies obtained from impacting droplets at substrate inclination of 20° . Arrows indicate the directions of incoming droplets.

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Figure 3.10: (d) SEM examination of splat morphologies obtained from impacting droplets at substrate inclination of 30° . Arrows indicate the directions of incoming droplets.

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Figure 3.10: (e) SEM examination of splat morphologies obtained from impacting droplets at substrate inclination of 40° . Arrows indicate the directions of incoming droplets.

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Figure 3.10: (f) SEM examination of splat morphologies obtained from impacting droplets at substrate inclination of 50° . Arrows indicate the directions of incoming droplets.

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Figure 3.10: (g) SEM examination of splat morphologies obtained from impacting droplets at substrate inclination of 60° . Arrows indicate the directions of incoming droplets.

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The author has found that in all the SEM photos, there are substantial numbers of “fingers” radiating from the edge of the splat. For small angles of substrate inclination (0° and 10°) as shown in **Figures 3.10(a)** and **3.10(b)**, fingers are uniformly distributed around splat circular circumference. At higher substrate inclinations ($\theta \geq 20^\circ$), as can be seen in **Figures 3.10(c)** to **3.10(g)**, the fingers tend to concentrate on one side of the splat in the direction of the particle spreading momentum. The direction of particle spreading momentum is the direction of the particle tangential velocity (or the velocity component parallel to the substrate surface) on impact. The development of fingers can be caused by the inefficient solidification behavior of the splat during spreading. Many experimental work by various teams have shown that when the substrate is cold, the gas and condensates entrapped at the material surface will desorb under the very hot spreading material and form a thin layer of gas that will limit the heat extraction through the substrate while on hot substrate, the quality of contact between the splat and the surface is better and so the cooling rate is higher. In this work, as the substrate was preheated before splats collection, the spreading splat is in good contact with the substrate. This causes a higher heat conduction rate to the substrate which results in the splat being solidified rapidly. However, due to the poor conductive material (zirconia) being sprayed, there are materials in the liquid state, especially those in the upper layers. This combines with the momentum of impact ejecting the liquid radially outwards to create fingers. With increasing substrate inclination, radial and equally distributed liquid flow is substituted with the oriented spreading flow. This results in the formation of fingers to radiate preferentially in the direction of particle spreading momentum instead of bursting uniformly as seen in the case of perpendicular impact.

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Another feature also caused by differential cooling through different layers through the thickness of the splat is the perimeter ridge observed in all the SEM photos. These ridges are at a higher elevation than the interior of the splats (analogous to the edge of the pizza pie). The ridge can be formed: due to heat conduction to the substrate, the bottom layers of the splat have a lower temperature, resulting in higher liquid viscosity. This impedes the flow and the spreading process. However, the upper layers are hotter and hence less viscous. Thus, the material continues to travel outwards in a radial direction whilst being retarded by the viscous forces of the lower layers. Eventually, the molten portion of the splat consumes its inherent kinetic energy and solidifies at the circumference of the splat forming the ridge.

A common feature evident from the SEM images regardless of the substrate inclination angle is the uniform cracking on the splat. These cracks are observed throughout the entire surface of the splat and when cracks meet or intersect, they are always perpendicular to each other. The perpendicular intersecting cracks are commonly caused by thermally induced stresses after non-uniform cooling and solidification of the splat. These stresses are biaxial and tensile in circumferential and radial directions and the eventual result will be the cracking of the splat to relieve these tensile stresses. These crack patterns are often observed in porcelain glazes or drying mud flats.

Lastly, the author finds that instances of spalling of splats from the substrates to be more prevalent at higher substrate inclination. Splats that peeled partially or completely from the substrates are common at substrate inclination angle of 60°. **Figure 3.10(g)** shows the imminent peeling off of the splat. This is attributed to lower adherence strength caused by the reduced particle normal

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velocity, i.e. the perpendicular component of impacting momentum is insufficient to provide good bonding to the substrate. At higher substrate inclination, the perpendicular momentum is reduced in exchange with the tangential component. An incoming particle with high momentum converts more of its kinetic energy towards the tangential direction at higher substrate inclination, thus elongating the splat in the process and reduction in adhesion strength.

3.6.1.2 Feature Analysis for SEM Images of Malformed Splats

Figure 3.11 shows some malformed splats which were rejected by the author as these cannot provide a reliable volume measurement with the WYKO[®] surface profiler. The malformed splats are those without clear boundaries and uncertain thicknesses of the interior. Splats exhibiting splashing, overlapping or severe pitting cavities in these experiments are categorized as malformed splats. The author finds it instructive to examine the causes for such malformed splats.

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Figure 3.11: Examples of malformed splats obtained. **(a)** Splashed splats showing ejected materials, **(b)** overlaying, two smaller splats deposit within a larger splat and **(c)** one splat overlaps partially on another splat.

Figure 3.11(a) presents the splashed splats with ejected materials in all directions and numerous unmelted particles embedded within the splats. The phenomenon is believed to be caused by two successive droplets impacting at the same location nearly simultaneously. The second incoming particle may have impacted on the splat whilst it is in formation, ejecting and scattering molten materials in all directions due to its high impact energy. The scattered materials subsequently solidify as solid particles which relocate and adhere to the splat before it solidifies. Due to the similar breakup process, some of the smaller droplets are

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detached from the original splat. If they are still liquid, they form smaller splats and some may overlay on larger splat as can be seen in **Figure 3.11(b)**.

Figure 3.11(c) shows the overlapping of two splats. Splat A forms first and spreads perfectly, before being overlaid by splat B. However, poor wettability of splat B to splat A causes low adherence between them and consequently, splat B peels off when it solidifies.

3.6.1.3 Determining the Points of Impact

Further analysis on SEM photos was carried out to determine the locations where droplets initially struck the substrate as the event could not be observed at first hand. As can be seen in **Figures 3.12(a) to 3.12(e)**, particles impacting obliquely at 20° to 60° produce elliptical shaped splats. Circular splats are obtained from 0° and 10° inclination angles as seen in **Figures 3.10(a) and 3.10(b)**. For the latter, the circular splats' impact locations must be presumed to be at the geometric center of the circle. In the case of elliptical shaped splats, the impact points are determined by two techniques; by (i) backtracking the radiating fingers to their originating point and (ii) geometrically determining the foci of the ellipse.

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(a)

(b)

(c)

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Figure 3.12: Comparison of the impact points of a droplet based upon (i) backtracking the radiating fingers on the left and (ii) determining the foci by formula method on the right for (a) 20°, (b) 30°, (c) 40°, (d) 50° and (e) 60° inclination angles.

The backtracking technique relies on the observation that the fingers radiate out from the point of impact of the droplet. By extrapolating the fingers' directions backwards, the extension lines are found to intersect at a single point in most of the cases. However, backtracking the large numbers of splats is labor intensive, an alternative method is found as replacement. It is observed in **Figures 3.12(a) to 3.12(e)** that the impact points lie close to one of the two geometric foci of the ellipse. Thus, by evaluating the foci by analytical geometry, an accurate location of

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the impact point is obtained, this following procedure shall be known as the geometric formula method.

For an ellipse with major and minor diameters, d_y and d_x respectively, with its center at $(0, 0)$, the foci will have the coordinates of $(c, 0)$ and $(-c, 0)$, as seen in **Figure 3.13**.

Figure 3.13: Geometry of an ellipse with major diameter, d_y and minor diameter, d_x showing two foci with the distance c from the center of the ellipse.

The distance of the focus from the center, c can be calculated as in **Equation 3.6** as,

$$c = \pm \frac{d_y}{2} e \quad (3.6)$$

where $d_y/2$ is the semi-major diameter and e is the eccentricity of the ellipse which is written as:

$$e = \sqrt{1 - \frac{d_x^2}{d_y^2}} = \sqrt{1 - \frac{1}{\psi^2}} \quad (3.7)$$

where ψ , the aspect ratio and d_y and d_x , the major and minor diameters, respectively, measured from SEM photographs.

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Justification of the two techniques is made by quantitative comparison of the impact locations, c as presented in **Table 3.2**. Fairly good agreement indicates the acceptability of assuming the impact location as one of the foci of the ellipse.

Table 3.2: Comparison of c , obtained by backtracking and geometric formula (Equation 3.6) methods.

Substrate Inclination, θ	Distance c in μm from the Center of Ellipse (0, 0)	
	Backtracking Method	Geometric Formula Method
20°	7.18	8.63
30°	18.20	16.61
40°	17.79	15.37
50°	42.19	38.96
60°	31.55	32.85

3.6.2 Spread Factors, ξ and Aspect Ratios, ψ

It can be seen from **Figure 3.14(a)** that the mode (value with the highest frequency of occurrence) for spread factors, ξ is increasing from 4.60 to 5.50, followed by a decreasing trend to 4.80 at 60° substrate inclination angle. As for the aspect ratios, ψ , the mode is increasing from 1.00 to 1.80 and 1.82 after a 60° increase in inclination angle, exhibiting a progressively elongated splat from circular ($\psi = 1.00$) to elliptical shape which can be observed from **Figure 3.14(b)**.

In comparison, the spread factors are more scattered than that of for aspect ratios. At 60°, the aspect ratios scatter in the range from 1.60 to 2.28.

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Figure 3.14: Population histograms for experimentally measured (a) spread factors and (b) aspect ratios for the case of 0°, 20°, 40° and 60° inclination angles. Each histogram is based on 50 splats.

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3.6.2.1 Influence of Substrate Inclination Angles on Spread Factors, ξ

Best fitting equations to all experimental measurements obtained from Microsoft Excel© (Microsoft Corporation, One Microsoft Way, Redmond, WA, USA 98052-6399) are shown in **Figure 3.15**. These equations indicate a quadratic relationship between spread factors and substrate inclination angles. The spread factor starts off at 4.60 at 0° substrate inclination and rises to a maximum of 5.50 at 30°. A value of 4.80 occurs at 60° substrate inclination angle.

Table 3.3 provides quantitative comparison between the experimental results for perpendicular impact (i.e. 0°) with the published data. In general, there is good agreement within the limits of practical experimental errors and in spite of the different spraying conditions and materials being used by other research groups.

Figure 3.15: Experimental spread factors, ξ against substrate inclination angles, curve fitted by quadratic functions (B: mode, A: upper and C: lower bounds). Mode and range for each inclination are based on 50 splats.

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Table 3.3: Spread factors, ξ obtained by atmospheric plasma-sprayed zirconia on various substrates based upon the published data.

Author	Substrate Material	Surface Roughness, Ra (μm)	Substrate Temperature, T (K)	Spread Factor, ξ
This work	Polished Mild Steel	0.50	723	4.62* (3.23-5.56)
Leger <i>et al.</i> (1995)	Steel	0.05, 0.40 or 9.00	573 - 773	4.90*
Leger <i>et al.</i> (1995)	Steel coated with Zirconia	0.20 or 4.00	573 - 773	4.70*
Vardelle <i>et al.</i> (1997)	Polished Stainless Steel	0.10	473 - 573	(3.50-5.50)
Kucuk <i>et al.</i> (2001)	Glass Microscope Slide	0.02	Not Reported	5.50* (4.80-6.20)

*Note: Average spread factors, ξ from experiments. Bracketed values indicate experimental ranges.

Three quadratic equations are curve fitted to the experimental data as can be seen in **Figure 3.15**. These equations, denoted as A, B and C represent the upper, mode and lower bounds of the data, respectively. In future, these equations can be applied in the author’s Substrate Cell Model (**Chapter 6**) to simulate the deposit profiles for different inclined substrates, which is the main reason for this work.

Although it is noted that the empirical data gathered are very specific to the zirconia/mild steel materials combination at surface roughness of Ra = 0.5 microns and same temperature (i.e. 723 K), it is believed the data can be widely adopted for the coating formation modeling. As seen in **Table 3.3**, the spread factors for zirconia particles sprayed on a range of substrate materials (glass, stainless steel and steel coated with zirconia), with different surface roughness (Ra values range from

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0.02 to 9 microns) and temperatures (from 473 to 773 K) differed. When considered together with the experimental scatter present, the percentage difference is approximately 10% and this value is tolerable for the coating formation modeling.

3.6.2.2 Spread Factors with respect to Particle Sizes

Figure 3.16 shows the experimentally measured spread factors with respect to particle sizes for substrate inclination angles of 0°, 30° and 60°. It is noted that the experimental data are largely scattered. A horizontal straight line at $\xi = 4.8$, 5.5 and 4.2 will provide a good match for particle diameters ranging from 5 to 40 microns for 0°, 30° and 60° inclinations respectively.

Figure 3.16: Experimental spread factors, ξ at 0°, 30° and 60° substrate inclination angles with respect to particle sizes. The experimentally measured data at 30° and 60° inclinations were encompassed and shaded with two different tones of grey for better viewing.

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From **Figure 3.16**, it is also noticeable that most of the particles are in the range from 5 to 35 microns in diameter compared to the feedstock powder which is in the range 22-125 microns. Very few larger splats have been found hence larger droplets are also absent. One explanation is that of material loss through surface vaporization during the droplets flight to the substrate. This results in more smaller droplets forming splats. Consequently, the entire powder size population may be shifted towards the smaller size. This explanation can be supported by the result presented by Wan *et al.* (1999) which showed that a 20 μm zirconia particle reduced to 15 μm after 6.5 ms of flight through Ar (40 l/min)-H₂ (12 l/min) plasma jet with a power input of 29.4 kW. A 25% reduction of particle size was encountered. In addition, this phenomenon was also observed by Kucuk *et al.* (2001), where the average particle size forming splat ranged from 35 to 55 microns while the average particle size of the feedstock was 80 microns. Another reason can be that larger splats formed from larger particles tend to be malformed, thus they were consciously deselected by the author. A few SEM photos of the malformed splats are shown in **Figure 3.11** and explained earlier.

3.6.2.3 Influence of Substrate Inclination Angles on Aspect Ratios, ψ

Figure 3.17 presents the influence of substrate inclination angles on aspect ratios. At angles approximately below 15°, the aspect ratios are close to unity, indicating that splats will be circular in shape. As the angle increases from 15° to 60°, the aspect ratio increases from 1.02 to 1.82, progressively elongating the splat from circular to elliptical shape simultaneously increasing the data scatter. This is attributed to the conversion of kinetic energy of incoming particle towards the particle spreading energy being more pronounced at higher inclination angle.

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Figure 3.17: Plot of aspect ratios, ψ against substrate inclination angles with curve fitted quadratic equations for mode (B), upper (A) and lower (C) bounds of the data. 50 splats per inclination were measured.

Table 3.4 presents the aspect ratios from current work and others for comparison. In the case of 0° substrate inclination, Table 3.4(a) shows a consistent trend in spite of different materials. For other substrate inclination angles at 30° and 60°, Table 3.4(b) shows data from Montavon *et al.* (1997). It is observed that the data from Montavon *et al.* (1997) in both cases are slightly higher.

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Table 3.4: (a) Compilation of the aspect ratios, ψ from the literature and comparison with the current work for 0° substrate inclination angle.

	This Work	Montavon <i>et al.</i> (1997)	Fukumoto <i>et al.</i> (2001)	Fauchais <i>et al.</i> (2001b)	Zhang <i>et al.</i> (2001a)
Powder Material	Zirconia	Astroloy	Nickel	Alumina	Molybdenum
Substrate Material	Mild Steel	Copper	Not Known	Stainless Steel	Mild Steel
Substrate Temperature, T (K)	723	293	723	573	473
Aspect Ratio, ψ	1.00* (0.93-1.11)	1.37* (1.25-1.49)	1.00*	0.92*	1.05*

*Note: Average aspect ratios, ψ from experiments. Bracketed values indicate ranges.

Table 3.4: (b) Comparison of the aspect ratios, ψ from the Montavon *et al.* (1997) with the current work for substrate inclination angles of 0° , 30° and 60° only.

Substrate Inclination Angle ($^\circ$)	0	30	60
This Work	1.00* (0.93-1.11)	1.13* (1.05-1.23)	1.86* (1.60-2.28)
Montavon <i>et al.</i> (1997)	1.37* (1.25-1.49)	1.62* (1.36-1.88)	2.10* (1.81-2.39)

*Note: Average aspect ratios, ψ from experiments. Bracketed values indicate ranges.

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3.7 Conclusions

Zirconia powder were atmospheric plasma sprayed on the mild steel substrates and single splats were isolated and examined by WYKO® surface profiler and Scanning Electron Microscopy (SEM). The substrates were inclined at fixed angles of inclination to study the effect of oblique impacts on splat morphologies. Dimensions of the isolated splats were measured by WYKO® surface profiler to deduce the spread factors, ξ and aspect ratios, ψ . It had been shown that there was a parabolic relationship between spread factor and substrate inclination angle. The substrate inclination angle also induced an elongation of the splat which was characterized by means of the aspect ratio parameter. The aspect ratio increased with the substrate inclination angle. Best-fitted quadratic equations have been proposed to represent the spread factor and aspect ratio.

Based on the SEM image analysis, features such as splashing, overlapping, overlaying, finger and ridge formation and cracking were observed on the splats. For elliptical splat, a study had been conducted to determine the point of impact of the droplet on the substrate by means of backtracking the fingers emerging from splat. The point of impact was found to coincide well with the geometrical foci of the ellipse.

