

Conceptual Design of a Low Pressure Cold Gas Dynamic Spray (LPCGDS) System

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfillment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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Signed this day of 2010

ABSTRACT

Low Pressure Cold Gas Dynamic Spray (LPCGDS) is a coating process that utilises kinetic energy instead of thermal energy to deposit powder particles (1-50 μm) to substrates at low temperatures ($<400\text{ }^{\circ}\text{C}$) without going through melting. The deposited coatings provide improved wear and corrosion protection to underlying surfaces while maintaining the original phase structure of the particles and minimising oxide formation and residual stresses associated with conventional thermal spray processes such as flame, arc and plasma spraying. Bonding occurs when particles impact velocities on the substrates exceed a certain critical velocity. This critical velocity depends on the propellant gas and particles characteristics, and the spray system components (gas supply, gas heater, powder feeder and the supersonic nozzle) design. Consequently, design optimisation of these parameters is a key to improve the coating quality and reduce the spraying costs.

This study develops an effective and efficient conceptual design of a LPCGDS system. Requirements for both the overall LPCGDS system and its individual components or sub-systems are established. Components variants that include off-the-shelf, customised and innovative solutions are generated. An evaluation of these variants is then carried out to determine components that best performs LPCGDS functions. Subsequently, an optimal spray system that meets the specifications of the LPCGDS system is assembled from these best components. Finally, a complete spray set-up that includes the spraying chamber, a gas and particle recovery system, the data acquisition and control system and, coating quality measurement equipment is established.

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NOMENCLATURE

A	cross-sectional area (m^2)
A_e	nozzle exit cross-sectional area (m^2)
A_p	average particle cross-sectional area (m^2)
A^i	nozzle powder entry point cross-sectional area (m^2)
A^*	nozzle throat cross-sectional area (m^2)
B	Brinell hardness number (BHN)
C	specific heat ($\text{J/kg}\cdot\text{K}$)
C_D	drag coefficient
C_p	gas constant-pressure specific heat capacity ($\text{J/kg}\cdot\text{K}$)
C_v	gas constant-volume specific heat capacity ($\text{J/kg}\cdot\text{K}$)
D	drag force (N)
D_c	damage number
D_o	discharge orifice diameter (m)
D_{th}	thermal diffusivity (m^2/s)
E	particle kinetic energy (J)
F	normal force (N)
F_p	accelerating force on the particle (N)
G_g	gas flow rate (kg/s)
G_p	powder particle flow rate (kg/s)
G_{pmax}	maximum possible powder particle flow rate through a nozzle (kg/s)
G_{prpm}	powder particle flow rate at a particular motor RPM (kg/s)
H	convective heat transfer coefficient ($\text{W/m}^2\text{K}$)
H_c	width of the band sprayed in one pass (m)
K	carrier gas pressure loss coefficient
L	particle penetration depth (m)
M	Mach number
M_e	nozzle exit Mach number
N_h	number of heating elements
N_u	Nusselt number
P	pressure (Pa)

P_a	ambient pressure (Pa)
P_e	nozzle exit pressure (Pa)
P_g	gas pressure (Pa)
P_h	necessary power of the heater (W)
P_{he}	power released in heating elements (W)
P_m	efficiency in terms of mass
P_o	stagnation pressure (Pa)
P_s	shock pressure (Pa)
P_{shock}	pressure behind the shock waves (Pa)
P^*	nozzle throat gas pressure (Pa)
Pr	Prandtl number
R	gas constant (J/mol·K)
Re	Reynolds number
Re_h	Reynolds number of the gas flow inside a heating element
R_h	ohmic resistance of a heating element (Ω)
T	temperature (K)
T_{ex}	gas temperature at the exit of a heating element (K)
T_h	heating temperature in a heating element (K)
T_{in}	gas temperature at the inlet of a heating element (K)
T_p	particle temperature (K)
T_m	particle melting point (K)
T_g	gas temperature (K)
T^*	nozzle throat gas temperature (K)
T_e	nozzle exit particle temperature (K)
T_o	stagnation temperature (K)
V	volume (m^3)
V_h	operating heater voltage (V)
V^*	nozzle throat gas volume (m^3)
Y	yield stress (Pa)
a_p	average particle acceleration (m/s^2)
c	speed of sound in materials (m/s)
c_p	particle heat capacity (J/kg·K)

c_g	gas heat capacity (J/kg·K)
d	diameter (m)
d_h	inner diameter of a heating element (m)
d_p	powder particle diameter (m)
$\left(\frac{dp}{dz}\right)_o$	interstitial pressure gradient at the discharge orifice (Pa/m)
$\frac{dv_p}{dt}$	particle acceleration (m/s ²)
g	gravitational force (N)
k	gas conductivity (W/m·K)
k_s	coefficient relating the shock wave velocity to material velocities
m	mass (kg)
m_p	average powder particle mass (kg)
m_t	mass of the powder particles discharged in a given time (kg)
r_p	powder particle radius (m)
t	time (s)
t_c	contact time (s)
v	velocity (m/s)
v_{crit}	critical impact velocity (m/s)
$v_{erosion}$	erosion velocity (m/s)
v_g	gas velocity (m/s)
v_{impact}	particle impact velocity (m/s)
v_p	particle velocity (m/s)
v_{pn}	normal component of particle velocity (m/s)
v_{pt}	tangential component of particle velocity (m/s)
v_w	velocity of motion of the coated surface with respect to the nozzle exit (m/s)
v^*	nozzle throat gas velocity (m/s)
x	distance (m)
z/d	nozzle exit-to-substrate spacing
σ_μ	particle UTS (Pa)
σ	shear stress (Pa)
ϵ	strain

•	
ε	strain rate
ρ	density (kg/m ³)
ρ_b	density of the flowing material (kg/m ³)
ρ_c	coating density (kg/m ³)
ρ_o	stagnation gas density (kg/m ³)
ρ_g	gas density (kg/m ³)
ρ_p	particle material density (kg/m ³)
ρ^*	nozzle throat gas density (kg/m ³)
θ	spray angle (°)
μ	viscosity (Pa·s)
γ	specific heat ratio (C_p/C_v)
δ	thickness (m)
δ_{c1}	thickness of the coating sprayed in one pass (m)

Subscripts

c	coating
e	nozzle exit
g	gas
h	heater
o	stagnation
p	particle

Superscripts

*	nozzle throat
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ABBREVIATIONS

AS - Arc spray

ASFR - Average solids flow rate

B - Barrel

BD - Barrel and diverging

BHN - Brinell hardness number

BMDB - Barrel multistage divergent + barrel

BOQ - Bill of quantities

BSE - Backscattered electron

CAD - Computer aided design

CB - Converging and barrel

CBA - Cost Benefit Analysis

CD - Converging and diverging

CDB - Converging and diverging + barrel

CGDM - Cold gas dynamic manufacturing

CGDS - Cold gas dynamic spraying

CNC - Computer numerical control

CS - Cold spray

DACS - Data acquisition and control system

DE - Deposition efficiency

DS - Detonation spray

ECGDS - Electrostatic force assisted cold gas dynamic spray

EDS - Energy dispersive spectrometry

FESEM - Field emission scanning electron microscope

FS - Flame spray

HPCGDS - High pressure cold gas dynamic spraying

HRTEM - High resolution transmission electron microscope

HV - Hardness value

HVOF - High velocity oxy-fuel

KE - Kinetic energy

LCS - Laser assisted cold spray

LPCGDS - Low pressure cold gas dynamic spraying

MSDS - Material safety data sheets

OM - Optical microscope

PGDS - Pulsed gas dynamic spraying

PLC - Programmable logic controller

PS - Plasma spray

RPM - Revolutions per minute

R&D - Research and development

SEM - Scanning electron microscope

TS - Thermal spray

UVA - Use Value Analysis

VDI - Verein Deutscher Ingenieure

WS - Window of sprayability

XRD - X-ray diffraction

1 INTRODUCTION

This chapter briefly introduces the research presented in this dissertation, its motivation, objectives and delimitation of scope. The specific themes to be investigated, the source of data and research methodologies are also defined. Furthermore, the contributions of the research are described. The chapter ends with an outline of the dissertation structure.

1.1 Research Motivation

The Cold Gas Dynamic Spray (CGDS) process is being increasingly relied upon by a variety of industries for the application of protective layers to surfaces to provide corrosion and wear resistance over and above providing thermal and electrical insulation. The process yields high purity metal alloy coatings with potentially superior characteristics, exhibiting higher hardness values compared with typical cold-worked and annealed materials (Karthikeyan, 2007).

Since the process involves temperatures that are below melting points of both the coating material and the surface being coated, the applied coating retains original properties of the coating material. This is a desirable attribute in the aerospace industry for the erosion protection of aerospace equipment. Nonetheless, the technology is not anywhere being practiced in Africa because of lack of knowledge and resources. The South African Department of Trade and Industry (DTI) through the National Aerospace Center of Excellence (NACoE) is taking the lead in such an initiative, trying to establish the technology in the South African aerospace industry and as a result promote its competitiveness to meet current and future market requirements.

Of the two CGDS processes, low pressure CGDS (LPCGDS) and high pressure CGDS (HPCGDS), the LPCGDS system is cheaper to operate, has a greater portability and is more flexible in automation than a HPCGDS system. Additionally, a LPCGDS system is more compatible with a number of system modifications. For instance, it can be used together with laser heating of the substrate. In this case, a gas heater is removed,

consequently increasing the system's portability and reducing operating costs. As such, this research seeks to explore the different or alternative components that could be used in the LPCGDS system, their advantages and disadvantages over each other. In order to have an efficient spray process, these system components will be designed quite well in order for them to operate at their maximum effective capacities.

1.2 Aim and Rationale of the Research

This dissertation proposes and develops the conceptual design of a LPCGDS system in order to come up with a low cost but efficient spray system. The aims of the dissertation are to:

- Develop requirements for the overall LPCGDS system and its individual components or sub-systems.
- Develop the spray system components variants that will include off-the-shelf, customised and innovative solutions for competitive technical and economic advantages.
- Select and evaluate the generated components variants and come up with an optimal overall cold spray system.

1.3 Delimitation of Scope

Considering the above aims, it is important to indicate that this research dissertation will have its own limitations. Consequently, it will not focus on the;

- Detailed design of a LPCGDS system nozzle, powder feeder and gas heater.
- Analysis of the gas-particle mixture flow inside and outside the nozzle.
- Deposition efficiency and adiabatic shear instability based mechanism for particles/substrate bonding in the LPCGDS process.
- Effect of the standoff distance, spray angle and shock wave formation on deposition efficiency.
- Characterisation of the LPCGDS resultant coatings.

1.4 Specific Themes to be Investigated

Based on the relevant literature, the first problem to be investigated will focus on:

- a) Defining the functional requirements/specifications to be embodied in the LPCGDS system and determining the system constraints and acceptance criteria.

The purpose of this investigation will be to establish the LPCGDS system functional characteristics, desired outputs/expectations of the system, performance and measurement criteria for all inputs and outputs, and boundaries of the process. This will lead to:

- b) Identifying an essential configuration of the LPCGDS system, establishment of the system structure/sub-systems and, finding suitable technical and economic solutions to fulfil the sub-systems:

This phase is meant to generate sub-system variants that fulfil the sub-functions for the LPCGDS system. This is followed by:

- c) Selecting suitable sub-system variants and firming them up into principle solution variants, evaluating these firmed alternatives and then establishing the final configuration for the conceptual design of a LPCGDS system.

The outcome of this stage is the establishment of the most economical and technical system to use in the LPCGDS applications.

1.5 Source of Data and Methodologies

The investigative procedures to be adopted will basically be guided by the stages highlighted in 1.4 above. The first step will be to:

- a) Gather information from research publications, manufactures and end users regarding the current CGDS systems.

This stage determines the specifications of LPCGDS systems, the systems inputs and outputs, measures of success for the systems outputs and boundaries of the process. During this stage, the specification/requirements list that will be used to eliminate sub-system variants that do not meet the system specifications is drawn up and elaborated. This phase leads to:

- b) Generation of respective sub-system variants through the use of similar designs, past experience, journals, reference models and brainstorming.

The purpose of this stage is to develop alternative sub-system or component designs for the LPCGDS system that meets performance specification objectives. During this stage an evaluation matrix which ensures that all requirements are accounted for is established for sub-system variants evaluation. After this stage follows the:

- c) Selection and evaluation of the developed sub-system variants through the use of a number of techniques such as: Use-Value Analysis (UVA), Cost-Benefit Analysis (CBA), the Guideline VDI 2225 (Pahl et al., 1996), decision/evaluation matrix, engineering analysis and benchmarking with competitive products.

An optimal cold spray system that meets the specifications of the LPCGDS system is established during this phase.

1.6 Contributions

The research presented in this dissertation contributes to the state of knowledge in the coating and surface restoration technology. It addresses key issues in the field of cold gas spraying such as; the advantages of CGDS over thermal spray (TS) processes, the effects of powder particles and propellant gas characteristics on the coating quality, effectiveness of different system components (gas heaters, powder feeders and supersonic nozzles), and system conditions that must be met to obtain superior quality coatings. Also, it describes the additional equipment that make up the complete cold spray process and, the different techniques used to assess quality of coatings obtained after spraying.

Moreover, the research provides an insight into the stages involved during conceptual design of products and as such, from a design perspective, it represents an alternative to conceptual design execution to designers. Use of screening matrixes, engineering analysis, Guideline VDI 2225 and the decision/evaluation matrixes within the requirements of the cold spray system set-up to select and evaluate feasible system component's variants is demonstrated. By and large, the conceptual design approach advocated in this research make certain that the utility of the designer's expertise and creativity is never compromised.

1.7 Outline of the Dissertation

The research dissertation is structured as follows; Chapter 1 introduces the research presented in this dissertation, Chapter 2 reviews the background literature relating to this study, Chapter 3 reviews the theory of the technique employed in carrying out the conceptual design of the LPCGDS system, Chapter 4 describes the generation of sub-system's variants for the LPCGDS system, their analysis and evaluation in order to establish the best possible overall spray system set-up, and Chapter 5 presents the achievements of the research, its limitations and recommendations for further study.

1.8 Conclusion

This chapter presented the motivation, aims and limitations of the dissertation. Also, it details what specific themes are to be investigated, how the research is going to be conducted and what its contributions are. The next chapter will give an overview of the CGDS technology literature related to this research. It further looks into how the LPCGDS system components and process parameters affect the overall performance of the system.

2 LITERATURE REVIEW

2.1 Introduction

The CGDS technology literature relevant to the research presented in this dissertation is reviewed in this chapter. A brief overview is given of the cold spray gas-flow model that uses isentropic relationships and linear nozzle geometry to show the relation between the particle velocity in the nozzle and the process parameters (such as particle diameter and density; gas pressure, temperature and density; and nozzle length). Moreover, the chapter involves analysing the LPCGDS system components (gas supply, gas heater, powder particle feeder and supersonic nozzle) and process parameters. It establishes how the system components, gas and particle properties affect the quality of coatings obtained from the spray system.

Lastly, a description of the auxiliary equipment that completes the system set-up is given. This consist of the spraying chamber where the actual spraying takes place, a gas and particle recovery system for recovering un-deposited particles, the data acquisition and control system (DACS) for controlling the spray process and, coating quality measurement equipment for assessing quality of the obtained coatings.

2.2 Background of the Cold Gas Dynamic Spray Technology

Performance of equipment, their reliability and life expectancy considerably depend on the development and application of various protective coatings (to their surfaces) that provide a unique combination of properties that cannot be achieved with traditional structural materials. One of the promising methods of protection against wear in modern engineering is CGDS and this research introduces the CGDS technology as an enabling process to meet the stringent requirements and improve the competitiveness and life of these machinery and mechanisms.

CGDS technology, often referred to as simply cold spray (CS) is a process of applying coatings by exposing a metallic or dielectric substrate to a high velocity (300- 1200 m/s) jet of small (1-50 μm) particles accelerated by a supersonic jet of compressed gas. This process is based on the selection of the combination of particle temperature, velocity and size that allows spraying at the lowest temperature possible (Papyrin et al. 2007). To obtain good quality coatings, these spray parameters should be selected carefully and then optimised.

The technology was initially developed in the mid-1980s at the Institute for Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences (ITAM of RAS) in Novosibirsk by Dr. Anatolii Papyrin and his colleagues. The Russian scientists successfully deposited a wide range of pure metals, metallic alloys, polymers, and composites onto a variety of substrate materials. In addition, they demonstrated that very high coating deposition rates of the order of 5 m^2/min are attainable using the CGDS process (Grujicic et al., 2003).

Consequently, CGDS facilitates the development of a new generation of highly resistant materials and surface treatments being utilised in corrosive environments, the aerospace industry and bio-implants. An example in this respect is titanium (Ti) and its alloys employed in the aerospace industry to coat or fabricate the aerospace engine components with fatigue and wear-resistant coatings to prevent erosion due to wear, corrosion, oxidation and extreme temperatures. Also, as CGDS is a 100% solid-state process with the crystalline structure of the powders completely retained in the coatings (see Appendix B1), the deposition in air of Ti coatings without significant oxidation and particle phase transformations represent an important technical achievement (Lima et al., 2002).

2.2.1 Other spray processes

CGDS will compete with traditional thermal spray (TS) processes such as high velocity oxy-fuel (HVOF) spray, plasma spray (PS), arc spray (AS), detonation spray (DS), flame spray (FS), 3D welding, wire cladding and laser sintering to apply protective coatings to parts and to repair worn-out parts. Figure 2.1 shows that gas temperatures in the CGDS process are the lowest of the spray coating processes and the particle velocities are some of

the highest. The major difference that separates CGDS from the conventional TS coating processes is that in TS processes, the coating material is heated to temperatures high enough to induce melting and consequently, the high heat input to the part being coated or repaired can be detrimental if the material of the part degrades. This problem is avoided in CGDS (Grujicic et al., 2003) given that the process is carried out at temperatures well below the melting points of both the coating and substrate materials with particles depositing in the solid state due to plastic deformation (Papyrin A.N., 2006).

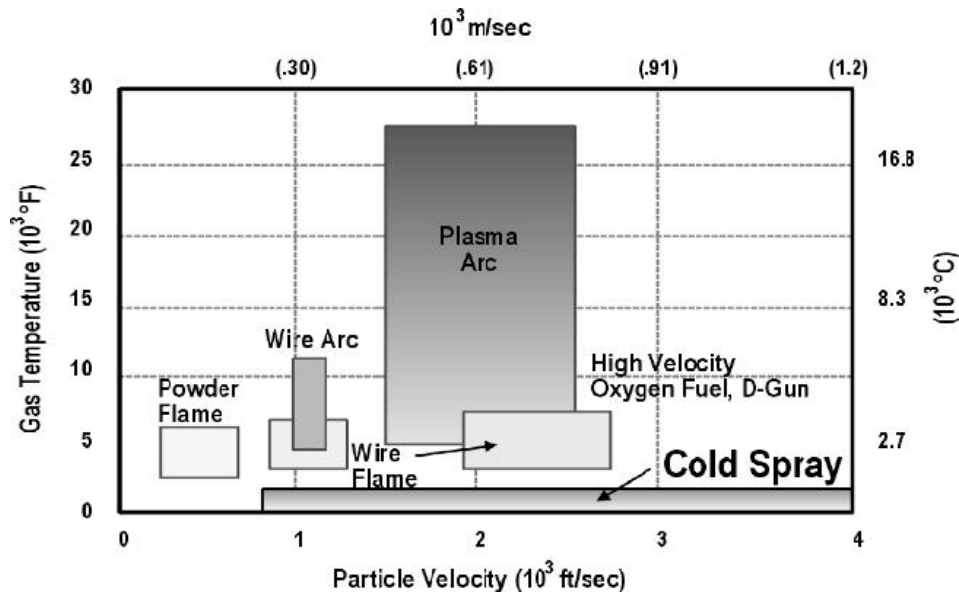
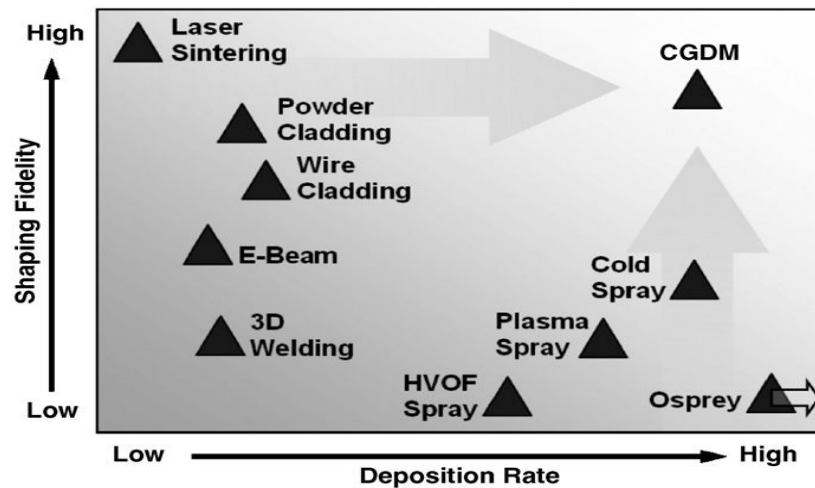


Figure 2.1: Temperature versus velocity regimes for TS processes compared to CGDS (Papyrin A.N., 2006)

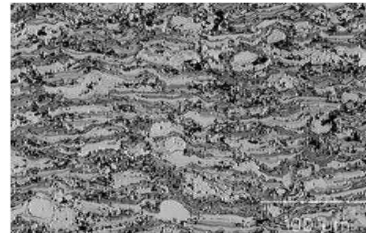
As illustrated in Figure 2.2(a), CGDS has got a high particle deposition rate coupled with a fairly good product shaping fidelity or conformity compared to its thermally based counterparts. It is the process ability to rapidly develop thick coatings and complex freestanding shapes that distinguish it from these TS techniques. As a result of combining the additive properties of CGDS with the subtractive properties of high-speed machining, a cold gas dynamic manufacturing (CGDM) process is utilised to rapidly manufacture efficient engineering components (Pattison et al., 2007). Additionally, Figure 2.2(b) shows that a cold sprayed Cu coating has a superior density and less oxide content (0.3 wt %) than a plasma sprayed coating (1.7 wt %), Figure 2.2(c) (Papyrin, 2006; Smith, 1999).



(a)



(b)



(c)

Figure 2.2: Comparison of CGDS with TS processes (a) deposition rate vs. shaping fidelity (Pattison et al., 2007b); (b) cold sprayed and (c) air plasma sprayed Cu coatings (Papyrin, 2006; Smith, 1999)

This non-thermal approach will allow a broader range of industrial alloys to be deposited more quickly, more accurately and with greater material integrity. As the CGDS process does not involve use of a high temperature heat source but rather the kinetic energy (KE) of particles to obtain bonding through plastic deformation upon impact with the substrate, it offers a number of advantages over the TS material deposition technologies that all suffer the detrimental effects of high temperature processing. Among these advantages, the most important are (Karthikeyan et al., 2004, Maev et al., 2008):

- Thermally and oxygen sensitive depositing materials (e.g. Cu and Ti) can be cold sprayed without significant material degradation.

- Segregations of the alloying elements during solidification do not occur during cold spraying. Consequently, attractive properties such as less porous and dense coatings are obtained.
- The amount of heat delivered to the coated part is relatively small so that microstructural, mechanical and chemical changes in the substrate material properties are minimal.
- Nanophase, intermetallic and amorphous materials which are not amenable to conventional TS processes due to their major degradation can be cold sprayed.
- Cold spray as a fabrication process develops industrial prototypes and advance new designs quickly and comparatively inexpensive compared to the usual prototyping processes.
- A CGDS coating include compressive rather than tensile stresses, with a wrought-like microstructure and a near theoretical density.
- CGDS joins chemically dissimilar materials with bonds that gradually transition from one material composition to another. Therefore, it offers a low-temperature alternative to welding.
- CGDS offers an increased operational safety due to the absence of high temperature jets and radiation, low noise level (70-80 dB), and the simplicity of technical implementation and operation.
- CGDS offers exciting new possibilities for cost-effective and environmentally friendly alternatives to technologies such as electroplating, soldering and painting.

2.2.2 Use of the CGDS technology

The CGDS technology is used to produce freeforms, protective coatings and performance enhancing layers. Typical protective coatings include copper-chrome layers for oxidation protection of structures, corrosion resistant aluminum coatings for oil industries and MCrAlY coatings for high temperature protection coats for thermal barriers. Figure 2.3(a) shows some components with protective coatings that were applied by the CGDS process (Karthikeyan et al., 2004).

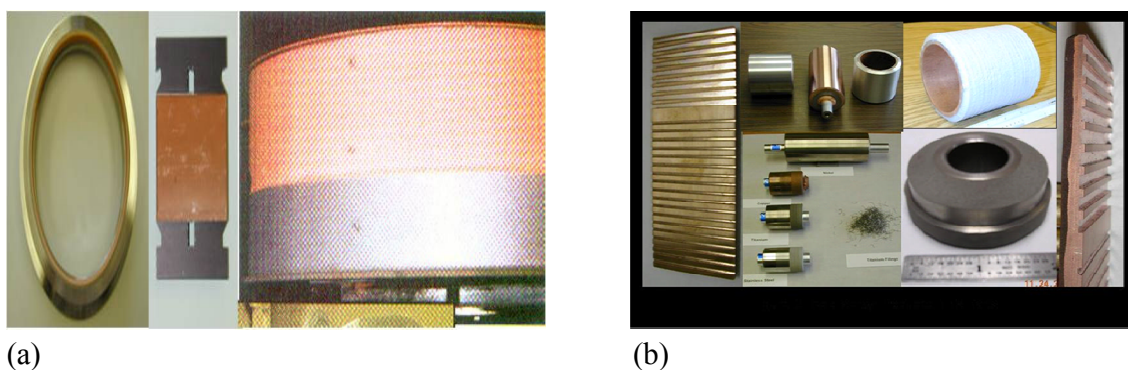


Figure 2.3: Typical cold spray produced (a) coatings and; (b) bulk forms (Karthikeyan et al., 2004)

Large size and shapes can be spray fabricated and geometrical features easily incorporated during spray preparation and later on machine finished. Figure 2.3(b) shows some bulk forms (rollers, sleeves and heat sinks) produced by CGDS. Such bulk forms are produced by spraying the material over an expendable mandrel, machining the ultrathick coating to required dimensions and then removing the mandrel by mechanical and/or chemical methods. Since the CGDS gun is frequently handled by a robot, CAD files can be used to control the spray pattern to produce near net shapes (NNS). Moreover, by controlling the feedstock composition, one can vary the deposit microstructure and composition to produce functionally gradient materials (FGM) and other special structures (Karthikeyan et al., 2004).

CGDS is able to generate a wide range of deposition layer thickness ranging from tens of microns up to a centimeter. In this regard, this process extends beyond the concept of coating a substrate, providing a means for developing 3-dimensional structures (McCune et al., 2000). Figure 2.4 demonstrates how CGDS is used as a surface repair and fabrication technique in the mold repair industry. A portion of the Al mold surface was damaged in operation and then a pure Al coating deposited on top of the damaged mold using a CGDS system. The sprayed mold is machined by a computer numerical control (CNC) milling machine using original tool paths of the mold and the original feature of the mold recovered (Lee et al., 2007).

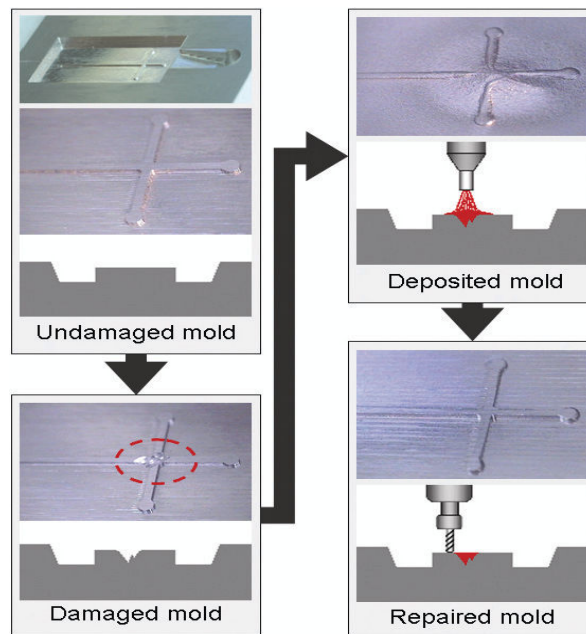


Figure 2.4: Mold repair (Lee et al., 2007)

Spot application of material by CGDS is also used to balance rotating parts such as shafts, wheels and rotors. The coating can match the substrate such as Al on an Al drive shaft or it could be a different material selected for its density or colour. Lastly, the intimate bond between the substrate and coating ensures maximum heat transfer and as a result, it is possible to spray Cu heat sinks directly on stainless steel or ceramics to improve their conductivity (see Appendix B2).

2.2.3 Coating quality

CGDS produces pure, dense and well bonded coatings of many metals (Al, Cu, Ni, Ti and Zn), alloys (SS, Inconels, Hastalloys, MCrAlYs) and composites (metal-metal like Cu-W, metal-carbides like Al-SiC, metal-oxides like Al- Alumina) (Karthikeyan et al., 2004). Microstructures of the spray coatings basically depend on operating conditions of the system and to obtain good quality coatings, the system and spray parameters should be chosen carefully.

Figures 2.5 give the polished cross-section microstructures of Al and Ni cold sprayed coatings and as shown, near theoretical densities are obtained in the as sprayed conditions. The Ni coating, Figure 2.5(a) obtained on spraying an Al substrate with Ni powder particles

has nearly the same density as an original Ni substrate, Figure 2.5(b). Further, the porosity of the coatings as measured by an image analyser is less than 3% which is an acceptable porosity level for sprayed coatings (Lee et al., 2009).

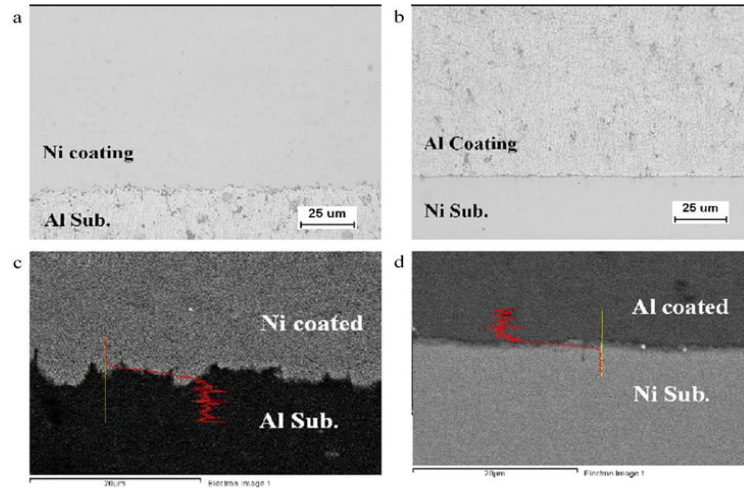
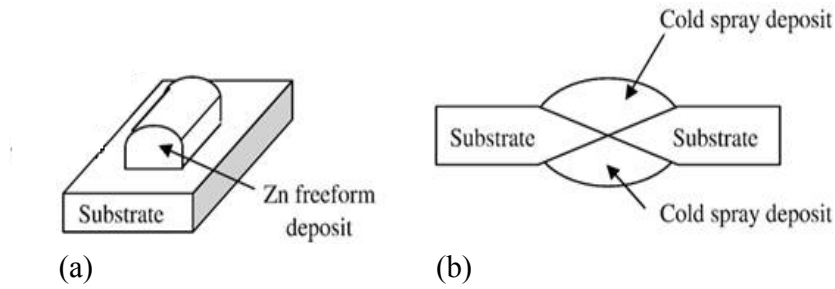


Figure 2.5: Microstructures of Al and Ni cold sprayed coatings (Lee et al., 2009)

Crack propagation in CGDS coats occurs along particle boundaries rather than through the deformed particles and, as such, mechanical properties of the coats are dictated by the mechanical interlocking strength between deposited particles (Cadney et al., 2008). Often, the dense cold sprayed coatings possess a higher hardness than the substrates hence provide sufficient protection to the substrates against wear and surface damages. Smooth hardness transition at the substrate/coating interface is observed and this increased hardness (of the depositions) is dependent on mainly two parameters; the porosity of the coating and the degree of cold work hardening experienced by the deposited particle. Higher hardness values ~ 300 GPa (for Ni) result from a higher degree of plastic deformation during deposition whereas lower hardness results if the coating is more porous (Karthikeyan, 2004).

Illustrated in Figures 2.6(a, b) is a schematic of Al substrate configurations used in both the cold spray freeform and weld geometries with Zn as the filler material (Cadney et al., 2008). Figure 2.6(c) subsequently presents the respective microhardness of the freeform and the weld deposits, with no significant difference between the measurements; the core of the weld having a microhardness of 33 ± 3.2 HV while the freeform a microhardness of 34 ± 2.5 HV. This similarity indicates that the CGDS process is reproducible for making

either welds or freeforms. Also, these cold sprayed weld and freeform hardness results are within the range of microhardness values for annealed (30 HV) and fully work hardened (35 HV) pure Zn, signifying that some work hardening occurs in CGDS (Cadney et al., 2008).



Schematic representation of the (a) freeform and (b) weld geometries (Cadney et al., 2008)

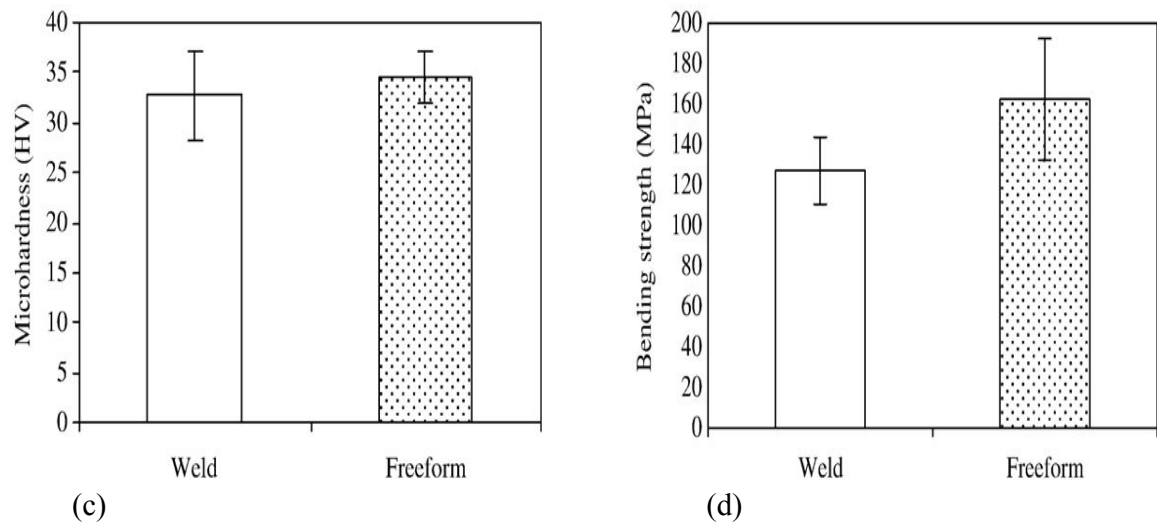


Figure 2.6: Freeform and weld mechanical properties measurements (c) microhardness and (d) bending strength (Cadney et al., 2008)

Figure 2.6(d) further presents the flexural strength properties for both configurations. The weld configuration has a bending strength of 127 ± 17 MPa while the freeform has a strength of 162 ± 30 MPa. No statistical distinctions can be made between the strength of these two configurations and their values are comparable to values for 99.95% pure Zn, soft tempered to 65% (Cadney et al., 2008) (see Appendix B3).

Due to work hardening that occurs during plastic deformation, cold sprayed coatings achieve a refined microstructure of the spray particles and can attain significantly higher hardness values than the conventional wrought materials (Champagne et al., 2007). Figure 2.7 show the hardness of cold sprayed and wrought (both annealed and fully worked) Al and Ni materials. Looking at Figure 2.7(a), cold sprayed Al has a Brinell hardness of 57 BHN whereas the annealed and fully worked Al have Brinell hardness values of 24 BHN and 43 BHN respectively. In addition, because of the strain hardening effect resulting from plastic deformation during particle impact, the microhardness of CGDS coatings is significantly higher than those of the feedstock powders. Nonetheless, adhesive strength of CGDS coatings decreases with increasing thickness of the coating. This is due to internal stresses that are induced in the coating during and after deposition (Klinkov et. al., 2005).

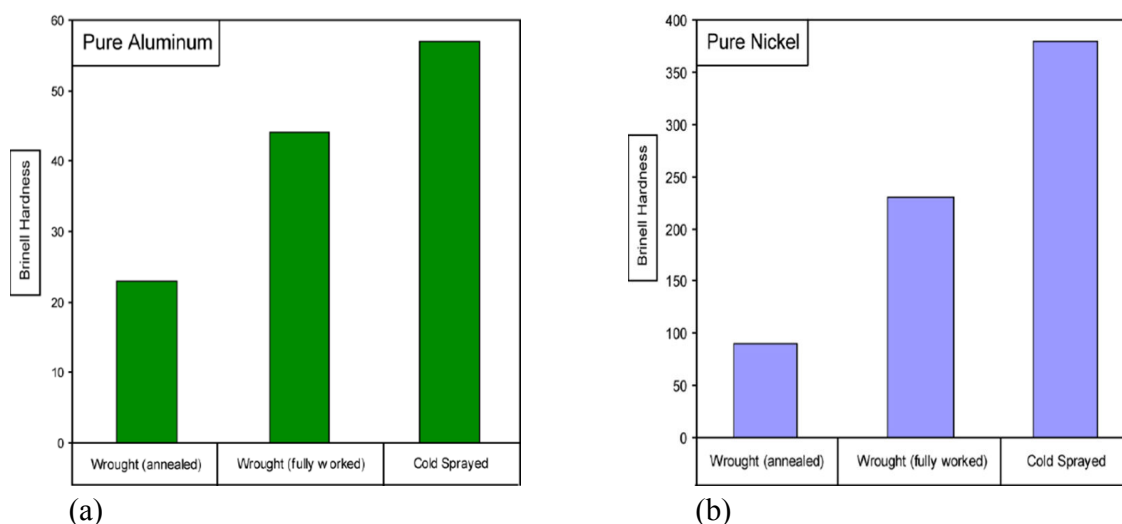


Figure 2.7: Hardness of cold sprayed against wrought materials (Champagne et al., 2007)

Table 2.1 gives data on properties of some CGDS coatings (Karthikeyan, 2004). It shows that; (1) CGDS produces coatings and freeforms with required density and strength; (2) cold sprayed coatings have near zero ductility in the as sprayed condition and post spray heat treatment is required to retrieve the ductility; (3) strength and modulus values of the sprayed coatings reach those of wrought material in some cases (such as 6061 Al alloys) (Karthikeyan, 2004).