The data collected will be applied in the author's Substrate Cell Model simulation in **Chapter 6** to predict coating formation.

CHAPTER 4

MODELING AND SIMULATION FOR PLASMA AND PARTICLE BEHAVIOR

4.1 Introduction

Particle size, velocity, temperature, dispersion behavior and melting state are the important parameters required in the modeling of coating formation in **Chapter 6**. In this chapter, a reliable and cost-effective method, i.e. the Computational Fluid Dynamics (CFD) approach to accurately determine the particle behavior in the plasma flame is described. The CFD modeling involves the plasma heat generation and plasma to particle interaction. The three-dimensional CFD domain of the model encompasses the torch inlet and the air region in front of the torch. The approach in modeling the plasma heat generation is by means of the conventionally adopted constant volumetric heat source model. The heat transfer from plasma to particles occurs in the air region and a one-way coupling is adopted.

From the literature review in **Chapter 2**, it was found that a number of numerical studies have been devoted to the modeling of the DC arc plasma spraying and the influences of process parameters on particle behavior. It had also shown that the turbulent and cooling effects caused by the entrainment of ambient air into the plasma jet affected the particle trajectories and their subsequent temperatures and velocities. These effects are expected to be more severe when the jet impinges on the substrate, leading to stagnation and the reversals of gas flow around the

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obstacle in the gas path. The experimental measurement given by Lapierre *et al.* (1994) indicated that the presence of the cooled substrate considerably increased the centerline plasma temperature by 22% at 5 mm elevation from the substrate surface.

In order to investigate the effects on flow and particles due to the substrate obstruction, three computational models as follows are constructed and the law-of-the-wall is utilized to account for the obstruction effect by the substrate towards the plasma flow.

- (i) A 3D computational domain without the substrate,
- (i) The same above domain with the inclusion of a substrate at a standard standoff distance of 80 mm in front of the nozzle and perpendicular to torch axis and
- (ii) The same above domain with the substrate at 60° inclination to the vertical plane.

The results of the effect of the substrate determine whether the inclusion of substrate into the CFD model is necessary before particle parameters are utilized in modeling the deposit formation in **Chapter 6**.

4.2 Plasma Heat Generation

The mathematical model was based on the fully elliptic Navier-Stokes system of differential equations with the Reynolds method of averaging the time dependent equations, together with the standard κ - ε turbulence model. The equations were solved by the FLUENT V6.02© commercial package (FLUENT Inc, 10 Cavendish Court, Lebanon, NH03766-1442). Before progressing to the description of the process, detail about the concept of Local Thermodynamic Equilibrium (LTE) is presented because it is important in simulating plasma spraying process.

4.2.1 Local Thermodynamic Equilibrium (LTE)

For torch with non-transferred arc, two phenomena, electrical breakdown and gaseous discharges occur in order to generate and maintain the plasma. Under such conditions, high mobility electrons are produced and they will receive energy from the applied electric field and subsequently transfer part of the energy to the heavy particles through elastic collisions. Even with excellent collisional coupling, there will always be a difference between electrons and heavy particles in terms of temperature. A parameter, E/p (where E is energy and p is pressure), plays an important role in determining the equilibrium situation for the plasma. For small values of E/p (p exceeds 10kPa), the electron temperature approaches the heavy particle temperature and this is one of the basic requirements for the existence of Local Thermodynamic Equilibrium (LTE) in plasma. This requirement is important because it permits plasma to be considered as continuous fluid with only single value properties, for instance thermal conductivity, density and so on.

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4.2.2 Geometry Models

The geometries of the three models developed using the commercial software GAMBIT V2.04© (FLUENT Inc., 10 Cavendish Court, Lebanon, NH03766-1442.) are shown in **Figures 4.1(a) to 4.1(c)**; i.e. one without and two including the substrates. The cylindrical computational domain (diameter x length) included the spray torch $\phi 8 \times 10$ mm, the nozzle $\phi 15.5 \times 7$ mm, the injection port $\phi 2 \times 35$ mm and the free space in front of the nozzle $\phi 160 \times 250$ mm. Larger free space in front of the nozzle for plasma flame is needed because of the intention of imposing atmospheric conditions on radial and axial boundaries. Dimensions of the torch were taken from the SG-100© (Praxair Surface Technologies Inc., N670 Communication Drive, Appleton, Wisconsin 54915). In **Figures 4.1(b) and 4.1(c)**, the substrates were 50 by 50 by 3 mm (thickness), following the size of the substrate used in the experiment in **Chapter 6**.

Although it is observed that there is a plane of symmetry with respect to YZ plane, three-dimensional instead of half the physical domain was modeled. The main reason is that with three-dimensional modeling, the effect of the carrier gas on the plasma jet, the transverse injection of the powder, three-dimensional character of turbulence structures and turbulent dispersion of particles can be captured. In addition, it also provides more flexibility to the current model so that in future, different shapes of sprayed substrates, including complex and non-symmetrical engineering components such as turbine blade can be included without any difficulty.

Figure 4.1: Computational domains for internal injection plasma spraying: (a) freestream model, (b) substrate model with perpendicular substrate and (c) substrate model with inclined substrate.

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4.2.3 Major Assumptions

Modeling a free turbulent and steady state DC plasma jet was based on the following assumptions:

1. The plasma gas was assumed to be in Local Thermodynamic Equilibrium (LTE) condition. This requirement is important because it permits plasma to be considered as continuous fluid with only single value of properties such as density, viscosity and so on.
2. Liu *et al.* (2000) simulated the plasma temperature and velocity without taking into account the effect of chemical reaction (i.e. dissociation and ionization of plasma gas) and compared their results with those of Eichert *et al.* (1996) who included the effect of chemical reaction. No significant difference was noted, thus, the plasma gas in this study was represented as a chemically inert gas with temperature dependent thermodynamic and transport properties.
3. The plasma flow was assumed to be optically thin and no radiation was taken into consideration. This is because from McKelliget *et al.* (1982) and Dussoubs *et al.* (1997), the heating of particles by gas radiation was negligible compared to convective heat transfer to particles.
4. The plasma flow was assumed to be incompressible for both inside and outside the plasma torch. This is reasonably justified as the calculated Mach numbers have the values of less than 1 [Appendix II].
5. In order to reduce the complexity of modeling, arc characteristics were not modeled. Therefore, Lorentz flow (flow induced due to the potential differences in electric and magnetic fields) was neglected in this analysis

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and the plasma heat was assumed to be generated by volumetric heat source which was based on power input and torch efficiency [Appendix III].

6. The SG-100© torch has the primary gas injected normally from gas injector into the torch and no swirl was present in the plasma heat generation.
7. In order to determine the significance of buoyancy force, Gr/Re_∞^2 (ratio of Grashof number to Reynolds number squared) was evaluated. From the calculation of this parameter, the value ranges from 10^{-4} to 10^{-7} . This means that inertia is the dominant force for flow acceleration in comparison with the buoyancy force. Therefore, operation of the torch was assumed to be in steady state with negligible gravity effect.

4.2.4 Governing Equations

Based on the above assumptions, there were five basic conservation equations needed for the modeling of plasma heat generation. The equations are described below.

4.2.4.1 Mass Conservation Equation

The mass conservation equation is the reflection of the continuum assumption. The physical meaning of this equation is that the fluid will occupy continuously every point of the space in the flow domain. **Equation 4.1** indicates the steady state of mass continuity equation.

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (4.1)$$

where ρ is the density and u is the velocity of the flow.

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4.2.4.2 Momentum Conservation Equation

The momentum conservation equation links the flow velocity of a fluid element with surface forces acting on it. It can be written in Cartesian tensor form as:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j} (-\overline{\rho u'_i u'_j}) \quad (4.2)$$

The additional term due to Reynolds stresses, $-\overline{\rho u'_i u'_j}$ represents the effect of turbulence. A common method to relate the Reynolds stresses to the mean velocity gradients is indicated in **Equation 4.3**.

$$-\overline{\rho u'_i u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} (\rho k + \mu_t \frac{\partial u_i}{\partial x_j}) \delta_{ij} \quad (4.3)$$

4.2.4.3 Standard κ - ϵ Equation

The state of a flow can be judged by the value of its Reynolds number. When $Re > 2400$, the flow will be turbulent. Based on the operating conditions, the Reynolds number is 15×10^3 [**Appendix IV**]. This shows that the plasma jet flow is turbulent and the standard κ - ϵ turbulence model was selected since local turbulence kinetic energy was necessary for determining the turbulent dispersion of particles in the particle dynamics and heat transfer formulation. The standard κ - ϵ equations are as shown in **Equations 4.4** and **4.5**.

$$\frac{\partial}{\partial x_i}(\rho u_i \kappa) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{Pr_{t,\kappa}} \right) \frac{\partial \kappa}{\partial x_i} \right] + 2\mu_t S_{ij} S_{ij} - \rho \epsilon \quad (4.4)$$

$$\frac{\partial}{\partial x_i}(\rho u_i \epsilon) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{Pr_{t,\epsilon}} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} \frac{\epsilon}{\kappa} 2\mu_t S_{ij} S_{ij} - C_{2\epsilon} \rho \frac{\epsilon^2}{\kappa} \quad (4.5)$$

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where $S_{ij} = \frac{1}{2} \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right]$

$$\mu_t = \rho C_\mu \frac{\kappa^2}{\varepsilon}$$

and five adjustable constants have been set as

$$C_\mu = 0.09; \quad \text{Pr}_{t,\kappa} = 1.00; \quad \text{Pr}_{t,\varepsilon} = 1.30; \quad C_{1\varepsilon} = 1.44; \quad C_{2\varepsilon} = 1.92$$

The last two terms in **Equations 4.4** and **4.5** represent the rate of production and destruction of κ and ε , respectively.

4.2.4.4 Energy Equation

Plasma flow is characterized by its high temperature in the core region and a sharp reduction along its radial direction. The variation of plasma temperature was determined by the transport equation for energy as in **Equation 4.6**. The first three terms on the right-hand side of the **Equation 4.6** represent energy transfers due to conduction, species diffusion and viscous dissipation, respectively. S_h is the source term accounting for the heat of chemical reaction or any other heat sources.

$$\frac{\partial}{\partial x_i} [u_i (\rho E + p)] = \frac{\partial}{\partial x_j} \left[k_{\text{eff}} \frac{\partial T}{\partial x_j} - \sum_n h_n J_n + u_i (\tau_{ij})_{\text{eff}} \right] + S_h \quad (4.6)$$

where

$$E = h - \frac{p}{\rho} + \frac{u^2}{2}$$

$$h = \sum_n Y_n h_n + \frac{p}{\rho} \quad \text{for incompressible flow}$$

$$h_n = \int_{T_{\text{ref}}}^T C_{p,n} dT$$

$$(\tau_{ij})_{\text{eff}} = (\mu + \mu_t) \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) - \frac{2}{3} (\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_j} \right) \delta_{ij}$$

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$$k_{\text{eff}} = k + \frac{C_p \mu_t}{Pr_t}$$

J_n is the diffusion flux, Y_n is the mass fraction of species n and T_{ref} is 298.15 K.

In this study, the volumetric heat source accounting for the thermal effect from the electric arc heating was included as the source term, S_h in the energy governing equation and defined as in **Equation 4.7**.

$$S_h = P_{\text{in}}''' = \frac{\eta_t EI}{V} \quad (4.7)$$

where P_{in}''' is the volume-averaged heat source, E the arc voltage, I the arc current and V the volume of the torch. Torch efficiency, η_t , which takes into account for the heat loss mainly through the cooling water in the plasma torch was assumed to be 67% after Ang *et al.* (2000).

4.2.4.5 Species Equation

In this study of Atmospheric Plasma Spraying (APS), there were two gases involved, argon gas and air. To solve the conservation equation for chemical species, FLUENT© predicted the local mass fraction of each species, Y_n through the solution of a convection-diffusion equation for the n^{th} species as in **Equation 4.8**.

$$\frac{\partial}{\partial x_i} (\rho u_i Y_n) = \frac{\partial}{\partial x_i} (\rho D_n + \frac{\mu_t}{Sc_t}) \frac{\partial Y_n}{\partial x_i} \quad (4.8)$$

where D_n is the diffusion coefficient for species n in the mixture and Sc_t is the

turbulent Schmidt number: $Sc_t = \frac{\mu_t}{\rho D_{nt}}$.

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4.2.4.6 Wall Functions

Owing to the presence of the solid substrate, the flow behavior and turbulent structure are considerably different from the free turbulent flows. The mean velocity is at a maximum far away from the wall and sharply decreases in the near-substrate region. High values of velocity fluctuations are found adjacent to the wall where the large mean velocity gradients ensure that turbulence production is high. To have an accurate representation of the flow in the near-substrate region, semi-empirical formulas called wall functions were used to link the viscosity-affected region with the wall and the fully-turbulent region.

Equations 4.9 and **4.10** show that the flow close to the wall is influenced by viscous effect and does not depend on freestream parameters. The mean flow velocity at adjacent element to the substrate, U_A strongly depends on the distance, y from the wall, plasma density, ρ and viscosity, μ and the wall shear stress, τ_w (Launder and Spalding, 1974). **Equations 4.9** and **4.10** are called the law-of-the-wall and were used as the wall functions (FLUENT Inc., 2001b).

$$U^* = y^* \quad y^* < 11.225 \quad (4.9)$$

$$U^* = \frac{1}{K} \ln(By^*) \quad y^* > 11.225 \quad (4.10)$$

where U^* and y^* are the dimensionless velocity and distance from the element to the substrate, K the von Kármán constant ($= 0.42$), B the empirical constant ($= 9.81$).

U^* and y^* are defined as:

$$U^* = \frac{U_A C_\mu^{1/4} \kappa_A^{1/2}}{\tau_w / \rho} \quad (4.11)$$

$$y^* = \frac{\rho C_\mu^{1/4} \kappa_A^{1/2} y_A}{\mu} \quad (4.12)$$

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where C_μ is the empirical constant ($= 0.09$), κ_A the turbulent kinetic energy at point A (near-substrate element) to the substrate and y_A the distance from point A to the substrate.

Reynolds' analogy between momentum and energy transports gives a similar logarithmic law for temperature (Petukhov and Polyakov, 1988). As in the law-of-the-wall for mean velocity, the law-of-the-wall for temperature employed in FLUENT© comprises the following two different laws:

- (i) **Equation 4.13** is the linear law for the thermal conduction sublayer where conduction is important (FLUENT Inc., 2001b).
- (ii) **Equation 4.14** is the logarithmic law for the turbulent region where effect of turbulence dominates conduction (FLUENT Inc., 2001b).

$$\frac{(T_w - T_A) \rho C_p C_\mu^{1/4} \kappa_A^{1/2}}{\dot{q}} = \text{Pr}_t y^* \quad y^* < y_T^* \quad (4.13)$$

$$\frac{(T_w - T_A) \rho C_p C_\mu^{1/4} \kappa_A^{1/2}}{\dot{q}} = \text{Pr}_t \left[\frac{1}{K} \ln(\text{By}^*) + P \right] \quad y^* > y_T^* \quad (4.14)$$

where T_A is the plasma temperature at adjacent element to the substrate, T_w is the substrate temperature, C_p the plasma specific heat capacity, $\dot{q}$ the heat flux to the substrate, y_T^* the non-dimensional thermal sublayer thickness and Pr_t the turbulent

Prandtl number: $\text{Pr}_t = \frac{\nu_t}{\alpha_t}$.

P was computed using the formula given in **Equation 4.15** by Jayatilke (1969).

$$P = 9.24 \left[\left(\frac{\text{Pr}}{\text{Pr}_t} \right)^{3/4} - 1 \right] [1 + 0.28 e^{-0.007 \text{Pr}/\text{Pr}_t}] \quad (4.15)$$

4.2.5 Operating and Boundary Conditions

The operating and boundary conditions as shown in **Table 4.1** were set and maintained the same for the three models since changes in the setting of the process parameters will alter the behavior of plasma gas, which will affect the subsequent processes.

Table 4.1: Operating and boundary conditions for plasma spraying simulation.

Operating Condition / Unit	Magnitude
Nozzle Diameter / mm	15.5
Torch Diameter / mm	8
Injector Diameter / mm	2
Injector Location	Internal
Current Input / A	900
Voltage / V	35
Torch Efficiency / %	67
Heat Source / W/m ³ [Appendix III]	4.1997 x 10 ¹⁰
Arc Gas Flow Rate (Argon Gas) / kg/s	1.9474 x 10 ⁻³
Carrier Gas Flow Rate (Argon Gas) / kg/s	1.1360 x 10 ⁻⁴
Turbulence Intensity at Arc Gas Inlet / % [Appendix IV]	4.83
Turbulence Intensity at Carrier Gas Inlet / % [Appendix IV]	6.09
Standoff Distance (from Nozzle Front Face) / mm	80
Powder Feedrate / g/min	9.6
Powder Size / μm	22 - 125

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The mass flow rates of arc gas and carrier gas were input at the inlets of the torch and injection port respectively. The Reynolds numbers of the arc and carrier gas flows imply that the effect of turbulence should be taken into account [Appendix IV]. The boundary condition for the turbulence model at inlets of the torch and injection port was turbulence intensity and characteristic length. The turbulence intensity, T_i is defined as the ratio of the root mean square velocity fluctuation to mean flow velocity and was calculated based on Equation 4.16.

$$T_i = \frac{\sqrt{u'^2}}{u} = 0.16(\text{Re}_{\text{HD}})^{-0.125} \quad (4.16)$$

where Re_{HD} is the Reynolds number calculated for the gas flowing through the respective inlets, on the basis of the hydraulic diameter as the characteristic length.

A volumetric heat source term inside the torch was assumed to account for the joule heating phenomenon. The radial and axial exit boundaries were selected a distance far away from the exit of the nozzle such that atmospheric boundary conditions were imposed there.

4.2.6 Thermodynamic and Transport Properties

In plasma spraying, high temperature environment exists and both thermodynamic and transport properties vary with temperature. Therefore, the temperature dependent thermodynamic and transport properties were prerequisite for the modeling work.

Two species of gas; argon gas and air existed in this modeling of atmospheric plasma spraying. Both the temperature dependent properties variations were adopted from Boulos *et al.* (1994) and input into the FLUENT© as piecewise linear profiles with respect to temperatures.

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4.2.6.1 Argon Gas

Argon gas was used as arc gas and carrier gas in the simulation. Its temperature dependent properties of density, specific capacity, thermal conductivity and viscosity are presented in **Figures 4.2(a) to 4.2(d)**, respectively.

Figure 4.2: (a) Variation of argon gas density with respect to temperature.

Figure 4.2: (b) Variation of argon gas specific heat with respect to temperature.

Figure 4.2: (c) Variation of argon gas thermal conductivity with respect to temperature.

Figure 4.2: (d) Variation of argon gas viscosity with respect to temperature.

4.2.6.2 Air

Similar to argon gas, its variations of thermodynamic and transport properties as presented in **Figures 4.3(a) to 4.3(d)** are density, specific heat capacity, thermal conductivity and viscosity, respectively.

Figure 4.3: (a) Variation of air density with respect to temperature.

Figure 4.3: (b) Variation of air specific heat with respect to temperature.

Figure 4.3: (c) Variation of air thermal conductivity with respect to temperature.

Figure 4.3: (d) Variation of air viscosity with respect to temperature.

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4.2.6.3 Mixture

Previous discussion concentrates on the pure thermodynamic and transport properties for argon gas and air. However, at the moment plasma gas is released into the atmosphere, entrainment and mixing of atmospheric air into the plasma jet (argon gas) occur. Thereafter, mixture properties are needed instead of pure species properties. Volume-weighted mixing law was applied for mixture density (Equation 4.17) while mass-weighted mixing law was adopted for the others properties (Equations 4.18 to 4.20).

a. Mixture Density

$$\rho = \frac{\sum_n V_n \rho_n}{\sum_n V_n} = \frac{\sum_n \frac{Y_n}{\rho_n} \rho_n}{\sum_n \frac{Y_n}{\rho_n}} = \frac{1}{\sum_n \frac{Y_n}{\rho_n}} \quad (4.17)$$

b. Mixture Specific Heat

$$C_p = \frac{\sum_n Y_n C_{pn}}{\sum_n Y_n} = \sum_n Y_n C_{pn} \quad (4.18)$$

c. Mixture Thermal Conductivity

$$k = \frac{\sum_n Y_n k_n}{\sum_n Y_n} = \sum_n Y_n k_n \quad (4.19)$$

d. Mixture Viscosity

$$\mu = \frac{\sum_n Y_n \mu_n}{\sum_n Y_n} = \sum_n Y_n \mu_n \quad (4.20)$$

where V_n is the volume fraction and Y_n is the mass fraction for species n .

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4.2.7 Solution Procedures

All the equations (mass, momentum, turbulence, energy and species) given earlier were solved by the FLUENT V6.02© commercial package in order to predict the velocity and temperature fields in a free plasma jet, issuing from the nozzle exit. FLUENT© uses the control volume technique to convert governing equations into algebraic equations that can be solved numerically. This numerical approach stores scalar variables at the center of the control volume. The face values of scalar variables are also required for the convection terms and their values are gained from interpolation. First order upwind scheme was adopted to calculate the face values of the scalar variables since the problem was convection-dominated flow. For pressure and velocity coupling, the SIMPLE algorithm was employed (Patankar, 1980 and Versteeg and Malalasekera, 1995).

For the solution algorithm, the segregated solver was selected. Using this approach, the resultant algebraic equations for the dependent variables in each control volume were solved sequentially by a point implicit (Gauss Seidel) linear equation solver in conjunction with an algebraic multigrid (AMG) method. This means that segregated approach solves a single variable field by taking all control volumes at the same time into consideration. It then solves for the next field variable by again considering all control volumes at the same time and so on (FLUENT Inc., 2001b). Finally, the solution was considered converged when the residuals of all the conservation equations decreased to 10^{-3} , except the energy equation, for which the criterion is 10^{-6} .

4.2.8 Results and Discussion

Investigation is carried out to reveal the effect of the substrate on plasma flow fields. Grid independence tests, verification of one-way coupled approximation and verification of plasma temperature with the published experimental result are conducted before detailed discussion on the effect of the substrate onto plasma flow fields is presented.

4.2.8.1 Grid Independence Tests

A series of grid independence tests were conducted on the mesh model at the beginning of the simulation process to ensure that optimized computational mesh was obtained. For the three models (freestream, perpendicular and inclined substrate models), grid independence tests have to be carried out for each model. All the mesh models were also examined for their mesh quality in terms of skewness (mesh distortion). Equivolume skew is a measure of skewness and defined as in **Equation 4.21** (FLUENT Inc., 2001a).

$$Q_{EVS} = \frac{(V_{eq} - V)}{V_{eq}} \quad (4.21)$$

where V is the volume and V_{eq} is the maximum volume of an equilateral cell, the circumscribing radius of which is identical to that of the mesh element.

The GAMBIT User's Guide (FLUENT Inc., 2001a) recommends that 3D elements with equivolume skew of 0.4 or less indicate high-quality meshes. All the models (freestream and substrate models) presented in this report have the maximum value of equivolume skew of 0.39. This means that none of the elements is degenerated and needs to be remeshed.

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During the tests, the models were executed and the plasma temperature and velocity magnitude were extracted from a cross section plane at $X = 0$ to monitor the effect of the mesh refinement. The results of grid independent tests for the three models are shown in **Figure 4.4**. In these figures, there are five contour lines for temperatures (i.e. 500, 1000, 2000, 5000 and 10000 K) and velocities (i.e. 30, 80, 200, 500 and 1000 m/s). These lines are selected because they cover the whole ranges of the computed temperature and velocity, and locate in the active zone of computation where high gradients of temperature and velocity exist.

For each model, three levels of refinement were considered, the coarse, medium and fine refinements, each having the number of elements which was in the ratio of 1x, 2x and 3x the number of elements of the coarse model respectively. From the comparisons of the contour lines of temperature and velocity amongst coarse, medium and fine models, no obvious discrepancy is noted, indicating that the coarse mesh models having 255226 elements, 261600 elements and 264311 elements, respectively are adequate. These mesh models are shown in **Figure 4.5**.

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Figure 4.4: Five contour lines of temperature (K) (left) and velocity (m/s) (right) for (a) freestream, (b) perpendicular substrate and (c) inclined substrate models at increasing levels of mesh refinement. Numbers in bracket indicate the number of elements.

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Figure 4.5: (a) Freestream coarse mesh model and (b) its section views A-A and B-B. Coarse mesh models (c) with perpendicular substrate and (d) with inclined substrate; and (e) enlarged vision of region C illustrating the clearer view of mesh density.

4.2.8.2 Verification of One-way Coupled Approximation

In this study, two parameters, i.e. particle loading ratio equals to 0.08 and the volume fraction (ratio of the volume of the particle to volume of the gas) equals to 3×10^{-5} , show that the particle to gas flow is dilute. However, these values refer to the overall loading ratio and volume fraction. There are regions where the local variations of the particle number density are probably higher, for instance at the vicinity of the injection plane, and thus the assumption of one-way coupling may not be valid in those regions. In order to further justify the assumption of one-way coupling used in this study, a two-way coupled run was conducted. A two-way coupling simulation implies that the heat and momentum transfers take place from the plasma to particle and in reverse. The processes of heating or cooling and acceleration or retardation are through the convective heat transfer and viscous drag force, respectively

The results of plasma temperature and velocity simulated using two-way coupled approach were compared with those with one-way coupling and shown in **Figure 4.6**, respectively. Three axial distances, i.e. at $Z = 13$ mm behind nozzle exit, $Z = 5$ mm and $Z = 15$ mm in front of nozzle exit were selected and their temperature and velocity distributions along Y direction were compared. Identical profiles are observed despite using two different approaches of simulation, indicating that the assumption of using one-way coupling is well-justified and sufficient to provide reasonable results in this study.

Figure 4.6: Comparison of (a) plasma temperature and (b) plasma velocity distributions at 13 mm behind nozzle exit, 5 mm and 15 mm in front of nozzle exit simulated using one-way (given by lines) and two-way (given by points) coupled approaches.

4.2.8.3 Verification on Plasma Temperature

In order to verify the author's numerical work, a model for torch with 6 mm nozzle diameter and 10 mm length as given by Murphy and Kovitya (1993) was generated. This model was simulated based on the operating conditions of 10.8 kW power input and 40 l/min of argon gas flow rate. The mathematical models, the assumptions and the volumetric heat source approach remained the same as discussed earlier.

Figures 4.7(a) and 4.7(b) show the comparison of the author's numerical results and experimental measurements from Murphy and Kovitya (1993). The comparisons were carried out for the temperature distributions along the Y direction at two axial distances from the nozzle front face; i.e. $Z = 5$ mm and $Z = 15$ mm. It is noted that for both cases, the temperature distributions along the Y direction are well predicted by the author's numerical model. At 5 mm from nozzle front face, less turbulence intermingling between the plasma flow at the core region and the ambient air results in the planar profile, with maximum computed plasma temperature of 10174.8 K while the experiment shows 11700 K (as enclosed in **Figure 4.7(a)**). Maximum percentage difference of 13% is calculated from **Equation 4.22**. Further downstream till 15 mm from nozzle front face, vigorous mixing decays the maximum plasma temperature till 5083.39 K for computation and 5920 K for experiment (as encompassed in **Figure 4.7(b)**). The maximum percentage difference is 14%.

$$\text{Percentage Difference} = 100 * \text{ABS}[(\text{Simulation} - \text{Experiment}) / \text{Experiment}] \quad (4.22)$$

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Figure 4.7: Comparison of plasma temperature distributions for the case where power input, 10.8 kW and argon flow rate, 40 l/min at (a) 5 mm and (b) 15 mm from nozzle front face. Largest discrepancy between experiment and simulation was encircled.

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As the modeling of plasma spraying involves a multidisciplinary approach with knowledge in fluid mechanics, thermodynamics, high-temperature reaction and heat and mass transfer, a percentage difference of 20% was always reported as acceptable. In this study, the maximum percentage differences for both cases are 13% and 14%, respectively and therefore are considered to be within the acceptable range for plasma spray modeling. This implies that the mathematical models applied, the assumptions made and the approaches utilized in this study in predicting the plasma temperature are reasonable.

4.2.8.4 Plasma Flow Fields

Figures 4.8 and **4.9** show plots of plasma temperature and velocity contours for perpendicular and inclined substrate models in the XZ plane while **Figures 4.10** and **4.11** are in vertical symmetry plane (YZ). Note that **Figures 4.8(a)** to **4.11(a)** show the temperature and velocity contours of the freestream model in which the positions of the substrates can be imagined to be in the dotted space.

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Figure 4.8: Comparison of plasma temperature contours for (a) freestream, (b) with perpendicular substrate and (c) with inclined substrate in XZ plane.

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Figure 4.9: Comparison of plasma velocity contours for (a) freestream, (b) with perpendicular substrate and (c) with inclined substrate in XZ plane.

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Figure 4.10: Comparison of plasma temperature contours for (a) freestream, (b) with perpendicular substrate and (c) with inclined substrate in YZ plane.

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Figure 4.11: Comparison of plasma velocity contours for (a) freestream, (b) with perpendicular substrate and (c) with inclined substrate in YZ plane.

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From **Figures 4.8** and **4.9**, it is observed that XZ plane views for both temperature and velocity contours are symmetric. This is an expected result since all the conditions applied on the boundaries are the same. As for YZ views in **Figures 4.10** and **4.11**, it is noted that the contours are not symmetrical about the torch axis; the reason is due directly to one-port carrier gas injection. The injection of carrier gas in the negative Y direction causes a slight divergence of plasma plume in the same direction.

Comparing the freestream and substrate results, the maximum values of plasma temperature and velocity exist at the upstream end of the plasma flow fields remain unaffected by the substrate as it is located at standoff distance of 80 mm which is too far from the torch to have any effect. It is noted that significant flow divergence occurs in the vicinity of the substrate. The substrate causes the plasma flame in the near-field region to spread radially outwards upon impinging the substrate.

More detailed views of the flow in terms of plasma velocity vector are shown in **Figures 4.12** and **4.13**. At the near-field region, the perpendicular substrate obstructs and diverts the flow into the upper and lower parts of the substrate in X and Y directions (see **Figures 4.12(b)** and **4.13(b)**). The plasma flame is deflected by the inclined substrate to flow along its surface towards the upper part of the substrate only, as shown in **Figure 4.13(c)**. All these phenomena can be explained as the plasma jet is diverged at the stagnation region (zero velocity) which is clearly a realistic phenomenon.

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Figure 4.12: Plasma velocity vectors for (a) freestream, (b) perpendicular and (c) inclined substrate models in XZ plane.

Figure 4.13: Plasma velocity vectors for (a) freestream, (b) perpendicular and (c) inclined substrate models in YZ plane.

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Figures 4.14(a) and 4.14(b) show the temperature and velocity variations along the centerline (axis) for the three cases, respectively. Initially, the plasma temperature increases rapidly inside the torch due to heating by high intensity arc. The high temperature leads to an expansion of argon gas and with constant mass flow rate; plasma velocity is subsequently increased as can be seen in **Figure 4.14(b)**. For approximately 20 mm in front of the nozzle front face, the temperature and velocity show only slight reduction. Beyond this region, dramatic drops in plasma temperature and velocity to ambient condition are observed. Near the nozzle exit, the plasma jet maintains its original speed and forms a core region. Surrounding the core are the mixing layers where the plasma jet mixes with the ambient stagnant air. At the end of 20 mm distance, the surrounding mixing layers will merge, resulting the decaying of plasma velocity and temperature.

It is seen that regardless of whether the substrate is present, plasma temperature and velocity reduce at the same rate. In the far field region away from the substrate, for freestream and substrate models, the plasma temperature and velocity merge into one another. This indicates that the range of influence of substrate on plasma temperature and velocity is short and only occurs in its vicinity, approximately 5 mm in front of inboard face, i.e. surface facing towards the flow of the substrate.

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Figure 4.14: Prediction of centerline axial distributions of (a) plasma temperature and (b) plasma velocity for freestream, perpendicular and inclined substrate models.

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Figures 4.15 to 4.18 show in detail the plasma temperature and velocity along the surface of the substrate as measured from its center (coordinates $X, Y = 0, 0$). The temperature and velocity plots are for the two parallel planes above the substrate surface; at an elevation of 5 mm and at a much lower elevation of 0.1 mm. The 5 mm elevation is chosen because above this elevation, the plasma velocity and temperature remain largely unaffected by the substrate when compared to the freestream values. At the lower elevation, more drastic interferences are seen. The distortions in the shapes of the curves at 0.1 mm elevation are apparent in both the perpendicular (**Figures 4.15 and 4.17**) and inclined (**Figures 4.16 and 4.18**) substrates. For convenience the physical length of the substrate is also shown along the X-axis of the plot.

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Figure 4.15: (a) Plasma temperature and (b) plasma velocity radial distributions at 0.1 and 5 mm elevations above the surface of the substrate for freestream and perpendicular substrate models in XZ plot.

Figure 4.16: (a) Plasma temperature and (b) plasma velocity radial distributions at 0.1 and 5 mm elevations above the surface of the substrate for freestream and inclined substrate models in XZ plot.

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(a)

(b)

Figure 4.17: (a) Plasma temperature and (b) plasma velocity radial distributions at 0.1 and 5 mm elevations above the surface of the substrate for freestream and perpendicular substrate models in YZ plot.

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(a)

(b)

Figure 4.18: (a) Plasma temperature and (b) plasma velocity radial distributions at 0.1 and 5 mm elevations above the surface of the substrate for freestream and inclined substrate models in YZ plot.

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For radial distributions in X direction, **Figures 4.15** and **4.16** indicate symmetric profiles for both freestream and substrate models. However, there is slight asymmetry observed near the centerline, especially for freestream model. This may be attributed to the numerical discretization error during the meshing process. Nevertheless, the error is insignificant with a difference of less than 5%.