Table 2.1: Properties of cold sprayed materials (Karthikeyan, 2004)

		Material Properties			
Material	Condition	Young's Modulus (GPa)	Yield Strength (GPa)	Ultimate Strength (GPa)	Strain (%)
Nickel	Bulk	207	59	317	0.3
	Cold sprayed	158	300	300	0.0002
	Heat treated	125	207	304	0.0956
Copper	Bulk	110	220		
	Cold sprayed	103	266		
	Heat treated	104	195		
6061 Aluminium	Bulk	65.5	83	152	18
	Cold sprayed		241	241	0
	Heat treated	51	91	157	18
Hastalloy C	Bulk	30			
	Cold sprayed	142			
	Heat treated				
CoNiCrAlY	Bulk	41			
	Cold sprayed	98			
	Heat treated				

Although heat treatment processes significantly reduce the coating hardness due to resultant stress releasing and grain coarsening (Guo et al., 2007), performance of CGDS coatings can be substantially improved by the heat treatments. Diffusion during annealing of the coatings close particle-particle interfaces which are just under compressive contact and therefore reduce the number of potential crack initiation sites (Gärtner et al., 2006b).

2.2.4 The CGDS system set-up

Since evolution of the technology in the mid-1980s, a number of CGDS systems have been developed. The systems can be either manufactured in a modular configuration so that they can be easily attached to motion control equipment to spray complex shapes or manufactured in a single cabinet to facilitate convenience of installation at different facilities to be worked on. Also, the systems can be designed in either manual or robotic configurations, and as fixed or portable systems. However, the main components of any CGDS system includes: source of a compressed gas, gas heater, powder feeder, the spray

gun assembly consisting of a pre-chamber and a supersonic nozzle, spraying chamber with a motion system, and a system for monitoring and controlling spray parameters.

To achieve the required particle-impact velocity, feedstock powder particles are injected into a supersonic gas flow that ensures proper momentum transfer to the particles. Due to their aerodynamic properties, inert gases such as helium (He) and nitrogen (N₂) or their mixture are preferred as the propellant gases, but dry air (79% N₂ - 21% O₂) can also be used as an alternative propellant. In order to compensate for the cooling associated with the rapid expansion of the working gas in the nozzle, an electric heater is used to preheat the gas to about 700 °C. Diagnostic ports to measure and control the gas temperature and pressure are incorporated in the nozzle. A powder feeder is used to feed powder particles to the nozzle and, the powders used are typically in the range of 1 to 50 µm in diameter. Conventional job handling systems such as the X-Y manipulator and a lathe are used to scan the spray beam over the substrate surface (Karthikeyan et al., 2007).

Furthermore, there are currently two commercially available variants of the CGDS system namely the low and high pressure cold gas-dynamic spray (LPCGDS & HPCGDS) systems. The two main clear cut distinctions of the LPCGDS system from the HPCGDS system are; the utilisation of low pressure gas (5-10 bars instead of 25-30 bars) and the radial injection of powder instead of axial injection (Maev et al. 2008).

Figure 2.8 shows a schematic of the LPCGDS system. The accelerating gas (usually air or N₂) is injected at low pressure (5-10 bars) and preheated within the gas heater to temperatures up to about 400 °C to optimise its aerodynamic properties. Solid powder particles are radially introduced downstream of the throat section of the supersonic nozzle, thus eliminating the need for a high pressure delivery system, which increases system portability, operational safety and significantly reduces spraying costs. Within the nozzle, static pressure is maintained below the atmospheric pressure ensuring that feedstock particles are effectively drawn in from the powder feeder by Venturi effect (Maev et al., 2008). This is achieved if the ratio of the cross-sectional area of the supersonic nozzle at the powder entry point, A^i (m²) to that of the throat, A^* satisfies Equation 2.1. Particles are then accelerated to supersonic velocities in the range of 300 to 600 m/s (Kashirin et al., 2002).

$$\frac{A^i}{A^*} \geq 1.3P_o + 0.8 \quad (2.1)$$

where;

P_o = gas pressure at the nozzle inlet (MPa)

Feedstock powder particles used in LPCGDS systems typically include ceramics. The majority of these ceramic particles do not become entrapped within the coating because they are sprayed at particle velocities well below their critical velocity. The role of the ceramics is to act as a hammer for increasing the density of the coating as well as improving the deposition efficiency (DE). Deposition efficiencies with this system typically do not exceed 50% (Kreye et al., 2006).

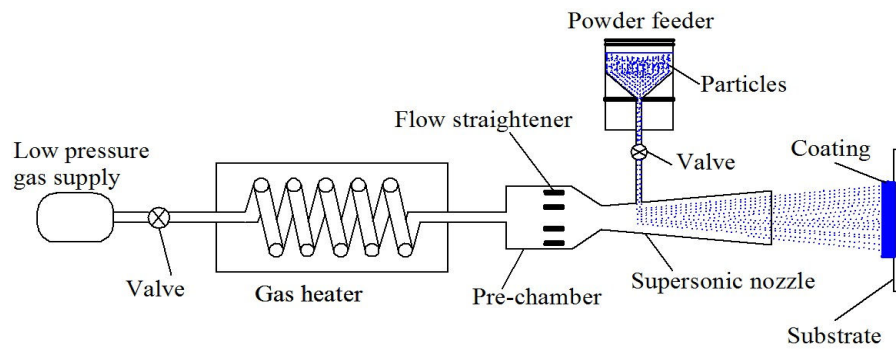


Figure 2.8: A typical LPCGDS device (Maev et al., 2008)

Since performance of a supersonic nozzle (in particular the Mach number) is determined primarily by the throat area, this construction for spray coating (as compared to HPCGDS) increases the operational stability of the system due to lack of nozzle throat wear. This is achieved as the powder does not pass through the throat and therefore does not induce wear, does not change nozzle assembly characteristics and hence does not affect the performance of the system as a whole. Wear of the nozzle walls occurs only in the supersonic portion of the nozzle and, this ensures a longer service life of the nozzle (Kashirin et al., 2002).

In HPCGDS systems (Figure 2.9), the accelerating gas (usually N_2 or He) is injected at high pressure (25-30 bars) and preheated up to 700 °C to also optimise its aerodynamic

properties. Solid powder particles are then metered into the gas flow upstream of the converging section of the nozzle at a higher pressure than the accelerating gas to prevent backflow of the carrier gas to the powder feeder. They mix with the propellant gas in the pre-chamber zone and are then axially fed into the nozzle. Within the nozzle, particles are accelerated to supersonic velocities in the range of 600 to 1200 m/s and the spray efficiency is very high, reaching up to 90% (Kreye et al., 2006).

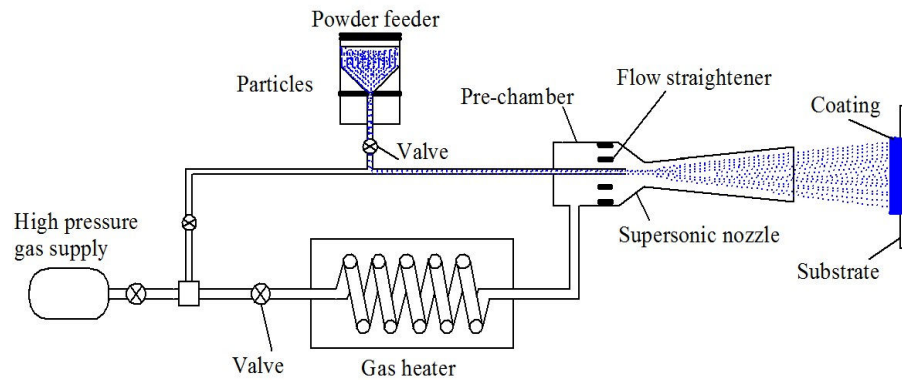


Figure 2.9: A typical HPCGDS device (Grujicic et al., 2004)

Preheating of the carrier gas to increase its temperature and resultantly increase its local sonic velocity at the nozzle throat is done to simply optimise its aerodynamic flow conditions and not increase particle temperature. The gas then converts the temperature (and pressure) into velocity as it is expanded in the nozzle. Figure 2.10 shows gas-particle conditions during nozzle traverse (Champagne et al., 2005a). Initially at the nozzle inlet (0.00 m), the gas has a higher temperature (690 °K) than the particles (300 °K) and consequently, particle temperature rises. However, as the carrier gas rapidly expands downstream in the diverging section of the nozzle (nozzle throat at 0.03 m), its temperature decreases below particle temperature, causing particle temperature to begin to decrease (Grujicic et al., 2003). Moreover, due to the fact that the contact time of spray particles with the hot gas is quite short to cause any significant heating of particles, the temperature of particles remains substantially below the initial gas preheat temperature and hence the name cold gas dynamic spray (see Appendix C).

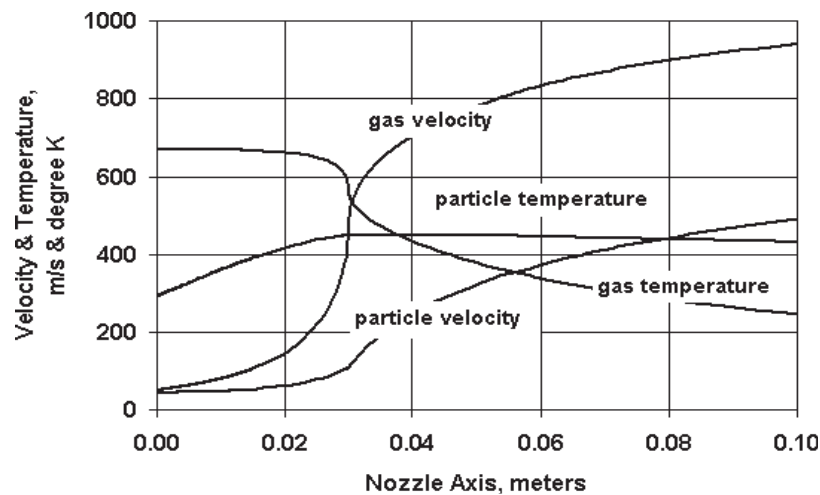


Figure 2.10: Gas-particle conditions during nozzle traverse (Champagne et al., 2005a)

2.2.5 The triple shock structure

A schematic of the supersonic impinging jet flow field is represented in Figure 2.11. On exiting the nozzle, the accelerating gas slows down as its pressure tries to adjust to the ambient pressure; and its impingement upon the substrate surface gives rise to the formation of a bow shock (stagnant) region in front of the substrate. This bow shock is formed by the rapid rate of change of momentum of the supersonic gas as it impacts the substrate generating a region of high density, high-pressure gas travelling at subsonic velocity radially outwards from the surface. The component of gas velocity normal to the substrate surface in this region is quite small relative to the nozzle-exit gas and particle velocities (Grujicic et al., 2004).

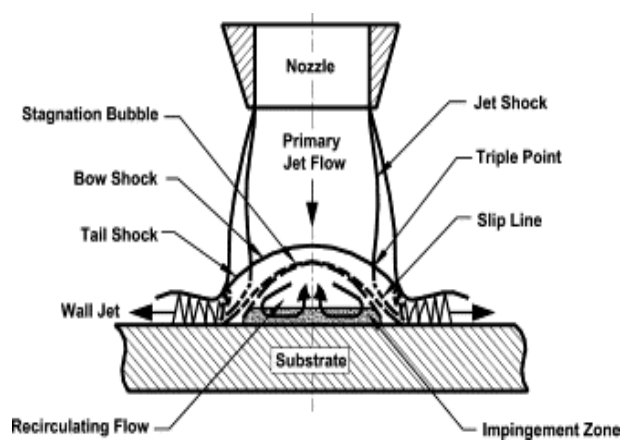


Figure 2.11: Schematic of a supersonic impinging jet flow field (Grujicic et al., 2004)

The bow shock decelerates any particles passing through it due to the opposing drag force and deflects any particles that are not impacting directly perpendicularly with the substrate (Novoselova et al., 2006). If the gas is not ideally expanded, jet shocks in the jet plume interact with the bow shock resulting in a triple-shock structure, with the third shock denoted as a tail shock. The interaction between the three shocks governs the flow field in the impingement zone (Grujicic et al., 2004).

The impinging jet flow field is divided into three main regions. The first region represents the main jet column in which the flow is primarily inviscid and contains expansion and compression shock waves for non-ideally expanding jets (see Appendix D1). The second region (impinging zone) involves the region of jet impingement onto the substrate and is characterised by large gradients which cause major changes in the local flow properties. A stagnation bubble containing re-circulating fluid with relatively low velocity is depicted within the impingement region and its presence affects pressure distribution over the substrate surface. The third region (radial wall jet) includes the area outside the impingement zone which contains the jet flow, redirected laterally outward after impingement (Grujicic et al., 2004).

Shock wave patterns formed during impact

On impact with the substrate, waves start spreading out from the point of contact into both the particle and substrate. The propagation velocity of these waves is finite; hence the zone of disturbance is limited by the envelope of these waves, which results in the formation of two shock waves, Figure 2.12.

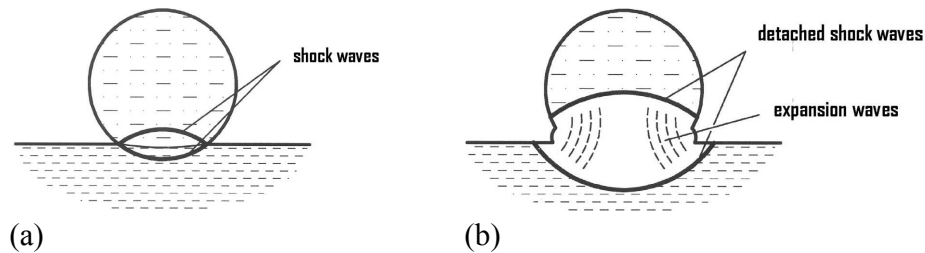


Figure 2.12: Formation of shock and expansion waves in both the particle and substrate, and inception of a jetting motion (Klinkov et al., 2005)

In the perturbed zone between the two shocks, pressures and temperatures are high, and the substrate/particle contact area increase with time. Initially, the boundary of the contact area moves outward at a velocity that is greater than the speed of the shock waves in the materials. Hence, the shock waves remain attached to the boundary or contact edge of the contact area (Figure 2.12(a)). When the velocity of the contact edge decreases below the shock velocity, then the shock waves detach from the contact edge, Figure 2.12(b). Thereafter, the perturbed zone is limited not only by shock waves but also partly by the free surface of the bodies. From the free surface, expansion waves start spreading into the perturbed zone and simultaneously, a jet of material is formed which is ejected away from the surface (Klinkov et al., 2005).

At the moment of impact, pressure behind the shock waves, P_{shock} (MPa) is given by Equation 2.2. This formula is based on a combination of an acoustic and an incompressible approach (Klinkov et al., 2005).

$$P_{shock} = \frac{1}{2} \left(\rho_p c_p v_p + k_s \frac{\rho_p v_p^2}{2} \right) \quad (2.2)$$

where;

ρ_p = density of the particle (kg/m³)

c = speed of sound in the materials (m/s)

v_p = velocity of particle on impact (m/s)

k_s = a coefficient that relates the shock wave velocity to material velocities

Particle DE is strongly dependent on stand-off distance as a result of the bow shock and the gas-particle relative velocity outside of the nozzle. Three distinct stand-off regions influence deposition performance differently: (1) the small stand-off region where the strength of the bow shock is high adversely affects deposition performance, (2) the medium stand-off region where the bow shock has disappeared and gas velocity remains above particle velocity (positive drag force), DE continues to increase; and (3) the large stand-off region where gas velocity has fallen below particle velocity (negative drag force), particles

begin to decelerate. For optimal deposition performance, the stand-off distance should be set within the medium stand-off region (Pattison et al., 2007a).

The effect of stand-off distance on a Ti coating porosity is shown in Figure 2.13(a). Porosity is 14% at 100 mm stand-off which is 4.5% more than the 9.5% porosity at 20 mm stand-off. The decrease is due to a short flight distance for particles which prevents a significant decrease in particle velocity that takes place at large stand-off. This is consistent with the notion that particle velocity is essential to achieve the required deformation necessary for minimisation of porosity in CGDS deposits. Nonetheless, the formation of 14% porosity at 100 mm stand-off show that CGDS can be utilised to fabricate porous structures. This is exploited for applications that require porous materials such as bio-materials and catalysts (Zahiri et al., 2009).

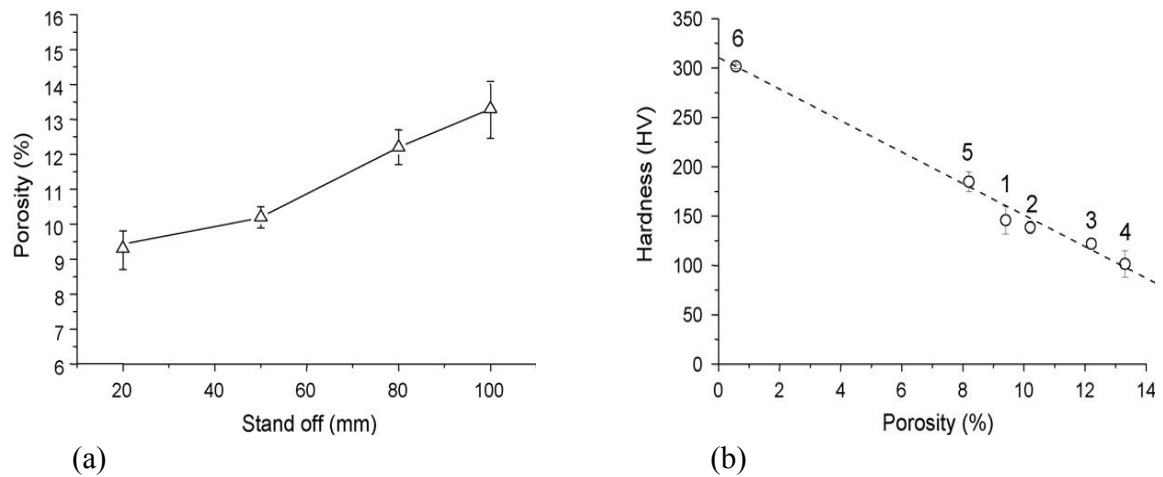


Figure 2.13: Volume fraction of a Ti coating porosity as a function of (a) stand-off distance and (b) hardness (Zahiri et al., 2009)

Coating microhardness is controlled by both the strain-hardening effect of the deposited particles and the shot-peening effect of the rebounded particles, which are in-turn negatively affected by an increase of the stand-off distance. Figure 2.13(b) illustrates hardness values of the cold sprayed Ti coating as a function of porosity and shows that a decrease in coating porosity leads to an increase in hardness of the deposit; for instance, a 13.5% decrease in volume fraction of porosity from 14 to 0.5% leads to an increase in hardness from 100 to 300 HV (Zahiri et al., 2009) (see Appendix D2 & D3).

Moreover, with a decrease of the stand-off distance the coating thickness increases. However, at a very short stand-off distance, the substrate surface or previously deposited coating is exposed to a relatively high gas temperature, thus increasing coating oxide contamination chances. Therefore, in a CGDS process, the selection of stand-off distance should compromise between high DE and low oxidation of coating for temperature susceptible materials (Li W.-Y. et al., 2008).

2.2.6 The bonding process

Particle deposition takes place in two stages; firstly deposition on the bare substrate and then deposition of new particles over previously deposited particles. Both processes are strongly dependent on particle velocity and, substrate and particle material properties. When the particle-laden gas jet impinges on a substrate, depending on particle velocity (v_p) three different phenomena occur. When v_p is low, the particles bounce or reflect off the surface. When v_p reaches moderate values, substrate erosion similar to grit blasting takes place. When v_p exceeds the v_{crit} required to achieve deposition, particles plastically deform and penetrate the substrate and one another forming a dense adherent coating (Karthikeyan et al. 2007) (see Appendix E1).

Additionally, impact conditions do not immediately cause deposition of particles to occur. Deposition is only observed after the surface has been exposed to particle impacts for a certain incubation time and becomes activated. This incubation time is a function of the impact velocity, decreasing with an increase in both the impact velocity and rate of particle flux in the gas flow. However, sufficiently fast particles become attached to non-activated surfaces (Klinkov et. al., 2005).

Mechanical bonding in CGDS is explained in Figure 2.14 (Balani et al., 2005a). On impact with the substrate under high local pressure, Figure 2.14(a) the solid particles undergo plastic deformation resulting from the conversion of the particle's KE into heat and strain energy. This deformation process result in the breaking-up of thin (oxide) surface films on the particles and the substrate (Ajdelsztajn et al., 2006), exposing their clean surfaces. Interfacial jets are formed during the impact (see Appendix E2, Figure 2.12) and they drive the ruptured oxides to the edges of the splat and eject them from the bonding spot.

The intensive deformation of particles and the substrate result in increased strain and temperature at the localised contact areas. This temperature increase is caused by adiabatic shear instabilities or jet/plastic flow during deposition (Figure 2.14(b)) and leads to thermal softening of the sprayed materials. The materials lose their shear strength and their resistance to shear flow is generally low, undergoing excessive deformation for any amount of imposed shear stress (Assadi et al., 2003). Interfacial instabilities (see Appendix E3) then form along the substrate/particle interface leading to the formation of interfacial rollups and vortices (Figure 2.14(c)). These rollups and vortices are responsible for the mechanical adhesive interlocking between the clean substrate and particles at the substrate/particle interface (Ajdelstajn et al., 2006).

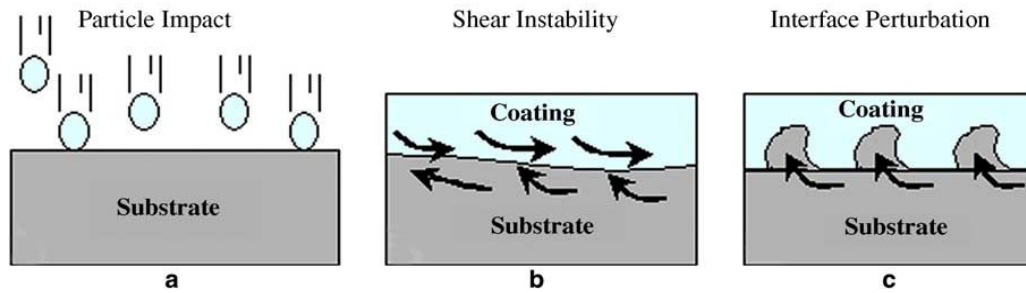


Figure 2.14: Schematic of the particle/substrate interface bonding; (a) particles impacting onto substrate, (b) differential flow velocities along interface, (c) generation of interface rollups and vortices (Balani et al., 2005a)

After a substrate/particle interface coating has formed, a localised deformation process then occurs between the impacting and already deposited particles. The localised adiabatic shear instability created at the particles boundaries promotes an intimate conformal contact (metallic bonding) between the adjacent clean particle surfaces and permits layers of deposited material to be built up rapidly (Ajdelstajn et al., 2006).

Due to very short particle/substrate and particle/particle contact times ($\sim 10^{-8}$ s), heat conduction and atomic diffusion is not considered to play a role in CGDS bonding. In TS processes where atomic diffusion is responsible for bonding, the thermal diffusion distance is given by $\sqrt{D_{th} t_c}$ (where D_{th} is the thermal diffusivity and t_c is the contact time). For the

typical CGDS values of $D_{th} = 10^{-6} \text{ m}^2/\text{s}$ and $t_c = 10^{-8} \text{ s}$, $\sqrt{D_{th} t_c}$ takes on a value of about $1.7 \times 10^{-6} \text{ m}$. This distance is only a fraction of the inter-atomic distance obtained in CGDS, hence, atomic diffusion is excluded as a bonding mechanism under CGDS deposition conditions (Grujicic et al., 2004), validating that the CGDS process is adiabatic (heat transfer is not considered).

The theory that CGDS bonding is by plastic deformation is supported by a number of experimental findings such as: (a) a wide range of ductile (metallic and polymeric) materials can be successfully cold sprayed while non-ductile materials such as ceramics can be deposited only if they are co-cold sprayed with a ductile (matrix) material; (b) the mean deposition particle velocity should exceed a certain minimum (material dependent) critical velocity to achieve deposition which suggests that sufficient KE must be available to plastically deform the solid material and disrupt the surface (oxide) films; and (c) the particle KE at impact is significantly lower than the energy required to melt the particle suggesting that the deposition mechanism is entirely a solid-state process (Grujicic et al., 2004).

Figure 2.15(a, b) shows images of a cold sprayed Al coating. The lack of defects and porosity (hence a good coating quality) at the particle/particle and particle/substrate interfaces suggests an adequate KE during deposition to break off the surface (oxide) films and generate intimate bonding at the interfaces. Further, Figure 2.15(c) shows evidence of overall plastic deformation (deformed grain inside the particles) and intense shear localisation at particle/particle boundaries in the coating indicated by arrows.

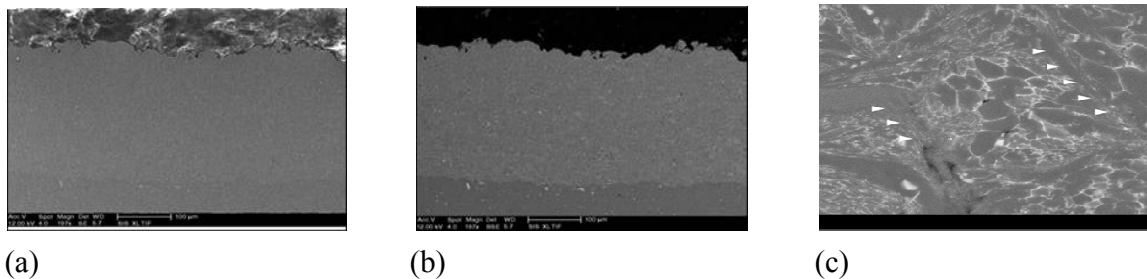


Figure 2.15: Cold-sprayed Al coating: (a) secondary electron image, (b) backscattered electron image, and (c) shear instabilities at the particle/particle boundaries and heavily deformed microstructures in the interior of the particles (Ajdelsztajn et al., 2006)

A heavy deformation of the particles is evident since they don't retain their original shapes but are rather flattened, mainly parallel to the substrate. This highly deformed microstructure in the coatings confirms that plastic deformation and interlocking of splats (each particle conformably shaping to the previous layer) is the mechanism responsible for bonding in CGDS (Ajdelstajn et al., 2006).

The nature and extent of particle deformation on impact depend on the damage number (a dimensionless group), $D_c = \frac{\rho v_{crit}^2}{Y}$ where ρ is the density of the particle material, Y is its yield stress and v_{crit} is the critical impact velocity. This value represents the ratio between inertial and strength-related forces at the critical velocity. The higher the value, the greater the extent of plastic deformation required to achieve bonding (Xu et al., 2006). Insufficient deformation result in increased porosity which then result in the deterioration of mechanical properties for the deposited material (Figure 2.13 (b)) (Zahiri et al, 2009).

2.3 The Gas-Particle Two Phase Flow

Two processes occur when the gas-particle mixture flows through the supersonic nozzle. There is conversion of the propellant gas thermal energy into KE and, transfer of momentum and heat from the gas to the particles. An analysis of the interaction between the carrier gas and spray particles under the approximation of a dilute two-phase flow is made in reference to a typical geometry of the CGDS converging-diverging (CD) nozzle (Figure 2.16) and involves a number of assumptions and simplifications such as (Grujicic et al., 2004, Maev et al., 2008);

- The gas obeys the perfect gas law, $PV = mRT$.
- There is no friction impeding the gas flow.
- The gas flow is adiabatic, i.e. no heat loss occurs to the surroundings.
- Steady-state conditions exist (C_p and C_v are assumed to be constant).
- Expansion of the gas occurs in a uniform manner without shock or discontinuities.

- Flow through the nozzle is one-dimensional; hence the flow velocity, pressure and density are uniform across any cross section normal to the nozzle axis.
- Particles do not influence gas conditions.

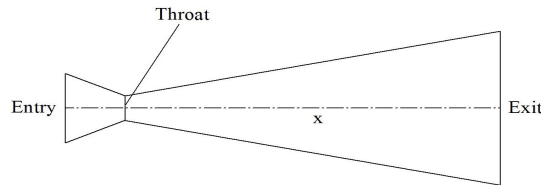


Figure 2.16: A CD nozzle geometry (Grujicic et al., 2004)

2.3.1 Isentropic gas flow

Gas flow through a CD (de Laval) nozzle is isentropic and the propellant gas characteristics rely on the gas properties. Figure 2.17 shows gas velocity (v_g) along the nozzle length and as indicated, the speed of the flow is subsonic ($M < 1$) before the nozzle throat and increases in this converging section as it narrows towards the throat because the mass flow rate is constant (Jodoin et al., 2006).

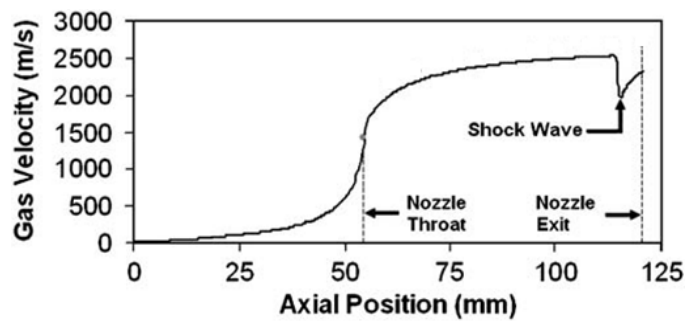


Figure 2.17: Gas velocity along the de Laval nozzle length (Jodoin et al., 2006)

At the nozzle throat where the cross sectional area is a minimum, v_g locally becomes sonic ($M=1$). In this condition the nozzle is said to be choked and the ratio of exit pressure (P_e) to inlet pressure (P_o) satisfies Equation 2.3 (Champagne et al., 2005a; Khazaei et al., 2008). As nozzle cross sectional area increases in the diverging section, the gas expands and its flow increases to supersonic velocities ($M > 1$). CD nozzles thus accelerate fluids that have choked at the throat to supersonic speeds in the divergent section. Oscillations of v_g near

the nozzle exit indicate that some shock waves are generated in the flow towards exiting the nozzle.

$$\frac{P_e}{P_o} \leq \left[1 - \frac{\{(\gamma-1)/2\}}{1 + \{(\gamma-1)/2\}} \right]^{\gamma/(\gamma-1)} \quad (2.3)$$

where γ = ratio of the gas constant-pressure and constant-volume specific heats (C_p/C_v)

The carrier gas flow originates from a large chamber where its velocity is 0. Before nozzle entry, its temperature (total gas temperature) is T_o (K) and pressure (stagnation pressure) is P_o (MPa). Both T_o and the mass flow rate of the gas, G_g (kg/s) are user controlled. Using basic dynamic and thermodynamic relations for a compressible fluid flow, gas temperature T^* at the nozzle throat (where the Mach number is unity) is expressed as (Grujicic et al., 2004);

$$T^* = \frac{T_o}{[1 + (\gamma-1)/2]} \quad (2.4)$$

where;

* = gas quantities under sonic conditions at the nozzle throat

Typically γ is set to 1.66 for monoatomic gases and 1.4 for diatomic gases. The gas velocity v^* (m/s) at the nozzle throat is equal to the speed of sound and is defined as;

$$v^* = \sqrt{\gamma R T^*} \quad (2.5)$$

where;

R = gas constant (J/kmol·K)

From the user selected gas mass flow rate, G_g the sonic gas density ρ^* (kg/m³) is computed from;

$$\rho^* = \frac{G_g}{v^* A^*} \quad (2.6)$$

where;

A^* = cross-sectional area of the nozzle throat (m^2)

Using the ideal gas law ($PV=mRT$), gas pressure at the nozzle throat, P^* is determined as;

$$P^* = \frac{m}{V^*} RT^* = \rho^* RT^* \quad (2.7)$$

Once the throat pressure P^* is computed, the stagnation pressure P_o can be calculated using the following isentropic relation:

$$P_o = P^* \left(\frac{T_o}{T^*} \right)^{\gamma/(\gamma-1)} = P^* \left(1 + \frac{\gamma-1}{2} \right)^{\gamma/(\gamma-1)} \quad (2.8)$$

Varying the nozzle cross-sectional area A (along the nozzle length) allows determination of the corresponding Mach number (M) from the following equation;

$$\frac{A}{A^*} = \left(\frac{1}{M} \right) \left[\left(\frac{2}{\gamma+1} \right) \left(1 + \frac{\gamma-1}{2} M^2 \right) \right]^{\gamma/(2\gamma-1)} \quad (2.9)$$

Once the Mach number is determined at a given cross-sectional area of the diverging section of the nozzle, the corresponding gas quantities (P_g , T_g , v_g and ρ_g) can be calculated using the following isentropic relationships;

$$P_g = P^* \left(\frac{\gamma+1}{2 + (\gamma-1)M^2} \right)^{\gamma/(\gamma-1)} \quad (2.10)$$

$$T_g = \left\{ \frac{T_o}{1 + [(\gamma-1)/2]M^2} \right\} \quad (2.11)$$

$$v_g = M \sqrt{\gamma R T_g} = M \sqrt{\frac{\gamma R T_o}{1 + [(\gamma-1)/2]M^2}} \quad (2.12)$$

$$\rho_g = \frac{\rho_o}{\left\{1 + [(\gamma - 1)/2]M^2\right\}^{1/(\gamma - 1)}} \quad (2.13)$$

Equations 2.10, 2.11, 2.12 and 2.13 are also used to compute the gas conditions at the nozzle exit if the exit cross-sectional area (A_e) is substituted for A in Equation 2.9 to get the corresponding M_e . These exit conditions reflect the true conditions of the gas at the nozzle exit only if a normal shock does not take place inside the nozzle. To prevent the shock from occurring, shock pressure (P_s) (Equation 2.14) is always maintained above the ambient pressure (P_a). If P_s is lower than P_a , a shock occurs and the subsequent gas flow is subsonic so that P_e is not given by Equation 2.10, but is rather equal to P_a (Grujicic et al., 2004);

$$P_s = P_e \left(\frac{2\gamma}{\gamma + 1} M_e^2 - \frac{\gamma - 1}{\gamma + 1} \right) \quad (2.14)$$

where;

e = gas quantities at the nozzle exit

Further, there is a maximum allowable, carrier-gas dependent length of the diverging section of the nozzle which, if exceeded, would give rise to the occurrence of a normal shock inside the nozzle. If longer nozzles are needed for specific applications, their cross-sectional area must remain constant after the maximum allowable value of the expansion ratio (A/A^*) is reached in order to prevent the normal shock from occurring inside the nozzle (Grujicic et al., 2003). On top of that, as nozzle length increases downstream of the nozzle throat, the boundary layer thickness also increases. This leads to a decrease of the effective nozzle cross-sectional area in comparison to the geometrical cross-sectional area. As a result, gas velocity decreases at the nozzle exit in comparison to the ideal gas flow velocity (Alkhimov et al., 2001). Hence, nozzle length must be optimised to prevent these adverse effects on gas velocity.

2.3.2 Particle velocity

Once gas conditions are characterised within the nozzle, particle velocity (v_p) is iteratively calculated down the length of the nozzle through use of a solid rocket nozzle particle drag relationship that predicts the accelerating force, F_p (N) on the particle to be (Grujicic et al., 2004);

$$F_p = m_p a_p = m_p \frac{dv_p}{dt}$$

$$m_p \frac{dv_p}{dt} = m_p v_p \frac{dv_p}{dx} = \frac{C_D A_p \rho_g (v_g - v_p)^2}{2} \quad (2.15)$$

where;

a_p = particle acceleration (m/s^2)

m_p = average particle mass (kg)

A_p = average particle cross-sectional area (m^2)

C_D = drag coefficient

t = time traveled by the particle from the nozzle throat (s)

x = axial distance traveled by the particle from the nozzle throat (m)

Under the condition of constant v_g , ρ_g and C_D , Equation 2.15 is integrated to yield;

$$\log \left(\frac{v_g - v_p}{v_g} \right) + \frac{v_g}{v_g - v_p} - 1 = \frac{C_D A_p \rho_g x}{2m_p} \quad (2.16)$$

With v_p small in comparison to v_g , Equation 2.16 is simplified as;

$$v_p = v_g \sqrt{\frac{C_D A_p \rho_g x}{m_p}} = v_g \sqrt{\frac{3C_D \rho_g x}{2d_p \rho_p}} \quad (2.17)$$

where ρ_p = particle material density (kg/m^3)

Substituting Equation 2.12 in Equation 2.17 gives the relation;

$$v_p = M \sqrt{\frac{\gamma R T_o}{1 + [(\gamma - 1)/2] M^2}} \sqrt{\frac{3 C_D \rho_g x}{2 d_p \rho_p}} \quad (2.18)$$

Equation 2.18 is consistent with experimental observations that the spray particle velocity is proportional to the square root of the ratio of the distance travelled x and the particle diameter d_p . An analysis of Equations 2.9, 2.11 and 2.12 indicates that gas velocity within the nozzle depends on the total gas temperature and nozzle geometry (i.e. the cross-sectional area at a given axial distance x), but not on gas pressure (under the condition of a constant drag coefficient). However, Equations 2.13 and 2.15 indicate that the initial

particle acceleration ($\frac{dv_p}{dt}$ at $v_p=0$) is linearly dependent on the stagnation pressure but independent of the total temperature. Thus, while the stagnation pressure does not affect the maximum particle velocity, it has to be sufficiently high to ensure that the spray particles velocity will approach the gas velocity over a relatively short length of the diverging section of the nozzle (Grujicic et al., 2004).