In **Figures 4.17(a)** and **4.17(b)**, the perpendicular substrate spreads the plasma flame and consequently results in wider radial distributions of plasma temperature and velocity. At 5 mm elevation, the substrate model tends to higher plasma temperature than that of the freestream model, as shown in **Figure 4.17(a)**. This is because under the near stagnation condition, there is a blowback of gas from the substrate. At close proximity to the surface (elevation of 0.1 mm), heat conducts through the substrate and reduces the plasma temperature of the substrate model compared to the freestream model. As for plasma velocity distribution in **Figure 4.17(b)**, the substrate surface retards the plasma velocity to stagnation condition, hence a zero plasma velocity along the substrate is observed.

For the inclined substrate, the standoff distance is 80 mm from the nozzle front face to the center of the substrate. Due to the incline, the lower half of the substrate has a shorter standoff distance while the upper half's standoff distance will be greater than 80 mm. The lower half of the substrate experiences higher temperature and velocity because of closer proximity to the torch and it guides the flow along the surface of the inclined substrate. Consequently, as can be seen in **Figures 4.18(a)** and **4.18(b)**, at 5 mm elevation, increases in plasma temperature of 400 K and velocity of 40 m/s compared to the freestream conditions at the center of the substrate are noted.

4.3 Particle Dynamics and Heat Transfer Formulation

Having obtained the converged solution for the plasma jet, particles were injected through the internal injection port and tracked throughout their flight within the computational domain. The particles were modeled in FLUENT© as discrete Lagrangian entities that received momentum and energy from the plasma in one-way coupling. This means that the transfers of heat and momentum are from the plasma to the particle only; i.e. in the process of particle heating or acceleration by the plasma, the particle does not cool down or retard the plasma. Particle in-flight behavior, i.e. particle velocity and particle temperature were predicted based on the Newton second law of motion and the energy balance equation, respectively.

4.3.1 Major Assumptions

Under the following assumptions, the motion (trajectory, velocity and acceleration) and thermal evolution (temperature, heat flux) of a particle were governed by viscous drag force and convective and latent heat transfers only, without requiring any correction factor to modify the drag and heat transfer coefficients.

1. Since plasma flow was issued at very high speed from the plasma torch, thus when particles were injected through injection port into plasma flame, the acceleration of particles was assumed to be the consequence of viscous drag force only. Comparatively, others forces, such as buoyancy force, Coriolis force etc were small and hence neglected.
2. Based on Kandasamy and Hideya (2002), Nylen *et al.* (1999) and Pfender (1985), thermophoresis force was only comparable with viscous drag force when there was a temperature gradient $\geq 10^7$ K/m or relative velocities of 1

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m/s. The latter effect was only important for very small particles ($< 10 \mu\text{m}$) which responded quickly to move with the thermal gradient. In this study, the maximum temperature gradient is approximately 10^6 K/m and the minimum particle injected is $22 \mu\text{m}$, and therefore it is reasonable to assume that the effect of thermophoresis force was negligible in particle acceleration.

3. Knudsen effect was neglected. Based on Joshi and Sivakumar (1992), correction for non-continuum i.e. Knudsen effect was significant for very fine particles ($D_p < 10 \mu\text{m}$). The particle diameters in this study are all greater than $22 \mu\text{m}$.
4. Particle-to-particle interaction was assumed to be absent. Based on the calculation and chart given by Ang *et al.* (2001), the distance between particles was dependent on the carrier gas flow rate and powder feed rate. The values of carrier gas flow rate and powder feed rate in this study provide the mean distance between two particles approximately 10 times of their mean diameter which is far apart for the avoidance of particle-to-particle interaction. The related load effect was neglected since dilute particle to gas flow is involved (volume fraction, $\frac{V_p}{V_\infty} \approx 3 \times 10^{-5}$) in this study.
5. The drag coefficient used in the **Equation 4.26** is based on smooth spherical particle. From the image of Scanning Electron Microscopy (SEM) (**Figure 4.19**), the particles are indeed spherical.

Figure 4.19: Image of Scanning Electron Microscopy (SEM) for yttria stabilized zirconia (Y_2O_3 stabilized ZrO_2).

6. Vaporization was not included in the model and the particle was also assumed to have uniform temperature distribution. This is because there are approximately one million of particles being injected in this study and it is not computationally feasible to consider internal conduction and vaporization for each individual particle. Secondly, it is due to software limitation. However, it is strongly believed that the conclusion of this thesis with regard to the effect of substrate on particle trajectories will remain positive and will not be affected considerably even if the internal conduction and vaporization are considered in future.

4.3.2 Governing Equations

The momentum transport equation coupled with stochastic tracking determined the particle motion and trajectory. For particle heat transfer formulation, particle heating, cooling, melting and solidification were governed by the energy transport equation.

4.3.2.1 Momentum Transport

From Newton second law of motion, the force acting on the particle is written as

$$\frac{d\mathbf{u}_p}{dt} = F_D \quad (4.23)$$

where F_D is the drag force per unit mass and is represented as:

$$F_D = \frac{3\mu C_D (\mathbf{u} - \mathbf{u}_p) \text{Re}_r}{4\rho_p D_p^2} \quad (4.24)$$

where Re_r is the relative Reynolds number and C_D is the drag coefficient which are defined as follows:

$$\text{Re}_r = \frac{\rho D_p (\mathbf{u} - \mathbf{u}_p)}{\mu} \quad (4.25)$$

$$C_D = a_1 + \frac{a_2}{\text{Re}_r} + \frac{a_3}{\text{Re}_r^2} \quad (4.26)$$

where a_1 , a_2 and a_3 are constants, applicable for smooth spherical particles for a range of Reynolds numbers (FLUENT Inc., 2001b).

4.3.2.2 Stochastic Tracking

In gaining the converged solution for free plasma jet, turbulence effect was taken into consideration. When a particle interacts with successive turbulence eddies, random variations in the instantaneous drag force acting upon the particle were considered in order to give more realistic prediction on particle trajectory. Thus, in **Equations 4.24** and **4.25**, instead of $\mathbf{u} = \bar{\mathbf{u}}$, the instantaneous value of fluctuating gas flow velocity was included to predict the dispersion of particles due to turbulence, that is $\mathbf{u} = \bar{\mathbf{u}} + \mathbf{u}'$. The value of velocity fluctuation $\mathbf{u}'$ of each eddy

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was assumed to obey the Gaussian probability distribution (Ahmed and Bergman, 2000 and FLUENT Inc., 2001b) so that;

$$\mathbf{u}' = \mathcal{G}\sqrt{\mathbf{u}'^2} \quad (4.27)$$

where $\mathcal{G}$ is a normally distributed random number and $\sqrt{\mathbf{u}'^2}$ the local root mean square (RMS) value of the velocity fluctuation. Since the value of turbulence kinetic energy was known at each control volume through the converged solution of the plasma free jet, the values of RMS fluctuating components could be obtained by assuming non-directional (isotropic) flow as:

$$\sqrt{u'^2} = \sqrt{v'^2} = \sqrt{w'^2} = \sqrt{2\kappa/3} \quad (4.28)$$

for κ - ε model.

4.3.2.3 Energy Transport

The concept of energy balance was adopted for convective and latent heat transfers from the surrounding plasma to the particle and vice versa. This means that two energy equations were applied to provide energy required for heating up or cooling down the particle and particle melting or solidification.

For particle heating or cooling phase, the energy equation is as shown:

$$hA_p(T_\infty - T_p) = m_p C_p \frac{dT_p}{dt} \quad \text{for } T_p < T_m \text{ or } T_p > T_m \quad (4.29)$$

The heat transfer coefficient, h in **Equation 4.29** was based on Ranz and Marshall (1952) correlation as shown in **Equation 4.30** (FLUENT Inc., 2001b).

$$Nu = \frac{hD_p}{k} = 2.0 + 0.6Re_r^{0.5} Pr^{0.33} \quad (4.30)$$

$$\text{i.e.} \quad h = \frac{k}{D_p} (2.0 + 0.6Re_r^{0.5} Pr^{0.33}) \quad (4.31)$$

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In **Equation 4.31**, thermal conductivity and Prandtl number were evaluated for continuous phase while relative Reynolds number was based on **Equation 4.25**.

For particle melting or solidification, the energy balance is defined as:

$$hA_p(T_\infty - T_p) = m_p H_f \frac{d\zeta}{dt} \quad \text{for } T_p = T_m \quad (4.32)$$

where

ζ is the liquid fraction.

4.3.3 Particle Properties

The injected particles namely, 8% yttria-partially-stabilized (Y_2O_3) zirconia (ZrO_2) provided by Saint-Gobain Norton K.K., Singapore was used in this simulation study. Its thermodynamic and physical properties were required in the simulation and shown in **Table 4.2**.

Table 4.2: Thermodynamic and physical properties of yttria stabilized zirconia.

Property	Value
Density ρ_p , kg/m ³	5890
Specific Heat Capacity C_p , J/kgK	*Eqn. below
Latent Heat of Fusion H_f , J/kg	7.06×10^5
Thermal Conductivity k_p , W/mK	2.4
Kinematic Viscosity ν_p , m ² /s	6.5×10^{-6}
Melting Point T_m , K	2988
Boiling Point T_b , K	5273
Surface Tension σ , N/m	0.5

* For $273 < T_p < 873$ K
$$C_p = 1.06343 \times 10^{-6} T_p^3 - 2.188953 \times 10^{-3} T_p^2 + 1.709671 T_p + 1.466367 \times 10^2$$

For $T_p > 873$ K
$$C_p = 678.5$$

4.3.4 Particle Size Distribution

The size of zirconia particles ranged from 22 to 125 microns. The manufacturer’s data in terms of percentage weight versus diameter was curve-fitted via a Roslin-Rammler distribution. This distribution of particle number density versus diameter from 22 to 125 microns in steps of 1 microns diameter was numerically introduced to the plasma flame through internal injection port with the

rate of 9.6 g/min under the specified carrier gas pressure. The Roslin-Rammler distribution assumes that an exponential relationship exists between the particle diameter, D_p and the mass fraction, Y_D of particles with diameter greater than D_p , (Equation 4.33). The actual and fitted particle size distributions are shown in Figure 4.20.

$$Y_D = \exp\left[-\left(\frac{D_p}{\overline{D_p}}\right)^m\right] \tag{4.33}$$

where $\overline{D_p}$ and m refer to the mean diameter and spread coefficient, respectively. The mean diameter and spread coefficient are 65.3 μm and 2.3489 respectively in this study.

Figure 4.20: Standard Roslin-Rammler distribution fitted to raw feedstock data.

4.3.5 Particle Behavior Distributions

There were large number of particles with different sizes, velocities and temperatures impacting at different locations simultaneously. In order to

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investigate the effect substrate on particle parameter distributions, the FLUENT© output data was further processed.

The processing method was based on statistical number averaging. The substrate was firstly divided into a number of cells with the dimensions of 1 mm x 1 mm. Particles arriving at each cell were counted and the mean values of particle parameters were calculated based on **Equation 4.34**. Then using the cell by cell data, contours were plotted.

$$\text{Number-averaged value} = \frac{\sum_{i=1}^{i=n_p} \phi_i}{n_p} \quad (4.34)$$

where ϕ represents the particle in-flight parameters, viz. size, temperature and velocity and n_p is the number of particles.

Figures 4.21 to 4.22 show the contour distributions of particles in terms of diameter, number of particles (concentration), temperature and velocity. In the left-hand side of **Figures 4.21** and **4.22**, the distributions are obtained from the freestream model at the same location as where a substrate would be placed. As for the right-hand side, **Figures 4.21** and **4.22** contour plots show the distributions for perpendicular and inclined substrate models, respectively.

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Figure 4.21: Comparison of contours of particle in-flight parameters: (a) diameter (microns), (b) number of particles (n_p), (c) surface temperature (K) and (d) velocity (m/s) for freestream (left) and perpendicular substrate (right) models. At top of the figures, arrows show direction of particle injection at torch.

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Figure 4.22: Comparison of contours of particle in-flight parameters: (a) diameter (microns), (b) number of particles (n_p), (c) surface temperature (K) and (d) velocity (m/s) for freestream (left) and inclined substrate (right) models. At top of the figures, arrows show direction of particle injection at torch.

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From the comparisons for **Figures 4.21** and **4.22**, no significant effect of the substrate is observed, regardless the angles of inclination on particle parameter distributions. In addition, both the freestream and perpendicular substrate models (**Figure 4.21**) indicate circular area of particle distribution covered by the spray particles. As for the inclined substrate, the impacting particles envelope an area of distribution similar to an ellipse, for both the freestream and substrate models, as can be seen in **Figure 4.22**. This is because as previously mentioned, the presence of the substrate affects the plasma characteristics significantly only at short range and thus the processes of heat and momentum transfers are mainly the same for both freestream and substrate models. The temperature and velocity of particles are not affected despite the changes of plasma characteristics in the vicinity or near-field of the substrate.

In **Figures 4.21(a)** and **4.22(a)**, larger particles are observed to accumulate at lower portion of the plasma jet while smaller particles populate the upper half of the substrate. This is caused by particles injected perpendicularly into the plasma jet, thus investing them with an initial downward momentum. The more massive particles have higher initial momentum which enables them to penetrate further into the jet and impact at lower part of the substrate.

The size factor also causes larger particles to have a lower temperature and velocity as can be seen in **Figures 4.21(c-d)** and **4.22(c-d)**. Larger particles have higher surface area exposed to the gas and the mechanism of momentum transfer but their greater mass requires higher amount of momentum from the surrounding plasma gas to achieve the same increase of velocity as the smaller particles. From dimensional analysis, the surface area is proportional to square of diameter while inertia depends on cube of diameter. The similar size factor also influences particle

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heating and cooling, in that heat transfer depends on the surface area and the heat capacity is related to the volume. In addition, the degree of penetration in the plasma flame also affects the particle temperature and velocity. By virtue of their greater mass, larger particles penetrate further through the plasma jet and populate at the lower periphery of the jet. The environment there has lower temperature and velocity, and therefore, larger particles receive lesser heat and momentum compared to smaller particles which reside in the core of the jet.

As a further observation of **Figures 4.21(c)** and **4.22(c)**, it is noted that the predicted particle temperature ranges between 4600 and 5800 K. This is because the particle is assumed to have uniform temperature distribution and therefore the particle temperature mentioned is referred as the surface temperature of a particle. At such high surface temperature, there is loss of mass due to vaporization and this may be one of the factors causing rather low deposition efficiency in the actual spraying process using the same operating conditions. There are other factors such as particle losses due to rebound and overspray at the substrate which are more dominant in affecting the deposition efficiency. However, the author believes that the qualitative conclusion; i.e. the insignificant effect of substrate on particle temperature should also hold for model taking internal conduction and vaporization into consideration, although the numerical results of particle temperature may change.

4.4 Conclusions

One of the objectives in this chapter was the development of a comprehensive model to predict the three-dimensional behavior for one-port injection of multi-sized particles of plasma spray. Particles emitting from the torch would disperse under the effect of turbulence and receive heat and momentum from the surrounding plasma. **Figure 4.23** summarizes the solution procedures for this chapter.

Another objective of this chapter was to investigate the influences of perpendicular and inclined substrates on plasma flow fields and particle behavior. From the numerical results, it was found that the existence of the substrates affected the plasma flow fields in the vicinity or near-field of the substrates. The area of influence was small, approximately within 5 mm in front of the substrate surface. However, the distributions of particle parameters, such as size, number concentration, temperature and velocity obtained from the models with substrate were unaffected and remained similar to the freestream condition. The main reason was that the environment for the heat and momentum transfer processes from the plasma to particles was mainly the same and therefore particle trajectories could not be altered just because the plasma characteristics were changed in the vicinity of the substrate. This finding, i.e. the insignificant effect of the substrate on particle characteristics of size, velocity, temperature and dispersion behavior will thus lead to the usage of particle behavior obtained from the freestream model for the coating formation modeling (**Chapter 6**).

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Figure 4.23: Flow chart of the solution procedures for particles laden plasma flow.

CHAPTER 5

IMAGING DIAGNOSTICS ON PARTICLE BEHAVIOR

5.1 Introduction

Numerical investigation on the effect of the substrate had been carried out in **Chapter 4**. The results showed that the presence of perpendicular and inclined substrates had a negligible influence on particle behavior distributions of size, velocity and temperature. As for the experimental investigation, a recently available imaging diagnostics system, known as SprayWatch© (Oseir Ltd., Hermiankatu, 6 A, 33720 Tampere, Finland) is employed to evaluate the influence of the substrate on the particle behavior. The SprayWatch© imaging diagnostics system is chosen because it has the advantage to submit overall indication on particle interaction with substrate, besides providing individual as well as integrated information on particle behavior.

This chapter describes the monitoring and measurements of the particle temperature, velocity and heading in the presence of different flat and inclined substrates by the SprayWatch© system. In the experiments, the flat substrates are inclined at 0° , 20° , 40° and 60° from the vertical plane and sprayed while subjected to imaging diagnostics system. The comparisons of results between with and without substrate present for different inclination angles are reported.

5.2 Substrate and Feedstock Powder

Figure 5.1 depicts mild steel substrate with dimensions of 50 by 300 by 3 (thickness) mm that was cut from sheet stock material. As the purpose of the substrate is only to provide an obstruction, its already smooth surface is not further treated.