Figure 2.18 illustrates a substrate fixture for spraying at different angles. Since only particles at a velocity larger than the critical velocity at normal impact (90°) are deposited on the substrate, the spray angle (θ) and thus the normal component of particle velocity (v_{pn}) (Equation 2.19) are a significant factor influencing DE (Li et al., 2003). As θ decreases from 90° , v_{pn} decreases and the tangential component (v_{pt}) increase. Because the deposition of particles depends on v_{pn} and the effect of v_{pt} is negligible, only particles with v_{pn} higher than the critical value will be deposited (Li et al., 2005).

$$v_{pn} = M \sqrt{\frac{\gamma R T_o}{1 + [(\gamma - 1)/2] M^2}} \sqrt{\frac{3 C_D \rho_g x}{2 d_p \rho_p}} \cdot \sin(\theta) \quad (2.19)$$

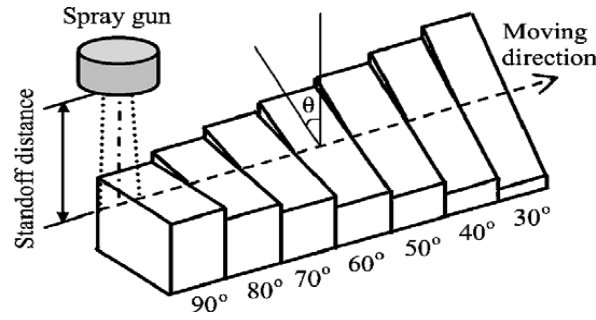


Figure 2.18: Sketch of a substrate fixture for spraying at different angles (Li et al., 2005)

The particle approaching angle (θ) at which v_{pn} is equal to the critical velocity is defined as the critical angle. This critical angle is a threshold, less than which no particle deposition occurs (Li et al., 2005).

2.3.3 Particle critical velocity

CGDS systems have a number of key process parameters that affect the quality of the sprayed surfaces and these include; the influence of nozzle design, gas density, particle size, temperature and velocity. Equation 2.18 gives the relation between the particle velocity in the nozzle, v_p and these parameters. To yield a good DE and reduce the operating time and wasted powder, optimum gas and particle parameters must be chosen. An empirical relationship between particle parameters and the critical velocity (v_{crit}) needed for a particle to successfully deposit on a substrate is summarised in Equation 2.20 (Assadi et al., 2003; Kim et al., 2005). It shows that v_{crit} is material dependent, being affected by particle density, strength, elastic-plastic properties and composition. The critical velocities of most metals and alloys for CGDS deposition are in the range of 500-700 m/s according to theoretical calculations and experimental works (Kim et al., 2005).

$$v_{crit} = 667 - 14\rho_p + 0.08T_m + 0.1\sigma_\mu - 0.4T_e \quad (2.20)$$

where;

T_m = particle melting point ($^{\circ}\text{C}$)

σ_μ = particle UTS (MPa)

T_e = particle exit temperature ($^{\circ}\text{C}$)

Particle preheating or vacuum annealing treatments help decrease the v_{crit} and resultantly increase DE. This results from the decrease of particle microhardness and an increase in particle ductility during the heat treatments (Ning et al., 2007) making it easier for particle deformation on impact. Taking Co for instance, $\rho_p = 8.8 \text{ g/cm}^3$, $T_m = 1495 \text{ }^\circ\text{C}$, $\sigma_\mu = 235\text{MPa}$ and according to Equation 2.20, v_{crit} without powder preheating is calculated to be 687 m/s. When a particle preheating temperature of 500 $^\circ\text{C}$ is applied, v_{crit} decreases by 200 m/s (Kim et al., 2005);

$$\begin{aligned} v_{crit} &= 667 - 14\rho_p + 0.08T_m + 0.1\sigma_\mu - 0.4T_e \\ &= 667 - 14(8.8) + 0.08(1495) + 0.1(235) - 0.4(500) \\ &= 687 - 200 \\ &= 487 \text{ m/s} \end{aligned}$$

At v_{crit} that's when adiabatic shear instabilities begin to form at the particle-substrate interface. Criterion for the instability is expressed mathematically by Equation 2.21 (King et al., 2008);

$$d\sigma = \frac{\partial\sigma}{\partial T}dT + \frac{\partial\sigma}{\partial\varepsilon}d\varepsilon + \frac{\partial\sigma}{\partial\dot{\varepsilon}}d\dot{\varepsilon} \leq 0 \quad (2.21)$$

where;

σ = shear stress (MPa)

ε = strain

$\dot{\varepsilon}$

$\dot{\varepsilon}$ = strain rate

Equation 2.21 state that at some point a maximum in σ occurs depending on T , ε and $\dot{\varepsilon}$. If thermal softening is dominant over strain hardening and strain rate hardening, strain localisation occurs, i.e., $d\sigma \leq 0$. When this condition is met, heat released by intense deformation near the interface further causes thermal softening which, in turn, facilitates plastic material flow. The material exhibits viscous-like behaviour and is pushed out rapidly towards the periphery of the particle forming a jet (Figure 2.12). It is the violent action of these jets that breaks down oxide films, enabling intimate contact and the formation of metallic bonds between the substrate and particles (King et al., 2008).

Schematically shown in Figure 2.19 is how v_{crit} and erosion velocity ($v_{erosion}$) vary with particle impact temperature. The area under v_{crit} denotes the lack of particle bonding and slight substrate erosion. The area above $v_{erosion}$ signifies strong substrate erosion because of too high a particle velocity or, in the case of soft particles hitting a hard substrate, no deposition as the particles pulverise. The area between v_{crit} and $v_{erosion}$ describes the window of sprayability (WS) whereby most of the impacting particles successfully deposit on the substrate. This WS region is limited by a region of brittle material behaviour or limited ductility at lower impact temperatures (Schmidt et al., 2006).

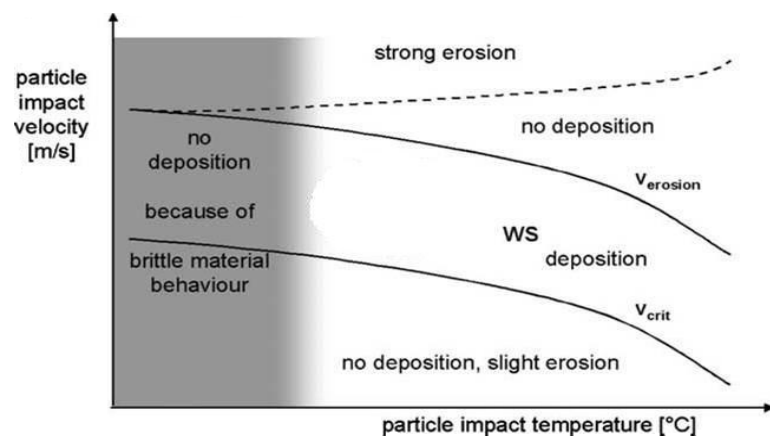


Figure 2.19: Particle velocity over particle temperature with WS (Schmidt et al., 2006)

By using relatively large particles, the minimum KE necessary for deformation and bonding with low particle critical velocities is easily obtained. However, smaller particles more closely follow the gas velocity and temperature, exiting with a higher velocity and lower temperature. Consequently, the particle velocities as calculated by Equation 2.18 and the critical velocity as determined by Equation 2.20 then allow an identification of the most favorable particle size to use to achieve maximum coating qualities.

Figure 2.20 summarises calculated critical velocities of spray particles (25 μm) for different metals and alloys over increasing density. Darker areas represent the range of critical velocities (according to different purities and thus mechanical properties) for the respective materials. The slight trend to decreased critical velocities for increasing density is superimposed by the influences of materials strength and melting temperature. The graph demonstrates that low density materials like Al have higher critical velocities (630-670

m/s) than high density materials like W (480-650 m/s). Most remarkably, Ta despite the high melting temperature of (3290 K) shows a similar critical velocity as Cu (Gärtner et al., 2006a).

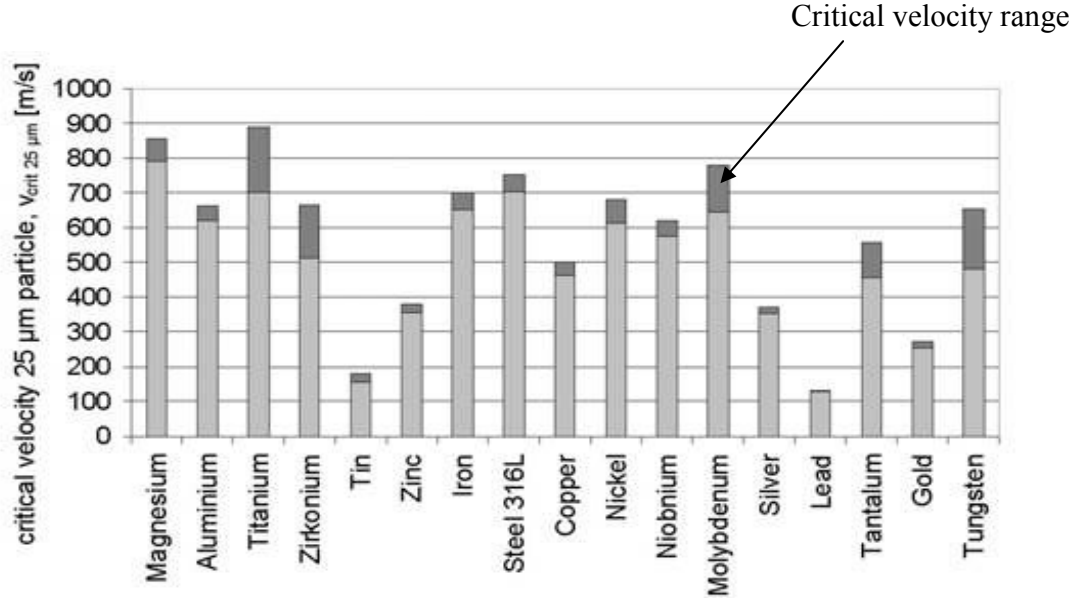


Figure 2.20: Critical velocities for various spray materials (25 μm) (Gärtner et al., 2006a)

2.3.4 Particle temperature

Spray particles temperature in the gas-particle mixture rises as thermal energy is transferred from the gas to them through convective heating. The convective heat transfer is defined as (Champagne et al., 2005a);

$$c_p \frac{dT_P}{dt} = \left(\frac{N_u k}{d_p} \right) \left(\frac{A_p}{m_p} \right) (T_g - T_p) \quad (2.22)$$

where;

c_p = particle heat capacity (J/kg·K)

N_u = Nusselt number

k = gas conductivity (W/m·K)

A_p = particle surface area (m²)

T_p = particle temperature (K)

T_g = gas temperature (K)

The Nusselt number is given by;

$$N_u = 2.0 + R^{0.5} Pr^{0.33} \quad (2.23)$$

where Pr = the Prandtl number

2.3.5 Particle deposition penetration depth

The volume (V) of the crater produced on impact is the particle face area (πr_p^2) times the penetration depth (L); and according to an empirical projectile penetration law (by Eichelberger and Gehring), the volume of the crater is expressed as (Champagne et al., 2005b);

$$V = \pi r_p^2 \times L = \frac{\left(4 \times 10^{-5}\right) E}{B} \quad (2.24)$$

where;

B = substrate Brinell hardness number (BHN)

E = particle kinetic energy (J)

r_p = particle radius (m)

The KE, E is given by;

$$E = \frac{1}{2} m_p v_p^2 = \frac{1}{2} \left(\frac{4}{3} \pi r_p^3 \rho_p \right) v_p^2$$

Thus,

$$V = \left(\pi r_p^2 \right) L = \frac{\left(4 \times 10^{-5}\right) (1/2) \left(4/3 \pi r_p^3 \rho_p\right) v_p^2}{B}$$

The penetration depth (L) is then given by:

$$L = \left(4 \times 10^{-5}\right) \left(\frac{2\rho_p r_p}{3} \right) \left(\frac{v_p^2}{B} \right) \quad (2.25)$$

As shown by the empirical relationship (Equation 2.25), the extent of particle/substrate interface mixing also depends on substrate hardness (B) (Champagne et al., 2005b) besides the particle density, size and impact velocity.

The solid-state particle bonding mechanism discussed above suggests and experimental observations confirm that it is desirable to maximise particle impact velocity on the substrate. While this can be accomplished by increasing P_o , for practical and economic reasons, it is desirable to maximise the particle impact velocity at a given level of P_o by properly selecting the type of the carrier gas, its T_o and by optimising the shape of the nozzle (Grujicic et al., 2003). Consequently, these parameters design optimisations will be key to improve the coating quality and reduce spraying costs.

In this context, development of portable LPCGDS systems has been of prime importance because such systems allow, in addition to the high-pressure systems, the application of coatings to structural elements difficult to be accessed such as surfaces of semi-closed volumes and reservoirs, and the repair and maintenance activities to be carried on sites. The primary advantages of radial powder injection in LPCGDS technologies are the high durability of the nozzles and simple design of the powder feeders. Also, low air pressure and radial injection of the powder leads to decreased gas consumption, sharply improving the economical feasibility of the LPCGDS processes within industrial environments (Maev et al., 2008).

However, since LPCGDS is a relatively young process, substantial research and development (R&D) efforts are needed to (Karthikeyan et al., 2004);

- Understand, analyse and control the process.
- Design and construct improved systems.
- Develop engineered coatings with desired properties for specific applications.
- Reduce process costs and lead-time.

The last few years have seen exponential growth of cold spray R&D around the globe. Considerable R&D efforts are being undertaken at various laboratories, academic institutions and industries. These studies include process diagnostics, modeling of the process and the jet, modeling of the coating formation, spray optimisation and application coating development. Europe, and in particular Germany is leading the technology development and applications.

2.4 LPCGDS System Components

Each LPCGDS system component design (Figure 2.8) must contribute to achieve a more effective acceleration of the particles and resultantly a more dense coating. The overall system setup should ensure constant technological parameters (P_o , T_o and G_g), a uniform concentration of particles in the gas jet and a wide-range variation of particle impact velocities with the substrate. These components include the gas supply system, gas heater, powder feeder and supersonic nozzle.

2.4.1 Gas supply system

Several gases are available for use as propellant media for the powder particles in LPCGDS systems and choice of the type of driving gas to use mostly depend on its aerodynamic properties. Given that under the same operating conditions different gases achieve different particle impact velocities and temperatures, the gas should ensure that the particles reach their respective critical velocities. This particle velocity is a major requirement that greatly influences selection of the driving gas. Figure 2.21 shows gas inlet pressure for the nozzle as a function of Cu particle impact velocity and temperature for both N_2 and He gases. At 0.5 MPa, use of N_2 results in particle velocities and temperatures of 290 m/s and 340 °C respectively, whilst with He particles achieve velocities and temperatures of 460 m/s and 275 °C (Li et al., 2006). This shows that He attains higher impact velocities but lower temperatures as compared to N_2 , indicating that particle velocity indeed depends on the type of driving gas (see Appendix F1).

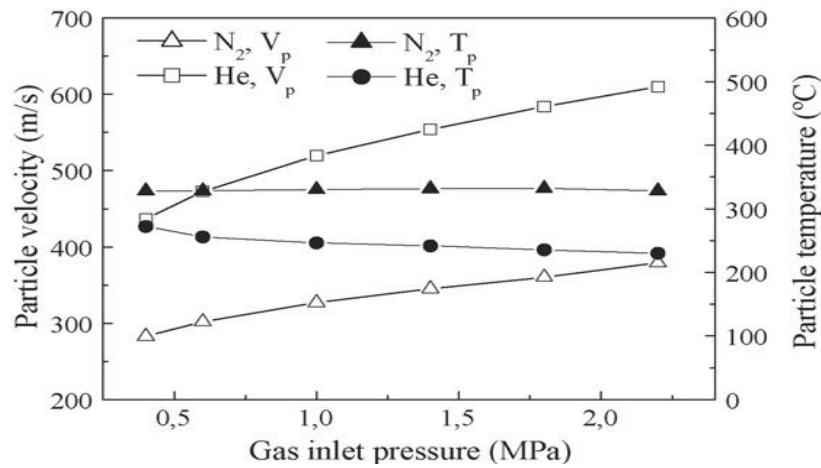


Figure 2.21: Effect of gas pressure on Cu particle velocity and temperature for both N₂ and He (Li et al., 2006)

Presented in Figure 2.22 is a scanning electron microscope (SEM) morphology of Al coatings obtained using different accelerating gases, 100 vol. % He and He-20 vol. % N₂. An unclear interface in Figure 2.22(a) indicates that use of 100% He provides a similar and near morphological coating structure to that of the substrate, implying better compatibility of deposition in terms of microstructural features at the interface. The addition of N₂ to He (Figure 2.22(b)) increases the mass of carrier gas and thereby decreases the sonic velocity of the gas (Balani et al., 2005b). A clear interface is obtained under these conditions and this signifies a different coating morphology compared to the substrate.

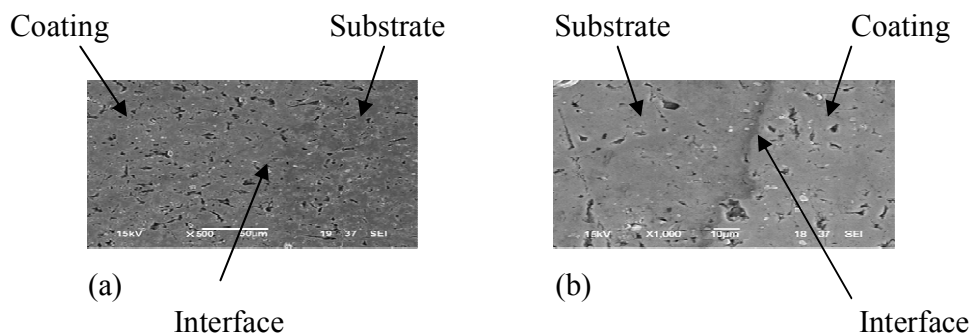


Figure 2.22: SEM micrograph showing coating-substrate interface for Al deposition onto 1100 Al substrate at (a) 100 vol. % He and (b) He-20 vol. % N₂ (Balani et al., 2005b)

Looking at Figure 2.19, an increase in particle impact temperature result in a decrease in the v_{crit} . Therefore, a gas type that transfers well its thermal energy to the powder particles

is desired to achieve a higher DE. The gas is supposed to have a low expansion coefficient so that it does not lose a lot of heat on expansion but rather transfers most of its energy to the particles.

As gas inlet pressure is increased resulting in higher gas densities, particles are accelerated to higher velocities (Li et al., 2006). Figure 2.23 shows process gas pressure as a function of the particle velocity and DE for W and Cu particles. Particle velocities increase for both materials with increasing gas pressure (Figure 2.23(a)), consequently resulting in an increase in their deposition efficiencies (Figure 2.23(b)). However, because of different material compositions, an increasing rate for the DE of each component is a little different (Shin et al., 2006).

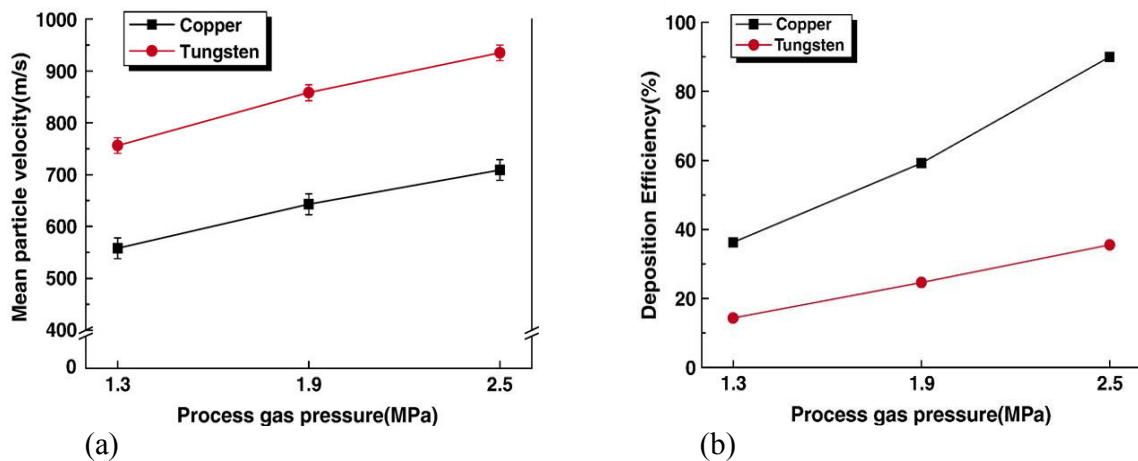


Figure 2.23: Process gas pressure versus (a) particle velocity and (b) DE (Shin et al., 2006)

Illustrated in Figure 2.24 are polished cross-section images of cold sprayed Al coatings with different pressure conditions. An appreciable difference in the images porosity levels as gas pressure increases from Figure 2.24(a) to (c) is observed showing that DE is in direct proportion to gas pressure. Figure 2.24(a) sprayed at 0.7 MPa is more porous with a DE of 5% while Figure 2.24(c) sprayed at a higher pressure of 2.5 MPa is denser with a DE above 30% (Lee et al., 2008). These DE values are low because during spraying, the majority of particles are not deposited but play a major role of peening already deposited particles, increasing the coating density.

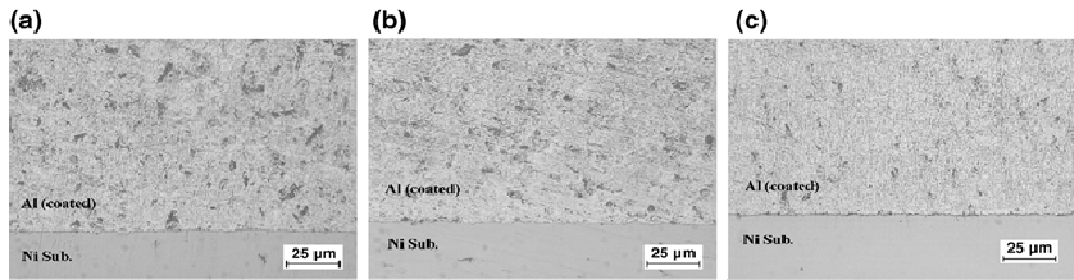


Figure 2.24: Polished cross-section images of Al coatings with different pressures, (a) 0.7 MPa, (b) 1.5 MPa and (c) 2.5 MPa (Lee et al., 2008)

Coating hardness is directly dependent on particle velocity and; with the velocity being a function of the ratio of specific heats and inversely proportional to the mass of carrier gas, it improves with a lower density and higher specific heat ratio of carrier gas (Balani et al., 2005b). Moreover, the hardness depends on the inertness of the gas to avoid oxidation of particles, a necessity in LPCGDS systems. Equally hard and good coatings can be obtained from spraying oxygen sensitive materials with the correct type of driving gas.

The gas delivery system must provide accurate working gas flow rate to the nozzle through the main gas line and ought to include a pressure relief valve as a safeguard of over pressurisation due to downstream clogging or supply regulator failure. Also, the gas should not be toxic to avoid suffocation of the personnel operating the spray system.

In addition, the type of gas to use depends on its cost. It has to be relatively cheap so that the LPCGDS system remains economically viable to utilise as a spray technology compared to the other alternatives. Therefore, the type of propellant gas and the pressure range to make use of in LPCGDS should be carefully selected to obtain excellent coatings. Illustrated in Figure 2.25 is how the gas supply requirements influence type of gas to use as the propellant.

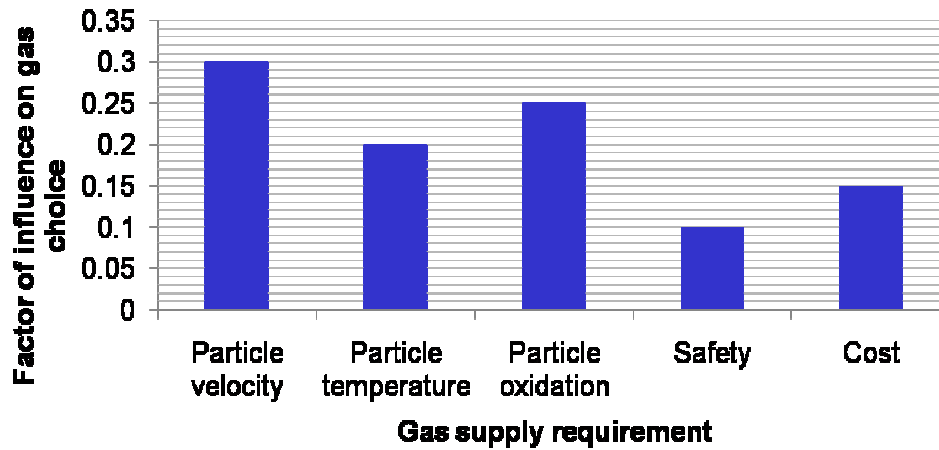


Figure 2.25: Gas supply requirements influence on the choice of propellant gas to use

2.4.2 The gas heater

Quite a number of gas heating concepts exist and, design of a LPCGDS gas heater is guided by the fundamental aim of increasing the aerodynamic properties of carrier gas in order to attain supersonic particle velocities in the nozzle. Choice of a heater to employ significantly contributes to the cost of the spray system. Thus, a heater that's easier and cheap to construct is required to lower down spray costs.

Compressed gas is heated to a controlled temperature (~ 400 °C) within the gas heater and then delivered to the supersonic nozzle. Analysing Equations 2.7 and 2.12, increasing T_o for a pressure (P_o) result in a decrease in ρ_g and an increase in v_g respectively. Looking at Equation 2.17, an increase in v_g outweighs the corresponding decrease in ρ_g , so drag on the particles increases (Gilmore et al., 1998) resulting in an increase in v_p also. A critical gas temperature is supposed to be reached below which no particle deposition occurs (Li et al., 2003) and it is at this critical temperature that particles are considered to have just attained v_{crit} (see Appendix F2). Apart from increasing v_p , preheating of the process gas also increases T_p and thereby facilitates particle plastic deformation upon impact. Figure 2.26 shows both Cu particle velocity and temperature increasing significantly with an increase in gas inlet temperature. A particle velocity of 290 m/s is achieved at 100 °C gas inlet temperature with a gradual increase to 360 m/s at 600 °C (Li et al., 2006).

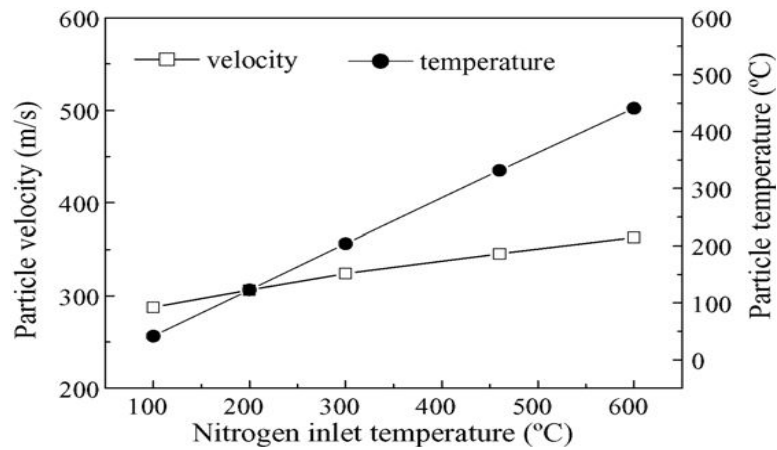


Figure 2.26: Effect of gas temperature on particle velocity and temperature (Li et al., 2006)

In addition, as indicated in Figure 2.27 an increase in T_p leads to a reduction in the v_{crit} as a result of particle thermal softening, an important factor in the bonding mechanism (Kreye et al., 2006), ensuring that more particles are successfully deposited on impact with the substrate. The critical velocities for both the 20 and 50 μm Cu particles are decreasing as their temperatures increase respectively.

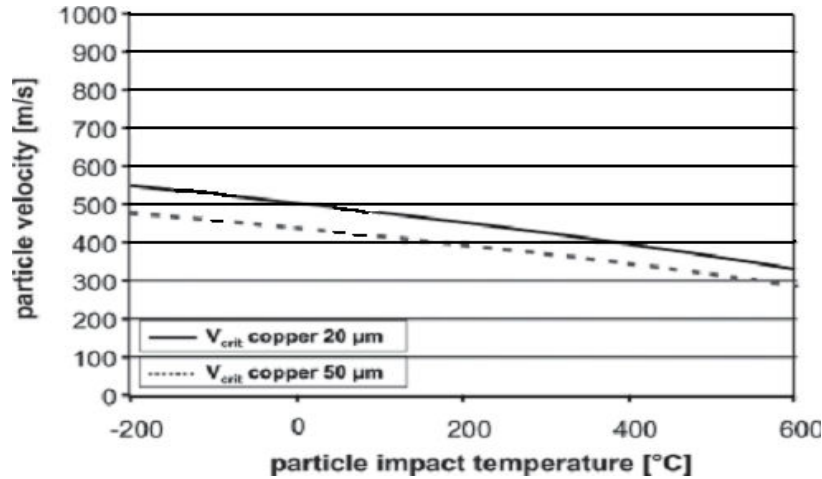


Figure 2.27: Particles critical velocity vs. impact temperature (Kreye et al., 2006)

Samples A and B in Figure 2.28 show the DE and W% in a W/Cu coating when the W-Cu particles are sprayed at room temperature and 600 °C respectively. Increasing T_p from room temperature (sample A) to 600 °C (sample B), the coating DE markedly increases together with the W% in the coating. This is so because of a decrease in the v_{crit} required for deposition as a result of an increase in T_p as explained in Figure 2.27 (Shin et al., 2006).

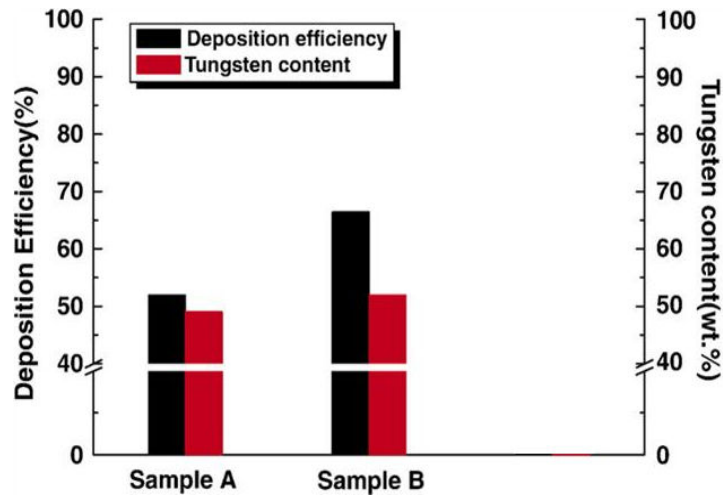


Figure 2.28: DE and W content; Sample A: room temperature powder and; Sample B: 600 °C powder (Shin et al., 2006)

Figures 2.29(a, c) further show that there are more pores (0.8%) present in the coating sprayed at room temperature. The interface of the W particles (Figure 2.29(c)) is not densely sound because of their high hardness. However, in Figure 2.29(b, d), an increase in T_p resulted in an increased deformation of the particles and a decreased porosity (0.2%) in the coating (Shin et al., 2006).

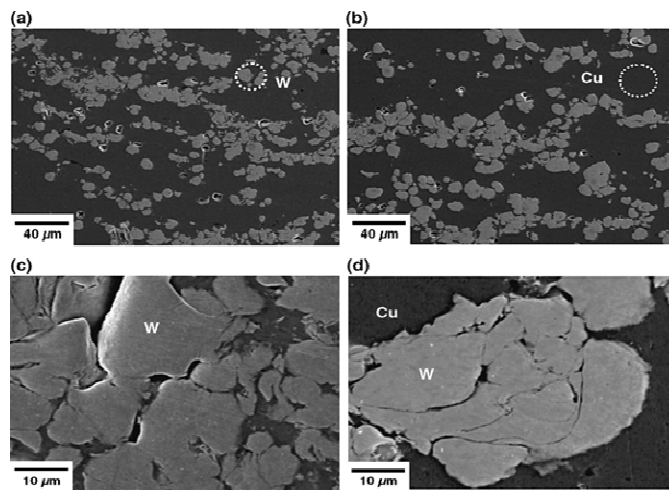


Figure 2.29: Cross section SEM micrograph of a W/Cu coating: (a), (c) room temperature powder; (b), (d) 600 °C powder (Shin et al., 2006)

Gas-mass flow rate (G_g) in the nozzle is related to T_o through the following relation (Jodoin et al., 2006);

$$G_g = \frac{P_o}{\sqrt{T_o}} A^* \sqrt{\frac{\gamma}{R} \left(1 + \frac{\gamma-1}{2}\right)^{\left(\frac{\gamma+1}{2-2\gamma}\right)}} \quad (2.26)$$

From Equation 2.26, G_g varies proportionally with $1/\sqrt{T_o}$, consequently increasing T_o is beneficial to the process as it reduces G_g (thus gas consumption), and therefore decreases spraying gas costs (Jodoin et al., 2006). Moreover, an increase in T_o help to overcome problems of low bond strength in LPCGDS coatings which are attributed to the extremely short timescales available for bonding to occur. However, increased T_o heighten the risk of nozzle fouling when spraying low melting point metals such as Al (Bray et al., 2008), hence, optimisation of gas heating without clogging the nozzle is essential. The LPCGDS system consequently requires a heater design that's easily operated to vary T_o according to the particle material being sprayed.

T_o is measured at the nozzle inlet by a thermocouple and controlled by a proportional temperature controller. Heating temperature (T_h) in the heater is given by (Papyrin et al., 2007);

$$T_h = T_{ex} - T_{in}$$

where T_{in} and T_{ex} are the gas temperatures at the inlet and exit of the heating element respectively. The heater must not introduce significant hydrodynamic resistance in operation in order to reduce power consumption, and also to maintain a constant T_o and v_p thus obtain uniform good quality coatings (Figure 2.26). To provide intense heat transfer from the heating element to the gas, it is necessary to ensure a developed turbulent gas flow in the heating element, which is reached with;

$$Re_h = \frac{\rho v d}{\mu} = \frac{4G_g}{\pi N_h d_h \mu} \geq 10^4$$

where Re_h is the Reynolds number of the gas flow inside the heating element; ρ , v , μ (Pa·s), and G_g are the density, velocity, viscosity and flow rate of the gas inside the heating element; d_h is the inner diameter of the heating element, and N_h is the number of heating elements. The total cross-sectional size of the heating elements should be at least two times greater than the nozzle-throat cross section (A^*) (Papyrin et al., 2007), i.e.,

$$N_h \frac{\pi d_h^2}{4} \geq 2A^*$$

The size of a gas heater to use in the LPCGDS system is of paramount importance. It should be light in weight to make it portable and be easily attached to motion control systems like robots. Also, the heater should have a few energy-intense units to conserve power. The necessary power of the heater (P_h) is expressed in terms of the flow rate, heating temperature, and heat capacity c_g of the gas as:

$$P_h = G_g c_g (T_{ex} - T_{in})$$

On the other hand, power released in heating elements (P_{he}) is determined by the ohmic resistance of the elements R_h and by the operating voltage V_h of the source, i.e.;

$$P_{he} = \frac{V_h^2}{R_h}$$

To avoid possible damage of the heater by overheating, the heater material temperatures are monitored and controlled accordingly. The high temperature resistant heating elements are also surrounded by an insulation chamber or any other suitable safety technique. Furthermore, the heater design should be easy to assemble and disassemble to reduce maintenance times and costs. Figure 2.30 shows how the gas heater requirements have an effect on the gas heater design to utilise in the LPCGDS system.

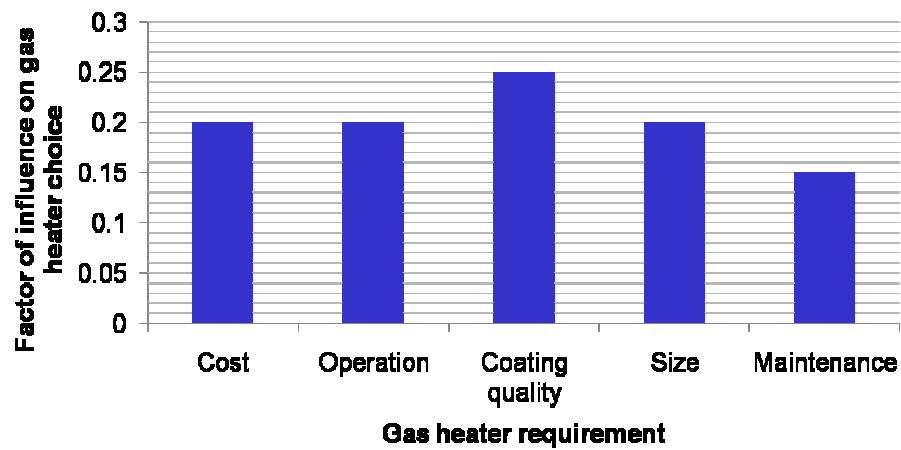


Figure 2.30: Gas heater requirements influence on the choice of gas heater to use

2.4.3 Powder feeder

There are three basic categories for powder feeders namely; gravity, volumetric and fluidised-bed feeders (Crawmer, 2004). The feeders are utilised for delivering a constant supply of feedstock material to the supersonic nozzle. Given that LPCGDS use finely divided powders, obtaining a reliable and consistent powder flow rate is a major challenge because of powder agglomeration and many traditional powder feeders become ineffective under working with such fine powders. Therefore, a powder feeder design that enhances good flowability properties of the fine particles is vital to achieve good coating qualities. This is a major requirement which greatly influences choice of the feeder to make use of in the spray system. Moreover, the dynamic characteristics of feeders do affect the accuracy of powder particle feeding and, these characteristics depend on the process operating conditions that include powder temperature, pressure and moisture content. As such, the feeders are equipped with a programmable feed controller for controlling and monitoring the powder flow rate.

The effect of particle mass feed rate on v_p (also known as the particle mass loading effect) is illustrated in Figure 2.31(a). The figure demonstrate that v_p decreases linearly with the mass feed rate, the decrease being attributed to the increased mass that the gas flow must accelerate (Gilmore et al., 1998). Since the mass feed rate is directly proportional to the feeder-feed rate, per se, to obtain a constant v_p to achieve uniform coatings, the feeder must be well designed to supply the particles with a minimum or no pulsations at all.

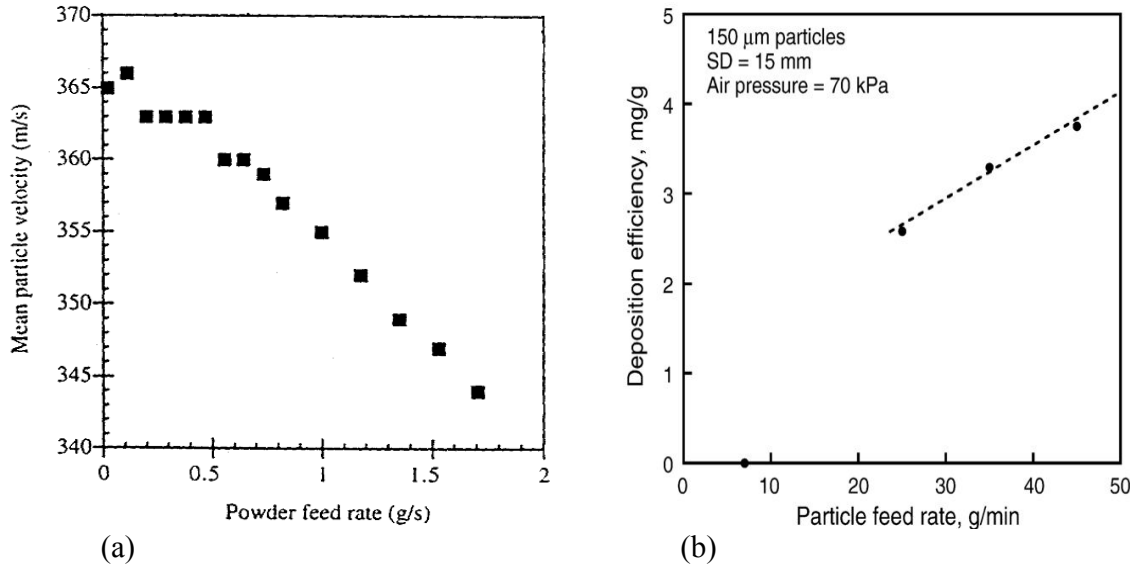


Figure 2.31: Effect of particle mass feedrate on (a) particle velocity (Gilmore et al., 1998) and; (b) DE (Xu et al., 2006)

Figure 2.31(b) presents the influence of particle mass feed rate on DE. As shown, no deposit forms on the substrate surface at a feed rate of 7 g/min, and there is a steady increase in DE for feed rates between 25 and 45 g/min (Xu et al., 2006). This implies that there is a certain minimum feed rate, specific to a particular application that must be achieved before deposition can start to occur.

In gravity powder feeders, particles flow from the hopper under gravity only whereby the bottom and top of the hopper are both vented to the atmosphere. Because of their mode of operation, they are cheap to manufacture and easy to maintain. However, variation and control of particle flow rate, an important requirement for the feeder, is not so easy in this type of feeder. If particles are larger than 0.5 mm in size, the influence of particle-air interactions is generally neglected in the determination of the powder discharge rate (G_p) or average solids flow rate (ASFR). G_p (kg/s) is thus well correlated by the expression of Beverloo as (Jing et al., 1999);

$$G_p = C\rho_b\sqrt{g}\left(D_o - kd_p\right)^{2.5} \quad (2.27)$$

where;

ρ_b = density of the flowing material (kg/m³)

D_o = discharge orifice diameter (m)

g = gravitational force (N)

The parameters C and k depend to a minor extent on the nature of material but commonly have values close to 0.58 and 1.5 respectively. The relationship presented in Equation 2.27 is satisfactory for cohesionless materials provided that $d_p > 0.5$ mm. If $d_p < 0.5$ mm, a modified Beverloo's expression, Equation 2.28 is employed to predict G_p because the effect of self-entrained or interstitial air on ASFR is now more significant (Jing et al., 1999);

$$G_p = C\rho_b \sqrt{g + \left(\frac{dp}{dz}\right)_o \frac{1}{\rho_b} \left(D_o - kd_p\right)^{2.5}} \quad (2.28)$$

where $\left(\frac{dp}{dz}\right)_o$ is the interstitial pressure gradient at the discharge orifice (Pa/m)

With $d_p < 0.5$ mm, particle flow rate fall off rapidly because of adverse interstitial pressure gradients set up as the material dilates on approaching the discharge orifice. Dilation of the solids is produced from the increase of particle mobility in the solids approaching the outlet, resulting in a difference in the flow velocity between the interstitial air and the particles. The consequent friction between the two phases, due to low porosities of the fine particles, produces an interstitial pressure gradient near the hopper outlet (Donsi et al., 1997). This pressure gradient results in a counter-current flow of air into the hopper from the discharge opening, which imposes a drag force that impedes and reduce particle flow rate from the hopper (Langston et al., 1996).

In the case of coarse particles ($d_p > 0.5$ mm), instead, owing to their higher porosities, the relative air-particle velocity induced by voidage changes inside the hopper is not sufficient to produce pressure gradients which can compete with the weight of the falling solids and, therefore, particle-air interactions are negligible (Donsi et al., 1997).

Conversely, in volumetric and fluidised-bed feeders, powder flow from the hopper is assisted and controlled by mechanical feeding devices. Because of these feeding devices, these two feeders are costly, although on the other hand their respective ASFR is easier to vary and control since it is directly proportional to the speed of rotation or feed rate of the feeding devices (see Appendix H2, Figure H4). The average discharge rate of powder particles through the mechanised hopper systems is calculated as (Whittles et al., 2005);

$$G_{p \text{ rpm}} = \frac{m_t}{t} \quad (2.29)$$

where;

$G_{p \text{ rpm}}$ = powder mass flow rate at a particular motor RPM (kg/s)

m_t = mass of the powder discharged in a given time (kg)

t = time taken to collect m_t (s)

Depending on the system in which they are operating, feeders may be pressurised or non-pressurised. As Equation 2.28 shows, G_p can be precisely regulated by properly controlling the interstitial pressure gradient in the hopper instead of allowing particle flow under pressure gradients generated by gravity only. Pressurised feeders make use of this concept by deliberately supplying air within the hopper and pressurising the particle flow to impose the interstitial pressure gradient. Particle flows in pressurised feeders can either be positive or negative flow. Positive flow is when the hopper pressure is greater than atmospheric and negative flow is when high pressure is created immediately below the orifice (Wu et al., 2003). Non-pressurised feeders are less expensive to operate and maintain compared to the pressurised feeders. If pressurised, they will include a pressure relief valve as a safety mechanism in case there is over pressurisation in the system.

Based upon the desired powder feeder performance, a number of feeder designs are available each having its own advantages and disadvantages as a function of application. Presented in Figure 2.32 is how the powder feeder requirements influence choice of powder feeder to utilise in the LPCGDS system.

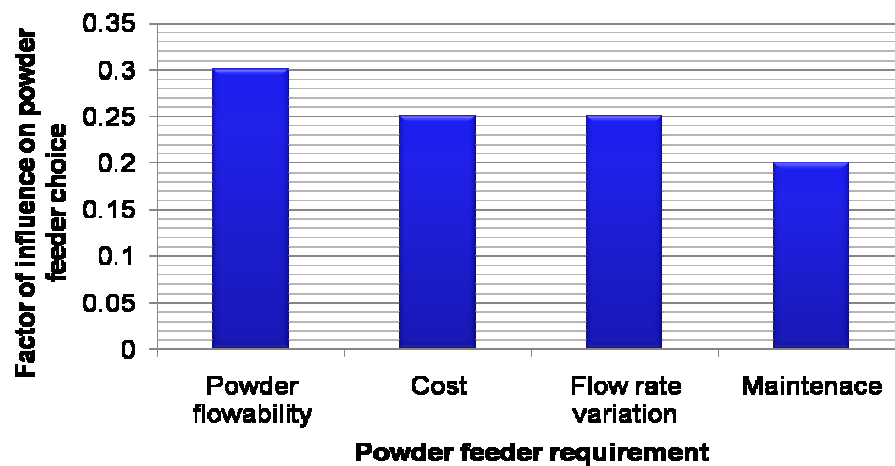


Figure 2.32: Powder feeder requirements influence on the choice of powder feeder to use

2.4.4 Powder particles

A variety of feedstock powders are utilised for corrosion protection, sealing, surface repair and fabrication purposes. Choice of the powder to use for a specific application primarily depends on the desired coating properties. These powders are manufactured using different production methods that include gas atomisation, mechanical milling and cryogenic grinding (grinding in liquid nitrogen). Depending on the production method employed to manufacture the powders, particles of the same material achieve different coating qualities under the same operating conditions (Papyrin et al., 2007). Additionally, the production method also determines cost of the feedstock powders which should be as low as possible to keep down the spraying costs.

Ideally particles should be free flowing, normally distributed and free of un-wanted fine particulates. Further, the particles may be blended with different constituents so that the coating deposit has properties tailored to a unique application. Figures 2.33(a, b) show typical SEM feedstock particles for a gas atomized Al-Sn binary alloy powder containing 5 wt.% Sn and 10 wt.% Sn. Both feedstock powders present near-spherical morphologies (shapes). Their size distribution given by laser diffraction analysis is shown in Figure 2.33(c) with volume mean diameters (VMD) of 20.2 and 15.2 μm respectively (Ning et al., 2009).

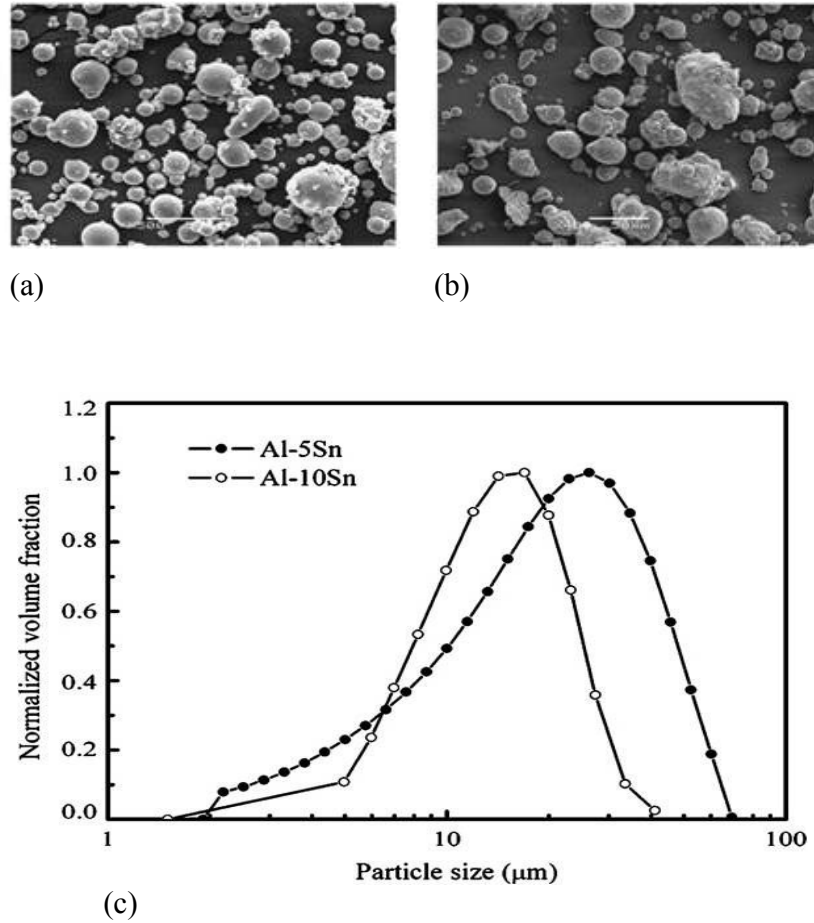


Figure 2.33: Al-Sn feedstock powders; (a) Al-5Sn, (b) Al-10Sn and (c) size distribution (Ning et al., 2009)

Based on Figure 2.31(a), to obtain a uniform deposit a repeatable powder feed rate (thus a constant v_p) must be achieved and this is possible if there is constancy in the powder particles characteristics. Among these characteristics, the most important are; particle size, morphology, moisture content, apparent density and the method of manufacture. The particles also ought to have a low oxide content to attain less oxide and dense deposits.

As presented in Equation 2.18, v_p scales proportionally with $1/\sqrt{d_p}$ and Figure 2.34(a) shows the effect of d_p on v_p . Increasing d_p decreases v_p because the ratio of surface area to mass, and therefore, the ratio of drag to mass (acceleration) decrease (Champagne et al., 2005a). In the case of He, a much high velocity of 700 m/s is attained at 10 μm and as d_p increases to 50 μm, the velocity decrease to 300 m/s. In view of this fact that d_p has an

effect on v_p , a key parameter in the LPCGDS technology, its selection is critical (see Appendix F3).

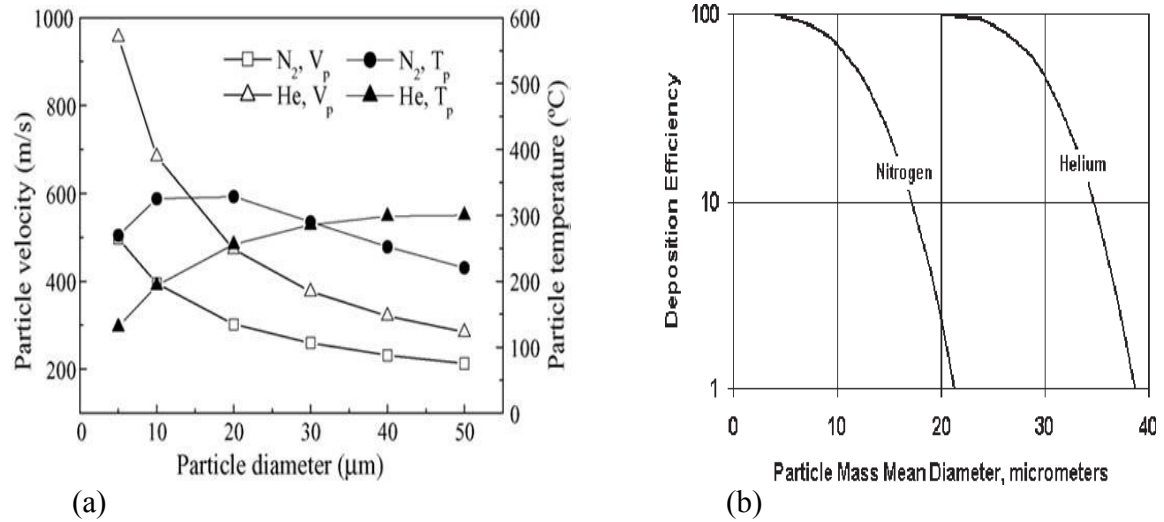


Figure 2.34: Effect of particle diameter on, (a) particle velocity (Li et al., 2006) and (b) DE (Champagne et al., 2005a)

Demonstrated in Figure 2.34(b) is the influence of d_p on DE where using both N₂ and He gases, DE can increase by two orders of magnitude with a two-fold decrease in d_p (Champagne et al., 2005a). Accordingly, porosity in the coatings decreases with a decrease in d_p . Figure 2.35 shows the microstructures at the interfaces of W/Cu coatings sprayed with different Cu sizes present in the W/Cu particle mixture. There is a higher W content, thus low porosity in the interface using small size Cu powder (20 μm) in Figure 2.35(b) compared to the other spray condition using large size Cu powder (50 μm), Figure 2.35(a) (Shin et al., 2006).

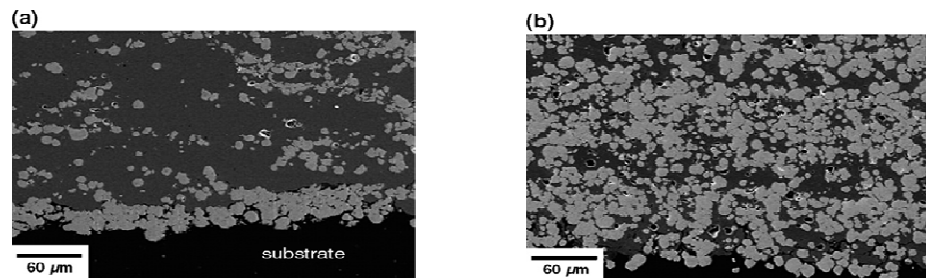


Figure 2.35: Cross sections of W/Cu coatings with different Cu sizes (a) 50 μm, (b) 20 μm (Shin et al., 2006)

Furthermore, if particles are too small (and light) they will be greatly decelerated within the stagnant region (Figure 2.11) and, when too large (and heavy) their deceleration within the stagnant zone will be modest. Consequently, the impact velocities of particles which are either too small or too large will be relatively low, thus maximum impact velocities will be attained by particles of an optimum size (and weight) (Grujicic et al., 2004). Upon the specification of a set of nozzle and gas parameters, including A_e/A^* , P_o and T_o , calculations can be done to determine the minimum d_p that yields the v_{crit} .

Particle deposition is primarily related to the readiness of the substrate and particle to deform, and its chances are high if the particle is substantially more plastic than the substrate. Accordingly, particles that have low cooling rates and as such do not lose much thermal energy transferred to them from the gas are required.

Nonetheless in practice, difficulty in feeding very fine powders usually limits the minimum size that is feasible to spray and also, aerodynamics imposes a certain minimum requirement of particle size for enduring the shock front encountered during particle impact with the substrate (Balani et al., 2005b). Therefore, a balance is required between particle size, shape and purity in order to achieve the minimum velocity levels for optimised depositions. Figure 2.36 illustrates the influence of powder particle requirements on the choice of feedstock powder to utilise.

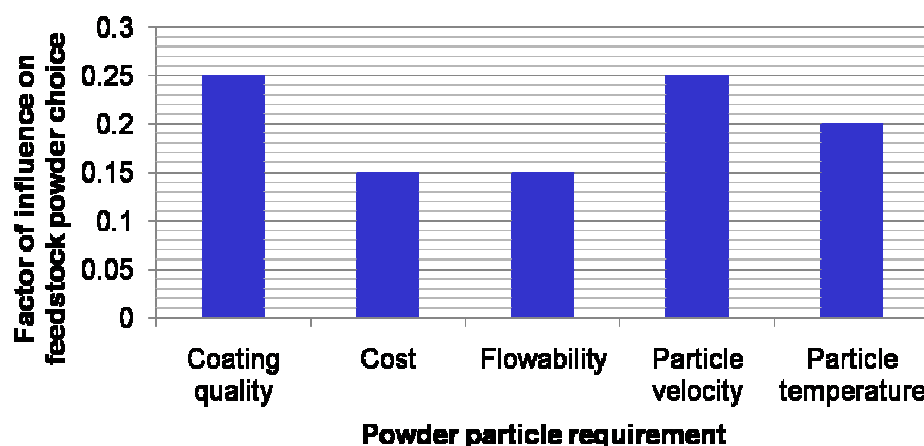


Figure 2.36: Powder particle requirements influence on the choice of feedstock powder to use

2.4.5 The supersonic nozzle

The supersonic nozzle is the main unit responsible for imparting supersonic speeds (ranging from Mach 2 to 3) to the gas-particle flow mixture. Generally, the nozzle exit velocity should not exceed Mach 3, in order to minimise the shock wave-particle interaction in front of the substrate (Ajdelsztajn et al., 2005). LPCGDS systems make use of the configuration where powder particles are radially injected into the downstream of the nozzle throat section, Figure 2.8. This makes possible use of a low pressure powder feeder that's light in weight and cheap to manufacture, thus keeping the spraying costs low.

A number of factors affect performance of the LPCGDS process, but none more so than the nozzle design (length, diameter, geometry and outlet cross-section configuration). A design that ensures acceleration of particles to velocities necessary to achieve deposition is required. Moreover, the nozzle should support transfer of thermal energy from the gas to the particles so that they deform and deposit easily on impact with the substrate.

Figure 2.37(a) shows the effect of nozzle length (x in Equation 2.18) on v_p and T_p . With an increase in x , v_p increases significantly but then increases gradually with the further increase. This is because effective particle acceleration is performed mainly in a limited length within the nozzle despite a longer nozzle.

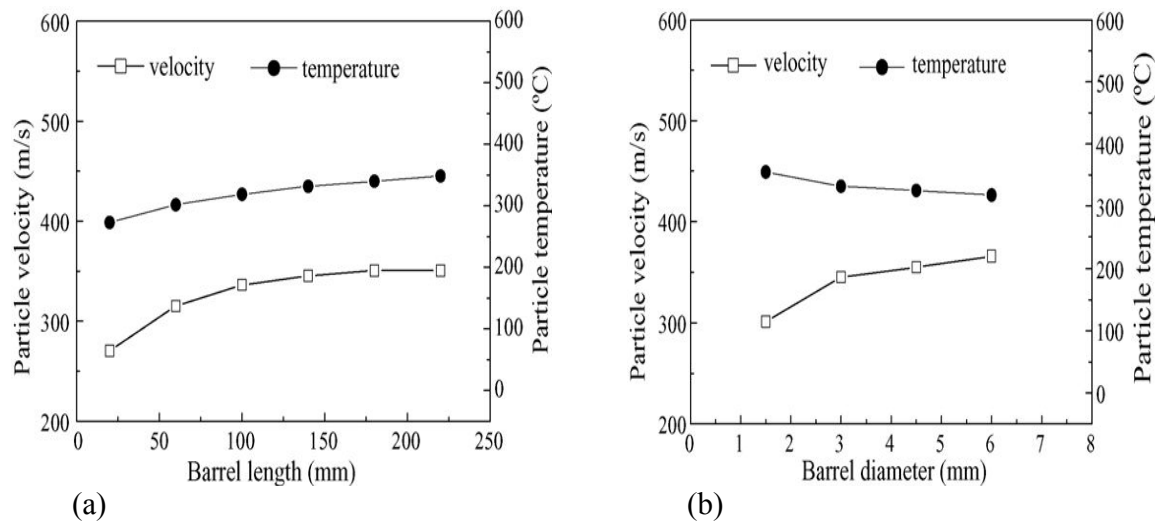


Figure 2.37: Effect of barrel (a) length and (b) diameter on particle velocity and temperature (Li et al., 2006)

Likewise, as shown in Figure 2.37(a), T_p increases with increasing nozzle length because the residence time of particles in the gas flow increases also. Figure 2.37(b) shows the effect of nozzle diameter on v_p and T_p . v_p increases significantly with an increase in nozzle diameter but then increases gradually with a further increase. However, T_p changes slowly and presents a tendency to decrease with increasing nozzle diameter. This is because with an increase in nozzle diameter, the gas expands faster resulting in its temperature dropping, thus T_p drops also.

Gas flow rate, G_g increase with an increase in nozzle throat diameter under the same inlet pressure, P_o resulting in both a high v_p and DE. To lower G_g and thus spraying gas cost, a nozzle with smaller throat is preferred. Therefore, selection of barrel diameter is compromised between the gas cost and particle deposition (Li et al., 2006).

To a great extent, nozzle geometry influences the career gas properties within the nozzle, as a result determining powder particle characteristics on exiting the nozzle. Illustrated in Figure 2.38 is how convergent-barrel (CB) and convergent-divergent (CD) nozzles affect v_g and v_p (Li et al., 2006). High velocities of 900 m/s for v_g and 450 m/s for v_p are obtained at the nozzle exit (175 mm) with a CD nozzle, while the velocities are relatively low with a CB nozzle, 500 m/s and 300 m/s respectively. Depending on the desired nozzle exit particle characteristics, different nozzle geometries are available for utilisation in LPCGDS.

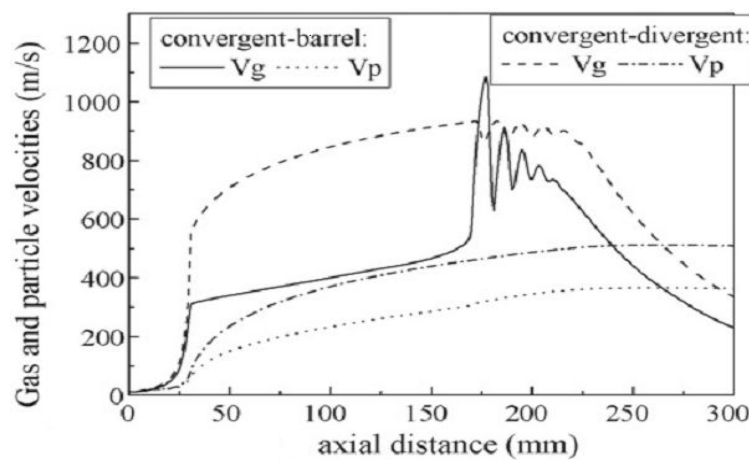


Figure 2.38: Effect of nozzle geometry on gas and particle velocities (Li et al., 2006)

The maximum possible particle flow rate through a nozzle ($G_{p\max}$) is approximately equal to one half of the gas flow rate (G_g) through it, i.e. $G_{p\max} = 0.5G_g$. G_g is given by (Papyrin et al., 2007);

$$G_g = P_o A^* \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{2(\gamma - 1)}} \sqrt{\frac{\gamma}{RT_o}}$$

For air:

$$G_g = \frac{0.04 P_o A^*}{\sqrt{T_o}}$$

As a result, using air as the driving media, the maximum flow rate of particles through a nozzle is given by;

$$G_{p\max} = 0.5G_g = \frac{0.02 P_o A^*}{\sqrt{T_o}}$$

Nozzle cross-section determines the particle profiles on exiting the nozzle and resultantly the coating pattern. Therefore, design and choice of a supersonic nozzle is defined by the essential point of achieving a certain minimum critical velocity, a uniform dense coating and a specific coating outline. Furthermore, nozzle cross-section has a bearing effect on the gas pressure loss coefficient of a nozzle. Thus, to minimise gas costs, a nozzle with a low gas pressure loss coefficient is vital for the LPCGDS system. The relation between the parameters of the main sub-systems (gas heater, powder feeder and nozzle unit) and the efficiency in terms of mass is defined as (Papyrin et al., 2007);

$$P_m = v_w H_c \delta_c \rho_c$$

where;

v_w = velocity of motion of the coated surface with respect to the nozzle exit (m/s)

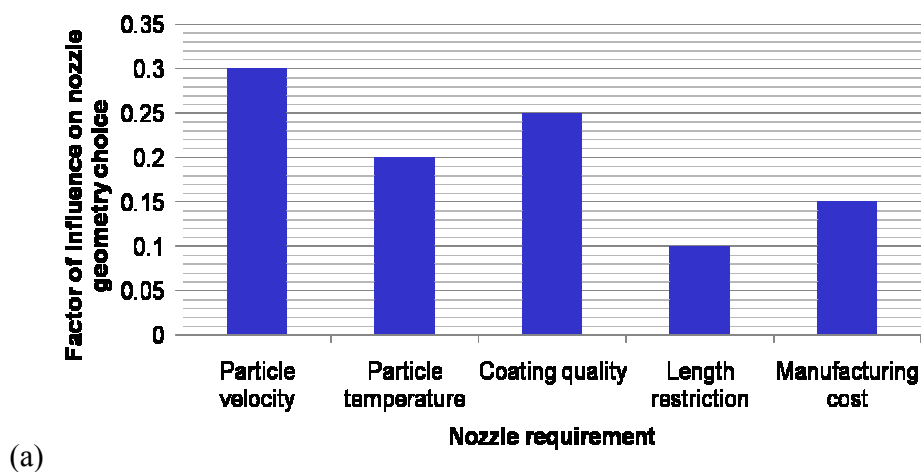
H_c = width of the band sprayed in one pass equal to the larger size of the nozzle-exit section (m)

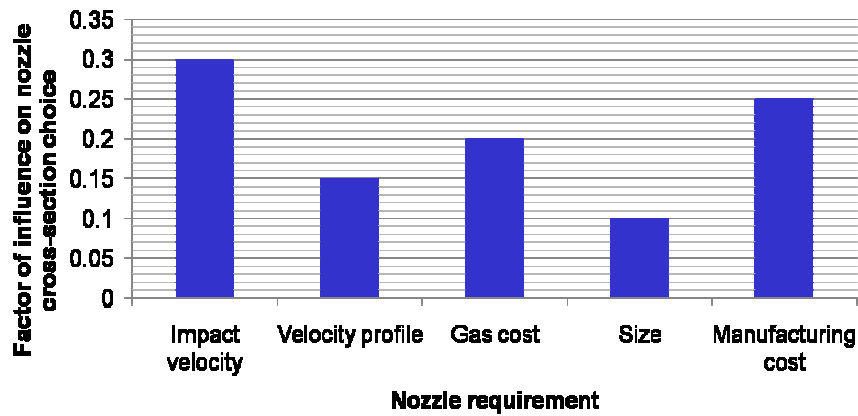
δ_{cl} = thickness of the coating sprayed in one pass (m)

ρ_c = coating density (kg/m^3)

Since in LPCGDS systems there is a maximum allowable value of the expansion ratio (A/A^*), this restricts the lengths and widths (H_c) of nozzles that may be used for accelerating the particles. This subsequently limits the areas where the spray system can be applied. A nozzle design that has lesser restrictions on its usage is therefore necessary so as to maximise the usage of the spray system.

The technology and therefore cost of manufacturing nozzles depend on their geometry and cross-section. Given that the nozzles are a consumable, they constitute a big percentage of spray costs and so, the type of nozzle to use is of importance in LPCGDS systems. Their design must allow for monitoring the temperature and pressure respectively of the propulsion gas on entering the nozzle. These nozzles are made from different materials such as stainless steel, tungsten carbide or plastic depending on the type of powder material being sprayed and, they should wear out internally at a slow rate to reduce their replacement times, hence cost. Figures 2.39(a, b) show respectively the influence of nozzle requirements on the nozzle geometry and cross-section to make use of.



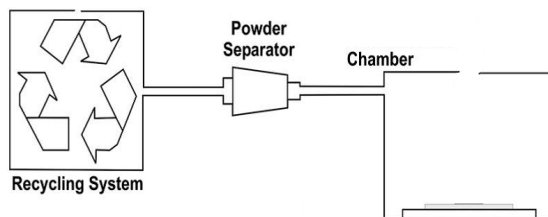


(b)

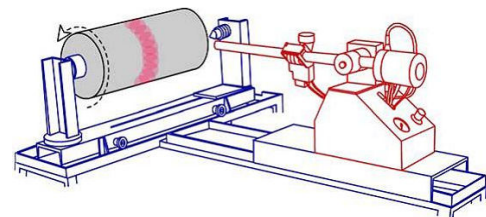
Figure 2.39: Nozzle requirements influence on (a) nozzle geometry and, (b) cross-section to use

2.5 Spraying chamber

Whenever possible, the spraying process should be done in a spraying chamber or fume hood (Figure 2.40(a)) housing the substrate and motion control system, Figure 2.40(b). In automated systems, the pre-chamber and nozzle assembly is mounted to the end of a robotic arm that is positioned by a hardware system and controlled by a personal computer (PC) using software (e.g. AutoCAD). The route of the nozzle is drawn using the software and, the nozzle move over the substrate along the route with a predetermined number of passes. When manually operated, the operator move and control the route of the nozzle over the substrate surface (see Appendix H4).



(a)



(b)

Figure 2.40: Schematic representation of (a) a recycling system configuration and (b) motion control system (Pattison et al., 2007b)

Effluent produced from the spraying process is a high-velocity jet of un-deposited powder particles and gas, which must be captured to protect process operators and the environment.

The chamber is properly ventilated to prevent explosions and suffocation of the personnel (Crawmer et al., 2004). Air suction fans provide sufficient suction-air velocity in the ductwork to draw the effluent from the spray chamber and; wet or dry dust collection equipment (e.g. powder separators and filters) are used for capturing un-deposited feedstock. A recycling system, Figure 2.40(a) then cleans up the gas for re-use.

The chart shown in Figure 2.41 represents the gas and powder costs associated with depositing 1 kg of Cu and Ti, using both N₂ and He - with and without recycling. Use of He recycling lead to gas costs of almost £0.8 per kg deposited, 3 times less the cost of spraying without He recycling. However, use of such expensive gases is made more cost-effective when using high-cost, high critical velocity powders that require an increase in DE (Pattison et al., 2007b).

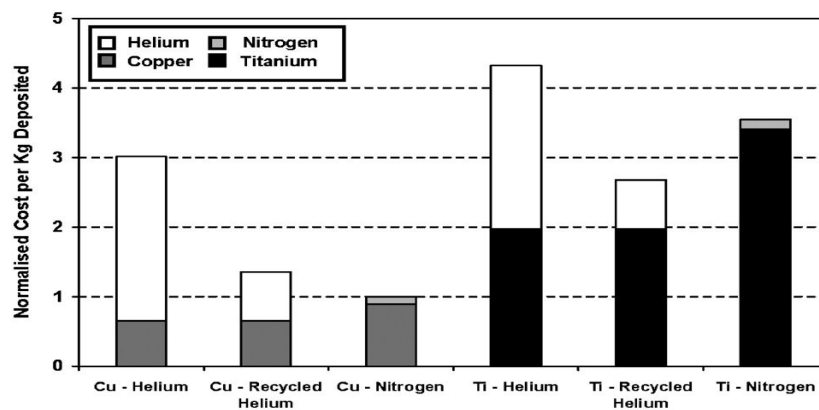


Figure 2.41: Chart showing the cost of deposition in terms of gas and powder used (Pattison et al., 2007b)

A variety of industrial gases are used for LPCGDS processing, including various inert gases. Although inert, serious harm can result from their misuse or mishandling, hence it is strongly recommended that respective material safety data sheets (MSDS) be consulted for proper storage and safe handling requirements of the feedstock materials and gases.

2.6 Data acquisition and control system

The data acquisition and control system (DACS) provides a convenient and precise process control while monitoring the system's settings and diagnostics. It ensures peak system

performance by accordingly adjusting powder feed rate, gas pressure and temperature in reference to the settings.

A pressure transducer is installed in the gas line to detect gas pressure before nozzle entry and, it produces an electrical signal to the DACS related to the pressure. This controller then regulates gas pressure by controlling electronic regulators and solenoid valves installed in the gas line. A flow meter is installed as an option to provide a precise measure of the flow rate and, for safety measures check valves are installed to prevent system over-pressurisation. Gas temperature is regulated by a thermocouple that's installed before the nozzle inlet. It converts the temperature proportionally into an electric voltage. This signal is processed in the DACS and then applied to a control rectifier which controls the gas heating by regulating current flowing to the heating element.

Powder flow rate from the feeder to the nozzle is measured through use of a piece of equipment that includes a light source and a sensor. The sensor determines particle flow rate based upon the amount of light it receives from the source that is able to penetrate the discharge line (Maev et al., 2008). It produces an electrical signal to the DACS related to the flow rate. The DACS then adjusts the flow rate by controlling the respective flow control mechanisms. In gravity-fed feeders, flow is controlled by varying the frequency and amplitude of oscillations imparted to their hoppers by vibratory motors whereas in volumetric powder feeders, flow is controlled by the rotational speed of the driving motor. The DACS controls flow in fluidised-bed powder feeders by varying the amount of feed gas supplied into the hopper.

The spray nozzle motion is controlled by a programmable robotic system and, the program that manipulates the robot is created using relevant software. The DACS provides not only real-time monitoring of these parameters, but the data is continuously collected and stored, and is available for subsequent analysis (Champagne et al., 2005b).

2.7 Coating quality analysis

Quality of LPCGDS coatings is mainly affected by the nature of impact of particles on deposition and the accompanying deformation processes. The quality analysis compares or

reference microstructures and properties of LPCGDS coatings with those of cold rolled electrolytic bulk material and TS coatings. Standard methods are used to characterise the coating properties for the as-sprayed states. These tests include; elastic modulus and coefficient of thermal expansion (CTE) measurements, hardness testing (Figure 2.42(a)), bond strength testing, wear resistance measurement (Figure 2.42(b)), and determination of the oxygen content and porosity levels by spectrometric analysis (field emission scanning electron microscope (FESEM) or optical microscope (OM)). A deeper view into the type of defects obtained, their stability and influence on recovery and recrystallisation is supplied by subsequent annealing procedures and respective analyses (Stoltenhoff et al., 2006).

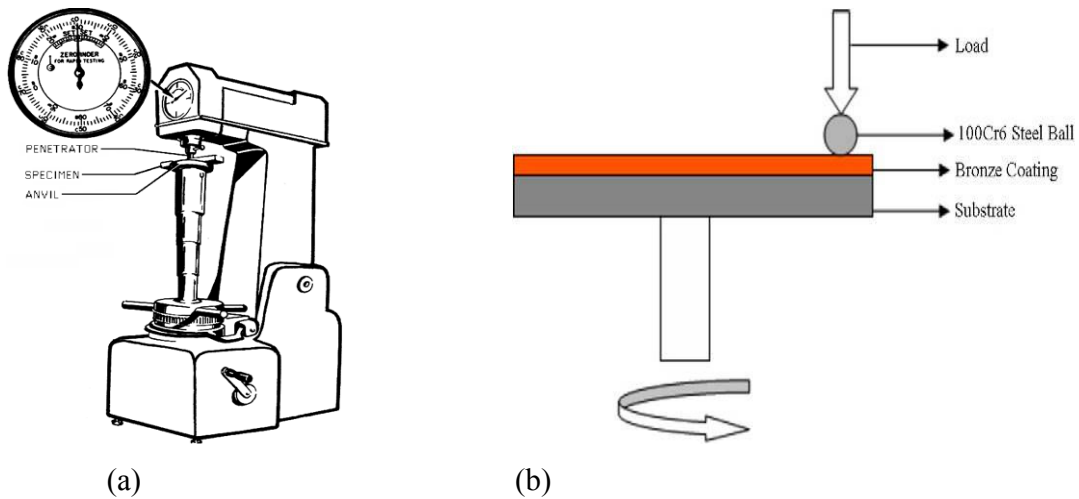


Figure 2.42: Schematic representation of (a) a Rockwell hardness tester and (b) wear (tribological) test apparatus (Guo et al., 2009)

The examined cross-sections are either polished or etched. When etched, particle/particle interfaces and also grain boundaries are rendered, revealing the highly localised particle deformation. By image analyses of etched coating cross-sections, the amount of well-bonded interfaces can be estimated and related to the overall particle/particle interface area (Stoltenhoff et al., 2006).