Figure 5.1: 3 mm thick of 50 x 300 mm of mild steel substrate used in this experiment.

A commercially available powder; yttria-partially-stabilized (8%) zirconia (YSZ) was used as the feedstock powder. Details on the powder have been described and presented in **Chapter 3, section 3.3.1**.

5.3 Experimental Setup

The experimental setup presented in **Figure 5.2** shows the plasma spray torch and the SprayWatch© CCD camera mounted on a traversing system.

Figure 5.2: Experiment rig showing the torch, substrate, SprayWatch© CCD camera and traversing system.

A model SG-100© plasma spray torch with a 15.5 mm nozzle diameter (Praxair Surface Technologies Inc., N670 Communication Drive, Appleton, Wisconsin 54915, USA) was used to spray powder at the atmospheric pressure. A roto-feed powder hopper, model 1264© (also from Praxair Surface Technologies Inc.) was used to introduce the powder at the rate of 9.6 g/min into the plasma torch via the internal powder injector. Argon was used as the primary and carrier gases and the standard process conditions for the torch are given in **Table 5.1**.

Table 5.1: Experimental spraying conditions.

Parameter / Unit	Magnitude
Powder Injector Angle / °	90
Nozzle Diameter / mm	15.5
Torch Diameter / mm	8
Injector Diameter / mm	2
Injector Location	Internal
Current / A	900
Voltage / V	35
Primary Gas Flow Rate (Argon) / psi (slm)	80 (72)
Carrier Gas Flow Rate (Argon) / psi (slm)	30 (4.2)
Powder Feedrate / g/min	9.6
Powder Size / μm	22-125
Standoff Distance / mm	80

The substrate was inclined by tilting the mounting fixture with the aid of spirit level and protractor. Four different inclination angles were chosen, starting from 0° to 60°, in steps of 20°. For each inclination angle, a fixture with a sharp pointer in front was mounted on the nozzle front face, as shown in **Figure 5.2** to assist in aligning the center of the plasma torch to the midpoint of the substrate. The plasma torch was elevated or lowered until the tip of the pointer was positioned rightly to the midpoint of the substrate. The standoff distance was maintained for each case at 80 mm between the nozzle front face and the midpoint of the substrate.

5.3.1 SprayWatch© CCD Camera Technical Information

The SprayWatch© system consists of a CCD camera with a minimum exposure time of 10 μs and real-time image processing software. The CCD detector

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is 640 pixels high by 480 pixels wide, each pixel being 9.9 by 9.9 μm^2 in physical size.

Besides providing a visual display of the spray plume, the system measures the primary parameters such as temperature, velocity and number of in-flight particles in the spray, as well as the secondary parameters such as particle brightness, heading and position. Amongst all the parameters, particle temperature, velocity and heading were monitored for different substrate inclinations.

The measurement of particle velocity is based on time of flight method (with the accuracy of ± 0.1 to 1 m/s depending on the velocity range); while the particle temperature measurement employs two-color pyrometry (with accuracy of ± 50 °C). The CCD detector in the camera is divided into two arrays to fulfill the needs of two different measurements. The left-hand side array as seen in **Figure 5.3** provides direct real time visual display of the spray. Streams of particles constantly flowing across the pixel array are identified by the high brightness of their emitted illumination. The particle tracks are frozen at each frame. The time of flight and length of each track are used to deduce the velocity of particle. The distance between beginning and ending points of each streak is measured by the number of pixels. The length of the exposure time (minimum of 10 μs) is the time of flight. Other measurements obtained from the two points are the particle heading and the particle count. The double-stripes filter on the right-hand side array seen in **Figure 5.3** is used for temperature measurement by means of two-color pyrometry.

A problem arises when imaging the spray at close vicinity to the substrate. In order to measure the velocity of the particles just before impact, the substrate must be placed at the boundary between the two arrays. The substrate thus blocks the particles from entering the right side temperature measurement array. Thus, the

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particle temperature cannot be recorded. More detailed explanations are provided in section 5.5.1.

Figure 5.3: Schematic illustration of particle behavior measurements in the two detector arrays in the SprayWatch© system.

5.3.2 Translation of Target Area along Substrate Surface

The CCD camera was mounted on a precision XYZ traversing platform and pointed towards the plasma flame such that the spray particles crossing the camera field of view before impacting on the substrate were in-focus. The movement of the traverse allowed very precise survey of different parts of the substrate surface. For all measurements, the target area was set to 25.4 x 21.2 mm with 6 mm depth of field (DoF).

The target area of the CCD camera was firstly moved to position 1 in Δy and Δz directions as illustrated in **Figure 5.4**. Starting from position 1, a total of nine positions were imaged incrementally along the substrate surface to capture all the particles approaching the entire substrate. The distance between target positions was maintained at 5 mm as shown in **Figure 5.4**.

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At each position, particles crossing the target area were imaged for approximately 10 seconds at the rate of 3 frames per second. In each frame, mean detected particle behavior was calculated by the data processing software. The average of the mean data of each frame over 30 frames taken in 10 seconds of measuring time provided the particle average behavior. The results presented in **section 5.5** are the average of the particle parameters.

Figure 5.4: Schematic diagram showing the incremental movement of CCD camera and hence the target areas to capture the images of particles impacting the substrate at different angles of inclination. Position 5 is the image corresponding to torch centerline.

The image captured at the substrate midpoint was referred as the position 5. At this position, the standoff distance between the nozzle front face to the substrate midpoint would be at 80 mm which was maintained as a constant distance for every

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angle of inclination of the substrate. This allows for consistent comparison of measurements obtained for different substrate inclinations. **Figure 5.5** shows the position 5 target areas of different substrate inclinations for which results will be compared later.

Figure 5.5: Schematic diagrams of the target areas at the substrate midpoint or position 5 at different angles of inclination of (a) 0° , (b) 20° , (c) 40° and (d) 60° .

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5.3.3 Particle In-flight Parameters Measurement

The measuring conditions of SprayWatch© equipment is provided in **Table 5.2**. After the setup was established, the torch was ignited and the powder was injected. The substrate was slid slowly in front of the plasma plume to obstruct the plasma jet. The camera was switched on to measure the particle temperatures, velocities and headings at position 1 for approximately 10 seconds. In the meantime, the substrate was fed into the X-axis away from the CCD camera unit to continuously expose new surface area to the spray, the purpose being to avoid a deposit mound growing which will affect the particle trajectories and obscure the camera line of sight. The CCD camera-torch axis distance was maintained at 350 mm throughout this experiment. The measurements were repeated for the other eight target areas by traversing the CCD camera incrementally.

Having made the measurements, the substrate was removed from the flame allowing the particles to spray freely into the ambient environment. Nine measurements were taken again by the camera retracing the same positions, as if the substrate was present. The measurement procedures for with and without substrate present were repeated for other substrate inclinations.

Table 5.2: Measuring conditions of the SprayWatch© equipment.

Parameter / Unit	Magnitude
Resolution / pixels	640 x 480
Sensitivity / bits	12
Focus Distance / mm	350
Exposure Time / μ s	10
Measurement Time / s	10

5.4 Definition of Particle Velocity Components

When a zirconia particle is fed through the vertical internal injection port with an initial velocity, its vertical velocity in the plasma jet is due to its initial vertical momentum while its horizontal velocity (parallel to the spray direction) is due to the drag force applied by the plasma gas. Thus, the trajectory takes a downward parabolic path. The resultant velocity of a particle at a given standoff distance is defined as U_p in this experiment. The particle will impact the substrate at an angle, α which defines the particle heading depending on the particle trajectory. The corresponding resultant particle velocity, U_p can then be resolved into the tangential velocity, U_{pt} (parallel to the substrate surface) and the normal velocity, U_{pn} (perpendicular to the substrate surface) components. The velocity components of an impacting particle are illustrated in **Figure 5.6**.

Figure 5.6: Schematic diagram of a molten droplet impacting on a flat inclined substrate.

5.5 Results and Discussion

The basic spray particle parameters studied so far are the speed and direction of the particles. The particle temperature measurement under the presence of the substrate cannot be monitored correctly because the substrate shields particles from the temperature array preventing particle temperature from being taken (**section 5.5.1**). In **section 5.5.2**, the images monitored at the substrate midpoint or position 5 for all the inclination angles are analyzed. Quantitative measurement results of particle behavior in the presence of substrate are discussed in **section 5.5.3**.

5.5.1 Average Temperature of Particles

Particle average temperature can only be measured in the freestream condition (see **Figure 5.7(a)**). In the setup with a substrate, which blocks the particles, the filter region will not image any of the particles beyond the substrate (see **Figure 5.7(b)**). The particle temperature will not therefore be measured. Substrate temperature also cannot be measured by this method because it will require the substrate to be visible in both filter stripes and some modification of the software. In addition, when the particles enter the filter region but are deflected by the substrate (see **Figure 5.7(c)**), the temperature measurement does not compute correctly because the parameters such as spray angle and divergence data are needed for temperature measurement. Hence, the temperature comparison is not discussed for this study. However, this study provides important information on the velocity and heading of the particles.

Figure 5.7: Images of particles (a) passing through the visual display array (left) and the double-stripes filter array (right) in the freestream condition, (b) impacting on the perpendicular substrate and (c) deflected by the substrate after impacting on the 60° inclined substrate. The substrates were added to the figures for clarity.

5.5.2 Still Image Analysis

Examples of the detected particle frames at freestream condition and with a substrate present at different inclination angles are presented in **Figures 5.8(a)** to

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5.8(e). The filter region was cropped since the temperature measurement is not discussed in this study.

It can be observed that with the increase in substrate inclination angle, particles rebound towards the upper region of the substrate. For 0° inclination angle, the particles rebound vertically in both upward and downward directions as shown in **Figure 5.8(b)**. The rebounding particles from the substrate inclined at angle of 60° are populated at the upper part of the substrate as can be seen in **Figure 5.8(e)**. On the other hand, at substrate inclination angles of 20° and 40° , the behavior of rebounding particles vary between the two extreme angles. In addition, more particles rebound from the substrate when substrate inclination angle increases. Hence, fewer particles are available to form a coating and therefore, spraying at higher inclination angle will result in lower deposition efficiency. **Figure 6.11** in **Chapter 6, section 6.5.1** shows the result of deposition efficiencies at different substrate inclination angles. Indeed, the result shows a decreasing trend when substrate inclination angle increases.

As a further observation in **Figure 5.8**, the trajectories of the streams of hot particles propelled by the plasma jet are not affected by the substrate. This can be clearly observed from the paths of the particles with substrate present and the freestream particles in **Figures 5.8(a) to 5.8(e)**. All of them travel towards the substrate at high speed, with no sudden change in the particle directions right before impact. Thus, the presence of the substrate does not influence the particle flow or trajectory significantly.

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Figure 5.8: Particles flow in (a) freestream condition and at different substrate inclination angles of: (b) 0°, (c) 20°, (d) 40° and (e) 60°. Each frame was captured at the rate of 1/3 s with exposure time up to 10 μ s.

5.5.3 Particle Behavior in the Presence of the Substrate

Besides presenting qualitative image analysis, quantitative data of particle velocity and heading are also collected by the SprayWatch© system. Results obtained from measurements taken along the substrate surface and at substrate midpoint in the case where the substrates present are compared with their freestream conditions and discussed in the following sections.

5.5.3.1 Average Velocity of Particles

Particle average velocities at the nine positions along substrate surface are presented in **Figures 5.9(a) to 5.9(d)**. At each data point, there are approximately 1500 measurements, indicating that the results are highly repeatable. In addition, it is noted that there is no measurement data at the location of 20 mm from midpoint of the substrate in **Figures 5.9(a) and 5.9(b)**. This is because the location of 20 mm for perpendicular (0°) and 20° inclined substrates is too far above from the center of the plasma torch and no particle is detected and measured.

As a further observation of **Figures 5.9(a) to 5.9(d)**, there are two large discrepancies; i.e. the difference about 30% at the extremities (as encircled in **Figures 5.9(a) and 5.9(b)**). However, in general, the particle average velocities measured in the freestream condition and with substrate introduced can be regarded to behave very similarly when considered together with the presence of experimental scatter. This is because as shown in **Figures 5.8(a) to 5.8(e)**, in-flight particles follow the similar trajectories and impact directly on the substrate, regardless of the presence of the substrate. Particles following the similar trajectories receive the same amount of momentum from the prevailing plasma and thus will show little difference in particle average velocity. The insignificant effect

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of perpendicular substrate on particle velocity was also noted in Cetegen and Yu (1999). In their experiment, a flat and perpendicular substrate introduced into the plasma spray had a minimal effect of less than 5% reduction of particle velocity. They suggested that particle motion was essentially ballistic and the particle velocity was not significantly affected by plasma flow divergence near the stagnation region.

Figure 5.9: (a) Particle average velocity profiles along substrate surface for 0° substrate inclination and its freestream condition.

Figure 5.9: (b) Particle average velocity profiles along substrate surface for 20° substrate inclination and its freestream condition.

Figure 5.9: (c) Particle average velocity profiles along substrate surface for 40° substrate inclination and its freestream condition.

Figure 5.9: (d) Particle average velocity profiles along substrate surface for 60° substrate inclination and its freestream condition.

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However, there are two effects influencing the particle average velocity profile, namely, particle segregation and local standoff distance. In the case where the substrate is placed perpendicularly, all the particles impacting on the substrate have to travel through the same standoff distance. The non-symmetrical particle velocity profiles in **Figure 5.9(a)** indicate that particles at lower portion of the substrate experience lower velocities than particles at the upper portion. This is attributed to the effect of particle segregation caused by initial momentum of powder due to vertical injection. Larger and therefore heavier particles tend to penetrate deeper into the plasma flame due to their higher initial momentum, whereas the lighter ones travel in the upper region of the spray jet due to their lower momentum which allows only partial penetration into the flame. Thus, larger particles tend to be more numerous at the lower part of the spray cone. Moreover, the smaller particle is accelerated towards the substrate by a smaller force owing to its lower cross-sectional surface area which is a function of square of the particle diameter. However, it also possesses lesser inertia compared to larger particle because its mass is a function of cube of diameter. In the competition between the drag force and inertia, the inertia is dominant, which leads to smaller particles being accelerated and decelerated faster than the larger particles.

The joint effects of initial vertical momentum and inertia cause the lower part of the substrate to be populated by larger particles with slower velocities. Conversely, the upper part of the substrate contains smaller particles with higher velocities. The effect of particle segregation on particle velocity was also reported in Ma *et al.* (2004), where the particle velocity was measured using Phase Doppler Anemometer (PDA).

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From **Figures 5.9(a) to 5.9(d)**, it is noted that the increase of substrate inclination changes the particle average velocity from an inclined profile to a flat profile. This is owing to the increase in local standoff distance between the nozzle front face and the upper part of the substrate. Due to the further traveling distance to the higher part of the substrate, particles may have reached the peak acceleration and start to decelerate during their transition through the plasma flame. Moreover, the lighter particles do undergo more rapid deceleration and thus have lower velocities. At the lower part, particles are being accelerated by the plasma gas before arriving at the substrate. Consequently, they reach higher velocities.

Figure 5.10 shows the effect of different inclined substrates on average velocities recorded at the substrate midpoint. The mean velocities of most particles range from 178 m/s to 200 m/s. At the 0° angle, the average velocity which is at 8% lower than the freestream velocity is the most affected by the substrate. Nevertheless, the velocities for the rest of inclination angles remain relatively undisturbed by the substrates. This again implies that particles are propelled from the torch with high momentum which resist deflection by the plasma gas. In spite of the different angles the substrate is oriented towards the torch, particles do not change their trajectories and thus their velocities remain unaffected.

Figure 5.10: Particle velocities, U_p detected at the substrate midpoint for various inclination angles (right) compared to the freestream condition (left).

5.5.3.2 Average Heading of Particles

Particle headings along the substrate surface are shown in **Figures 5.11(a) to 5.11(d)**. There is a general trend between the particle headings defined by α angle for freestream condition and with substrate for each inclination angle. With the substrate midpoint being the reference location, particle headings at the upper region for both conditions (freestream and with substrate) increase, while they behave in an opposite manner in the opposite section. This can be supported by the image analysis mentioned previously. Particle flux moving in the upward direction, i.e. above the horizontal reference has a positive α angle whereas the downward particles possess a negative α angle. This is an expected result due to the cone shape of the particle plume.

Figure 5.11: (a) Particle average headings along substrate surface for 0° substrate inclination compared to its freestream condition.

Figure 5.11: (b) Particle average headings along substrate surface for 20° substrate inclination compared to its freestream condition.

Figure 5.11: (c) Particle average headings along substrate surface for 40° substrate inclination compared to its freestream condition.

Figure 5.11: (d) Particle average headings along substrate surface for 60° substrate inclination compared to its freestream condition.

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It is seen from **Figures 5.11(a) to 5.11(d)** that the average headings of particles in the presence of the substrates are slightly increased in the positive α angle direction for all inclination angles. This is due to the aerodynamic ramp effect of the inclined substrate which deflects more particles to the upper region of the substrate than the lower part. However, the deviation is only between 5° to 10° and can be considered to be insignificant.