The LPCGDS system can be simulated through the ABAQUS/Explicit 6.7-2 finite element analysis method to observe how the parameters responsible for the bonding between the impacting particle and the substrate affect the quality of the resultant coating. This

modelling account for strain hardening, strain-rate hardening, thermal softening and heating due to frictional, plastic and viscous dissipation upon particle impact (Kumar et al., 2009).

2.8 Conclusion

The CGDS technology literature relevant to this dissertation has been reviewed and it has been established why cold spraying is generally preferred for some applications over TS technologies, the main reason being the elimination of the deleterious effects of high temperature such as oxidation. Also, it was noted that the particle KE at impact is typically lower than the particle melting energy signifying that the deposition mechanism is chiefly a solid-state process.

This chapter points out that the most important parameter in the CGDS process is v_p . An analytical solution for v_p at the nozzle exit, Equation 2.18 has been analysed to show how v_p relates with various gas, process and feed powder parameters. This velocity should exceed a minimum v_{crit} , Equation 2.20 on impact with the substrate and only particles whose velocity exceeds this value can be effectively deposited, resultantly producing the desired coating. Conversely, if particles do not reach this threshold velocity they actually bounce off or erode the substrate, Figure 2.19. In addition, it's shown how the resultant coating surface quality depends on the gas parameters, powder feeder design, nozzle geometry and powder feedstock characteristics. These must be critically chosen to obtain excellent results. The influences of LPCGDS system requirements on the selection of components to use in the spray system are presented graphically.

Lastly, a brief overview of the spraying chamber, a gas and particle recycling system, the DACS and, coating quality evaluation criteria is given. The following chapter will focus on the methodology used in conceptually designing the LPCGDS system.

3 METHODOLOGY

3.1 Introduction

Presented in this chapter is a model showing the aspects of a conceptual design process, the approach employed and the working steps followed in conceptual design of the LPCGDS system. The chapter details how the design process proceed from the task clarification stage to establish a LPCGDS system's requirements list, through the identification of the system components/sub-systems and the overall system structure, the generation, screening/selection and evaluation of sub-system variants, to the final documentation of the complete LPCGDS system set-up.

Use of both a screening matrix to narrow down the sub-system variants from a large number to a more manageable number for further evaluation; and an evaluation matrix in relation to the VDI 2225 guidelines (Pahl et al., 1996) for the evaluation procedure of the established variants to obtain an optimum system is demonstrated.

3.2 Model for a Conceptual Design Process

Figure 3.1 is a model showing the basic aspects of a conceptual design process. The process initiates with a starting point description of the design task or problem and qualities needed for coming up with a good design. A representation or schematic of the problem solution is then developed followed by the search process. Based on the representation, the search process is performed as an iterative loop of generating alternatives, evaluating their worth and redesigning them (Campbell et al., 2002) to improve their performance. Lastly, a final conceptual design is assembled to complete the conceptual design process (see Appendix G).

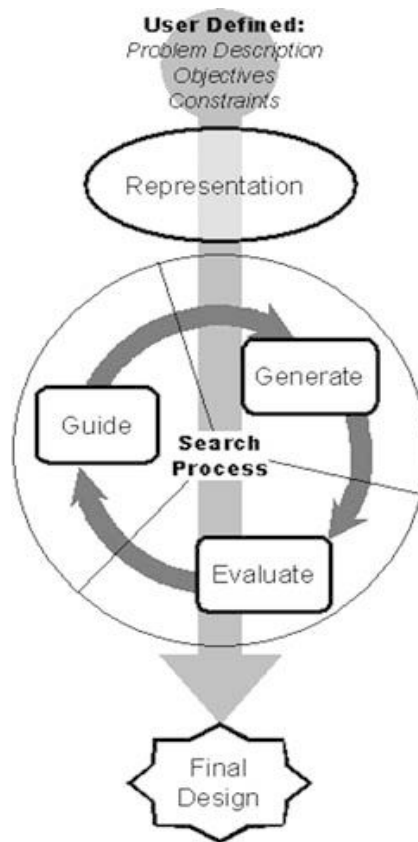


Figure 3.1: Aspects of a conceptual design process (Campbell et al., 2002)

3.3 Working Steps for the Conceptual Design of a LPCGDS System

Based on the model in Figure 3.1, flow of work during the conceptual design of a LPCGDS system is generated as illustrated in Figure 3.2 (Pahl et al., 1996). In principle, clarification of the LPCGDS system task is the first step (to establish a LPCGDS system's requirements list) followed by establishment of a system structure, the search and selection for sub-system variants (working principles) to fulfil these sub-systems, combining and firming up the selected variants, to their evaluation to get the best system set-up or principle solution.

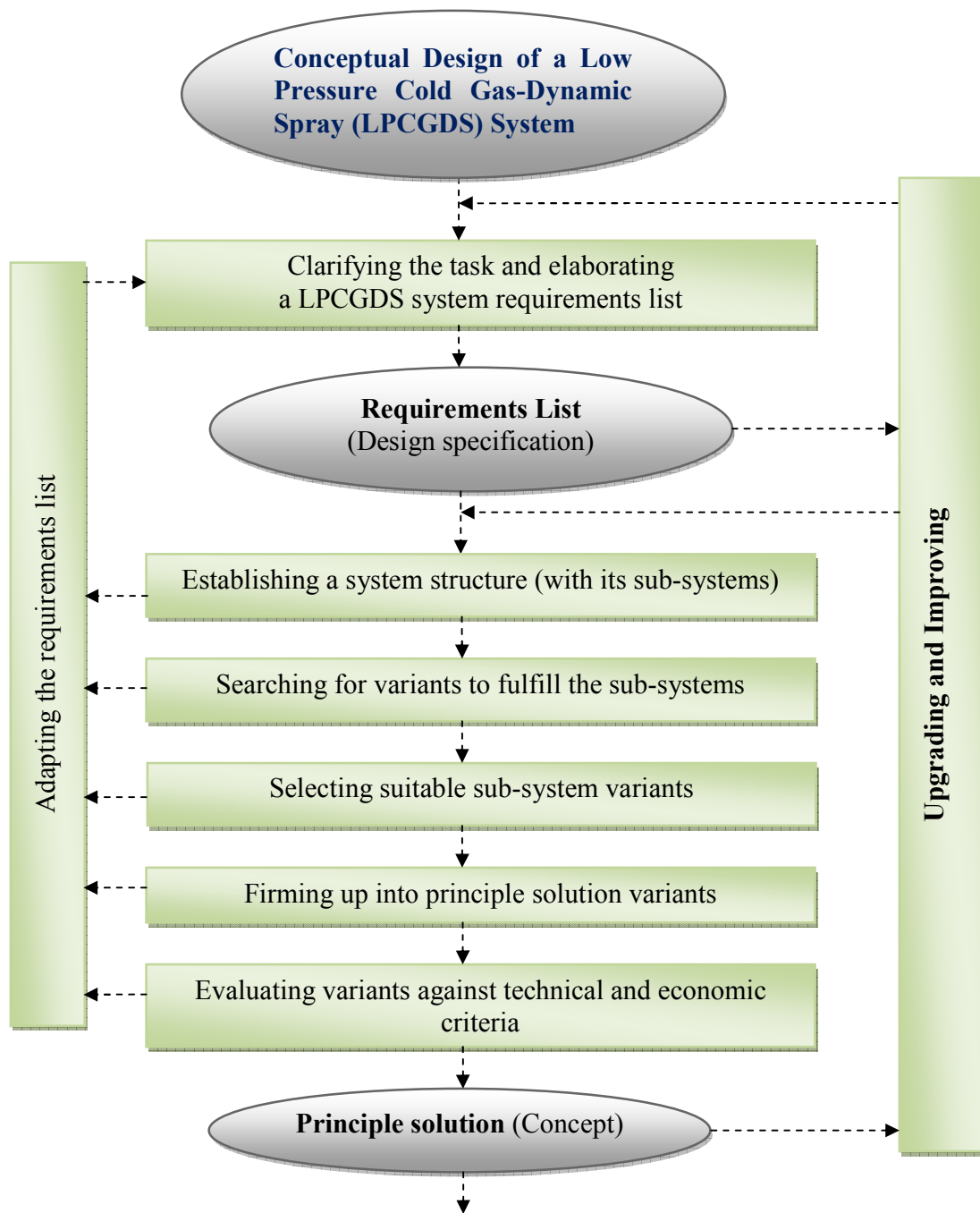


Figure 3.2: Working steps for the conceptual design of a LPCGDS system (Pahl et al., 1996)

Legend



A description of the activities involved in each step is listed below. Although the descriptions may give the impression that the steps are sequential and independent from each other, the iterative nature of application of the process as illustrated in Figure 3.2 is kept in mind throughout the system design (Khandani, 2005). Also, the steps followed in the design process show how the results of each prior step provide a basis for the subsequent step.

3.3.1 Clarifying the task and establishing a LPCGDS system requirements list

This phase of the design process make clear the necessary function that has to be fulfilled by the LPCGDS system. After clarifying the task, a LPCGDS system requirements list is drawn-up. This is done in reference to a checklist shown in Table 3.1 which reflects the general and specific constraints that the system must satisfy.

Table 3.1: Checklist for drawing up a requirements list (Pahl et al., 1996)

Main Headings	Examples
Geometry	Size and space requirement of the system components
Kinematics	Velocity of the gas-particle flow
Forces	Weight of the system components
Energy	Pressure and temperature of the gas-particle flow
Signals	Inputs and outputs signals, programming software
Safety	Protective systems, operational, operator and environmental safety
Material	Physical & chemical properties of the initial materials and final product
Maintenance	Cleaning and repair of the system
Ergonomics	Man-machine relationship
Production	Achievable product quality and tolerances
Quality control	Measuring and monitoring system parameters
Assembly	Special regulations, installation
Recycling	Waste disposal, reprocessing, reuse
Costs	Manufacturing costs

The requirements list (Table 3.2) outlines the LPCGDS system's constraints. The exact attributes essential about the system are highlighted in this list to help eliminate all but optimum system components. The following method is implemented for its compilation (Pahl et al., 1996);

- Asking what objectives the system must satisfy and the properties it must have.
- Determining the systems physical and functional characteristics.
- Analysing and quantifying the risk elements in the system.
- Establishing process control points, measuring criteria and measures of success for the inputs and outputs.
- Focusing on the checklist and determining the quantitative and qualitative data.
- Specifying demands and wishes clearly.

Table 3.2: Layout of a LPCGDS system requirements list (Pahl et al., 1996)

Requirements list for a low pressure cold gas-dynamic spray system	
d w	Requirements
Specify whether item is d or w	Objective or property with quantitative and qualitative data

d - demand
w - wish

The distinction between demands and wishes is important since sub-system variants screening/selection depend on the fulfilment of demands, while evaluation bears on only such variants as already meet the demands. This requirements list is updated continuously as indicated by the information feedback loop in Figure 3.2 and will be consulted always for successive decisions. The loop helps to stop development of unviable variants to minimise costs. Furthermore, besides affecting design of the LPCGDS sub-system variants, these requirements also influence one another; hence they are treated as guidelines throughout the design process.

3.3.2 Conceptual design

After establishing a LPCGDS system requirements list, the system structure is constructed and several sub-systems variants will be generated, screened, elaborated and evaluated based on both the overall system and the respective sub-systems requirements lists. This conceptual design phase resultantly determines the principle LPCGDS system set-up and it involves the following steps;

(a) Establishing the LPCGDS system structure

Once the overall LPCGDS system's requirements list has been established, the sub-systems are derived and then a system structure as indicated in Figure 3.3 is created, which is a graphical representation of the sub-systems (sub-system 1, sub-system 2 and sub-system 3) with their relationships organised in a logical manner. These sub-systems are organised in terms of flows; specifically flows of energy, matter and information through and between them (Maier et al., 2009) and are intended to facilitate the discovery of sub-systems variants (v1, v2 and v3).

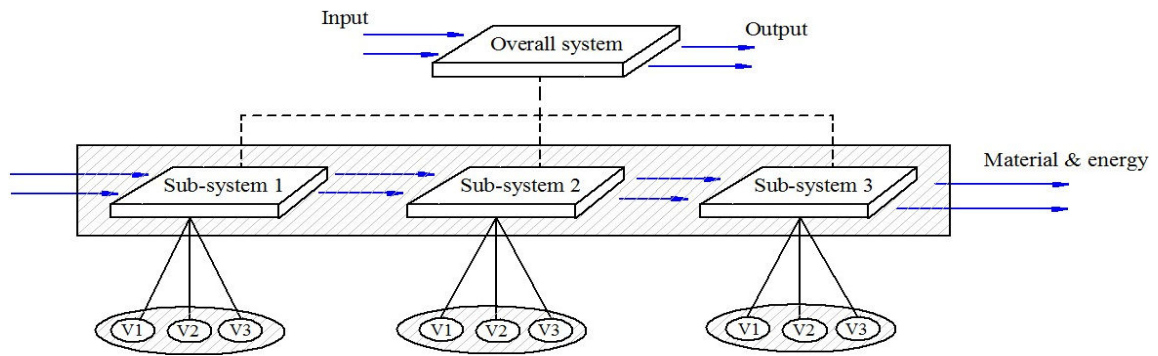


Figure 3.3: System structure diagram (Maier et al., 2009; Pahl et al., 1996)

(b) Searching for suitable LPCGDS sub-systems variants

Sub-systems variants are then generated based on the produced respective sub-systems requirements lists. These variants reflect the physical effect needed for the fulfillment of a given sub-system function; and also its geometric and material characteristics. All in all, they are generated by variation of firstly their physical effects and then their form design features (surfaces, motion and materials) that are essential for the sub-systems (Pahl et al., 1996). Areas of risks (technical, cost and schedule) in the variants are identified for use as both screening and evaluation criteria in the respective later stages.

(c) Selecting suitable variants and firming up into principle solution variants

The number of variants proposals that are created for each sub-system will be reduced at the earliest moment for the evaluation stage. The criteria used for the screening process considers variants that are compatible with the overall system structure (and with one another) and those that fulfill the demands of the respective requirements list. A quick systematic and approximate screening procedure, Table 3.3 (Ulrich et al., 2008) will be utilised to facilitate this selection process.

In the screening matrix (Table 3.3), selection criteria of the variants are placed in the first column and the respective variants to be selected in the subsequent columns. A reference variant (either industry standard or an off-the-shelf component) that will be utilised as the benchmark for the selection process is placed in the last column and its performance is rated using 0's. This reference meets the minimum requirements desired for each specific

component. The other variants are then rated against the reference and those that perform better than the reference are rated with +’s, variants that perform similarly compared to the reference are rated with 0’s and those that perform worse than the reference are rated with –’s (Ulrich et al., 2008).

Table 3.3: A screening matrix (Ulrich et al., 2008)

	Sub-system variants					
Selection criteria	v1	v2	v3	v4	v5	REF.
Quality of coating	+	0	-	0	0	0
Particle velocity	0	0	-	+	-	0
Manufacturing cost	+	+	+	0	+	0
Safety	+	+	+	+	+	0
Ease of use	0	+	0	0	0	0
Size	+	0	-	-	+	0
Pluses	4	3	2	2	3	
Same as	2	3	1	3	2	
Minuses	0	0	3	1	1	
Net score	4	3	-1	1	2	
Rank	1	2	5	4	3	
Continue	Yes	Yes	No	Yes	Yes	

Ranking of the variants follows after their rating. The pluses, same as, and minuses are summed up and the total for each category entered in the lower rows of the matrix. The net score is calculated by subtracting the number of minuses from the number of pluses. The variants are finally ranked according to their scores and those with +ve high totals selected (variants v1, v2, v4 and v5). However, the discarded variants are analysed to see if there are no good ones that would either have been degraded by a single bad feature so that two or more variants can be combined to preserve the better than qualities while canceling the worse than features (Ulrich et al., 2008). Selected solutions are further refined and firmed

up before a final evaluation that utilises more detailed and quantified criteria (Pahl et al., 1996).

(d) Evaluation of the selected sub-system variants to establish the optimum LPCGDS system make-up

An evaluation of a variant is meant to determine its strength or value with respect to its sub-system's constraints. It involves an assessment of the variant's technical, safety, environmental and economic values against the demands of the respective sub-system's requirements list. Figure 3.4 shows the steps involved from variants generation up to their evaluation (with reference to Table 3.3 and Table 3.4).

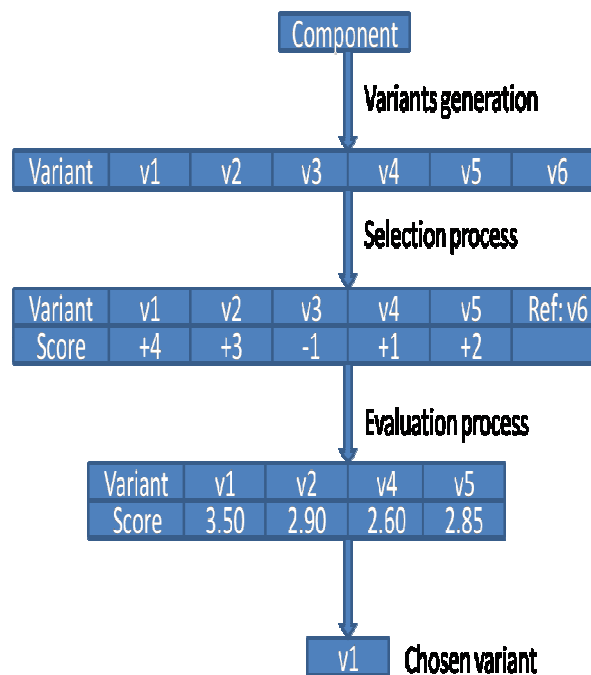


Figure 3.4: Steps involved from variants generation up to the evaluation process

Determination of each sub-system optimal variant (from the selected variants in the screening matrix, Table 3.3) will be done in two steps. Firstly, the constraints or requirements that each sub-system is supposed to meet are analysed for each variant in detail. After that, in accordance with the Guideline VDI 2225 (Pahl et al., 1996), the different variants are then evaluated based on an established evaluation matrix (Table 3.4)

that ensures all the LPCGDS system requirements are meet. Other techniques used to evaluate these selected variants include: Use-Value Analysis (UVA), Cost-Benefit Analysis (CBA), engineering analysis and benchmarking with competitive products (see Appendix H).

In an evaluation matrix, the desirable attributes or criteria for the sub-system (taken from the respective requirements list) are ranked in order of importance and placed in column 1 of the matrix. These attributes include factors such as particle velocity, safety, manufacturing considerations, the ease of fabrication and assembly, cost, durability, maintenance, size and portability. Weights representing relative importance of each attribute to the choice of a sub-system variant are assigned to each criterion and placed in column 2 of the matrix. The weights are assigned on a basis of 0 to 100%. Suppose the cost criteria has a weight of 30% in influencing the variant choice (Table 3.4) and is twice as important to the choice of the variant as size, a weight of 15% would be assigned for size (Khandani, 2005).

Table 3.4: An evaluation matrix (Pahl et al., 1996)

		Sub-system variants							
		v1		v2		v4		v5	
Criteria	Weight %	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating
Manufacturing cost	30	4	1.20	4	1.20	3	0.90	2	0.60
Particle velocity	25	4	1.00	2	0.50	2	0.50	4	1.00
Maintenance	20	4	0.80	3	0.60	4	0.80	3	0.60
Size	15	2	0.30	2	0.30	2	0.30	3	0.45
Safety	10	2	0.20	3	0.30	1	0.10	2	0.20
Total score			3.50		2.90		2.60		2.85

Next, the variants being evaluated are rated against the stated criteria. They are placed in subsequent columns of the matrix and a rating factor is assigned to each variant, based on how well that variant satisfies the given criterion. The rating factor is on a scale of 0 to 4, with a 0 score implying unsatisfactory performance, a 1 just tolerable performance, a 2 adequate, a 3 good and lastly a 4 implies very good performance (Pahl et al., 1996). Taking for example variant v1 on the criterion of manufacturing cost, each score or rating (4) that a variant achieves on a criterion is multiplied by the criterion weighting factor (30 %) to get a weight rating (1.20). These weight ratings are then summed up for each variant to get a total score (3.50). On the basis of this evaluation, the best variant will be chosen as the one with the highest summed up score (variant v1) (Jones, 1970).

3.3.3 Principle solution

In order to obtain an optimum overall LPCGDS system set-up, none of the above steps (a to d) may be skipped. The best overall system set-up will be constructed from the assembly of the chosen optimum sub-system variants; and the physical and geometrical compatibility of these combined variants will be ensured to assure a smooth flow of energy, material and signals. Also, this principle solution will be required to meet the criteria of the overall task, whether they are hard engineering requirements, such as space or power, or softer areas of concern such as economic or ethical requirements (Ruder et al., 2007). Finally, a bill of quantities (BOQ) of the overall spray system is compiled. This consists of the total components making up the system, their size and cost.

3.4 Conclusion

The chapter shows how the conceptual design process adopted progress from the task clarification stage to establish a LPCGDS system's requirements list (which specifies the systems information) up to constructing a complete LPCGDS system set-up. Accordingly, the produced requirements list (Table 3.2) not only reflects the initial position but, since it is continually reviewed (Figure 3.2) also serves as an up-to-date working document (Pahl et al., 1996).

A system structure that clearly defines the existing sub-systems and their relationships is established, facilitating the subsequent search for sub-system variants. An increase in the number of generated sub-system variants increases the probability of selecting the most appropriate ones (Borissova et al., 2006). Firstly all unsuitable variants are eliminated based on a screening matrix. The screening matrix trims down the feasible variants from a fairly large number to a more manageable number for further evaluation. During evaluation of the variants, the chief criteria are of a technical and economic nature. This evaluation stage answers the question; how does the variants project onto the requirements list and it results in the assembly of the optimum chosen sub-system variants to obtain the best overall LPCGDS system set-up.

The LPCGDS system's crux will be properly formulated in the next chapter in order to make clear its constraints and then generate the principle solution (Figure 3.2).

4 LPCGDS SYSTEM GENERATION AND ANALYSIS

4.1 Introduction

This chapter entails designing and generating a complete LPCGDS system. In accordance with Figure 3.2, firstly specifications of the overall spray system, systems inputs and outputs are determined; followed by the establishment of a system structure and the search for sub-system variants to fulfil their functions. The variants generated on each respective sub-system all have one ultimate function but different techniques to achieve it. During the chapter, requirements for the sub-systems are also drawn up and these will be used to eliminate variants that do not meet the respective sub-systems specification objectives.

Further presented is the selection and evaluation of sub-system variants developed to determine which variant is best for each sub-system. Determination of each optimum variant will be basically done in two steps. Firstly, the constraints or requirements that each sub-system is supposed to meet are analysed for each variant in detail. After that, in accordance with the Guideline VDI 2225, the variants are then evaluated based on an evaluation matrix established that ensures all the system requirements are met. The best variant on each sub-system is chosen by considering the one that attains the highest weight rating. Some of the techniques also employed in the evaluation includes: CBA, engineering analysis and benchmarking with competitive products. The overall system design is then assembled from the chosen best variants.

Also looked into is the system auxiliary equipment that includes the spraying chamber, gas & particle recycling system and different measures used to assess quality of the resultant coating. Measurement criteria for gas temperature, pressure and flow rate; particle flow rate from the feeder and their velocity on exiting the nozzle are also determined. The chapter ends with the compilation of the system's BOQ.

4.2 Clarifying the Task and Establishing a LPCGDS System Requirements List

The research conceptually design a LPCGDS system that will be utilised for fabrication, surface restoration and coating purposes. This spray system will be technically and economically viable, attaining uniform, dense and less porous coatings. From sections 2.2 - 2.7, the desired LPCGDS system properties are that;

- The system must impart supersonic velocity (300-600 m/s) to the feedstock powder particles to achieve deposition.
- The propellant gas must be heated enough ($\sim 400\text{ }^{\circ}\text{C}$) to increase its aerodynamic properties but not to melt and oxidise the particles in order to achieve low porous quality coatings ($<3\%$).
- The powder feeder must operate at atmospheric pressure (~ 10 bars) to increase the system's portability and significantly reduce spray costs (of using a high-pressure delivery system).
- Gas-particle mixture flow must be uniform to achieve uniform coatings, thus a constant powder flow rate from the feeder is required.
- The spray gun must be portable for easy attachment to a robot or an X-Y manipulator.
- The overall system must be effective and not expensive to construct.

After clarifying the task, a requirements list for the overall system is established and illustrated in Table 4.1. The requirements are arranged in accordance with the guidelines of Table 3.1.

Table 4.1: Requirements list for the overall LPCGDS system

Requirements list for the overall LPCGDS system	
d w	Requirements
w	1. <u>Geometry</u> All components should have the minimum possible dimensions to be able to attach to a robot
d	2. <u>Kinematics</u> A supersonic gas-particle velocity (of ~300-600 m/s) should be achieved to obtain particle deposition (Figure 2.20)
d	A constant gas-particle concentration should be maintained to get uniform coatings (Figure 2.31(a))
d	Powder particles to be radially feed into the nozzle after the throat to enable use of a low weight & cost powder feeder operating at atmospheric pressure (Figure 2.8)
w	3. <u>Energy</u> System to achieve a 70% DE
d	System to operate at a constant P_o (<10 bars) and T_o (<400 °C) to make use of a low pressure powder feeder and avoid particle oxidation respectively
d	4. <u>Signals</u> Should be able to measure P_o and T_o using respective transducers in order to control v_p and thus the coating quality (Figures 2.23(a) & 2.26)
d	5. <u>Safety</u> The system should have safety measures (e.g. check valves) to prevent accidents
d	It must be able to contain an explosion
d	6. <u>Quality</u> Coatings must be less porous (<3 %) (Figure 2.5)
w	7. <u>Operation</u> It should be operated by a non-specialist
d	8. <u>Recycling</u> Should be able to recycle the driving gas (Figure 2.40(a)) and easily dispose un-deposited particles to reduce operating costs
w	8. <u>Transport</u> It must be moved quickly and easily from place to place

4.3 Establishing the LPCGDS System Structure

The above formulation clarify, with respect to the LPCGDS functional relationships, that the system task is the application of coatings by exposing a substrate to a high velocity jet of small particles accelerated by a supersonic jet of compressed gas. The process is governed by particle velocities (300-600 m/s), gas temperatures ($<400\text{ }^{\circ}\text{C}$), atmospheric air pressure (~ 10 bars) and a constant supply of the feedstock particles from the powder feeder. Individual sub-systems that make up the overall system are derived from the requirements list in Table 4.1 and then the overall system structure drawn up. These sub-systems include the gas supply, gas heater, powder feeder, supersonic nozzle, spray chamber and DACS.

According to Figures 2.8 and 3.3, the overall LPCGDS system structure is derived in Figure 4.1 whereby the driving gas is supplied from a gas supply and passes through a gas heater where it's heated to a pre-set temperature. Powder particles are then injected (radially) downstream of the throat section of the nozzle into the gas stream from a powder feeder. This gas-particle mixture then exits the nozzle at supersonic speeds, impacting on a substrate housed in a spray chamber. The DACS is used to control and monitor the process parameters.

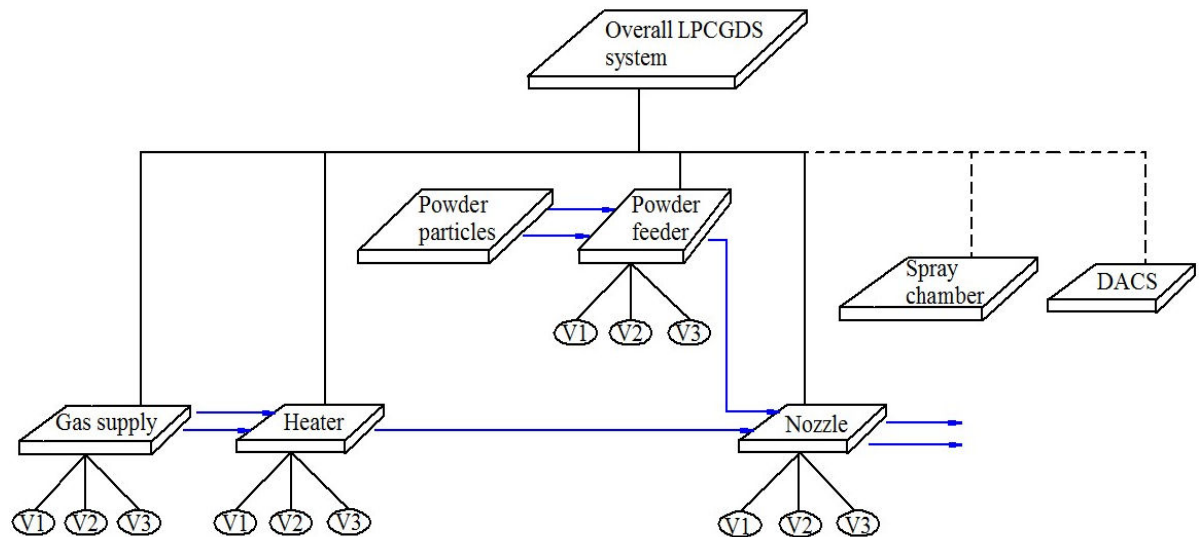


Figure 4.1: LPCGDS system structure (Maier et al., 2009; Pahl et al., 1996)

Having established the LPCGDS system structure, generation of the various sub-systems variants, their selection and evaluation follows.

4.4 Gas Supply

4.4.1 Gas supply requirements list

Quite a number of both naturally occurring and commercially produced gases exist. Gas type influences particle velocity (Figure 2.21) and resultantly the process DE (Figure 2.34(b)). Considering the gas supply literature in section 2.4.1, Table 4.2 illustrates the requirements for the propellant gas to be used in the LPCGDS system.

Table 4.2: Requirements list for the gas supply

Requirements list for the gas supply	
d w	Requirements
d w	1. <u>Forces</u> Pressure supply must range from 5 to 10 bars in order to utilise a low pressure powder feeder operating at atmospheric pressure (Figure 2.8) The gas must be of a lower molecular weight to achieve higher DE (Figure 2.22)
d w	2. <u>Material</u> The gas must be inert to avoid oxidation of the particles and have good aerodynamic properties to achieve high speeds The gas must not expand extremely
d	3. <u>Signal</u> Must be able to measure gas supply pressure and flow rate to enable control of v_p (Figures 2.23(a) and 2.31(a))
d	4. <u>Cost</u> The gas must be cheap and recyclable to reduce spraying costs
d d	5. <u>Safety</u> In case of passage blockages developing along the line and to avert gas explosions, the system must be able to relieve the gas pressure using e.g. pressure relief valves The gas must not be toxic

4.4.2 Gas supply variants selection

Based upon the gas requirements list (Table 4.2), a number of gases are chosen and screened in Table 4.3 for use as the propellant gas. Air is taken as the reference for the screening process. Mainly considered for the type of gas to use are its aerodynamic properties and cost, which if not carefully considered can render the process uneconomical. Choice of the gas also largely depends on the nature of the gas to avoid oxide contamination of the resultant coating structure.

Table 4.3: Gas supply variants screening matrix

	Gas supply variants					
Selection criteria	Helium (He)	Propane (C ₃ H ₈)	Nitrogen (N ₂)	Argon (Ar)	Nitrous oxide (N ₂ O)	Air
Particle impact velocity	+	-	+	0	-	0
Particle impact temperature	-	+	0	+	+	0
Particle oxidation	+	+	+	+	0	0
Molecular weight	+	-	+	-	-	0
Cost	-	-	-	-	-	0
Safety	0	-	0	0	-	0
Pluses	3	2	3	2	1	
Same as	1	0	2	2	1	
Minuses	2	4	1	2	4	
Net score	1	-2	2	0	-3	
Rank	2	4	1	3	5	
Continue	Yes	No	Yes	Yes	No	

From Table 4.3, He, N₂, Ar and air (which constitute - N₂ 79% + O₂ 21%) are selected for further evaluation.

4.4.3 Gas supply variants evaluation

Due to its monoatomic character, a larger specific heat ratio and a lower molecular weight (0.179 kg/m^3) (Equation 2.12), He is a much easier gas to work with for the driving gas (in place of N_2 and air) providing the highest possible supersonic gas-particle flow velocities and higher deposition efficiencies (Figure 2.34(b)). This results in obtaining denser coatings. Moreover, because of its ability to achieve a higher degree of particle bonding and compaction, He processed coatings display more compact structures and higher hardness values along cross-sectional surfaces (Balani et al., 2005b).

Since use of He generates a high degree of plastic deformation leading to high-density coatings, these coatings are highly stressed and undergo rapid corrosion kinetics compared to use of N_2 (1.251 kg/m^3) and air (1.292 kg/m^3). For this reason, N_2 and air sprayed coatings may present inferior hardness but their performance in terms of corrosion resistance fares better than the coatings deposited with He. Addition of N_2 in the He carrier gas accordingly helps improve the corrosion resistance of its coatings (Balani et al., 2005b). Further, owing to the higher degree of impact experienced in He processing, a higher temperature is experienced at the impact points and hence, generation of undesired oxides is more probable in He processed coatings (Stoltenhoff et al., 2006) compared to those of N_2 and air.

He is very expensive making its use economically impractical (Maev et al., 2008). Although the greater deposition efficiencies experienced when spraying with He generate powder-cost savings, these are small compared to the high gas costs. Recycling reduces the gas costs significantly but still cannot be justified for relatively cheap powders (Pattison et al., 2007b). Ar (1.784 kg/m^3) has properties much like He, but is relatively cheaper (although they are both expensive). Like He, it's also inert and as such, there is no in-flight oxidation of particles resulting in less oxide coatings. However, it is 10 times denser than He, thus harder to pump resulting in velocities lower than when using He.

Supersonic velocities obtained by N_2 and air are lower than with He, limiting the range of coatings that they can produce (see Appendix F1 and Figure 2.21). Also, an increased porosity is observed in the N_2 processed coatings indicating a fall in hardness values

(Balani et al., 2005b). On the other hand, N₂ is considerably less expensive while being equally capable of providing an oxygen free environment. As shown in Figure 4.2, use of N₂ (at 30 bars and 25 °C) is less costly, leading to gas costs of ZAR1.68 (£0.14) per minute, over 83 times less the cost of using He at the same conditions (Bray et al., 2008).

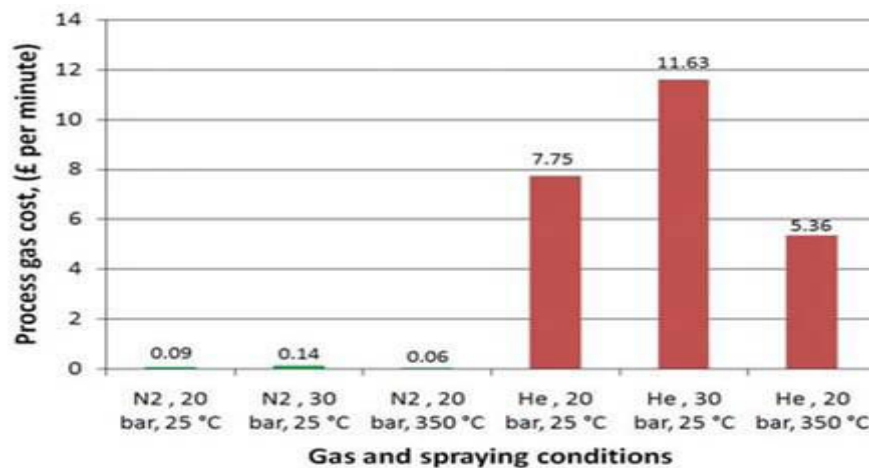


Figure 4.2: Comparison of process gas costs (Bray et al., 2008)

Air offers the least expensive alternative but has the narrowest range of applications, being generally limited to those processes that are not extremely sensitive to the presence of oxygen at low temperatures (Maev et al., 2008). However, with air as the accelerating gas, particle temperatures at the nozzle exit are much higher compared with N₂ and He gases owing to its low expansion coefficient (Li et al., 2006). This helps lower down the particle critical velocities needed for deposition, subsequently increasing DE and reducing spraying costs.

Although He and Ar are non-toxic, they do not satisfy the human body's need for oxygen and are thus asphyxiates (suffocates). They are highly dangerous in closed areas since they are difficult to detect (as they are colorless, odorless and tasteless), resulting in death due to asphyxiation/suffocation. Leakage of N₂ into an enclosed space displaces oxygen, and therefore represents an asphyxiation hazard too. The suffocation happens with few warning symptoms, since the human body is a relatively slow and a poor low-oxygen sensing system. Conversely, air has no biological side effects even in the case of leakages, thus is the safest gas to make use of. These gases have been evaluated in Table 4.4 based on Figure 2.25 to obtain the best gas to make use of as the propellant media for the powder particles.

Table 4.4: Evaluation of the gas supply

		Gas supply variants							
		Helium		Nitrogen		Argon		Air	
Criteria	Weight %	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating
Particle velocity	30	4	1.20	3	0.90	2	0.60	3	0.90
Particle oxidation	25	4	1.00	3	0.75	4	1.00	2	0.50
Particle temperature	20	2	0.40	3	0.60	4	0.80	4	0.80
Cost	15	1	0.15	3	0.45	2	0.30	4	0.60
Safety	10	2	0.20	3	0.30	2	0.20	4	0.40
			2.95		3.00		2.90		3.20

Since air has the highest weighted rating of all the gases from the table, it is considered to be the most cost-effective gas to make use of as the propellant for the particles. An air compressor will be used to provide the required air pressure of ~5-10 bars.