The particle average headings, α towards the substrate midpoint at various inclination angles are compiled together in **Figure 5.12**. In general, an increase in substrate inclination angle has diverted the particle heading in a linear relationship. On average, an increment of inclination angle by 1° increases the particle heading by approximately 0.05° . This effect is insignificant as a substrate inclination from 0° to 60° results in only 4.5° change in the particle average heading. It is also noted that there are negative values of particle average heading for freestream and 0° inclination angle, indicating that the particles impact the substrate in a slightly negative α angle direction. This is attributed to the initial downward momentum of particles when injected through one powder injection port.

Figure 5.12: Impacting particle headings at different substrate inclination angles at substrate midpoint.

5.5.3.3 Particle Tangential and Normal Velocities

Using the heading data (α) and the substrate inclination (θ), the particle velocity can be resolved into two components; tangential and normal velocities that are parallel and perpendicular to the substrate respectively. The tangential velocity component plays an important role in the splat spreading process and the normal velocity component determines the effective bonding of splat to the substrate or underlying splats. A higher tangential velocity component tends to elongate the splat into an elliptical shape while an increase in normal velocity leads to high adherence strength between splat and the substrate. In the absence of tangential velocity, the splat tends to be circular in shape. A few SEM photographs as shown in **Figures 3.10(a) to 3.10(g)** in **Chapter 3, section 3.6.1.1** indicate the progressive elongation of splats from circular to elliptical shape as well as higher tendency of

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peeling off the splats from the substrate when substrate inclination angle increases. Therefore, it is necessary to investigate the effect of different substrate inclinations on both the velocity components, as this can provide an insight on the changes of splat morphology and coating adherence with respect to substrate inclinations.

The tangential and normal velocity components of the detected particle were derived from the average velocity, the particle heading angle, α obtained from the measurement system and the applied inclination angle, θ . Since α is small compared to θ , the components are simply functions of the cosine and sine of θ . It is noted from **Figure 5.13(a)**, the particle tangential velocity behaves in a linearly increasing trend as the substrate inclination angle increases. The plot indicates that the tangential velocity starts off at the value of 2 m/s downwards at 0° inclination angle and rises till the maximum of 169 m/s at 60° . In general, the increment of 10° in substrate inclination angle has resulted in the increase of the particle tangential velocity by maximum of 25%, hence highly sensitive towards the substrate inclination angle.

In **Figure 5.13(b)**, it is expected that the particle normal velocity decreases with the increase of substrate inclination angle. Particle normal velocity (194 m/s) occurs for perpendicular substrate and gradually reduces to 97 m/s at 60° inclined substrate. Approximately, there is a 25% reduction in particle normal velocity for every increment of 10° in substrate inclination angle.

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Figure 5.13: (a) Particle tangential velocities at various inclination angles.

Figure 5.13: (b) Particle normal velocities at various inclination angles.

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From **Figures 5.13(a)** and **5.13(b)**, for the perpendicular substrate, the normal velocity component is higher than the tangential velocity component, indicating that the splat is in circular shape with sufficiently good bonding with the substrate. With an increase of the substrate inclination, the normal component is reduced in exchange with the tangential component, which promotes splat elongation to an elliptical shape. The reduced normal velocity component results in poorly adhered splat on the substrate. Conversely, the increasing trend of tangential velocity component with respect to substrate inclination angle yields more rebounded particles after impacting, as can be observed in **Figures 5.8(b)** to **5.8(e)**.

5.6 Conclusions

The in-flight behavior of particles when subjected to aerodynamic disturbance due to substrates at various inclination angles were experimentally investigated by means of SprayWatch© imaging diagnostics equipment. A qualitative evaluation of real time images of the particles close to the substrate surface showed that because of high momentum possessed by the particles, there were negligible changes in their trajectories or headings right before impacting on the substrates in spite of the presence of the substrates.

A more detailed quantitative evaluation of particle average velocity and heading data collected by SprayWatch© system also revealed that in general, particle average velocities behaved almost similarly regardless of whether the substrate was present. The average headings slightly increased positively for all inclination angles due to the aerodynamic ramp effect of inclined substrates.

For a better understanding of the effect of inclination angles, particle behavior such as velocity, heading, tangential and normal velocity components at substrate midpoint were compared. Although the particle velocity and heading were negligibly affected, the inclination angle had an apparent significant effect on the tangential and normal velocity components of the particle purely due to the trigonometric consequence and not as a result of the substrate influence. The increase in substrate inclination angle by 10° increased the tangential and reduced the normal components, both by approximately 25%. The increased tangential velocity with substrate inclination angle implied higher splat elongation to elliptical shape and large number of particles rebounded off the substrate resulting in reduced deposition efficiency.

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The experimental result of insignificant effect of the substrate at different inclination angles on particle velocities has qualitatively verified the numerical finding discussed in **Chapter 4**. Since then, the author will use the particle behavior from the freestream model discussed in **Chapter 4** in the coating formation modeling (**Chapter 6**).

CHAPTER 6

MODELING AND EXPERIMENT ON DEPOSIT FORMATION

6.1 Introduction

A semi-empirical methodology of predicting coating formation by the plasma spray process henceforth referred as Substrate Cell Model (SCM) has been developed and described in this chapter. The SCM relates the incoming particle behavior distributions with the empirical equations of spread factor and aspect ratio to produce the splats of known dimensions. The SCM performs integration or reconstruction of the deposit build-up of individual splats. In this chapter, a series of simulations is carried out to generate deposits on substrate inclined at 0° to 60° at 10° steps under stationary spraying.

In order to verify the simulated deposits, experiments under the same conditions are conducted and the detailed description on the experimental procedures is included in this chapter as well. Fairly good agreement is achieved from the comparison of the computed and experimentally gained deposits. Also presented in this chapter are the experimental investigations on the effect of substrate inclinations on deposition efficiencies and porosities.

6.2 Numerical Method

In SCM, the approach used combined simulation and empirical testing. The former part consisted of Computational Fluid Dynamics (CFD) model to solve the single phase gas temperature and velocity behavior in the plasma plume as well as the dynamic and thermal behavior of the particles. The empirical part of the approach made use of the curve-fitted equations for splat geometries from splat measurement experiments. The solution procedures can be summarized as shown in **Figure 6.1**. For convenience, brief review on single splat experiment and CFD simulation from **Chapters 3** and **4**, respectively are provided before discussing the concept of SCM.

Figure 6.1: Flow chart of the solution procedures.

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6.2.1 Review on Chapter 3: Experiment on Individual Splats Geometric Characterization

Carefully conducted experiments were carried out and presented in **Chapter 3** to capture individual splats deposited by droplets impacting on a substrate that was rapidly traversed across the spray plume. As described in **Chapter 3**, the overlapping and coincident splats were minimized and individual splats were later randomly identified on the substrate and their thicknesses and lengths measured by means of a high resolution WYKO NT-2000© optical surface profiler (Veeco Tucson Inc., 2650, East Elvira Road, Tucson, AZ 85706, USA.). From the thickness and area of the splat measured, it was possible to calculate its volume and thus deduced the diameter of the originating droplet by means of principle of volume conservation.

From **Chapter 3**, the spread factor, ξ , is defined as the ratio of equivalent splat diameter to droplet diameter, i.e.

Eq. 3.1:
$$\xi = \frac{d_e}{D_p}$$

while the aspect ratio, ψ is defined as the ratio of major diameter to minor diameter of the splat, as in **Equation 3.5**.

Eq. 3.5:
$$\psi = \frac{d_y}{d_x}$$

Polynomial curves for spread factor (ξ) and aspect ratio (ψ) were best-fitted over the plotted data from the large sample of the splats (50 splats per inclination).

Equations 6.1 and 6.2 list the fitted polynomial equations.

$$\xi = -0.0009\theta^2 + 0.0557\theta + 4.6024 \quad [R^2 = 0.9447] \quad (6.1)$$

$$\psi = 0.0003\theta^2 - 0.0062\theta + 1.0252 \quad [R^2 = 0.9823] \quad (6.2)$$

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where θ is the inclination angle. Both geometric parameters for any inclination angle of the substrate were defined by the above equations.

6.2.2 Review on Chapter 4: Modeling and Simulation for Plasma and Particle Behavior

Coating formation is the final stage in plasma spraying process. In the modeling of coating formation, particle in-flight behavior, namely: size, number density, temperature, velocity and dispersion were required. These were determined by Computational Fluid Dynamics (CFD) simulation using the FLUENT V6.02© commercial package (FLUENT Inc., 10 Cavendish Court, Lebanon, NH03766-1442). The numerical and experimental investigations from **Chapters 4 and 5** respectively revealed that the obstruction provided by a substrate had insignificant effect towards particle behavior. Therefore, the finite volume mesh for the freestream model, which included only the torch and the free space in front of the torch for the spray plume was used (refer to **Figure 4.1(a)**).

In the simulation, a steady state thermal fluid solution for the plasma jet comprising of velocity and temperature fields was firstly obtained. On the basis of the plasma velocity and temperature fields, the particle dynamics and temperature were calculated by the drag force and convective thermal energy heat transfer models respectively. During the particle in-flight transition through the plasma jet, a particle received heat energy raising its temperature to melting point as well as increased its velocity through momentum exchange with the plasma gas. The individual temperature and velocity of each particle were different and depended on its size (diameter) and path through the plasma flame. The different trajectories of particles in the plasma jet also determined the impact sites of particles on the

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substrate plane. All the particle in-flight parameters and spatial dispersion characteristic will then be processed by the Substrate Cell Model (SCM) to predict the resulting coating profiles for different substrate inclination angles.

6.2.3 Substrate Cell Model (SCM)

Substrate Cell Model (SCM) is a FORTRAN© program. In the SCM, the substrate of dimensions 50 by 50 mm was numerically subdivided into a matrix of square cells of microscopic dimensions. From trial and error, discretization of substrate into 8 μm x 8 μm cells is found to be optimum, with a residual error of less than 2%; i.e. the difference between the total cell area under coverage and the splat area, as given in **Equation 6.3**. **Table 6.1** shows various cell sizes and the corresponding maximum errors in discretizing the substrate

$$\text{Error (\%)} = 100 * \text{ABS} \left[\frac{\frac{\pi d^2}{4} - (\text{Number of Cells} \times \text{Area of Single Cell})}{\frac{\pi d^2}{4}} \right] \quad (6.3)$$

Table 6.1: The maximum errors resulting from using different cell sizes.

Cell Size / μm x μm	Error / %
6 x 6	1
8 x 8	2
10 x 10	6
12 x 12	9

For every incoming droplet, the program calculated the resulting splat thickness and the expected diameter based upon the spread factor when the particle was impacting normally to the substrate (zero inclination angle). However, when particle was impacting at an inclined angle, the expected lengths along the major

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and minor axes of the ellipse were calculated by the aspect ratio. The model worked out the number of cells to be covered by the splat at the locality of the impact. The procedures were repeated for all the particles. The splat thicknesses were accumulated at the overlapping region to finally build up the deposit.

6.2.3.1 Modeling Assumptions for Substrate Cell Model (SCM)

1. It was assumed that molten particles formed perfect circular discs upon impacting the perpendicular substrate without any splashing phenomenon or breakup in the case of impact at normal to the substrate. For oblique impact, the resultant splat was assumed to be elliptical in shape. Both assumptions are reasonably justified by the SEM micrographs of the splats shown in **Figure 3.10**.
2. Porosity was neglected in the simplified model. In the accumulation of splats, porosity or voids tend to form in the interfaces between splats. The porosity formation can be considered in the future work.
3. **Table 3.3** shows the experimental spread factors for zirconia particles sprayed on a range of substrate materials (glass, stainless steel and steel precoated with zirconia) with different surface roughness (Ra values range from 0.02 to 9 microns) and temperatures (from 473 to 773 K). Despite the wide ranging substrate conditions, the variation of spread factors is not significant when considered together with the presence of experimental scatter. Thus, the substrate was assumed to be smooth and the spread factor for zirconia droplet spreading on previously coated zirconia layer was assumed the same as zirconia on smooth steel substrate.

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4. Not all particles emitting from the plasma torch form splats due to particle losses through vaporization, overspray and rebound from the substrate, the latter being more severe at higher inclination angle. In order to account for the particle losses in the simulation, the total number of incident particles was reduced by the experimentally derived Deposition Efficiency (DE) of the process. Detail on the DE measurement is further described in **section 6.3.2.3**. Resulting DE with respect to substrate inclination angle is presented in **Figure 6.11**, **section 6.5.1**.

6.2.3.2 Modeling of Single Splat for Perpendicular and Oblique Impacts

From a simplified viewpoint, a single spherical droplet, with incident temperature (T_p), velocity (U_p) and diameter (D_p), transforms into a circular splat with diameter, d during perpendicular impact as can be seen in **Figure 6.2(a)**. In the case of droplet impacting at an inclination angle, an elliptical splat with major diameter, d_y and minor diameter, d_x , is obtained as shown in **Figure 6.2(b)**. For different impacting angles, the impact location is also different. It is at the center of the circular splat while at one of the foci of the ellipse for the elliptical splat.

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Figure 6.2: Perfect formation of (a) a circular splat from perpendicular impact and (b) an elliptical splat after a molten droplet impacting at an oblique angle on discretized substrates.

At each impact location, the equivalent diameter, d_e was calculated from

Equation 6.4.

$$d_e = \zeta D_p \tag{6.4}$$

The particle diameter, D_p was known from the spatial distribution of CFD simulation result (e.g. **Figure 4.21(a)**) and the spread factor, ζ could be obtained from best-fitted **Equation 6.1**.

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In the case of perpendicular impact, the splat diameter, d equals to the equivalent diameter. For oblique impact, it is necessary to convert the equivalent splat of circular shape to an elliptical splat having the same area by reshaping it with the aspect ratio, ψ . The aspect ratio, ψ was empirically obtained as a best-fitted **Equation 6.2**.

The transformation of a circular splat of the equivalent diameter to an elongated splat was based upon conservation of volume. For same thickness, the areas were equivalent.

Area of elliptical splat = Area of equivalent splat of circular shape

$$\pi \frac{d_x}{2} \frac{d_y}{2} = \frac{\pi d_e^2}{4}$$

$$d_x d_y = d_e^2 \quad (6.5)$$

From **Equations 3.5** and **6.5**, the major diameter, d_y and minor diameter, d_x could be computed from the following:

$$d_x = \frac{d_e}{\sqrt{\psi}} \quad (6.6)$$

Substituting **Equation 6.6** into **Equation 6.5** gave,

$$d_y = d_e \sqrt{\psi} \quad (6.7)$$

Thus, the dimensions of the elliptical splat were known.

The circular splat with diameter, d and elliptical splat with major diameter, d_y and minor diameter, d_x were then formed on the discretized $8 \mu\text{m} \times 8 \mu\text{m}$ cells as seen in **Figures 6.3(a)** and **6.3(b)**, respectively.

Figure 6.3: (a) Circular splat and (b) elliptical splat where the cells shaded in grey were covered by the splat. (c) Enlarged views of regions A and B illustrating cells inclusion in the area of splat for splat thickness calculation.

In order to determine the cells to be involved for splat thickness calculation, the root locus of ellipse, r was calculated from **Equation 6.8**. For the case of circular splat, d_x equaled d_y in **Equation 6.8**. Any cell with its centriodal coordinate (x, y) that fell inside the circumscribing circle or ellipse ($r < 1$) as depicted

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schematically in **Figure 6.3(c)** was considered as part of the splat and assigned a splat thickness t .

$$\text{Root locus of ellipse, } r = \left(\frac{x}{d_x/2} \right)^2 + \left(\frac{y}{d_y/2} \right)^2 \quad (6.8)$$

The splat thickness, t was derived based on the concept of conservation of volume, i.e. the volume of the splat equaled the volume of the originating droplet.

Volume of the splat, V_s = Volume of the droplet, V_p

$$\frac{\pi d_e^2}{4} t = \frac{\pi D_p^3}{6}$$

Therefore, the thickness of the splat was,

$$t = \frac{2D_p^3}{3d_e^2} \quad (6.9)$$

or as a function of spread factor,

$$t = \frac{2D_p}{3\xi^2} \quad (6.10)$$

6.2.3.3 Modeling of Multiple Overlapping Splats

In the real case, there is large number of particles and each particle has its own time of arrival. Upon impact, the subsequent droplet forms splat that conforms and overlaps the previously deposited splat. In this study, simple addition of their individual splat thicknesses was carried out at the overlap region. The transient behavior of the deformation and interaction of multiple splats forming onto the substrate are being considered in future.

Figure 6.4 schematically shows the concept of two splats overlapping initially. Based on this concept, the process of summation was repeated for all the

particles. The cumulative effect finally yielded the coated deposit. The summary of the solution procedures for Substrate Cell Model (SCM) is clearly depicted in **Figure 6.5**.

Figure 6.4: (a) Schematic illustration of the Substrate Cell Model depicting the thickness build-up of two overlapping elliptical splats on the cells. Each cell recorded the accumulated height of splats that happened to overlap, as seen by sectional view through section X-X and (b) enlarged view A at the overlap region.

Figure 6.5: Flow chart of the solution procedures for SCM.

The output of the FORTRAN© simulation was then post-processed by using digital plotting software SURFER V8.01© (Golden Software, Inc., 809 14th Street Golden, Colorado, 80401-1866 USA). Three-dimensional profiles, integrated volumes, thicknesses and widths for the computed deposits were thus obtained.

6.3 Experimental Procedure

For the purpose of verifying the numerical results, experiments under the same conditions as the numerical work were conducted. Forming deposits experimentally at stationary mode under different substrate inclinations required three steps. Firstly, substrate was cut and grit-blasted to obtain sufficiently rough surface as required for the deposit to adhere. Secondly, an experiment rig was designed to expose different inclined substrates located at 80 mm in front of the nozzle front face to the spray plume for 5 seconds. Lastly, high precision metrology Coordinate Measurement Machine (CMM) system ‘MahrVision OMS 400©’ was utilized for deposit measurement as to obtain the deposit characteristics of volume, thickness, width and length.

6.3.1 Substrate Preparation

3 mm thick mild steel substrates were cut into the size of 50 by 50 mm. The substrates have to be grit-blasted to increase the coating bond strength and promote mechanical keying. The substrates were grit-blasted perpendicularly at pressure of approximately 100 psi. Sample of substrates before and after grit-blasting are shown in **Figure 6.6**. After grit-blasting, the Surftest 301© surface roughness profiler (Mitutoyo, Japan) was used to measure the roughness of the substrates. The mean arithmetic surface roughness, R_a is 50 microns. Lastly, the substrates were kept in the desiccant chamber until they were needed for the spraying.

Figure 6.6: 50 by 50 mm mild steel substrates in raw state (left) and after grit-blasting (right).

6.3.2 Plasma Sprayed Deposit Experiment

6.3.2.1 Feedstock Powder

The ceramic powder used in this study was zirconia doped with 8% yttria supplied by Saint-Gobain Norton K.K., Singapore. Description regarding the powder can be referred to **Chapter 3, section 3.3.1**.

6.3.2.2 Experiment Setup

The investigation was carried out using a model SG-100© plasma torch (Praxair Surface Technologies Inc., N670 Communication Drive, Appleton, Wisconsin 54915, USA) with internal powder injector of 2 mm diameter. Argon was used as plasma-forming and carrier gases. Details of the spray conditions were the same as listed in **Table 3.1**.

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A photo of the experiment rig showing the torch and substrate is depicted in **Figure 6.7(a)**. Spirit level and protractor as seen in **Figure 6.7(b)** were used to measure the substrate inclination angle, which was varied by means of the tilting mechanism behind of the substrate. The substrate inclination angle is defined as the angle between the vertical plane (Y-axis) and the substrate surface. For every inclined substrate, a constant standoff distance of 80 mm was set between the nozzle front face and the center of the substrate.

Figure 6.7: (a) Setup for plasma sprayed deposit experiment, with 50° inclined substrate located at 80 mm in front of the nozzle front face. (b) Changing of the angle of inclination to 10° by tilting mechanism with the assistance of protractor and spirit level.

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In order to obtain the deposit mount under 5 seconds of stationary spraying, a movable shutter plate that acts like a camera shutter was firstly held manually in front of the substrate. When the spray system was operating in a steady state, the cover plate was lifted momentarily to expose the substrate to the spray particles for 5 seconds. At the end of 5 seconds, the cover plate was dropped to block off the spray particles.

In the series of experiments, inclination angles ranging from 0° to 60° with 10° intervals were investigated. 3 substrates were sprayed for each angle and a total of 21 substrates were sprayed for 7 different inclination angles.

6.3.2.3 Deposition Efficiency

As highlighted in the modeling assumptions in **section 6.2.3.1**, the deposition efficiency with respect to substrate inclination angle is required to account for particle losses in the simulation. To the author's best knowledge, no relevant data was available from public sources and therefore it is needed to be determined from experiment.

Deposition efficiency is defined as the ratio of the weight of powder deposited on the substrate, W_D to the weight of powder ejected from the torch, W_I as shown in **Equation 2.17**.

Eq. 2.17:
$$DE (\%) = \frac{W_D}{W_I} \times 100$$

Experiments were conducted to evaluate the influence of the substrate inclination angle on the deposition efficiency. In this experiment, the substrate was weighed before and after 5 seconds of stationary spraying by a precision balance [Mettler Toledo (S) Pte. Ltd.] with an accuracy of ± 0.01 g. The weight difference

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gave the actual amount of powder deposited on the substrate. The amount of powder delivered by the torch was calculated from the feedrate (g/s) and spray time (s). The feedrate was firstly obtained by spraying powder without igniting the torch and collecting the powder on a large plastic sheet on the floor over a fixed spraying time and with all other process conditions remaining the same. The weight of powder collected on the plastic sheet was calculated by the difference in the weights of plastic sheet before and after spraying. This weight represented the amount of powder ejected from the torch.

6.3.2.4 Measurement Technique

The deposit profiles were measured by a Coordinate Measurement Machine (CMM) system 'MahrVision OMS 400©' supplied by MAHR (Mahr Federal Inc., 1144 Eddy Street, P.O.B 9400, Providence, RI 02940), as shown in **Figure 6.8**. The CMM consists of a laser sensor, which focuses from point to point for three-dimensional surface profile measurement.

To measure the deposit profile, the substrate with deposit was placed on the traversing stage. The laser beam was focused at a starting point and the coordinates were reset to (0, 0, 0). The scanning laser was then moved in a zigzag pattern to measure the profile heights of the deposit. The measurement data was then post-processed by the digital plotting software SURFER V8.01©. The three-dimensional profile of the deposit, its integrated volume, maximum thickness, width and length were thus computed.

Figure 6.8: High precision metrology Coordinate Measurement Machine (CMM) system ‘ MahrVision OMS 400©’.

6.4 Geometric Characterization of Deposit

In plasma spraying, injected particles are heated and accelerated in the plasma jet and subsequently propelled towards the substrate. Upon impact, a particle associated with its velocity and temperature forms into a “pancake” shape. The formation of the well-formed splat from its globular form also depends on the substrate characteristics. **Figure 6.9(a)** shows the schematic of a circular splat after a droplet impacts perpendicularly on the substrate. Under oblique impact, an elliptical splat is expected with its major and minor diameters dependent on the conditions as in perpendicular impact including the oblique angle and velocity of impact. Detail of the effect of inclination angle on the splat morphology can be found in **Chapter 3**. For each inclination angle, prolonged accumulation of splats subsequently forms a large measurable deposit with pores, unmelted particles and foreign substances embedded in it, see **Figure 6.9(b)**. The deposit obtained has close similarity with the constituent splats in term of aspect ratio.

The deposit aspect ratio ψ_D is defined, as the ratio of major diameter, W_y to the minor diameter, W_x of the elliptical shaped deposit. With the increase of substrate inclination angle, the disk shape of deposit will be distorted forming a narrow and elliptical shape which has aspect ratio, ψ_D of greater than unity. Illustration of the geometric shape of an elongated deposit is shown in **Figure 6.10**.

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Figure 6.9: (a) Schematic of a spherical droplet impacting perpendicular on a substrate. (b) Successive pilling up of splats with pores, unmelted particles entrapped to form a deposit under stationary spraying.

Figure 6.10: Characterization of an elongated deposit gained under stationary spraying in geometric term.

6.5 Results and Discussion

In this section, the experimental results on deposition efficiency and deposit porosity at different substrate inclinations are studied. Following, comparison of the computational results with those obtained from experimental measurements is presented. Three aspects, namely deposit volume, maximum deposit thickness and deposit aspect ratio, ψ_D are compared.

6.5.1 Influence of Substrate Inclination Angles on Deposition Efficiencies

The mean and range of deposition efficiencies of the process for different inclination angles are presented in **Figure 6.11**. Parabolic curved fitted equation is included at the lower right corner, indicating the quadratic relationship between the deposition efficiency and substrate inclination angle. This equation was utilized to cut off a fraction of particles across all sizes from the amount of incoming particles provided by FLUENT© and thus determining the accurate number of input particles to the SCM.

In **Figure 6.11**, it is noted that the maximum deposition efficiency occurs at 0° substrate inclination angle with the value of 40% and gradually drops till a minimum of 25% at 60° . One of the reasons attributed to this trend is the change of particle impacting momentum with substrate inclination angle. When impacting at higher substrate inclination angle, the particle momentum in the normal direction (i.e. perpendicular to the substrate surface) is reduced in exchange with its tangential component (i.e. parallel to the substrate surface). Particle with lower normal momentum component does not have sufficient energy to adhere and thus leads to lower deposition efficiency. This has been noted from the previous results described in **Chapter 5**. Referring to **Figure 5.13**, the particle tangential velocity

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component increases whereas the normal velocity component decreases with increasing substrate inclination angle. The increased tangential component of velocity results in more rebounding particles while the reduced normal component yields a lower particle impacting momentum. Thus, the deposition efficiency exhibits a decreasing trend with respect to substrate inclination angle.

Figure 6.11: Deposition efficiency of the process showing the decreasing trend with increasing of substrate inclination angle. At the lower right corner, curve fitted quadratic equation relates the deposition efficiency with substrate inclination angle.

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Table 6.2: Collection of the deposition efficiencies from the reported literature along with the current work for the case of perpendicular impact.

	Operating Condition	Powder Material	Substrate Material	Deposition Efficiency (%)
This work	900 A, 35 V, Ar (72 l/min)	Agglomerated YSZ	Grit-blasted Mild Steel	32-48
Fincke and Swank (1992)	900 A, 34 V, Ar (47 l/min)-He (22.2 l/min)	Zirconia (AI-1075)	-	40-65
Leblanc <i>et al.</i> (1997)	800 A, 34-42 V, Ar (50 l/min)-H ₂ (2 l/min)	Fused YSZ	Grit-blasted Mild Steel	55
Jewett <i>et al.</i> (1997)	500-600 A, Ar (40 l/min)-H ₂ (7-12 l/min)	Crushed YSZ	Grit-blasted Steel	48-51
	500-600 A, Ar (40 l/min)-H ₂ (7-12 l/min)	Hollow Sphere YSZ	Grit-blasted Steel	51-60
Kucuk <i>et al.</i> (2001)	600 A, 70 V, Ar (40-50 l/min)-H ₂ (12 l/min)	YSZ	Glass Slide	7-25

In **Table 6.2**, the deposition efficiencies of plasma-sprayed zirconia gained from the open literature along with the current work for the case of perpendicular impact are listed. It is noted that from the comparison, fairly good agreement in general is obtained except for Kucuk *et al.* (2001). In Kucuk *et al.* (2001) study, the substrate sprayed was a glass slide which is relatively smooth compared to the grit-blasted mild steel substrate used in this study. A rougher surface promotes mechanical adhesion between splats and the substrate and thus improves deposition efficiency.

6.5.2 Influence of Substrate Inclination Angles on Deposit Porosities

Figure 6.12 shows the mean value of deposit volumes gained by experimental scanning and weighing. The scanning method involves laser based measurement by Coordinate Measurement Machine (CMM) while weighing method measures the mass of deposit and calculates the volume by dividing the zirconia density of 5890 kg/m^3 . The former method will include the porosity of the deposit but no porosity is measured by the latter method. The difference in volumes between the two methods of measurement is possibly the amount of porosity inherent in the deposit. The percentage of porosity is estimated from **Equation 6.11**.

$$\text{Porosity (\%)} = 100 * \left[\frac{(\text{Scanned} - \text{Weighed}) \text{ Deposit Volume}}{\text{Scanned Deposit Volume}} \right] \quad (6.11)$$

In **Figure 6.12**, an increasing trend of porosity with substrate inclination angle is noted. The increase in porosity is partly because the normal component of particle momentum decreases with substrate inclination angle as elucidated earlier. With smaller impacting momentum, the particle will not effectively cover the roughened surface of the substrate or previously deposited splats, i.e. lower impacting momentum of molten particle produces a porous deposit.

The same trend was also found in Leigh and Berndt (1997), who reported the increase of porosity from 2.1% to 4.5% for $\text{Cr}_3\text{C}_2\text{-NiCr}$ and from 2.5% to 4.2% for NiAl when the substrate inclination increased from 0° to 40° . The quantitative discrepancy is due to the different types of spray powder used. In their study, metallic powders were sprayed. Metallic powder is easier to be melted, spreads and adheres on the substrate or previously deposited layers as metallic powder has lower melting point and lower viscosity at higher temperature compared to the ceramic powder, thereby resulting in a denser deposit.

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Figure 6.12: Deposit volumes gained by CMM scanning and by weighing at different substrate inclinations for 5 seconds of stationary spraying. Deposit porosity was estimated from the difference in the deposit volumes.

6.5.3 Comparison of Computational and Experimental Results

The results obtained from the single splat experimental spraying on flat substrate at different substrate inclinations from 0° to 60° in 10° steps were used to predict the spread factors and aspect ratios of individual splats. These were later used to predict the spread and shaping of deposit in stationary spraying mode by means of the Substrate Cell Model (SCM). The spatial distribution of particles in terms of size distribution of CFD simulation was also utilized by the SCM to shape and accumulate the splats on the substrate to form the deposit.

The simulated deposit should reflect the actual width and thickness of the deposit. **Figures 6.13(a) to 6.19(a)** show the SCM prediction of the three-dimensional deposit profiles for a substrate inclined at 0° to 60°, with 10° intervals

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respectively after a spray duration of 5 seconds. An experimental confirmation provides a valuable insight on the influence of substrate inclination angles on the deposit profiles. The experimentally obtained deposits sprayed under the same conditions and later measured by a laser based Coordinate Measurement Machine (CMM) are shown in **Figures 6.13(b) to 6.19(b)**.

The good agreements between the predicted and the experimentally measured deposit profiles in the peak thickness, width and length indicate that the concept of the SCM is a feasible one.

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Figure 6.13: (a) Computed deposit profile and (b) experimentally obtained deposit of 0° substrate inclination angle showing the three-dimensional deposits (left) and illustrating the deposit contours (right). Arrows indicate the direction of incoming particles.

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Figure 6.14: Similar to layout of Figure 6.13 for 10° substrate inclination angle.

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Figure 6.15: Similar to layout of Figure 6.13 for 20° substrate inclination angle.

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Figure 6.16: Similar to layout of Figure 6.13 for 30° substrate inclination angle.

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Figure 6.17: Similar to layout of Figure 6.13 for 40° substrate inclination angle.

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Figure 6.18: Similar to layout of Figure 6.13 for 50° substrate inclination angle.

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Figure 6.19: Similar to layout of Figure 6.13 for 60° substrate inclination angle.

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6.5.4 Side Elevations of Deposit Mounds in XZ and YZ Plane Views

More detailed views in XZ and YZ planes for both the simulated and experimentally obtained deposits are shown in **Figures 6.20** and **6.21**, respectively. As clearly depicted in the figures, the region of the substrate surface exposed to the particle plume is expected to retain more molten splats and thus growing more rapidly to form a bell-shaped topography. This bell-shaped morphology can be observed throughout every substrate inclination angle. With the increase of substrate inclination angle, the maximum deposit thickness of the bell-shaped topography shows a decreasing trend.

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Figure 6.20: (a) Computed deposits on substrate at different inclination angles in XZ plane.

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Figure 6.20: (b) Experimentally gained deposits on substrate at different inclination angles in XZ plane.

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Figure 6.21: (a) Computed deposits on substrate at different inclination angles in YZ plane. Arrows indicate the directions of incoming particles.

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Figure 6.21: (b) Experimentally gained deposits on substrate at different inclination angles in YZ plane. Arrows indicate the directions of incoming particles.

6.5.5 Deposit Volumes and Thicknesses at Different Substrate Inclination Angles

Figure 6.22 shows the comparison of deposit volumes gained by means of experimental spraying and simulation. The experimental results are indicated with error bars while white square symbols represent the computational results. The experimentally sprayed deposits were scanned by a laser based Coordinate Measurement Machine (CMM) to measure the height profiles which were subsequently integrated to yield the total volume of the deposits. The volumes obtained will include the porosity inherent in the deposits. The computed (simulated) volumes which did not model the porosity formation are slightly lower compared to the experimentally obtained volumes, as indicated clearly in Figure 6.22. The difference in volumes between the computational and the experimental remains unaffected by the inclination angle.

Figure 6.22: Deposit volumes gained from simulation ($\square$) and experiment ($\blacksquare$) by CMM scanning after 5 seconds of stationary spraying at different substrate inclinations.

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Figure 6.23: Comparison of the computed and experimentally gained deposit thicknesses for 0° to 60° substrate inclinations. Values in brackets indicate the percentage difference between the experimental and simulation results.