4.5 Gas Heater

4.5.1 Gas heater requirements list

Temperature of the gas and thus particle temperature influence particle velocity (Figure 2.26, Equation 2.18) and critical velocity (Figure 2.27). Furthermore, particle deposition is not realised below a certain inlet gas temperature (see Appendix F2). Above this threshold, the DE increases with inlet gas temperature, consistent with increasing particle velocities (Van Steenkiste et al., 1999). Heating a gas can be accomplished using several heater types. Some heaters are directly immersed in the gas stream, while others are better suited for heating a pipe or vessel containing the gas. Requirements for the development of gas heater variants are derived from section 2.4.2 and illustrated in Table 4.5.

Table 4.5: Requirements list for the gas heater

Requirements list for the gas heater	
d w	Requirements
w	1. <u>Geometry</u> It should have the minimum possible dimensions and a few energy-intense units to conserve power
d	2. <u>Forces</u> Should have a light weight (<10 kg) to be able to attach to a robot (Figure 2.40 (b))
w	3. <u>Energy</u> To be connected to a 240 V supply
d	Must heat gas to a temperature of ~ 400 °C for different applications
d	Must maintain a constant T_o to get a constant v_p thus uniform coatings (Figure 2.26)
d	4. <u>Signal</u> Temperature of gas exiting the heater must be easily measured and adjusted to enable control of the respective T_p and v_p (Figure 2.26)
w	Heater material temperatures must be monitored to prevent damage to itself and the surroundings
d	5. <u>Operation</u> Should not introduce significant hydrodynamic resistance in operation to reduce power consumption
d	Must reach a necessary ohmic resistance, be reliable and convenient in use
d	6. <u>Maintenance</u> It should be easily repaired and cleaned without having to disassemble the whole heater to cut down on down times
d	6. <u>Costs</u> Must be simple to manufacture to reduce production costs
d	7. <u>Safety</u> The gas heater should be safe to operate and the heating element surface should not be heated above a temperature determined by the structural strength of the element material to avoid heater damage

4.5.2 Gas heater variants generation

Different gas heaters are developed based on the gas heater requirements list in Table 4.5 and their applications described to give an idea of how they heat the gas.

a) Parallel tube heater

In a parallel tube heater, Figure 4.3 gas passes through parallel tubes heated by an electric current and, these tubes are connected into the electric circuit in series. Cold gas from the supply first enters the primary contour formed by the casing and pipes support, and then enters the secondary contour consisting of parallel tubes. Heat transfer to the gas in the heated tubes is mainly by radiation and convection. After being heated within the tubes, it then leaves the heater and enters the nozzle (Johnson, 2005).

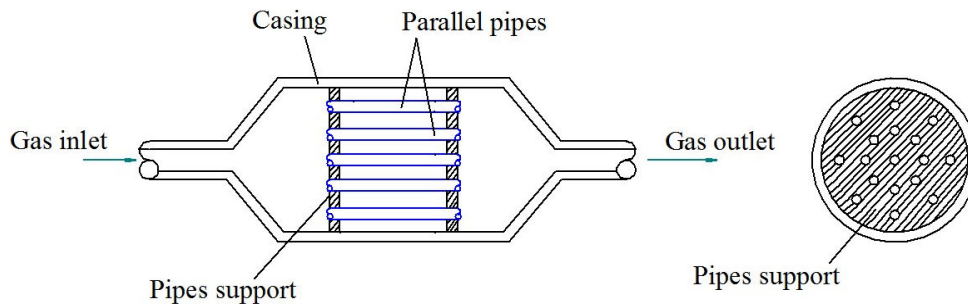


Figure 4.3: Parallel tube heater (Johnson, 2005)

b) Filament heater

A filament heater, Figure 4.4 consists of metal filaments (core of the heater), the surfaces of which are coated with insulation layers. Cold gas enters from the inlet end and flows past the coated filaments up to the outlet. An electric current (of density j) passes along the filaments. The Joule heat released by this process is transmitted from the filaments to the outer surface of the insulation layers by heat conduction. From the outer surfaces of the insulation layers, thermal energy is radiated into the gas space, heating up the gas (Tsymbalov et al., 1971). The gas is also heated by conduction as it contacts surfaces of the hot insulation layers. On exiting the heater, the gas is now at an elevated temperature.

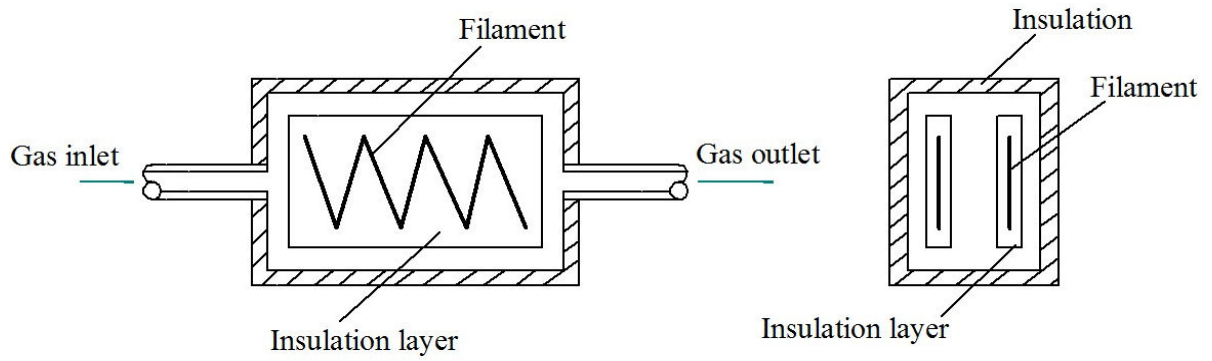


Figure 4.4: Filament heater (Tsymbalov et al., 1971)

c) Flat panel heater

A flat panel heater is illustrated in Figure 4.5. It consists of two electrically heated panels that have a casted serpentine gas passage. Gas enters the heater from the entry end and flows in the heater along the winding passage to the exit. As the gas travels in this passage, it gathers heat from the hot panels by convection and conduction. This winding passage intensifies residence time of the gas in the heater, ensuring the gas is heated to preset temperature.

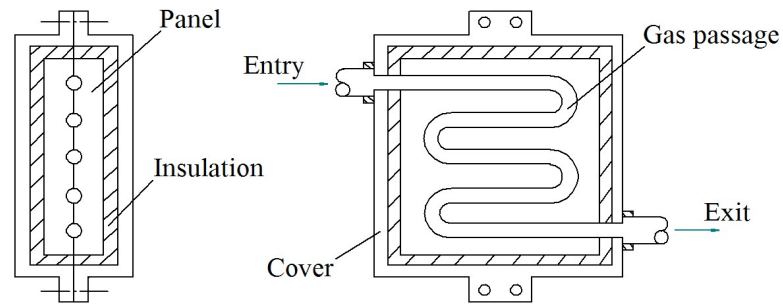


Figure 4.5: Flat panel heater

d) Coil heater

Figure 4.6 shows a coil heater (Papyrin et al., 2007) whereby a straight tube heating element is wound or coiled into a spiral and connected to an electric circuit to effect heating. Cold gas enters the input end of the coil heater and follows the geometry of the hot coil to the output end where it exits being hot. Heat transfer to the gas from the coil is primarily by conduction and convection.

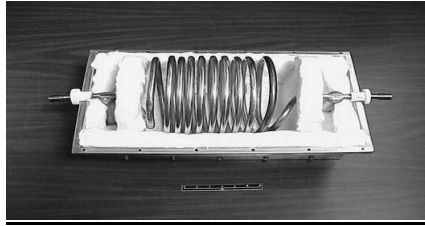


Figure 4.6: Coil heater (Papyrin et al., 2007)

Coil heaters are capable of producing high heat in relatively small areas due to their broader surface area coverage, and they are especially effective in generating heat when allowed to transfer heat directly through contact.

e) Bar heater

In a bar heater, Figure 4.7 electrically heated bars are mounted in an array and immersed in a vessel chamber through which gas flows. Gas enters the space between the entry and bars firstly, and thereafter enters the region consisting of the hot bars where it will be heated before exiting the heater. As the figure presents, the bars make a gas circulation passage that improves the residence time of gas in the heater, thus high heater efficiency. Since the bars are immersed in the heater chamber, their potential is fully utilised through a combination of radiation and convection heating of the gas. The bars can also be modified with fins to increase surface area for enhanced heat transfer.

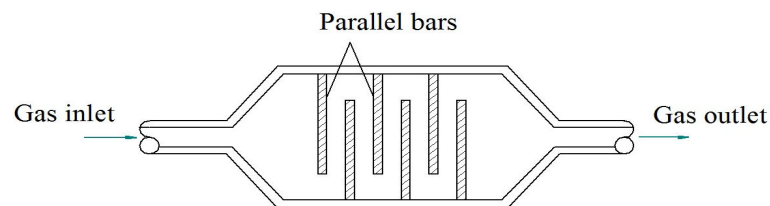


Figure 4.7: Bar heater

f) Perforated plate matrix heater

A perforated plate matrix heater shown schematically in Figure 4.8 (Krishnakumar et al., 2003) essentially consists of a stack of high thermal conductivity perforated plates alternating with also high thermal conductivity spacers. These plates and spacers are

connected to an electric circuit for heating purposes. As gas enters the heater from its supply, convective heat transfer between itself and the hot perforated plates takes place on three surfaces: the front face of the plates, the tubular surface of the perforations and on the back face of the plates. The gaps in between the plates ensure uniform flow distribution by continuous re-headering and create turbulence which enhances heat transfer between the gas particles.

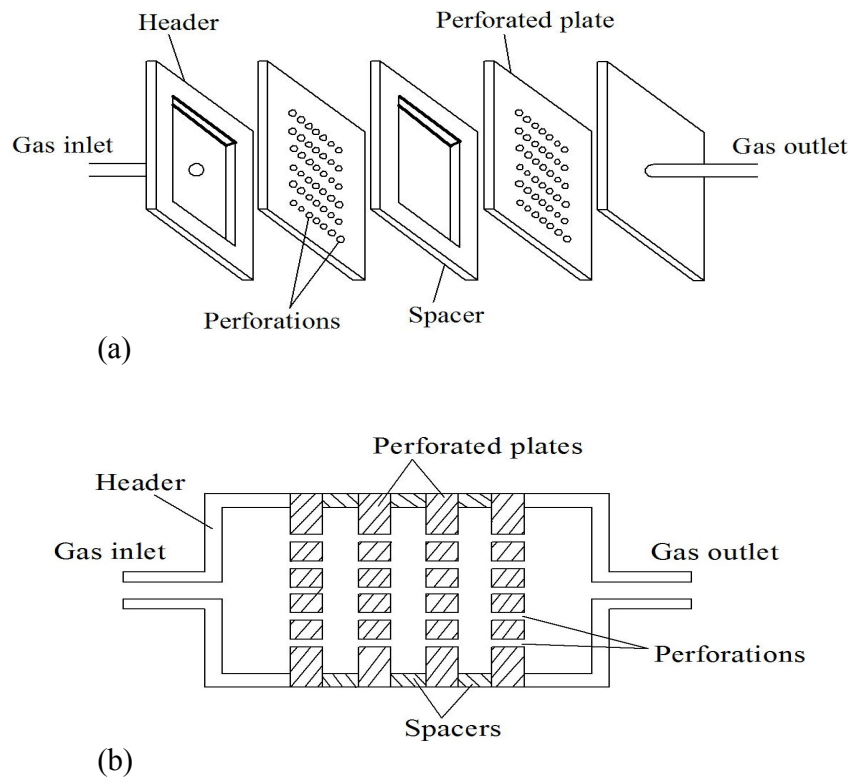


Figure 4.8: Perforated plate matrix heater; (a) isometric view, (b) cross-sectional view (Krishnakumar et al., 2003)

4.5.3 Gas heater variants selection

Mostly looked at in the screening of the gas heater (Table 4.6) is its cost and ability to be easily adjusted to enable control of particle temperature. Also of importance is its weight so that it can be easily carried around during spraying applications and that it conveniently be attached to the end effector of a multi-axis robot or other motion control systems. The filament heater is taken as the reference for the screening process.

Table 4.6: Gas heater variants screening matrix

	Gas heater variants					
Selection criteria	Parallel tube	Flat panel	Coil	Bar	Perforated plate	Filament
Ease of control	+	-	+	0	0	0
Weight	-	-	+	0	-	0
Manufacturing cost	+	+	+	+	+	0
Power consumption	0	-	0	-	-	0
Reliability	+	0	+	+	+	0
Safety	0	-	+	0	0	0
Pluses	3	1	5	2	2	
Same as	2	1	1	3	2	
Minuses	1	4	0	1	2	
Net score	2	-3	5	1	0	
Rank	2	5	1	3	4	
Continue	Yes	No	Yes	Yes	Yes	

Based on the gas heater variants screening matrix in Table 4.6, the parallel tube, coil, bar and perforated plate heaters are selected for further analysis and evaluation.

4.5.4 Gas heater variants evaluation

The parallel tube heater is simple in construction and most reliable in operation. It allows reaching a necessary ohmic resistance for gas heating easily and has a substantial decrease in its hydrodynamic resistance. Its temperature can be controlled within 2% of the set point temperature after the system reaches steady-state operation (Balani et al., 2005). However, a considerable amount of power (compared to the coil heater) is needed to electrically heat the several numbers of tubes in the heater to achieve the gas-heating effect.

Like a parallel tube heater, a coil heater is also simple, highly reliable and safe to operate. Its ohmic heating does not introduce any admixtures into the driving gas and correspondingly into the coating, resulting in chemically pure coatings (Papyrin et al., 2007). In addition, it provides consistent and exact outlet gas temperatures to obtain a constant corresponding particle velocity (Figure 2.26). This assures getting coatings with uniform consistent structures too. A coil heater has a smaller space requirement and lightweight making it more portable, thus allowing it to be easily mounted onto a motion control system. Its design facilitates replacement of the coil element without disassembling the complete heater resulting in reduced maintenance time and increased productivity. Also, due to its lower wattages requirement, a coil heater is cheaper to run.

In a bar heater, there is little control or flexibility over heat output and consequently the outlet gas temperatures are inconsistent. This results in varying particle impact velocities, (Figure 2.26) adversely affecting uniformity of the deposits. Also, it uses a lot of power, hence is relatively expensive to run. The bar heater together with the parallel tube and perforated plate heaters all have withdrawable elements that need the heater to be completely disassembled during maintenance and this increase maintenance time & cost, and reduce productivity.

A perforated plate heater is highly effective. The small flow passages in the plates ensure a high heat transfer coefficient and, the heat transfer rate in the back face of the plates is also high due to the resulting turbulence (Krishnakumar et al., 2003). However, this type of heater is expensive to construct and control of the system temperature is complex. Also, both itself and the bar heater have increased weights making them un-portable for the purpose of being carried around or attached to a robot. These gas heaters have been evaluated in Table 4.7 based upon Figure 2.30 with the evaluation criteria placed in column 1 of the table.

Table 4.7: Evaluation of the gas heaters

		Gas heater variants							
		Parallel tube		Coil		Bar		Perforated plate	
Criteria	Weight %	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating
Coating quality	25	4	1.00	4	1.00	2	0.50	4	1.00
Operation	20	4	0.80	4	0.80	3	0.60	3	0.60
Manufacturing cost	20	3	0.60	4	0.80	3	0.60	2	0.40
Size	20	3	0.60	4	0.80	4	0.80	3	0.60
Easy maintenance	15	2	0.30	4	0.60	3	0.45	2	0.30
			3.30		4.00		2.95		2.90

Considering the total weight ratings for each heater, the coil variant type obtained a higher score (4.00) of all the four. It is thus selected as the most viable heater to utilise in the LPCGDS system.

4.6 The Powder Feeder

4.6.1 Powder feeder requirements list

Various feeders are utilised for the injection of powder particles into nozzles and a number of factors condition the development of these feeder variants. Given that the nozzle injection point is at a lower pressure than the atmospheric pressure, (Equation 2.1) atmospheric air is used for powder transport from the hopper to the nozzle. In this case non-pressurised feeders (<10 bars) are utilised in the LPCGDS applications. From section 2.4.3, Table 4.8 gives a requirements list for all the other constraints considered in coming up with the different powder feeder designs.

Table 4.8: Requirements list for the powder feeder

Requirements list for the powder feeder	
d w	Requirements
d	1. <u>Kinematics</u> Feed-rate of particles should be easily controllable and adjustable to regulate the particle mass loading effect (Figure 2.31(a)) thus coating density
d	2. <u>Forces</u> It must operate at atmospheric pressure (~10 bars) and be non-pressurised (Figure 2.8) to reduce its cost and weight
d	3. <u>Signal</u> Particle flow rate must be easily measured in order to regulate the flow rate
d	4. <u>Operation</u> Must provide a reliable and uniform controlled supply of the powder with minimal or no pulsing to achieve a constant v_p (Figure 2.31(a))
w	Be able to feed more than one type of particles into the nozzle at the same time to spray composite materials
d	5. <u>Costs</u> It must be cheaply and easily made to reduce its cost of production
w	No special tools needed to disassemble the feeder
d	6. <u>Maintenance</u> It should be easily repaired without having to disassemble the whole feeder to reduce down times
w	To be easily and quickly cleaned within ~10-15 min to reduce stoppage times
w	Re-filling of powder to be done within ~2-3 min and must be done whilst the feeder is in operation

4.6.2 Powder feeder variants generation

Taking into account the powder feeder requirements in Table 4.8, various types of powder feeders are generated.

a) Screw feeder

The screw feeder, Figure 4.9 (Rhodes et al., 2001) comprises a powder hopper that contains the powder, a hopper lid for the periodic addition of powder, a fine particle screw and a screw shell, a motor drive and the powder outlet.

As the screw rotates, particles are forced to move under gravity from the hopper into the screw shell where they are conveyed by the screw to the outlet of the feeder and deposited directly into the nozzle. The progressive pitch screw allows material to be drawn off from the hopper for the entire length of the hopper bottom to ensure a steady material flow. Near vertical walls of the hopper prevent material bridging with non-free flowing powders and the differential pitch profile of the screw compress the particles (as they move to the outlet) to form a positive and continuous pressure seal. Powder feed rate is proportional to the rotational speed of the screw (see Appendix H2, Figure H4), and as such it's regulated by varying the speed at which the motor drive rotates (Equation 2.29).

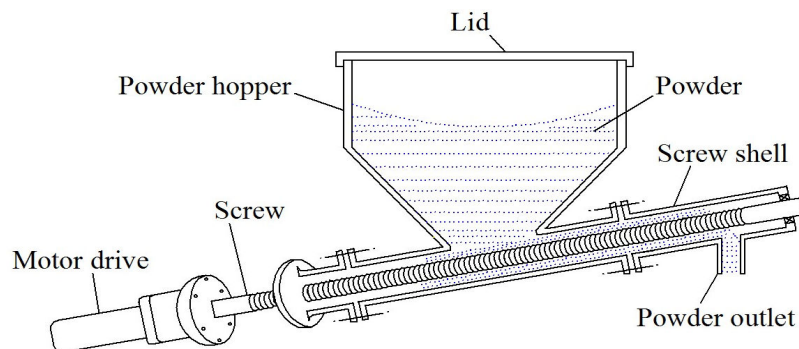


Figure 4.9: Screw feeder (Rhodes et al., 2001)

b) Rotary airlock feeder

With reference to Figure 4.10, a rotary airlock feeder consists of a hopper, an ultra-fine powder rotor connected to a motor drive, and a rotor body/case. It utilises a positive-displacement mechanism (rotor) to deliver precise parcels of powder to the powder-fed delivery tube leading to the nozzle. The rotor consists of segmented pockets and as it rotates within the bed of powder, it collects or picks-up (Marcus et al., 1990) particles from the hopper. After going through a half revolution, it then delivers the particles to a powder-

fed delivery tube that leads to the conveying gas stream in the nozzle. As the name implies, the feeder provides a pressure seal that prevents backflow of particles into the hopper in the event that a high pressure is existing below the rotor than in the hopper.

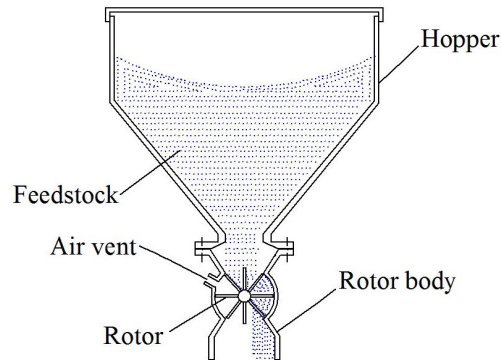


Figure 4.10: Rotary airlock feeder (Marcus et al., 1990)

Since the rotary airlock feeder is a positive displacement device, the powder feed rate is proportional to the rotational speed of the rotor (Equation 2.29). The motor drive has a variable speed control enabling the particles to be fed at a controlled and variable rate into the gas stream (Rhodes et al., 2001).

c) Gravity feeder

Discharge of powder particles from a gravity feeder, Figure 4.11 is fairly simple since they only flow under gravity to the point of injection on the nozzle. Flow rate depends on the level of particles in the hopper and, it needs to be full always so that the gravity head of particles is approximately constant to achieve a consistent feed rate. Uneven and somewhat sporadic particle flow often occurs when the hopper nears an empty condition.

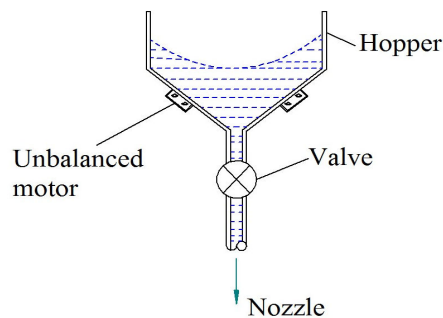


Figure 4.11: Gravity feeder

Due to flow of particles under gravity only in this feeder, it is difficult to provide a uniform particle feed rate because of powder agglomeration and clogging within the hopper itself. To reduce this problem and thus improve particle flow, unbalanced motors are mounted to the body of the hopper imparting a vibratory motion which helps minimise particle agglomeration. Powder feed rate is set proportional to the speed of rotation of the unbalanced motors and, an increase in their rotation results in a proportional increase in the feed rate. A valve is included in the powder discharge line to help adjust the flow.

d) Fluidised bed feeder

As shown in Figure 4.12, a fluidised bed feeder consists of a supply hopper (1) that contains the powder particles (9). The carrier gas conduit (5) passes through the bottom portion of the hopper and it incorporates a powder pickup device (3) which has powder intake orifices (6) within the hopper below the level of the powdered solids. The feed gas is admitted to the bottom of the hopper and gas distributor (8) by tube (7) and passes through the static mass of solids to the zone of fluidisation where the powder particles become suspended in the gas. When the carrier gas passes across the powder intake orifices (6) it creates a venturi effect that draws in powder from the hopper through the orifices and into the carrier conduit (5) where it conveys the powder to the nozzle (Maev et al., 2008).

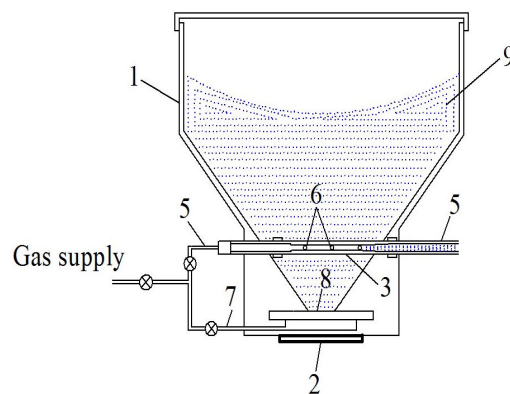


Figure 4.12: Fluidised bed feeder (Maev et al., 2008)

The feeder is equipped with a vibrator (2) which is used to maintain the powder in loose free-flowing form and permeable to the passage of gas. Powder feed rate is controlled by

varying the venturi effect that is created when the carrier gas passes across the powder intake orifices (6). To maintain a constant feed rate, a constant carrier gas flow rate and pressure should be achieved in the carrier conduit (5). Too much feed air or non-uniform distribution of that air in the gas distributor (8) results in extremely violent fluidisation causing the gas conduit (5) or nozzle to mainly draw air only and reduce the powder flow rate; resultantly the efficiency of the system reduces. Pressure in the carrier conduit (5) is kept slightly above the nozzle entry pressure (P_o) in order to be able to feed the powder particles into the nozzle and prevent their back flow.

e) Rotating wheel feeder

A rotating wheel feeder, Figure 4.13 utilises a continuous circumferential groove in a powder-feed wheel, which fills with powder by gravity, to move the powder particles from the pick-up area to the powder outlet. The powder outlet is then connected to the nozzle by a powder-fed delivery tube. As the carrier gas flows through the nozzle, it creates a vacuum in the powder-fed delivery tube that sucks the powder out of the wheel groove at the powder outlet into the nozzle (Crawmer, 2004). In this case the nozzle is said to be aspirating. A mechanical stirrer helps to maintain a more consistent powder bed density above the feed slots, ensuring uniform filling of powder in the groove.

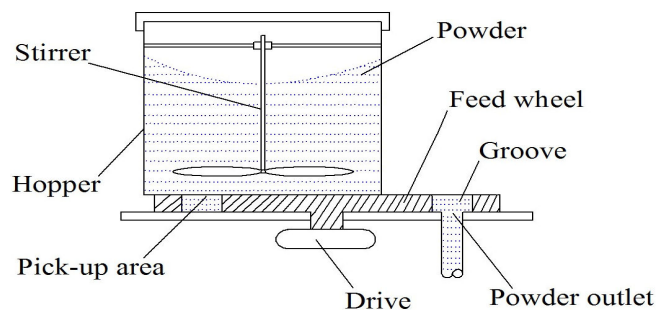


Figure 4.13: Rotating wheel feeder (Crawmer, 2004)

Essentially, a rotating wheel feeder is a positive displacement feeder, and as such the powder feed rate is proportional to the rotational speed of the wheel. The drive of the wheel can be varied in speed, ensuring a control of the particle feed rate (Crawmer, 2004).

f) Pump feeder

A pump feeder (Figure 4.14) consist of a vacuum pump, feed gas, powder hopper, the powder feeding line, 4 valves (1,2,3,4) made of special elastic tubes that can be opened and closed mechanically by pistons and a defined volume (dose). Instead of using the pneumatic convey for particle transport through the feeding line to the nozzle (like in most powder feeders), it uses the dense phase convey concept (see Appendix H2, Figure H7). The pressure difference between valves 4 and 3 is responsible for feeding the particles; instead of the feeding gas flow rate. When valves 3 and 4 are closed and valves 1 and 2 are open, powder is aspirated out of the hopper into the dose due to the pressure drop produced by the vacuum pump. After that, valves 1 and 2 are closed and valves 3 and 4 opened. Now the powder is pressed out of the dose into the powder feeding line (Dvorak, 2006).

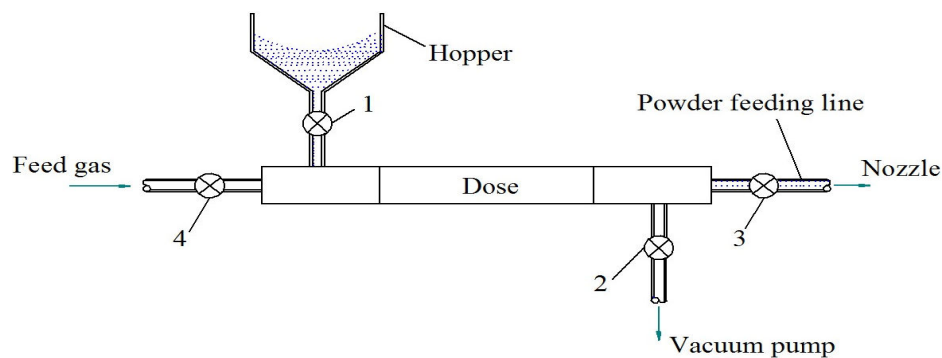


Figure 4.14: Pump feeder (Dvorak, 2006)

Particle flow rate is controlled by mechanical variation of the volume of the dose within in a given range. Since no mechanical parts are in the contact with the powder, no excessive wearing of the parts is experienced. Furthermore the system is self-cleaning (Dvorak, 2006).

4.6.3 Powder feeder variants selection

During screening of the powder feeder variants in Table 4.9, the main constraint considered is the feeder ability to dispatch a uniform controlled supply of the powder with minimal or no pulsing to obtain a constant feedrate and thus constant particle velocity, Figure 2.31(a). The fluidised bed feeder is taken as the reference for the assessment process.

Table 4.9: Powder feeder variants screening matrix

	Powder feeder variants					
Selection criteria	Screw	Rotary air lock	Gravity	Rotating wheel	Pump	Fluidised bed
Ease of control	+	+	-	0	0	0
Size	0	0	+	0	-	0
Manufacturing cost	+	+	+	+	-	0
Maintenance	0	+	0	+	0	0
Reliability	+	+	-	0	0	0
Pluses	3	4	2	2	0	
Same as	2	1	1	3	3	
Minuses	0	0	2	0	2	
Net score	3	4	0	2	-2	
Rank	2	1	4	3	5	
Continue	Yes	Yes	No	Yes	No	

According to the powder feeder variants screening matrix, Table 4.9 the screw, rotary air lock, rotating wheel and fluidised bed powder feeders are selected for further evaluation.

4.6.4 Powder feeder variants evaluation

By virtue of its design, a rotary air lock feeder provides the most positive means of delivering powder in an accurate and consistent manner. Erratic flows caused by powder lumping or bridging and other problems such as pulsation are easily overcome by the positive feeding nature of the rotor. This ensures that uniform coating microstructures are easily attained. Rotary air lock feeder maintenance is simple; the wear resistant blades can be exchanged comparatively easy, without disassembling the feeder. This helps cut down on downtimes, effectively increasing the production times.

In a fluidised bed feeder, powder feed rate is controlled at a constant rate by the regulated amount of feed gas supplied into the hopper. A vibrator is also mounted to the base of its main body to maintain the powder in loose free-flowing form making it easier to control the powder feed rate. A fluidised bed feeder does not experience the pulsing sometimes exhibited by rotary and screw feeders. It however experience powder mass flow variations as a function of variations in either carrier gas supply or nozzle back-pressures (Maev et al., 2008). This results in varying particle velocities (Figure 2.31a), and as a result, the deposition of un-desired non-uniform coatings on the substrate. The fluidised bed feeder requires a lot of maintenance compared to the other three that includes; cleaning of the not easily accessible gas distributor and powder pickup device when blocked; and maintaining an air tight hopper container. Moreover, its design introduces a slow turnaround of different powders as compared to its other variants. An advantage of such a feeder is that it does not rely on mechanical systems and their associated instrumentation, and so, breakdowns are minimised.

Like the rotary feeder, a screw feeder is relatively insensitive to downstream pressure variations because of the positive, mechanical aspects of the particle metering. This ensures a constant gas mass loading effect (Figure 2.31), thus a uniform deposit. However, powder pulsing at times occurs in this feeder related to the screw pitches, resulting in un-wanted particle feed rate variations. These pulsations can be damped by using a cyclone mixer or by changing the length and internal diameter of the powder-feed hose. Further, the screw feeder (together with both the rotary air lock and rotating wheel feeders) has a variable speed drive facilitating the delivery of different controlled flow rates of particles into the gas stream (Rhodes et al., 2001). This allows varying particle velocity, and as a result the microstructure of the coating to produce special structures (Karthikeyan et al., 2004). With the screw feeder, there is need to completely disassemble it to replace the worn out screw in order to maintain its respective powder transfer efficiency; thus its maintenance times are high.

Although the rotating wheel powder feeder is also relatively insensitive to downstream pressure variations because of the positive particle-metering wheel, it's not particularly accurate or reproducible with respect to powder flow rate. This is because powder pulsing

often occurs in this feeder related to the feed slots. As a result, non-uniform deposit microstructures are obtained. Nevertheless, it is simple in construction, inexpensive and robust. Because of its simplicity, it is the most affordable of the four feeders. Cost of producing the rotary and screw feeders is almost the same but fairly less than the expensive fluidised bed feeder variant. Not much maintenance is done on the rotating wheel feeder except cleaning the clogged circumferential groove. Based upon Figure 2.32, Table 4.10 illustrates an evaluation of the powder feeder variants.

Table 4.10: Evaluation of the powder feeder

		Powder feeder variants							
		Screw		Rotary air lock		Fluidised bed		Rotating wheel	
Criteria	Weight %	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating
Powder flowability	30	3	0.90	4	1.20	2	0.60	2	0.60
Flow rate variation	25	4	1.00	4	1.00	3	0.75	3	0.75
Manufacturing cost	25	3	0.75	3	0.75	2	0.50	4	1.00
Easy maintenance	20	3	0.60	3	0.60	2	0.40	4	0.80
			3.25		3.55		2.25		3.15

From the table, the rotary air lock feeder is well balanced regards the evaluation criteria. It has the highest weighted rating of 3.55 and is thus considered as the most excellent feeder to use in the LPCGDS system.

4.7 Powder particles

4.7.1 Powder particle requirements list

Different powder particles are used in the LPCGDS systems and, optimum particle characteristics have to be carefully selected in order to achieve a good quality coating and a reduction in the cost of spraying. These particle characteristics or parameters influence the DE and include - particle size (Figure 2.34), shape, angularity, hardness, roughness factor, density (Equation 2.18) and porosity. Taking into account section 2.4.4, Table 4.11 illustrates a requirements list for the factors considered in coming up with optimum particles to utilise.

Table 4.11: Requirements list for the particles

Requirements list for the particles	
d w	Requirements
d w	<u>1. Geometry</u> Particles must be microscopic in size (1-100 μ m) for them to be easily carried by the carrier gas The shape of the particles must be irregular to achieve greater speeds
d	<u>2. Energy</u> Particles must have low cooling rates
d	<u>3. Material</u> Particles must have a low oxide content to achieve less oxide, uniform and dense coatings
d w	Should be free flowing and free of un-wanted fine particulates to obtain less porous deposits, hence high strength (Figure 2.13(b)) Particles to be ductile/plastic for easy deposition
d	<u>4. Cost</u> Particles must be cheap to reduce spray costs
d	<u>5. Safety</u> Particles must not be corrosive for operator safety
d w	<u>6. Recycling</u> Un-deposited particles to be recyclable and re-usable to reduce spraying costs Waste must not require special disposal method

4.7.2 Powder particles variants selection

Particle size plays an important role in determining coating microstructure, which affects the mechanical and thermal properties of a coating. Based upon the particle requirements list (Table 4.11), a number of particle sizes are chosen and screened in Table 4.12 for use as the feedstock material. Mainly considered for the size is the ability to flow freely without any pulsations. 50-100 μ m particles are taken as the reference size range for the screening.

Table 4.12: Powder particles size screening matrix

	Powder particle sizes				
Selection criteria	< 1 μm	1-10 μm	10-50 μm	> 100 μm	50-100 μm
Particle velocity	-	+	+	0	0
Particle temperature	-	-	0	0	0
Quality of coating	-	+	+	-	0
Manufacturing cost	-	-	0	+	0
Ease of use	-	0	0	+	0
Pluses	0	2	2	2	
Same as	0	1	3	2	
Minuses	5	2	0	1	
Net score	-5	0	2	1	
Rank	4	3	1	2	
Continue	No	Yes	Yes	Yes	

Considering the results of the screening matrix for the powder particle size (Table 4.12) and difficulties that emerge from the handling and feeding of ultrafine powders in CGDS systems, particles greater than 1 μm are chosen for further assessment.

4.7.3 Powder particles variants evaluation

Feedstock powder particles size, shape, ductility and method of production all affect the spray process characteristics. Although fluid dynamics have proven that smaller particles are generally faster than larger ones, as particles approach the substrate, small particles lose much velocity as compared to large particles, Figure 4.15. The larger and heavier particles (22 μm) have sufficient momentum to maintain a critical velocity and they are able to penetrate the bow shock (Figure 2.11), while the smaller lighter particles (1 μm) are decelerated to the point where they will no longer undergo deformation on impact, leading to poor bonding with the substrate (Ajdelsztajn et al., 2005).

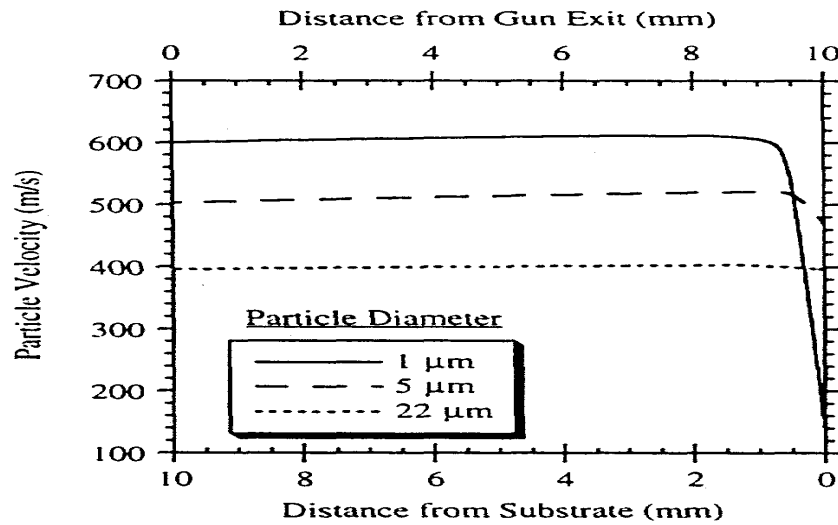


Figure 4.15: Particle deceleration near substrate (Gilmore et al., 1998)

Different heat conduction behaviors within different particle sizes also affect the critical velocities for bonding. For very small particles, origination of shear instability necessary for deposition is difficult because of high cooling rates arising owing to high gradients of temperature inside them. Also, finer particles are subjected to higher hardening velocities during powder production and possess higher static characteristics of the material because of their finer structure (Gärtner et al., 2006b). Moreover owing to a greater area/volume ratio, finer particles often have higher surface contamination such as oxide layers, which have a significant effect on bonding. All these effects lead to an increase in the critical velocity for finer particles.