Figure 6.23 shows the quantitative comparison between the computed and experimentally measured peak thicknesses for all substrate inclination angles. The maximum deposit thickness occurs at 0° substrate inclination in both cases, with the computed value of 1.66 mm and the experimental value of 1.84 mm. The deposit thickness decreases to a minimum of 0.66 mm (simulation) and 0.68 mm (experiment), both are at 60° substrate inclination. In addition, the percentage difference was calculated between the simulated coating thickness and the average value of the experimentally measured thickness. From the calculation, it is noted that the best prediction occurs at 60°, followed by 40°, 30°, 0°, 20°, 50° and the worst is at 10°. No specific trend for the accuracy of prediction is observed. This may partly due to the uncertainties of the experiment, as the way of controlling the deposition time is carried out manually and the number of experiments repeated at

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each angle of inclination is low (i.e. three experiments per inclination angle). However, it is strongly believed that the overall accuracy of the model is satisfactory as all the computed thicknesses are noted to be within the experimental ranges of the coating thicknesses, except for 50°.

For both deposit volume and peak thickness, reducing trends with increasing substrate inclination angles are notable in **Figures 6.22** and **6.23**. This is because the deposit characteristics such as volume and thickness are a reflection of the deposition efficiency, i.e. the lower the deposition efficiency, the lower the values of the deposit characteristics. In addition, at higher substrate inclination angle, particle plume diverges and covers larger spray area and therefore, the particle concentration is dispersed. Consequently, the maximum deposit thickness decreases with substrate inclination angle.

6.5.6 Deposit Aspect Ratios, ψ_D at Different Substrate Inclination Angles

Deposit aspect ratio, ψ_D is the ratio of the major to minor diameters of elliptical shaped deposit. **Figure 6.24** shows the influence of substrate inclinations on deposit aspect ratios, ψ_D which gained by means of experiment and simulation. From the comparison, fairly good agreement is noted, with the maximum percentage difference of 17% occurs at 10°. The best prediction of the aspect ratio is at 60° with only 0.65% percentage difference.

As a further observation in **Figure 6.24**, at angles less than 15°, the experimental deposits have an aspect ratio, ψ_D close to unity, indicating that the deposits will be in circular shape. Increasing the inclination angle till 60°, a gradual rise is seen until it reaches a maximum of 1.83. This implies that the deposit is elongated to an elliptical shape with the W_y of nearly 2 times larger than its

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counterpart, W_x . The experimental and computed deposit contours are given earlier in **Figures 6.13 to 6.19**. In the case of 0° , the deposit takes up a circular shape. The morphology of the deposit is elongated to form a narrow and elliptical shape with increasing substrate inclination angle. This is because at higher substrate inclination angle, the particle spreading momentum increases and promotes the spreading of individual splat to an elliptical form. Overlapping of such splats subsequently gives rise to an elliptical deposit.

Figure 6.24: Aspect ratios of deposits, ψ_D at different substrate inclinations gained by means of experiment (■) and simulation (□).

6.5.7 Possible Explanations for the Inaccuracy of Computational Prediction

Deposits obtained from the Substrate Cell Model (SCM) have been compared with those obtained from the experiment in terms of deposit volume, thickness and aspect ratio. The computed deposit volume differs from the measured volume by a maximum of 32%. The numerical values from the thickness and

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aspect ratio comparisons differ with a percentage of less than 17%. However, both the computational predictions and experimental measurements indicate the decrease of deposit volume, thickness as well as the increase of aspect ratio as the substrate inclination angle increases. This implies that the model is capable of predicting the behavioral trends of deposit characteristics.

There are few possible reasons for the numeric discrepancy and are summarized as follows:

1. Porosity inherent in the deposit was not modeled in the SCM. As a result, the predicted deposit volumes are lower compared to the experimentally measured volumes. For the deposit thickness and aspect ratio, the computed values are all consistently less than their experimental counterparts. This is also partly due to the exclusion of porosity in the modeling.
2. The assumption of linear accumulation of material vertical to the substrate was made in each cell. This superposition condition may be another possible source of inaccuracy in the prediction of deposit volume, thickness and aspect ratio.
3. In the computational modeling, the plasma torch under study would be in the ideal working condition. In fact, due to aging and wear of cathode and anode, the geometry may differ from the brand new equipment. Hence, the simulated plasma and particle behavior may differ from those of measurements, which subsequently affect the deposit characteristics.
4. It was assumed that particle to particle interaction was absent. In reality, particle to particle collision will be present to some extent and may result in the changes of particle trajectories during their transition in the plasma

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flame. This may affect the particle dispersion and result in the inaccuracy prediction on deposit characteristics.

Because of the underlying assumptions, it is always difficult to carry out both simulation and experiment under identical conditions. Therefore, the agreement achieved in this study can be considered acceptable.

6.6 Conclusions

The Substrate Cell Model (SCM) for the prediction of deposit profiles at different substrate inclinations was developed. This was a semi-empirical model that combined curve-fitted quadratic equations from experimentally measured spread factor and aspect ratio and output particle dispersion data from CFD analysis. The computed deposits when compared with experimental measurements under the same conditions showed a reasonably good agreement. As for the deposit thickness as well as deposit aspect ratio, the best prediction was observed to be at 60° substrate inclination while 10° gave the worst prediction. In the case of comparison for deposit volume, the computed volumes which excluded the inherent porosity were slightly lower than the experimental volumes for all the inclination angles.

In addition, the experimental results revealed that the increase of substrate inclination angle would lead to the reduction of deposition efficiency and increase of porosity. This was mainly attributed to the conversion of particle impacting momentum to particle spreading momentum at higher substrate inclination angle. The higher particle spreading momentum consequently promoted the elongation of deposit that resulted in higher deposit aspect ratio, as predicted in the simulation as well as in the experimental measurement. Other than that, the deposit characteristics such as deposit volume and thickness from both experiment and simulation decreased with increase of substrate inclination angle. The lower deposit characteristics at higher substrate inclination were, to a certain extent, the result of the reduction of deposition efficiency.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

In this study, there are few conclusions that can be drawn. The following sections summarize the major findings from this study.

7.1.1 Modeling of Plasma Plume and Particle Dynamics and Heat Transfer

A numerical model representing plasma spray process was developed and simulated by means of Computational Fluid Dynamics (CFD) method using FLUENT V6.02© commercial package. This model consisted of two stages; the first being to solve a steady state thermal fluid solution comprising of temperature and velocity fields for the plasma plume. The solution for the first stage was based on the fully elliptic Navier-Stokes equations, together with the volumetric heat source model and the standard κ - ϵ turbulence model. As for the second stage, the particles were introduced as discrete Lagrangian entities through the internal injection port to the plasma flow and subsequently exchanged heat and momentum with the plasma plume in one-way coupling. Under the effects of turbulent dispersion and particle segregation, each particle had its own trajectory during its transition in the plasma flame. Thus, it had the exact parameters of temperature and velocity calculated from the energy balance equation and the Newton second law of motion, respectively.

7.1.2 Modeling and Experiment on the Effect of Substrate Obstruction

Numerical investigation was also carried out using FLUENT© to reveal the effect of perpendicular and inclined substrates on the behavior of plasma flow fields and in-flight particles. It was found that only in the vicinity of the substrates, the flow temperature and velocity were strongly affected; the rest of the flow fields remained relatively undisturbed by the presence of substrates. Therefore, no difference was observed between the particle behavior distributions, namely size, velocity and temperature obtained from the freestream and substrate models.

The numerical finding was supported experimentally by images captured using SprayWatch© imaging diagnostics equipment. From the images, the streaks of particles propelled from the plasma torch towards different inclined substrates were clearly shown to follow similar paths as the freestream particles. As a further verification, the quantitative measurements of particle velocity by the SprayWatch© equipment showed that the average velocity of particles was negligibly affected by the substrate. Instead, it depended on the particle size and its traveling distance.

7.1.3 Experiment on Individual Splats Characterization

The single splat capture experiment was conducted by fast traversing flat and inclined substrates in front of the plasma torch to minimize the overlapping splats. The three-dimensional shapes of isolated splats were randomly identified and later measured by WYKO NT-2000© surface profiler. From the plotted data of 50 measurements per inclination, polynomial equations were curved-fitted for spread factor and aspect ratio and shown as follow:

$$\text{Spread factor, } \xi = -0.0009\theta^2 + 0.0557\theta + 4.6024 \quad [R^2 = 0.9447]$$

$$\text{Aspect ratio, } \psi = 0.0003\theta^2 - 0.0062\theta + 1.0252 \quad [R^2 = 0.9823]$$

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In addition, the splats were subjected to Scanning Electron Microscopy (SEM) inspection. From the SEM images, various interesting features such as splashing, overlapping, overlaying, finger and ridge formation and cracking were observed on the splats. It was also noted that the oblique impact created elliptical splat morphology with its point of impact as one of the foci of the ellipse.

7.1.4 Modeling and Experiment on Deposit Formation

A semi-empirical model, referred as Substrate Cell Model (SCM) was developed to predict deposit volume, thickness, width and length. In the SCM, the database of the likely shape, thickness and size of splats obtaining from the splat measurements was related to the incoming particle distributions predicted by the CFD to produce the splats of known dimensions at locations of impact. A deposit was generated after successive overlapping of multiple splats. From substrate inclination angles of 0° to 60° in steps of 10° , the simulated deposits have reasonable to good agreements with the experimental measurements under the same conditions. Both the computed and experimentally gained deposits showed a reducing trend of deposit characteristics of volume and thickness with substrate inclination angle. As for the numeric comparison, the best prediction for deposit thickness and aspect ratio occurred at 60° (with percentage difference less than 1%) and the worst at 10° ($\approx 17\%$).

In addition, experiment measurements regarding deposition efficiency and porosity were conducted. The results indicated that at lower substrate inclination angle, a denser deposit with higher deposition efficiency was obtained.

7.2 Recommendations for Future Work

1. It was shown that the Substrate Cell Model (SCM) was practicable to model and predict deposit characteristics at different inclination angles with good agreement with the experiments. In the future, the SCM can be improved to predict the deposit profiles on continuously varying curved surfaces of realistic engineering components. The deposition on these surfaces can be implemented by representing the curved surface geometry as locally flat facets, each facet having individual inclination.
2. Existence of porosity was neglected in the present model. A model to account for the porosity needs to be considered in future. From the published literature, there are different possible sources of porosity, such as peripheral curl up of individual splats, overflowing of liquid over solidified splat, entrapment of gas between splats, presence of unmelted particles, etc. It is necessary to firstly conduct an experimental study to determine the dominant source of porosity before developing a model to account for the porosity.
3. The current modeling made the assumption that particle to particle interaction was absent. It is suggested that this assumption is eliminated in the future work to enhance the particle dispersion resulting from particle to particle collision.
4. Currently, deposition efficiency was utilized to reduce the amount of particles lost through vaporization, rebounding and overspraying. In future, a mathematical model is required to determine the exact amount of incident particles in the simulation.

APPENDIX I

LIST OF PUBLICATIONS

Conferences attended:

1. **Kang C.W.**, Ng H.W. and Yu S.C.M., 6-8 Dec 2004, *Splat Morphology and Spreading Behavior due to Oblique Impact of Droplets in Plasma Spray Coating Process*, The 13th International Conference on Processing and Fabrication of Advanced Materials, Singapore : p. 984-998.
2. **Kang C.W.**, Ng H.W. and Yu S.C.M., 1-3 Feb 2005, *Simulation of Thermal Spray Coatings at Different Substrate Inclinations*, Proceeding of the First International Conference on Modeling, Simulation and Applied Optimization, Sharjah, UAE: Numerical Methods-1, Paper ID: 342.

Other conference:

1. Ng H.W., Remesh K., Devasenapathi A., Yu S.C.M. and **Kang C.W.**, 22-25 June 2003, *Simulation on Deposit Topology in the Plasma Spray Process*, 2nd International Conference on Spray Deposition and Melt Atomization and 5th International Conference on Spray Forming, Bremen, Germany : p. 8-53 – 8-65.

Journals:

1. **Kang C.W.** and Ng, H.W., 2006, *Splat Morphology and Spreading Behavior due to Oblique Impact of Droplets onto Substrates in Plasma Spray Coating Process*, Surface and Coatings Technology, 200 : p. 5462-5477.
2. **Kang C.W.**, Ng H.W. and Yu S.C.M., 2006, *Comparative Study of Plasma Spray Flow Fields and Particle Behavior Near to Flat Inclined Substrates*, Plasma Chemistry and Plasma Processing, 26 : p. 149-175.
3. **Kang C.W.**, Ng H.W. and Yu S.C.M., 2006, *Imaging Diagnostics Study on Obliquely Impacting Plasma-Sprayed Particles Near to the Substrate*, Journal of Thermal Spray Technology, 15(1) : p. 118-130.
4. **Kang C.W.**, Ng H.W. and Yu S.C.M., *Simulation of Thermal Spray Coatings at Different Substrate Inclinations*. (Accepted for publication in Journal of Thermal Spray Technology).

APPENDIX II

MACH NUMBERS CALCULATION

- (I) Inside the torch where the maximum plasma temperature is 11660 K and the maximum plasma velocity is 1115.07 m/s**

The specific heat capacity of argon gas, C_p is 3708.62 J/kgK and the gas constant, R is 208.12 J/kgK.

$$C_v = C_p - R$$

$$= 3708.62 - 208.12 = 3500.50 \text{ J/kgK}$$

$$\gamma = \frac{C_p}{C_v} = \frac{3708.62}{3500.50} = 1.0595$$

$$\text{Sonic velocity} = \sqrt{\gamma RT} = \sqrt{(1.0595)(208.12)(11660)} = 1603.47 \text{ m/s}$$

$$\text{Mach number} = \text{max velocity} / \text{sonic velocity} = 1115.07 / 1603.47 = 0.70 < 1$$

Since the calculated Mach number is less than 1, it is appropriate to assume the flow is incompressible.

- (II) Outside the torch where the maximum plasma temperature is 11641 K and the maximum plasma velocity is 1090.74 m/s**

The specific heat capacity of argon gas, C_p is 3671.09 J/kgK and the gas constant, R is 208.12 J/kgK.

$$C_v = C_p - R$$

$$= 3671.09 - 208.12 = 3462.97 \text{ J/kgK}$$

Appendix II

$$\gamma = \frac{C_p}{C_v} = \frac{3671.09}{3462.97} = 1.0601$$

$$\text{Sonic velocity} = \sqrt{\gamma R T} = \sqrt{(1.0601)(208.12)(11641)} = 1602.64 \text{ m/s}$$

$$\text{Mach number} = \text{max velocity} / \text{sonic velocity} = 1090.74 / 1602.64 = 0.68 < 1$$

Again, the Mach number is less than 1, the flow is assumed as incompressible.

Also, it has shown in the calculation that the Mach number is higher inside the torch than outside, which is clearly a realistic phenomenon.

APPENDIX III

ENERGY SOURCE CALCULATION

Power Output Calculation

Based on the operating conditions stated in **Table 4.1**,

Current input = 900 A

Voltage = 35 V

Power input = $I E = 900 \times 35 = 31.50 \text{ kW}$

With torch efficiency of 67%,

Power output = $31.50 \times 0.67 = 21.11 \text{ kW}$

Geometry Dimension

Torch dimension (diameter x length) = $\phi 8 \times 10 \text{ mm}$

Torch volume = $\frac{\pi(0.008)^2}{4}(0.01) = 5.0265 \times 10^{-7} \text{ m}^3$

Energy Source

Energy source needed for FLUENT© calculation is energy per unit volume.

$$\frac{\text{Energy}}{\text{Volume}} = \frac{21.11 \times 10^3}{5.0265 \times 10^{-7}} = 4.1997 \times 10^{10} \frac{\text{W}}{\text{m}^3}$$

APPENDIX IV

TURBULENCE INTENSITY CALCULATION

Argon Gas Properties

$$\text{Argon gas density, } \rho_{Ar} = 1.6228 \text{ kg/m}^3$$

$$\text{Argon gas viscosity, } \mu_{Ar} = 2.1250 \times 10^{-5} \text{ kg/ms}$$

(I) Arc Gas Inlet

$$\text{Argon gas volume flow rate, } Q = 72 \text{ slm} = 1.20 \times 10^{-3} \text{ m}^3/\text{s}$$

$$U = \frac{Q}{A} = \frac{1.2 \times 10^{-3}}{\frac{\pi}{4}(0.008)^2} = 23.8732 \text{ m/s}$$

$$\text{Re}_{HD} = \frac{UD_{noz}}{\mu_{Ar}} = \frac{1.6228 \times 23.8732 \times 8 \times 10^{-3}}{2.1250 \times 10^{-5}} = 14585.0086$$

$$\text{Turbulence intensity} = 0.16(\text{Re}_{HD})^{-0.125} = 0.16(14585.0086)^{-0.125} = 4.83\%$$

(II) Carrier Gas Inlet

$$\text{Argon gas volume flow rate, } Q = 4.20 \text{ slm} = 7 \times 10^{-5} \text{ m}^3/\text{s}$$

$$U = \frac{Q}{A} = \frac{7 \times 10^{-5}}{\frac{\pi}{4}(0.003)^2} = 9.9030 \text{ m/s}$$

$$\text{Re}_{HD} = \frac{\rho_{Ar} UD_{noz}}{\mu_{Ar}} = \frac{1.6228 \times 9.9030 \times 3 \times 10^{-3}}{2.1250 \times 10^{-5}} = 2268.7890$$

$$\text{Turbulence intensity} = 0.16(\text{Re}_{HD})^{-0.125} = 0.16(2268.7890)^{-0.125} = 6.09\%$$

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