Powders with large particle sizes are cheaper than smaller ones making their use more cost effective. Besides, in practice, difficulty in feeding very fine powders usually limits the minimum size that is feasible to spray.

By using relatively large particles, the minimum KE necessary for deformation and bonding with low particle velocities is easily obtained (Maev et al., 2008). Also, larger particles deform more easily than smaller particles, achieving successful deposition at low critical velocities. On the other hand, use of smaller particles results in higher deposition efficiencies than larger particles (Figure 2.34(b)). As a result, the coating produced from the

finer powder particles is more dense and plastic than the coating produced from the larger and coarse particles which will be more porous.

However, considering the size dependence of v_{crit} , Figure 4.16 there is an optimum size range where particle impact velocity (v_{impact}) is significantly higher than v_{crit} . It is in this size range where successful particle deposition is achieved. On the left hand side of this range, there would be no deposition or insufficient bonding. On the right hand side of this range, v_{crit} and v_{impact} are nearly parallel, which leads to a comparatively wide range in which coatings show increased porosity at decreased DE with larger particle sizes (Schmidt et al., 2006).

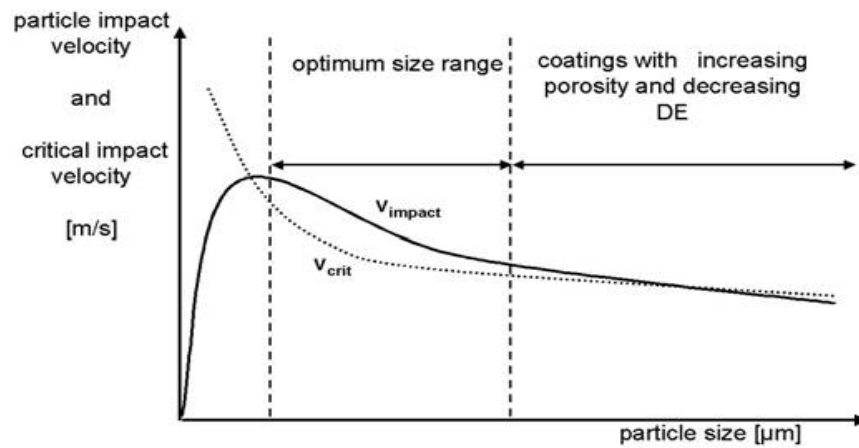


Figure 4.16: Particle impact and critical velocities over particle size (Gärtner et al., 2006a; Schmidt et al., 2006)

In relation to Figure 2.36, an evaluation of the different particle size ranges is done in Table 4.13 to find an optimum particle size range which has a relatively high nozzle exit velocity and is fairly unaffected by the subsonic gas flow downstream of the shock (Helfrich et al., 2006).

Table 4.13: Evaluation of the powder particles sizes

		Powder particle size							
		1 -10 μm		10 - 50 μm		50 - 100 μm		Above 100 μm	
Criteria	Weight %	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating
Particle velocity	25	4	1.00	4	1.00	3	0.75	2	0.50
Coating quality	25	4	1.00	4	1.00	3	0.75	2	0.50
Particle temperature	20	2	0.40	3	0.60	4	0.80	4	0.80
Cost	15	1	0.15	2	0.30	3	0.45	4	0.60
Flowability	15	2	0.30	3	0.45	3	0.45	4	0.60
			2.85		3.35		3.20		3.00

From the table, to achieve maximum deposition efficiencies and coating qualities, particles in the size range 10-50 μm will be considered as the feed material in the LPCGDS applications.

Nonetheless, it's not just particle size that affects DE in LPCGDS but particle morphology as well. Acceleration of spherical and non-spherical (granular) particles is different and leads to different v_p under the same spray conditions due to a difference in their respective drag coefficients. The non-spherical particles are more suited for spraying because their drag coefficient is larger (Fukanuma et al., 2006), and they will achieve higher velocities during impact resulting in greater DE.

In addition, granular and rough surfaced particles are better suited to bond to the substrate because they possess a higher surface area and a larger number of irregularities that increase the possibility of mechanical interlocking (Ajdelstajn et al., 2005). Figure 4.17 compares the bond strengths of coatings prepared from spherical and granular particles and

as shown, the bond strength values for the coatings prepared from irregular granular powders are higher than those for coatings prepared from spherical powders for the same particle impact velocity (Kumar et al., 2009).

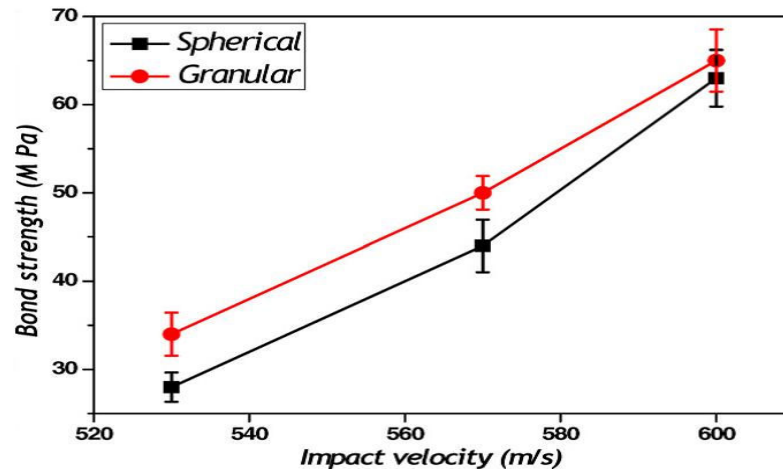


Figure 4.17: Bond strengths of coatings using spherical and granular particles (Kumar et al., 2009)

Additionally, irregular morphology increases particle stress concentration during impact because the load cannot be uniformly distributed as observed in spherical particles. This stress concentration at the surface of the particles facilitates occurrence of a localised shear deformation and the extensive disruption of the surface oxide layers present in the powders, leading to an intimate contact between particles (Ajdelstajn et al., 2006). Hence granular powders achieve coatings that are less porous and have low oxide content.

Figures 4.18(a, b) shows respective SEM images of etched Cu coatings prepared from irregular granular and smooth spherical powders. Coatings prepared from granular particles, Figure 4.18(a) are relatively denser than the coatings prepared from smooth spherical particles Figure 4.18(b). From Figure 4.18(a), it is difficult to distinguish the inter particle boundaries and inter granular boundaries because of the higher cohesive bonding created among the granular particles on impact (Kumar et al., 2009); whereas in Figure 4.18(b), the inter particle boundaries are easily distinguishable because of the less cohesive bonding created among the smooth particles.

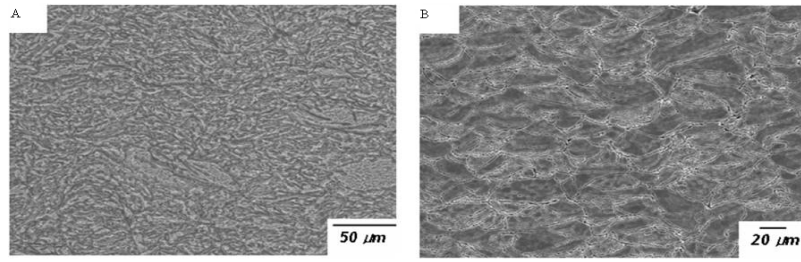


Figure 4.18: Cross section of etched Cu coatings prepared from (a) granular powders and (b) smooth spherical powders (Kumar et al., 2009)

Metals and their alloys readily form coatings with good bonding and high densities compared to ceramics and plastics. Moreover too hard particles result in a bad tensile strength coating with pores and, on the other hand, too soft particles result in a bad bonding strength. Therefore particles of an average hardness are preferable for the LPCGDS process.

4.8 The Supersonic Nozzle

4.8.1 Nozzle requirements list

Various LPCGDS nozzle geometries and cross-sections are available for the propulsion of powder particles and these influence v_p differently. A number of constraints are considered in design of the nozzles and these include; (1) ability of the nozzle to reach supersonic velocities (300-600 m/s) needed in LPCGDS to effect deposition of particles onto the substrate, and (2) based upon Figure 2.8, particles are to be radially introduced into the nozzle after the throat section.

In addition, another important constraint to consider is associated with machining of the nozzle. Since the nozzle is a consumable, it must be easily and cheaply produced to reduce the nozzle costs. In view of the nozzle literature reviewed in section 2.4.5, Table 4.14 illustrates the requirements list for the nozzle and this will be employed in the generation of nozzle variants.

Table 4.14: Requirements list for the nozzle

Requirements list for the nozzle	
d w	Requirements
d	1. <u>Kinematics</u> v_p at nozzle exit must reach supersonic speeds (300-600 m/s) in order to achieve sound particle deposition, thus good quality coatings
d	Particles must be radially injected into the nozzle after the throat (Figure 2.8) to enable use of a low pressure feeder to reduce both feeder weight and cost
w	2. <u>Forces</u> Must have a low weight together with the pre-chamber (~1.4 kg) for easy attachment to a motion control system (Figure 2.40(b))
d	3. <u>Energy</u> Should ensure a good transfer of thermal energy to the particles
d	4. <u>Signal</u> It must allow measurement of both pre-chamber P_o and T_o using respective transducers in order to control these two parameters and as a result v_p (Figures 2.21 & 2.26)
d	5. <u>Operation</u> It must have a low gas pressure loss coefficient to minimise spray gas costs
w	Particles must not stick inside the nozzle to avoid reducing the effective cross-sectional area of the nozzle, as a result maintaining its efficiency
d	It should wear out internally at a slow rate to reduce its replacement times, hence cost
d	6. <u>Costs</u> Must be easily and cheaply machined to reduce nozzle costs
d	7. <u>Assembly</u> Must be replaced quickly and easily without using special tools
w	8. <u>Maintenance</u> The nozzle must be easy to clean to reduce operating down times
d	9. <u>Safety</u> The operator should be protected from nozzle contact burns

4.8.2 Nozzle geometry variants generation

Nozzle geometry significantly influences v_p and T_p in the gas-particle mixture, resulting in particles achieving different velocities for different nozzle geometries operating under the same conditions (Figure 2.38). For a perfect gas with constant specific heats, the nozzle exit pressure P_e at which supersonic flow occurs inside the nozzle is described by Equation 4.1 (Champagne et al., 2005a; Khazaei et al., 2008) as;

$$P_e \leq P_o \left(\frac{2}{\gamma+1} \right)^{\gamma/(\gamma-1)} \quad (4.1)$$

This condition is assured of when the gas stream is compressed as it passes through a nozzle throat, after which it expands according to gas dynamic theory (Zahiri et al., 2009). At the throat, gas velocity is sonic, and the nozzle is choked. When nozzle cross sectional area increases (diverges) from the throat area resulting in gas expansion, it is during this expansion that the gas accelerates reaching supersonic velocities. The supersonic gas exerts a drag force on the particles accelerating them to supersonic velocities also. As explained in Figure 2.38, different gas and particle velocities are obtained on exiting the nozzle with different nozzle geometries. Considering Equation 4.1 and the nozzle requirements in Table 4.14, various nozzle geometries are developed and explained below.

a) Converging and diverging nozzle

In a converging and diverging (De-Laval type) nozzle (CD), Figure 4.19 the accelerating gas from the gas heater first enters the convergent section of the nozzle. In this section the speed of the gas stream is subsonic and increases as the nozzle narrows, becoming sonic at the throat. As nozzle cross sectional area increases in the diverging section, the gas expands and its flow increases to supersonic velocities.

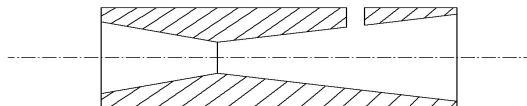


Figure 4.19: Converging and diverging nozzle (Papyrin et al., 2007)

Powder particles are radially injected into the flow downstream of the throat where according to Equation 2.1; the static pressure in the nozzle is smaller than atmospheric pressure. The particles are thus drawn from the feeder by Venturi effect and accelerated by the rapidly expanding gas (Papyrin et al., 2007).

b) Barrel and diverging nozzle

The barrel and diverging nozzle (BD), Figure 4.20 consists of a barrel section followed by a diverging section. Gas from the heater first pass through the barrel section to the nozzle throat before it enters the diverging portion. In the diverging section, the gas rapidly expands to supersonic speeds with its pressure dropping. According to Equation 2.1, static pressure at the powder entry point downstream of the throat is maintained below atmospheric pressure ensuring that particles are effectively drawn in radially from the powder feeder by Venturi effect. The supersonic gas exerts a drag force on the particles accelerating them to supersonic velocities up to the nozzle exit.

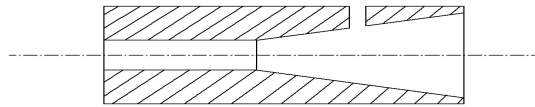


Figure 4.20: Barrel and diverging nozzle (Gedzevicius et al., 2006)

c) Barrel nozzle

As shown in Figure 4.21, the barrel nozzle (B) consists of a barrel cross-section only. Gas from the heater approaches the nozzle throat in a barrel section. Because of the reduction in cross-sectional area of the barrel at the throat, gas pressure at the throat is high such that the nozzle is choked. Gas speed at the throat is sonic and; as gas flows downstream the throat it slowly expands with its speed increasing to supersonic speed.

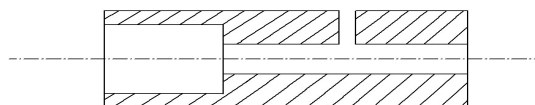


Figure 4.21: Barrel nozzle

As illustrated in the diagram, particles are radially fed into the gas flow downstream of the throat and accelerated up to the nozzle exit. At the powder entry point, static pressure is maintained below the atmospheric pressure ensuring that feedstock particles are effectively drawn in from the hopper by Venturi effect (Maev et al., 2008).

d) Converging and diverging + barrel nozzle

The converging and diverging + barrel nozzle (CDB) consists of a convergent section, followed by a diverging section and then a barrel section as shown in Figure 4.22 (Papyrin et al., 2007). From the gas heater, the driving gas enters the converging section where its flow is subsonic, increasing to sonic speed at the throat. On leaving the throat into the diverging section area, gas flow rapidly expands to supersonic speeds.

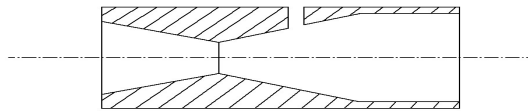


Figure 4.22: Converging and diverging + barrel nozzle (Papyrin et al., 2007)

Powder particles are radially fed into the gas stream in the diverging section under gravity flow from the feeder since the nozzle pressure at the injection point is less than atmospheric (Equation 2.1). This two phase flow accelerates along the diverging section and then enters the barrel part of the nozzle. The barrel section maintain a constant nozzle cross-sectional area after the maximum allowable value of the expansion ratio (A/A^*) is reached in order to prevent normal shocks from occurring inside the nozzle (Grujicic et al., 2003). Design of the barrel part is meant to access areas difficult to reach with short nozzles (after reaching their maximum allowable expansion ratios).

e) Converging and barrel nozzle

Figure 4.23 presents a schematic of the converging and barrel nozzle (CB). The pre-heated propellant gas is injected into the convergent section of the nozzle where its flow speed is subsonic. As gas flows in this narrowing converging section towards the throat, its speed increases because the mass flow rate is constant (Jodoin et al., 2006). At the throat, its flow

becomes sonic and; on leaving the throat the gas expands slowly to supersonic velocities (Li et al., 2006).

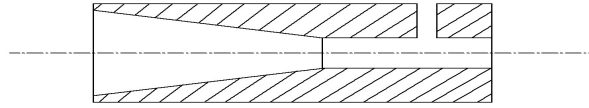


Figure 4.23: Converging and barrel nozzle (Papyrin et al., 2007)

Powder particles are radially metered into the gas flow from the feeder downstream of the throat and are accelerated by the gas to supersonic velocities. Flow of particles from the hopper is under gravity since the nozzle pressure at the particle entry point is lower than atmospheric, Equation (2.1).

f) Barrel-multistage divergent + barrel nozzle

The barrel multistage divergent + barrel nozzle (BMDB), Figure 4.24 has a barrel entry section followed by several diverging sections and then a barrel exit section. It consists of a common powder particles injection point, so that the exits of the diverging sections pick up the particles in that one region. Gas from the heater pass through the common barrel entry section to individual barrel sections before getting to the several nozzle throats. As cross sectional areas for the various diverging sections increase, their gases expand and their flows increase to supersonic velocities. Powder particles are radially injected into the flows downstream of the throats where the static pressure in the nozzle is smaller than atmospheric pressure (Equation 2.1). As a result, particles are drawn from the feeder by Venturi effect and accelerated by the rapidly expanding gases (Papyrin et al., 2007) to the barrel exit section where they exit as a common jet.

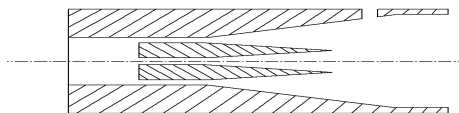


Figure 4.24: Barrel multistage divergent + barrel nozzle (Papyrin et al., 2007)

4.8.3 Nozzle geometry variants selection

Based upon the nozzle requirements list (Table 4.14), the main constraint considered in screening the nozzle geometry variants in Table 4.15 is the geometry effect on particle acceleration and resultantly the coating quality. The BD nozzle is made reference during the screening.

Table 4.15: Nozzle geometry variants screening matrix

	Nozzle geometry variants					
Selection criteria	CD	B	CD + B	CB	BMD + B	BD
Particle velocity	+	-	+	0	+	0
Particle temperature	0	+	0	+	0	0
Quality of coating	+	-	+	+	+	0
Operation	+	-	+	-	-	0
Manufacturing cost	0	+	-	0	-	0
Pluses	3	2	3	2	2	
Same as	2	0	1	2	1	
Minuses	0	3	1	1	2	
Net score	3	-1	2	1	0	
Rank	1	5	2	3	4	
Continue	Yes	No	Yes	Yes	No	

In view of the results for the nozzle geometry variants screening matrix, Table 4.15 the CD, CD+B, CB and BD nozzles are chosen for further evaluation.

4.8.4 Nozzle geometry variants evaluation

Figures 4.25 and 4.26 shows microstructures of cold sprayed Cu coatings deposited using CB and CD nozzles respectively. A dense coating is deposited using the CB nozzle

combination in 4.25(a) similar to the one deposited using the CD nozzle, shown in Figure 4.26(a). However, from Figure 4.25(b) more pores are present in the coating sprayed by the CB nozzle compared with that sprayed by the CD nozzle, Figure 4.26(b). This is because of the lower v_p yielded with the CB nozzle (Li et al., 2006) compared to the CD nozzle. Consequently, in order to achieve less porous coatings using a CB nozzle, gases with good aerodynamic properties like He are used as driving gas. Nevertheless these gases are expensive, hence spray costs increase.

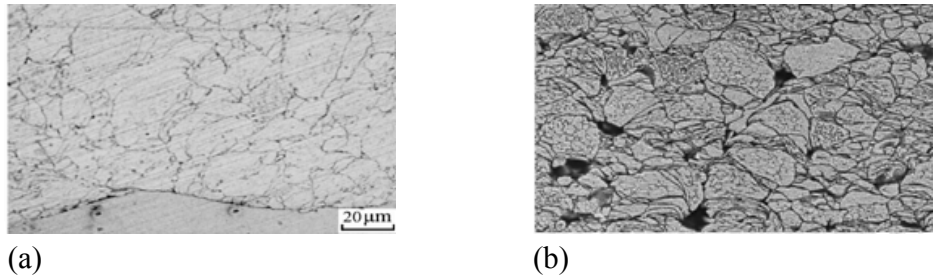


Figure 4.25: Cu coating deposited using a CB nozzle (Li et al., 2006)

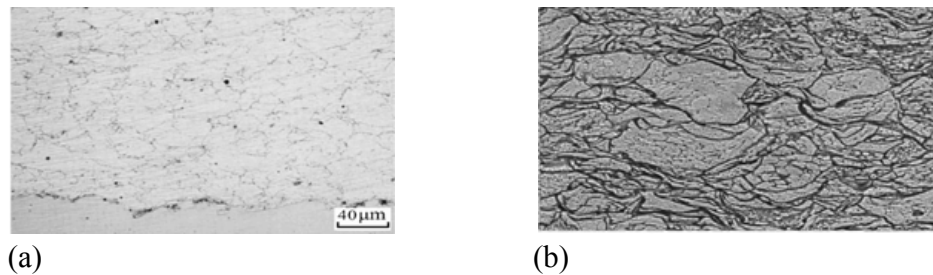


Figure 4.26: Cu coating deposited using a CD nozzle (Li et al., 2006)

Further, the micro-hardness of coatings sprayed with the CB and BD nozzles are less than those of the coatings deposited by the CD and CDB nozzles. The difference is attributed to the lower v_p yielded with the former nozzles.

Figures 4.27 (a, b) respectively show that for the CD nozzle (and thus a CDB nozzle), gas pressure and density decrease significantly to a very low value upon leaving the nozzle throat (at 25 mm) due to the fast gas expansion. Accordingly, high particle velocities are achieved resulting in higher deposition efficiencies. In contrast, for the CB nozzle, gas pressure and density are not significantly decreased along the nozzle up to the exit (at 170 mm) resulting in low particle velocities. Oscillations of gas variables outside the nozzle exit

indicate that shock waves are generated and these are more obvious for the CB nozzle. This is because at exit, the high pressure gas expands sharply to the atmosphere for the CB nozzle while for the CD nozzle the gas has already expanded gradually from the throat (Li et al., 2006).

In a BD nozzle, gas pressure at the throat to choke the flow is not as high as in CB, CD and CDB nozzles such that gas expansion through the diverging zone is less and per se, its acceleration. This results in low particle impact velocities and consequently, less dense deposits.

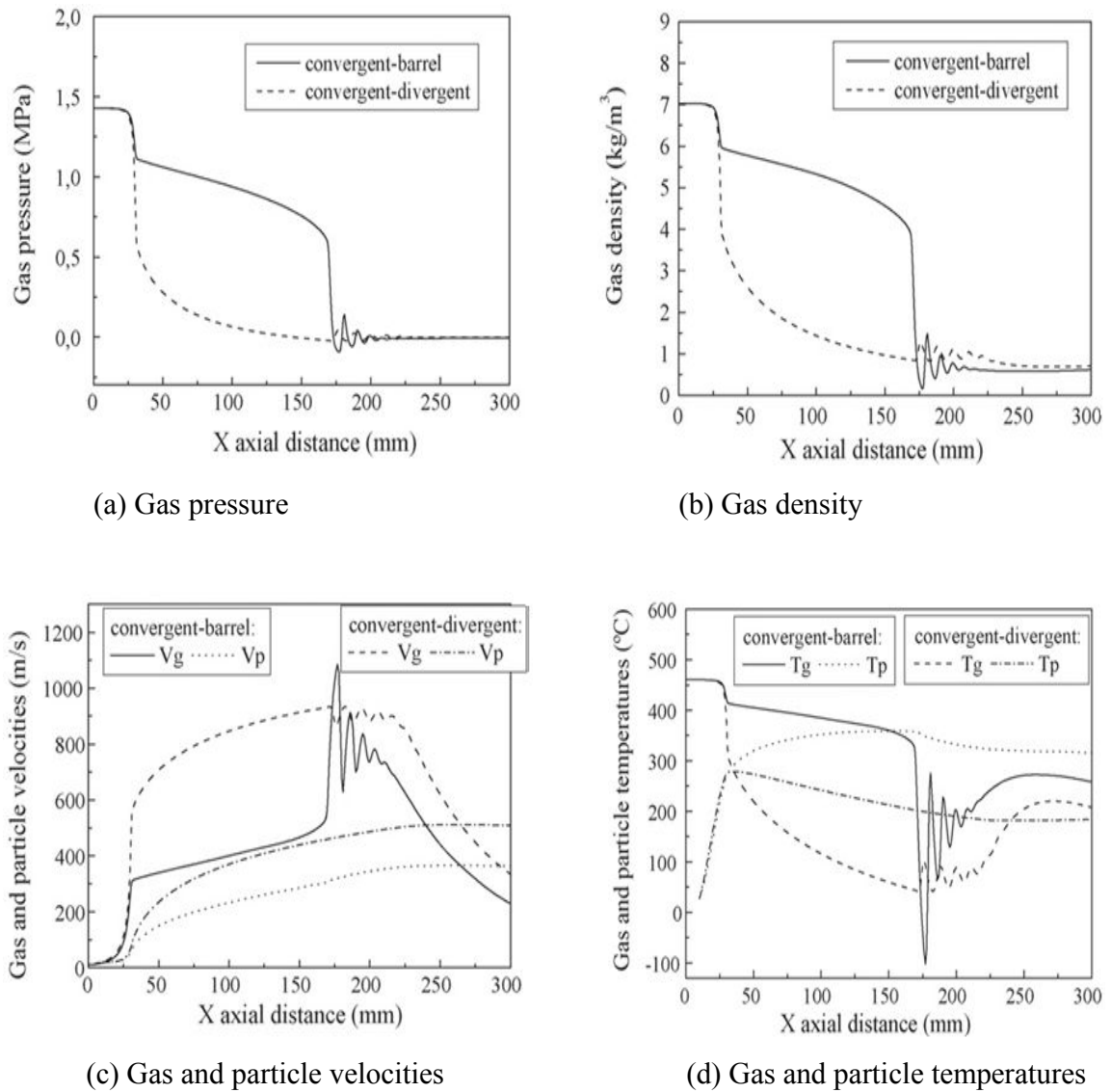


Figure 4.27: Acceleration of the gas and particles for CB and CD nozzles (Li et al., 2006)

As presented in Figures 4.27 (c, d), with a CB nozzle, particles at the exit achieve a relatively low velocity but a high temperature compared to using CD (and CDB) nozzles owing to low gas expansion in the barrel section. This high particle temperature helps reduce the v_{crit} needed for deposition (Figures 2.19 & 2.27).

Nozzle length determines the length of time that the particles are accelerated in a carrier gas jet and resultantly their nozzle exit velocity (Figure 2.37(a)). Both the CD and BD nozzles are shorter than the CB and CDB nozzles. Lengths of the former two construction types are limited by the maximum allowable value of the expansion ratio (Grujicic et al., 2003). As a result, the CD and BD nozzles are utilised in applications where strict space requirements are to be met. The CB and CDB nozzles have a distinct advantage of offering additional particle heating by the gas due to the extended elongated barrels. This helps lower down the v_{crit} necessary for deposition (Figure 2.27) such that gases with moderate aerodynamic properties, hence not expensive can be used successfully to deposit particles.

Production of the BD and CB nozzles is simple and cheap compared to the CD nozzle alternative. Most expensive to produce of all the nozzles is the CDB nozzle. Table 4.16 in conjunction with Figure 2.39(a) illustrates an evaluation of these different nozzle geometries in order to get the most favorable to use in LPCGDS applications.

Table 4.16: Evaluation of nozzle geometry variants

		Nozzle geometry variants							
		CD		BD		CD + B		CB	
Criteria	Weight %	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating
Particle velocity	30	4	1.20	2	0.60	4	1.20	2	0.60
Coating quality	25	4	1.00	1	0.25	4	1.00	2	0.50
Particle temperature	20	2	0.40	2	0.40	3	0.60	4	0.80
Manufacturing cost	15	3	0.45	4	0.60	1	0.15	4	0.60
Length restriction	10	3	0.30	3	0.30	3	0.30	4	0.40
			3.35		2.15		3.25		2.90

The table shows that the CD variant satisfactorily meets all the evaluation criteria. With a summed up weight rating of 3.35, it is chosen as the best concept for the nozzle geometry.

4.8.5 Nozzle cross-section variants generation

Nozzle outlet cross-section determines the spray pattern of powder particles on exiting the nozzle, thus the build-up profile of the applied coating. Considering the requirements list of Table 4.14, a variety of cross-section configurations for the spray nozzle is produced (in reference to a CD nozzle) and these are described below.

a) Rectangular nozzle

As shown in Figure 4.28, a rectangular CD nozzle consists of a rectangular cross-section. The converging and diverging sections are both rectangular. Nonetheless, this nozzle can

have a conical section for the converging part if desired, together with a round throat. However, it will maintain its respective rectangular diverging cross-sectional configuration. Particles exiting the nozzle outlet have a rectangular cross-sectional profile.

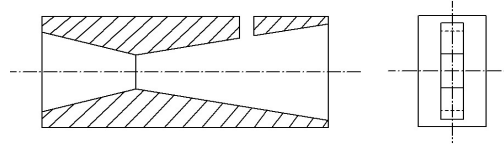


Figure 4.28: Rectangular nozzle (Papyrin et al., 2007)

b) Square nozzle

The square CD nozzle consists of a square cross-section as indicated in Figure 4.29. Both sections, converging and diverging have square outlines. On the other hand the converging section and the throat area can be made circular (to reduce manufacturing costs) but still the nozzle retains a square form for the diverging section. A square particle profile is attained when particles leave the nozzle exit.

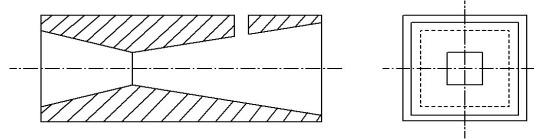


Figure 4.29: Square nozzle (Gulati et al., 2009)

c) Circular nozzle

Figure 4.30 schematically illustrates the cross-section of a circular/conical CD nozzle. Both the converging and diverging sections are circular. On exiting the nozzle, together the gas and powder particles obtain a circular profile.

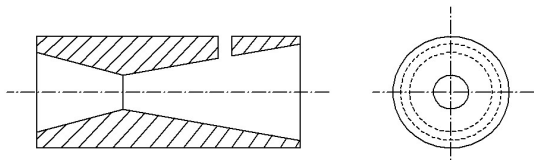


Figure 4.30: Circular nozzle (Papyrin et al., 2007)

d) Elliptical nozzle

The elliptical CD nozzle consists of an elliptical cross-section as represented in Figure 4.31. The converging and diverging sections both have elliptical outlines. An elliptical gas-particle profile is attained when the mixture leave the nozzle exit.

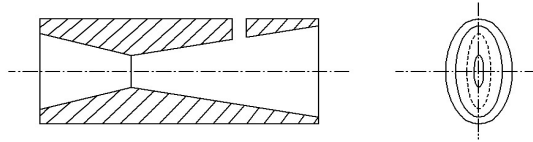


Figure 4.31: Elliptical nozzle (Gulati et al., 2009)

4.8.6 Nozzle cross-section variants evaluation

Career gas pressure loss coefficients (K) for various nozzle exit-to-substrate spacing's (z/d) are shown in Figure 4.32 for the square, circular and rectangular nozzles. The pressure loss coefficient values are almost insensitive to z/d for all the three nozzles. However, the pressure loss coefficient for the circular nozzle is lowest, around 25% and 65% lower than those for the square and rectangular nozzles respectively. Consequently, high gas pressure is required for the rectangular nozzle and least gas pressure is required for the circular nozzle to achieve the same particle impact velocity (Equations 2.13 and 2.15). As such, gas spray costs are reduced for the circular nozzles followed by square and lastly rectangular nozzles (Gulati et al., 2009).

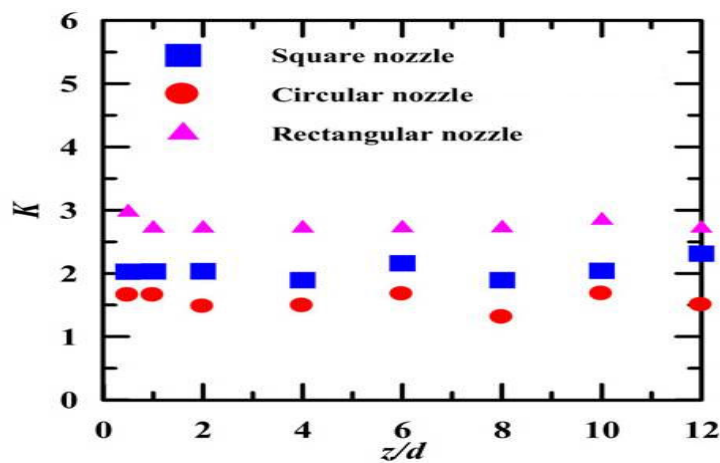


Figure 4.32: Variation of gas pressure loss coefficient with nozzle exit-to-substrate spacing for the square, circular and rectangular nozzles (Gulati et al., 2009)

Rectangular (and square) nozzles decrease the effect of particle deceleration (Figure 4.15) in the compressed layer in front of the substrate by decreasing the thickness of the compressed gas layer ahead of the coated surface (Papyrin et al., 2007). This facilitates extensive plastic deformation of particles on impact, ensuring dense coatings. In addition, particle velocity profiles are different comparing the circular, elliptical, rectangular and square nozzles. Rectangular and square nozzles provide a more uniform particle velocity across the nozzle exit whilst for circular and elliptical nozzles, the particle velocity profile is parabolic in shape (Papyrin et al., 2007).

Coating profiles achieved from circular, elliptical, rectangular and square nozzles are also different, being characteristic of their respective cross-sections. Illustrated in Figure 4.33 are the coating profiles for the circular and rectangular nozzles. Because of their respective buildup profiles, circular nozzles are utilised in small areas requiring a thick buildup of the coating whereas large areas requiring flat coatings are effectively sprayed with rectangular nozzles.

Nozzle Shape	Spray Pattern	Buildup Profile
		
		

Figure 4.33: Coating pattern and profile (Supersonic Spray Technology)

Fabrication of elliptical nozzles is more complex than all the other three cross-sections, requiring specialised equipment. Rectangular and square section nozzles are manufactured in a similar fashion that's costly compared to that for circular nozzles. The former two nozzles are fabricated in two pieces to achieve the rectangular and square cross-sections, welded and then machined to the final configuration whereas the circular nozzles are of one-piece construction and are machined using standard fabrication practices. Moreover, because of their cross-sections, the circular and elliptical nozzles have a reduced weight compared to the rectangular and square nozzles, and as such are more portable. This helps

reduce the weight of the spray gun, making manual operations more comfortable. Considering Figure 2.39(b) an evaluation of these nozzle cross-section alternatives is carried out in Table 4.17 to obtain the finest nozzle cross-section.

Table 4.17: Evaluation of the nozzle cross-sections

		Nozzle cross-section variants							
		Rectangular		Square		Circular		Elliptical	
Criteria	Weight %	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating	Rating	Weight rating
Impact velocity	30	4	1.20	4	1.20	3	0.90	2	0.60
Manufacturing cost	25	2	0.50	2	0.50	4	1.00	1	0.25
Gas cost	20	4	0.80	4	0.80	3	0.60	2	0.40
Velocity profile	15	1	0.15	2	0.30	4	0.60	3	0.45
Size	10	3	0.30	3	0.30	4	0.40	4	0.40
			2.95		3.10		3.50		2.10

With the highest weight rating of 3.50, the circular variant is found to be preferable to the other alternatives. Therefore, a circular cross-section will be utilised for the supersonic nozzle.

4.8.7 Nozzle stepping

All the nozzles described above for both nozzle geometry (section 4.8.2) and cross-section (section 4.8.5) are non-stepped nozzles. Nonetheless, they can also be stepped depending on the desired nozzle exit particle parameters. Figure 4.34 illustrates a circular CD nozzle in the stepped (Figure 4.34(a)) and un-stepped (Figure 4.34(b)) configurations.

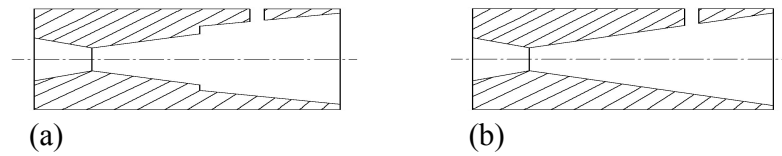


Figure 4.34: Circular CD (a) stepped and (b) un-stepped nozzle (Ajdelstajn et al., 2005)

Nozzle stepping allows obtaining a more uniform profile of particle velocity and expands the range of size of particles reaching the critical deposition velocity (Papyrin et al., 2007). However, non-stepped nozzles are more cost effective as opposed to stepped nozzles since their design minimise nozzle erosion (Ajdelstajn et al., 2005) although on the other hand it promotes the formation of undesirable shock waves inside the nozzle. Moreover, the technology for manufacturing non-stepped nozzles is less costly than the one for producing stepped nozzles; thus, non-stepped nozzles are more preferable to use in LPCGDS applications (see Appendix H3).

4.9 Overall LPCGDS System Design

The schematic layout of an overall LPCGDS system configuration is shown in Figure 4.35. This is an assembly of chosen components (from sections 4.4 to 4.8) that best performs LPCGDS functions. The portable system is utilised in either manual or automatic applications. Compressed air is supplied by an air compressor (1) to an air receiver (2), passes through a pressure relief valve (3), a pneumatic valve (4) and a flow meter (5) to the coil heater (6). From the heater, it first enters the nozzle pre-chamber (7) and then the supersonic CD nozzle (11) where it's accelerated to a supersonic velocity and exhausts into the atmosphere.

After P_o is reached in the nozzle pre-chamber, electric power is supplied to the heater and air is heated there to a set temperature. When the system reaches a steady-state regime in terms of G_g , T_o and P_o , the electric drive for the rotary airlock feeder (15) is switched on and feedstock particles are injected into the nozzle. A programmable logic controller (PLC) automatically sustains G_g , T_o , P_o and G_{prpm} through a pneumatic valve (4), a thermocouple (8), a pressure transducer (9) and the electric drive for the feeder respectively.

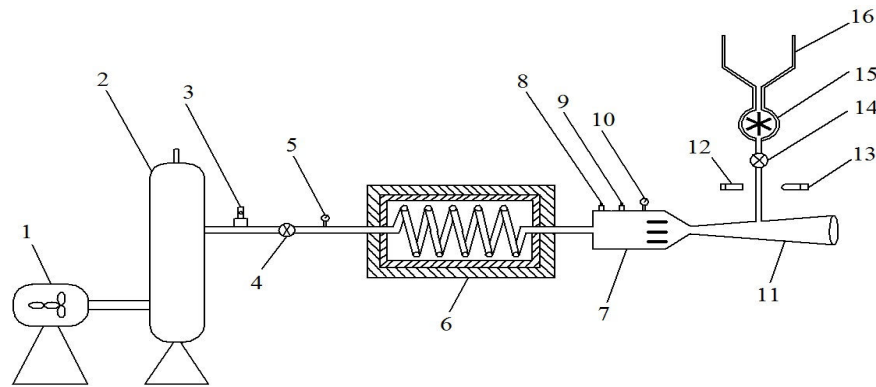


Figure 4.35: Layout of a LPCGDS system design; (1) air compressor, (2) air receiver, (3) pressure relief valve, (4) pneumatic valve, (5) flow meter, (6) coil heater, (7) pre-chamber, (8) thermocouple, (9) pressure transducer, (10) pressure gauge, (11) CD nozzle, (12) light sensor, (13) light emitter, (14) ball valve, (15) rotary airlock feeder and, (16) hopper

The pre-chamber and nozzle assembly are compact and light in weight, constituting a spray gun. In manual operations, the gun is hand held, thus its flexibility and weight are important (Kreeger, 1994). The hand-held gun ensures a total control of the coating position and profile, allowing a quick response to spray angle and stand-off distance variations. The system is automated when spraying critical tolerance, difficult-to-reach and complex parts. When automated, the lightweight gun is attached to a robot or any other travel displacement system that controls the path it traverses. The path traversed corresponds to the cross-sectional geometry of the deposit to be built and the deposit description is pre-programmed in the PLC (see Appendix H4).

Gas conditions are stabilised firstly and then the spray gun is moved into position before pressing the powder-trigger on the gun to open the powder feed line and start spraying. Pressurised air (~10 bars) is supplied to the coil heater, Figure 4.36 from the air receiver via a flexible non-conductive high-pressure hose. This PLC controlled in-line 3.8 kW coil heater achieves temperatures as high as 650 °C. Power is delivered to the coil resistance element from a 240 V power supply using high current braided copper leads. The coil element is manufactured of a high temperature resistant tungsten pipe and is surrounded by a ceramic support which avoids possible heater damage when the coil overheats. This coil and ceramic support assembly is then embedded in a thermally insulated aluminum enclosure that minimises heat losses and guarantees no warming of the outer housing even

after several hours of operation. A high temperature, flexible braided stainless steel hose connects the heater to the nozzle pre-chamber. To decrease temperature losses, fiber-frax insulation with a protective casing is mounted on the corrugated metal hose (Papyrin et al., 2007).

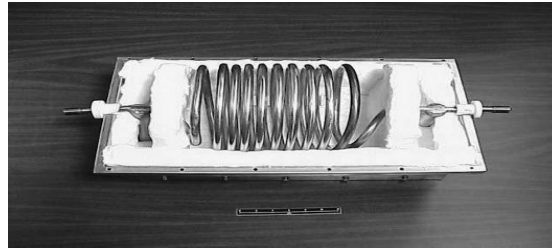


Figure 4.36: Coil Heater (Papyrin et al., 2007)

Figure 4.37 show the rotary airlock feeder with a drilled top flange where the hopper body will be bolted and, a slotted rotor with flexible blades that picks-up powder particles from the hopper. These blades bend a little when discharging and return into the normal position on reaching the lower part of the feeder body after discharging. The rotor is connected to a variable speed drive (VSD) that alters its rotational speed according to the PLC, thus particle feed rate. The feeder provides a particle feed rate in the range of 0.1-10 g/s (Masuda et al., 2006).

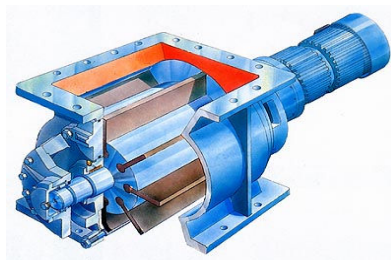


Figure 4.37: Rotary feeder (Masuda et al., 2006)

This feeder has outstanding feed characteristics due to the use of a rotor that precisely meter and convey particles from within the hopper. To assist in maintaining a continuous flow within the hopper, an agitator or mechanical stirrer is installed inside the hopper. The agitator vibrates in a rotational manner, in the process keeping the powder in loose form. Particles are delivered to the nozzle from the feeder through a flexible braided stainless steel feed line.

The one-piece constructed CD nozzle (Figure 4.38) is made of either stainless steel or WC, has a circular (un-stepped) geometry and is machined using standard fabrication practices. The converging section of the nozzle is as short as possible in order to attain the required Mach 1 gas velocity at the nozzle throat quickly (Grujicic et al., 2003).



Figure 4.38: An axisymmetric supersonic CD nozzle unit (Papyrin et al., 2007)

Feedstock powder particles are often contaminated with surface oxide films on their surfaces. With proper manufacturing, storage and handling of the particles, the thickness of this film is kept small enough not to affect the DE and thus the coating quality (see Appendix J). Since particles are radially injected downstream of the nozzle throat (Figure 4.35), this particular configuration uses 6-10 bars compressed air for the carrier gas.

4.9.1 Operating parameters of the LPCGDS system

The relationship between the nozzle expansion ratio, A/A^* , and the resultant Mach number M is given by Equation 2.9. Figure 4.39 shows the M for different values of A/A^* , and for several values of the specific heat ratio, γ . The results obtained of the M versus A/A^* relation defined by Equation 2.9 are displayed as solid lines (Grujicic et al., 2004).

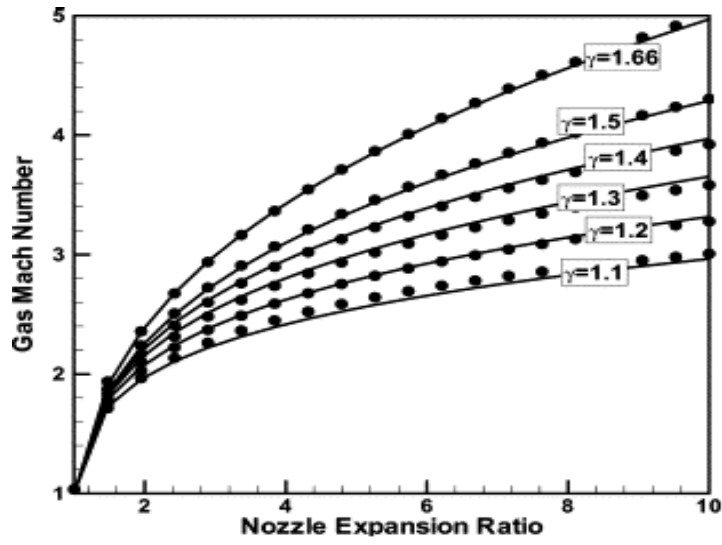


Figure 4.39: Variation of the gas Mach number with the nozzle expansion ratio and the gas specific-heat ratio, γ (Grujicic et al., 2004)

Since air is primarily a mixture of nitrogen and oxygen, it is considered as a diatomic gas and thus $\gamma = 1.4$. From Figures 4.35 and 4.39, assuming an axisymmetric nozzle with a diverging length of 100 mm (and particles being introduced into the nozzle 30 mm after the throat), a 2.7 mm throat diameter, and an exit diameter of 8 mm, this results in a $M_e = 3.7$. The subsequent ρ_g at the exit is given by Equation 2.13 as;

$$\begin{aligned} \rho_g &= \frac{\rho_o}{\left\{1 + \left[(\gamma - 1)/2\right]M_e^2\right\}^{1/(\gamma - 1)}} \\ &= \frac{1.292}{\left\{1 + [(1.4 - 1)/2] \times 3.7^2\right\}^{1/(1.4 - 1)}} \\ &= 0.0478 \text{ kg/m}^3 \end{aligned}$$

Spraying Cu powder with $d_p = 25 \text{ }\mu\text{m}$, $\rho_p = 8.960 \text{ g/cm}^3$ at a feeding rate of 10.0 g/s and employing the following processing conditions: $T_o = 500 \text{ K}$, $P_o = 10 \text{ bar}$ and the nozzle assumed to be operating under the condition of a constant C_D whose value is set to 1, the velocity of particles on exiting the nozzle is given by Equation 2.18 as;

$$\begin{aligned}
v_p &= M_e \sqrt{\frac{\gamma R T_o}{1 + [(\gamma - 1)/2] M_e^2}} \sqrt{\frac{3 C_D \rho_g x}{2 d_p \rho_p}} \\
&= 3.7 \times \sqrt{\frac{1.4 \times 8314 \times 500}{1 + [(1.4 - 1)/2] \times 3.7^2}} \sqrt{\frac{3 \times 1 \times 0.0478 \times 0.07}{2 \times (25 \times 10^{-6}) \times 8960}} \\
&= 691.26 \text{ m/s}
\end{aligned}$$

This achieved particle velocity is above the critical velocity range needed for deposition by 25 μm Cu particles, Figure 2.20.

4.10 Auxiliary Equipment

In addition to the above designed system components, the auxiliary equipment completes the LPCGDS system set-up. It consists of the spraying chamber which houses the substrate and motion equipment (an XY manipulator system or robot), a feedstock powder particle recovery system, the DACS and, coating quality measurement equipment.

4.10.1 The spraying chamber

Figure 4.40 shows a typical spraying chamber arrangement. During manual spray, the operator holds, move and control the path of the spray gun over the substrate. To automate the process, the spray gun is attached to a robot that is positioned by a hardware system and controlled by a PLC using software (e.g. AutoCAD). The path of the nozzle is drawn using the software and this PLC program provides the capability of coating the substrate with multiple passes at set overlaps. The number of passes the nozzle makes in front of the substrate controls the thickness of the coating. In addition, the chamber is mounted with a cooling fan to eliminate heat build-up and a blow-out panel in case of over-pressurisation inside the enclosure.

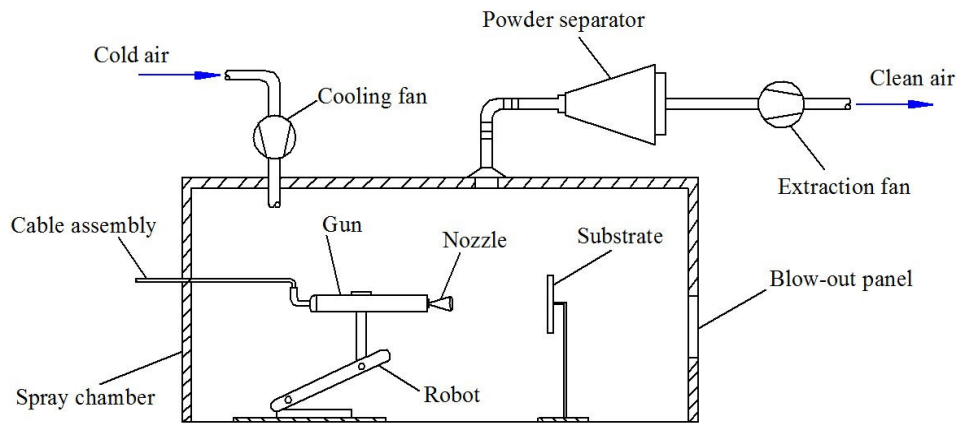


Figure 4.40: Spraying chamber arrangement

Before spraying, the substrate is subjected to pre-processing by silica (silica sandblasting) or is grit blasted with alumina (Aluminium oxide powder) removing grease, dust and loose materials on the substrate to make certain that there is minimal contamination to interfere with the bonding between the spray particles and substrate, resulting in an increase in DE. Silica sandblasting also elevates the substrate surface roughness resulting in an increase in particle deposition because many holes/recesses are created where the particles can deposit.

The substrate has to be able to withstand the heat of the supersonic gas-particle mixture jet and if it's sensitive to thermal stress, it will be preheated slightly to ambient conditions to minimise thermal shock effects during deposition. Pre-heating the substrate also helps improve the DE by lowering the v_{crit} necessary to form the bond. At these pre-heating moderate temperatures, the substrate's chemical composition won't be affected and this can be accomplished with the heated gas jet before the particles are introduced. Moreover, the substrate and feedstock powder materials must have compatible chemical, mechanical and thermal properties.

Deposition is mostly favourable if the substrate is harder than the particle. In this case, initiation proceeds easily even if there is no substrate pre-processing. As well, it is difficult to initiate deposition onto non-metals and soft metals (Papyrin et al., 2007).

4.10.2 Feedstock powder particle recovery system

When spraying with expensive coating powder it is imperative to recover the un-deposited particles, re-cycle and re-use them in order to reduce the spraying costs. Design of the spray chamber (Figure 4.40) allows it to retain the un-deposited particles, which are then drawn into powder separators by an extraction fan or a high-flow rate blower. The powder separators are periodically reverse-pulsed to remove the over-sprayed powder which is then sieved and supplied back to the powder feeder for re-use. After particles are filtered, the clean air is released into the atmosphere. Besides recovering the powder particles, the recovery system helps minimise contamination of both the internal and external spraying environments, ensuring that their atmospheres remain inert to prevent fires and explosions (see Appendix H4, Figure H17).

4.10.3 The data acquisition and control system

System components are controlled and monitored automatically by the DACS. It consists of a processor, monitor, control and communication hardware, software and a PLC. The pneumatic valve, gas heater and powder feeder are all interfaced to the PLC (Figure 4.41) that ensures peak system efficiency by monitoring gas pressure in the gas line, current supply to the heater and the rotational speed of the powder feeder motor. The operator observes how the system is behaving and communicates to the PLC through the user interface and; if there is need to change the system's settings, this is done through this interface. The PLC also controls the particle recovery system and provides remote control of motion devices such as a Cartesian XY system or robot.

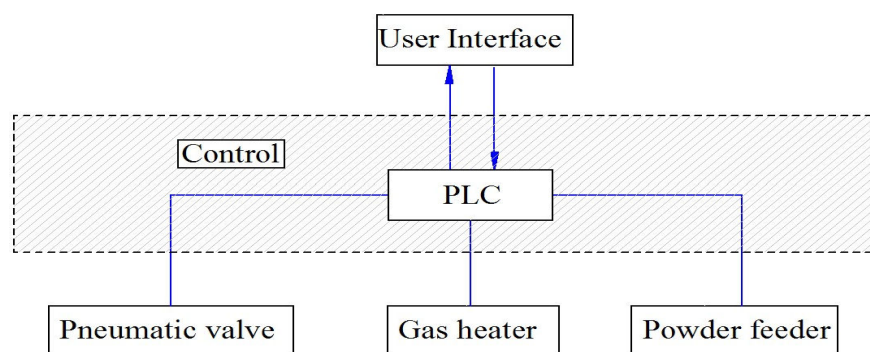


Figure 4.41: Illustration of a PLC-user interface (Papyrin, 2006)

The pre-chamber and nozzle assembly, Figure 4.42 contains ports for a temperature thermocouple (type K) and pressure transducer for monitoring temperature and pressure respectively of the air within the chamber before nozzle entry. The thermocouple sends a feedback electrical signal that is proportional to air temperature levels in the pre-chamber to the PLC, which internally compares the feedback signal with the set point temperature. The PLC then provides a signal to a temperature control rectifier to control the current supplied to the coil, regulating the air heating (Maev et al., 2008). This assures a precise temperature control and ensures process repeatability. In addition to process control, air (and material) temperatures are monitored so as to prevent the heater from overheating, guaranteeing a safe and reliable operation. In the case of an abnormal increase in air temperature, the PLC switches power supply off and gives a warning signal.

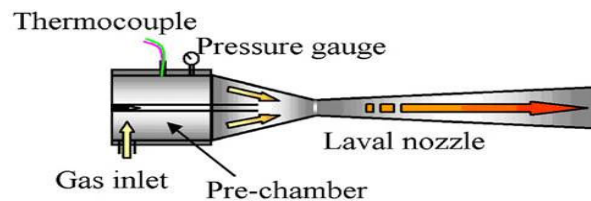


Figure 4.42: Pre-chamber and nozzle assembly (Li et al., 2007)

The pressure transducer, Figure 4.43(a) produces an electrical signal to the PLC related to the air pressure levels in the pre-chamber. The PLC then adjusts the pressure to the pre-set value by controlling the pneumatic valve installed in the air line. A pressure relief valve (Figure 4.43(b)) is installed in the air line from the air receiver before the pneumatic valve as a safeguard of over pressurisation due to downstream clogging and, a mass flow meter, Figure 4.43(c) is installed after the pneumatic valve to directly monitor air flow rate through the heater. Both the desired air pre-chamber P_o and T_o are entered through the user interface (Figure 4.41) on the control console.



Figure 4.43: Diagrams of (a) pressure transducer, (b) pressure relief valve and (c) mass flow meter (DeForce et al., 2006)

A powder particle metering device that includes a light sensor and a light emitter is used to monitor particle flow rate in the discharge line from the hopper to the nozzle (Figure 4.35). The sensor receives a certain amount of light that is able to penetrate the discharge line from the emitter (Maev et al., 2008). This amount of light is proportional to the powder flow rate in the discharge line. It then sends an electrical signal to the PLC that compares the signal with the set point flow rate. Subsequently the PLC adjusts the feeder motor speed (RPM), controlling the flow rate. This closed loop control of the motor speed maintains accurate and consistent feed rates, which are easily reproduced.

Illustrated in Figure 4.44 is a velocity measuring system for the particles emerging from the nozzle. After passing through the nozzle, the high velocity flying particles form a distribution/alignment rod with a certain diameter in the measured region. A high speed camera unit is used to monitor the particle velocity and a laser device for particles illumination. These two units are connected to a microcomputer data processor which is used for system controlling, calculation and display. A multi-pulse imaging technique is used in this system; during one exposure of the camera, three or more laser pulses are emitted (Figure 4.44(a)) and then a particle's stretch image is obtained (Figure 4.44(b)). The length between the (3) particle points on the camera detector is measured by an image-processing algorithm and converted into velocity by dividing it by the pulse time-interval (Raletz et al., 2006), as shown in Figure 4.44(c).

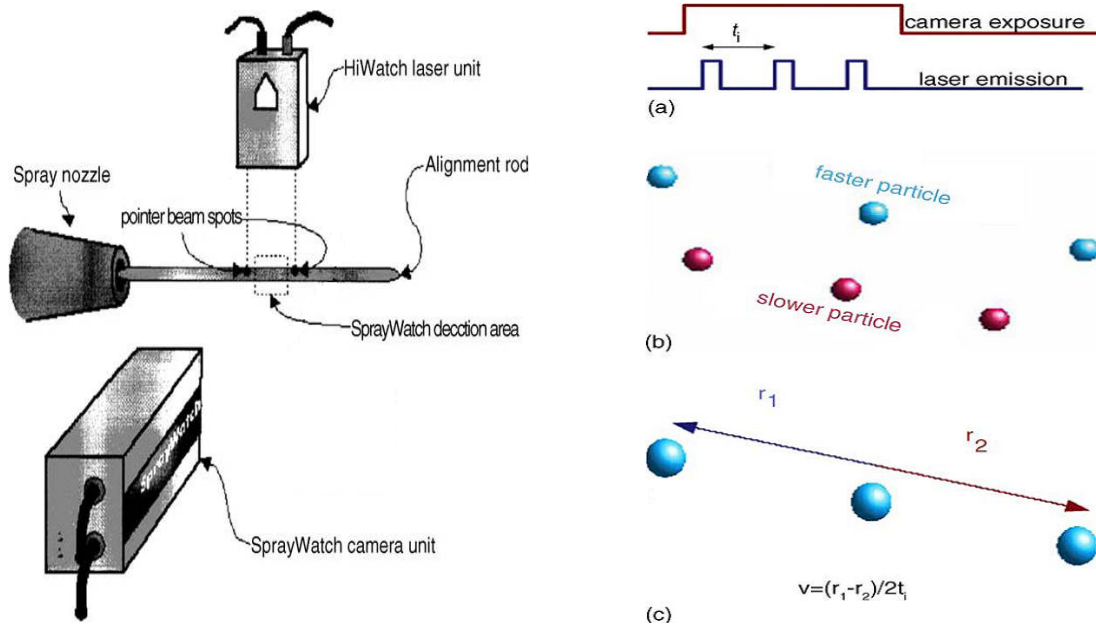


Figure 4.44: Particle velocity measuring system (Wu et al., 2005)

4.10.4 Coating quality measurement

Quality of LPCGDS coatings is characterised by their; density, shear and hardness strength, corrosion and wear resistance, porosity, oxygen content levels and electrical resistivity. Tests to determine the resultant quality of a coating to be cold sprayed on a particular surface are conducted on samples fabricated from the same material as the surface.

(a) Powder particles

Quality management in LPCGDS coatings starts by focusing on the properties and selection of spray particles given that their deformation behaviour is strongly dependent on their microstructure, with respect to grain size as well as the content and distribution of oxides. Powder specimens to be examined and characterised are prepared by sprinkling the powder particles on wet carbon paint and then gently blowing excess particles from the paint surface. After the paint dries, the specimens are examined under respective microscopes (Champagne et al., 2005b).

The particles cross-sections and morphologies are examined with either a field emission scanning electron microscope (FESEM) or an optical microscope (OM); while

spectrometric methods using a commercial analyser (Leco TC300) are applied for the quantitative analysis of particles oxygen content (Stoltenhoff et al., 2006). Moreover, a laser-scattering particle size distribution analyser (Horiba LA-910) is used to determine the size distribution of the powder. This technique uses laser scattering from the particles suspended in solution to determine the size distribution (Champagne et al., 2005b).

(b) Coating

Microstructural examinations on resultant coatings in order to gain information on coating thickness and porosity as well as on particle/substrate and particle/particle bonding are performed on polished coating cross-sections in the as-polished and etched states (cross-sections slightly eroded with an etchant of FeCl_3 for a better observation of coating microstructure). Metallographic coatings cross-sections are used for the analysis with the samples being first mechanically thinned using grinding paper or sectioned with a diamond cut-off saw. To avoid contamination, diamond polishing media and diamond suspension are used throughout the grinding, rough polishing, and final polishing steps (Champagne et al., 2005b).

Either an energy-dispersive spectrometry (EDS) or a high-resolution transmission electron microscope (HRTEM) is used to evaluate the interface between the substrate and coating to determine the extent of mixing. Figure 4.45(a) shows an EDS image of a Cu coating and, there is clear evidence of forced mixing between the deposited Cu particles and the substrate, demonstrating the tenacious nature of the LPCGDS bonding mechanism (Champagne et al., 2005b). Presented in Figure 4.45(b) is an EDS image of the interface between an Al substrate and the deposited particles, also demonstrating the immense deformation of particles on impact.

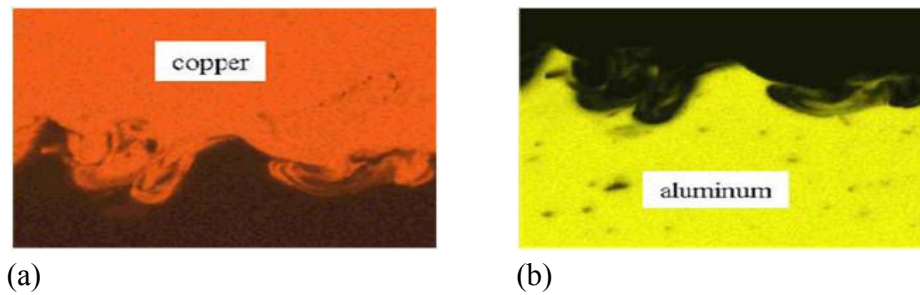


Figure 4.45: EDS X-ray mapping showing mechanical mixing between coating material and substrate for (a) Cu and (b) Al deposits (Champagne et al., 2007)

Coating porosity is determined by a digital image analysis of the polished cross-sections using a software package (Axio Vision 4.3, KS 300) whilst the coating phase analysis is done by X-ray diffraction (XRD). Thickness measurements are performed by a number of techniques that include OM, SEM, FESEM and backscattered electron (BSE). In addition, microstructural analysis of annealed samples are used to study recovery and recrystallisation of LPCGDS deposits after heat treatment processes and, the effect of these processes on grain growth and possible interactions with trapped oxides.

Shear test

The substrate-coating bonding strength is an important parameter considered for the use of LPCGDS coatings during thermo-mechanical loading conditions, and thus, the level of bonding should be known for a particular application. The triple-lug shear test method, Figure 4.46 is used to determine this substrate-coating bonding strength.

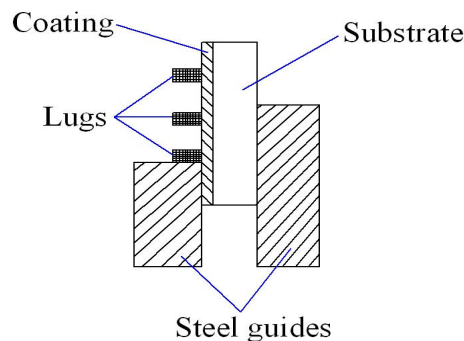


Figure 4.46: Schematic of a shear test fixture (Champagne et al., 2005b)

A thermosetting epoxy adhesive is applied to surfaces of the coating and 3 clean, dried, and abrasive-blasted rectangular lugs. The lugs are then glued to the coating, cured and inserted into a fixture or steel guides. The fixture is then placed in a load frame (Instron model 1331 on an Instron 8500 Plus Dynamic Testing System) and a calibrated downward load used to stress each lug to failure at the substrate-coating interface. The ratio of the normal force required to shear off the coating attachment area to the cross section attachment area, (F/A) yields the shear strength of the bond (Champagne et al., 2005b).

Hardness test

Vickers microhardness tests are performed on the cross-section of the deposits to determine their hardness. A Vickers hardness indenter (Figure 4.47) with a specific load (P) is applied to the coating surface for a particular period of time and the size of the indentation depth formed on the surface measured. More than 10 indentations for each sample are done and the depths averaged to evaluate the coating hardness from the respective load and hardness vs. indentation depth curves (Marot et al., 2006).

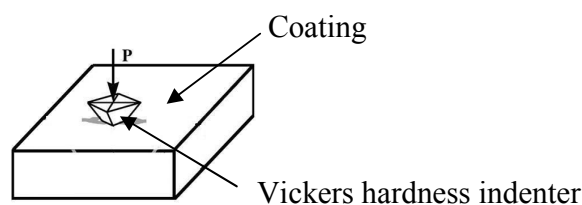


Figure 4.47: Schematic representation of a Vickers microhardness test (Marot et al., 2006)

Corrosion test

The corrosion behaviour of cold sprayed coatings is evaluated by a salt spray corrosion test. Coated samples with their edges polished are placed in a cabinet (~ 308 K) under an aqueous spray (a solution of 5 wt % NaCl in deionised water). The samples are observed at regular intervals and the time taken for the first appearance of rust spots on their surfaces noted (Zhang et al., 2003). Further, weight losses from the samples after exposure to the salt spray for a particular time frame are measured and compared to determine the deposit that has better corrosion resistance properties (see Appendix I1).

Abrasive wear test

The respective coatings abrasive wear rates are measured on test samples using an abrasion tester. These tests are performed in dry conditions in air atmosphere at room temperature. Firstly, the initial weight of the sample is measured before it is moved horizontally under a loaded rotating wheel covered with (SiC) emery paper. The sample is then moved against the abrasive wheel at different loading times (Figure 4.48) after which the weight loss is measured using an electronic balance (Morks et al., 2006). Similar graphs are constructed for different coatings and their relative abrasion resistances compared (see Appendix I2).

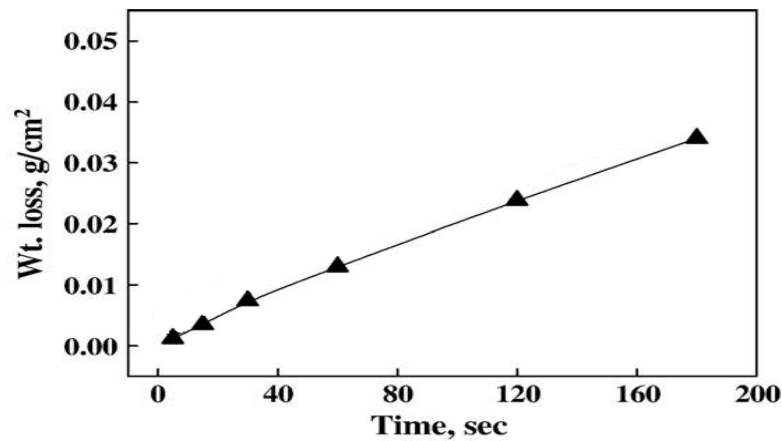


Figure 4.48: Abrasive wear rate of a coating (Morks et al., 2006)

Electrical resistivity

A collinear 4-probe tester is used for measuring the coatings electrical resistivity. The tester determines the coating resistance by passing a measured direct current through the sample between the outer probes and measuring the resulting potential difference between the inner probes. The resistance is then calculated from the measured potential and current values using the correction factors associated with the geometry of the sample and the probe spacing (Kumar et al., 2009).

4.11 Bill of Quantities

Having established the complete LPCGDS process, its BOQ is created (based on off-the-shelf components). This BOQ is presented in Table 4.18, showing the sizes of the system

components and their costs. The total price for the overall spray system arrangement is approximately **ZAR 486 158.75**. However, this unit price does not include the PLC, a travel displacement system and consumables such as the feedstock powder and nozzles. Moreover, without the spray chamber the unit costs approximately **ZAR 362 408.75**.

Table 4.18: Bill of Quantities

Component	Size	Cost (ZAR)
Air compressor	0-15 bars	28 139.33
Air receiver	400 Gallons	12 540.00
Pressure relief valve	0-15 bars	216.00
Pneumatic valve	0-15 bars	397.42
Flow meter	0-25 l/m	142.56
Gas heater	3.8 Kw	185 625.00
Gun	1 kg	33 185.92
Thermocouple	50-700 °C	434.63
Pressure transducer	0-15 bars	750.00
Pressure gauge	0-15 bars	50.63
Light sensor	10-36 V/DC	692.38
Light emitter	10-36 V/DC	28.43
Ball valve	0-15 bars	156.00
Rotary airlock feeder + hopper	0.1-1 g/s	61 875.00
Air supply hose	-20°C to 500°C	892.50
Powder supply hose	-20°C to 70°C	103.95
Electrical cable	2.5 mm	54.00
Spray chamber	booth, ventilation and filter system	123 750.00
Gas delivery system	manual control	37 125.00
Total		486 158.75

4.12 Conclusion

Presented in this chapter is the development of a LPCGDS system together with its auxiliary equipment. Initially, a requirements list for the overall system is generated (Table 4.1) which subsequently facilitates the development of its system structure, Figure 4.1. Generation of the system's respective components variants then follows (sections 4.4 - 4.8). These alternatives are generated by variation of both their physical effects and form design features. Using approximate selection matrixes, alternatives that do not sufficiently satisfy the requirements of the respective component's requirements list and those of the overall system are dropped out for the later step of evaluation.

After the selection process, an evaluation of the chosen variants is done to assess the variant that yields good DE and resultantly reduce the operating costs. The assessment is done based on the respective evaluation matrix constructed in accordance with the Guideline VDI 2225 (Pahl et al., 1996). Two main constraints that govern the assessment of each variant are its cost of production and effect on the quality of the sprayed coating or restored surface. The other criteria utilised in the evaluation include techniques such as CBA, engineering analysis and benchmarking with competitive products. During the evaluation process, optimum variants are determined to be; air, a coil heater, a rotary air lock feeder, granular powders in the 10-50 μm particle size range and an un-stepped CD nozzle with a circular cross-section. These are assembled into an overall system, Figure 4.35.

Also analysed is the system's auxiliary equipment utilised for; (1) recovery of un-deposited powder particles, (2) monitoring and controlling the system variables, and (3) assessing the quality of deposits. Lastly, a BOQ for the complete system is compiled showing components sizes and their costs. The next chapter discusses achievements of the research, its limitations and gives recommendations for further study.

5 CONCLUSION AND FUTURE WORK

5.1 Introduction

In this research, a conceptual design of a LPCGDS system was developed. Initially the LPCGDS system's task was clarified to establish its requirements list, and then followed the identification of the system components/sub-systems and the overall system structure, the generation, selection and evaluation of sub-systems variants, to the final assembling of the overall spray system. Also, additional equipment for the spray process was discussed, together with the techniques used to assess the quality of coatings obtained.

Underlined in this chapter are the accomplishments of the previous chapters, the achievements of the research in terms of meeting the aims, the limitations of the research and suggestions for future work.

5.2 A Brief Overview of Previous Chapters

Chapter 1 introduced the research presented in this study, its motivation, objectives and delimitation of scope. Also, it details what specific themes were investigated, how the research was carried out and what its contributions were.

The CGDS technology literature related to this dissertation was reviewed in Chapter 2. The advantages of CGDS over traditional TS processes such as laser sintering, PS, AS and HVOF (Figure 2.1) were elaborated. Chief amongst these advantages is the retention of original microstructural, mechanical and chemical material properties for both the substrate and powder particles, and the elimination of the undesired effects of high temperature such as oxidation (Karthikeyan et al., 2004). This is because the amount of heat involved in the process is relatively small and typically lower than the particle melting energy, signifying that the deposition mechanism is chiefly a solid-state process (Figure 2.14, Appendix B1).

An analytical solution that shows how v_p varies in relation to different process parameters (T_o , ρ_g , ρ_p and d_p) was represented by Equation 2.18. This velocity should exceed a minimum v_{crit} , Equation 2.20 on impact with the substrate and only particles whose velocity exceeds this value can be effectively deposited. Particles that do not reach this threshold velocity actually bounce off or erode the substrate, (Figure 2.19). The v_{crit} is material dependent, being affected for instance by particle strength, density and composition. Further in the chapter, it was discussed how the coating quality depend on the gas parameters (Figure 2.21 & 2.22), powder feeder design (Figure 2.31), powder feedstock characteristics (Figure 2.34) and nozzle geometry (Figure 2.38). To obtain good quality deposits, these parameters must be critically chosen. Also, the influences of various LPCGDS system requirements on the choice of components to use in the system were analysed and presented graphically.

This chapter ends with a description of the extra equipment making up the spray process. These include; (1) the spraying chamber that houses the substrate, gun and motion control system, (2) a gas and particle recycling system for recovering and recycling the gas and undeposited particles for re-use, (3) the DACS for controlling and monitoring powder feed rate, gas pressure and temperature respectively, and (4) coating quality evaluation equipment.

The methodology adopted in conceptual design of the LPCGDS system was outlined in Chapter 3. It shows that the design process initiates from the task clarification stage to establish a LPCGDS system's requirements list, (Table 3.2). Accordingly, this list is updated continuously as indicated by the information feedback loop in Figure 3.2 and will be consulted always throughout the design process. The loop helps minimise design costs by avoiding the development of unviable system components.

Furthermore, the chapter illustrated the generation of a system structure (Figure 3.3) after coming up with the system requirements list. This system structure clearly defines the existing sub-systems and their relationships, facilitating the search for sub-systems variants or alternatives. From the large number of sub-system variants generated, suitable variants are selected for further evaluation based on a screening matrix (Table 3.3). During evaluation (Table 3.4), each selected variant's technical, safety, environmental and

economic values are assessed against the demands of its respective requirements list. Moreover, techniques such as the UVA, CBA, engineering analysis and benchmarking with competitive products are also used to evaluate the variants. This evaluation stage will result in the assembly of the best chosen sub-system variants to generate the optimal overall LPCGDS system set-up.

Chapter 4 presented the actual establishment of the complete LPCGDS system and its auxiliary equipment. To begin with, the system's crux was properly formulated in order to make clear its constraints. A requirements list for the overall system (Table 4.1) was then generated, in turn facilitating the development of its system structure (Figure 4.1). Generation of variants for the system's respective components (gas heater, powder feeder, propellant gas, powder particle, nozzle geometry and cross-section) then followed (sections 4.4 - 4.8). These alternatives were created by variation of both their physical effects and form design features.

Using a respective screening matrix, variants that do not satisfactorily satisfy the constraints of both the sub-system and the overall system were eliminated. After this screening process, an evaluation of the selected variants was done to choose the variant that yields good DE and resultantly reduce the operating costs. The assessment was done based on the respective evaluation matrix constructed in accordance with the Guideline VDI 2225 (Pahl et al., 1996). Two main constraints that governed the assessment of each variant were its production cost and effect on the quality of the sprayed coating. Other techniques utilised in the evaluation include CBA, UVA, engineering analysis and benchmarking with competitive products.

According to the gas supply variants screening matrix, Table 4.3 He, N₂, Ar and air were selected for further evaluation as the propellant gas. Evaluating these gases in Table 4.4, air was chosen as the economical gas to utilise. The parallel tube, coil, bar and perforated plate heaters were selected for further analysis and evaluation from the gas heater variants screening matrix, Table 4.6. Their evaluation in Table 4.7 presented the coil heater as the most feasible heater to employ for the propellant gas pre-heating. Considering the powder feeder variants screening matrix, Table 4.9 the screw, rotary air lock, rotating wheel and fluidised bed powder feeders were selected for further evaluation. Results of their

evaluation in Table 4.10 proved the rotary air lock feeder to be the feasible feeder to use for the delivery of powder particles to the nozzle.

Because of difficulties experienced with the handling and feeding of ultrafine powders in LPCGDS systems, particles greater than 1 μm were selected for further evaluation from the powder particle size screening matrix, Table 4.12. Evaluation of these particles in Table 4.13 showed that in order to achieve maximum deposition efficiencies and coating qualities, particles in the size range 10-50 μm must be used as the feedstock material. Moreover, granular powders were preferred over spherical ones since they achieve less porous and low oxide content coatings.

Nozzle geometry alternatives selected from the nozzle geometry variants screening matrix (Table 4.15) for further assessment included the CD, CD+B, CB and BD nozzles. The outcome of their evaluation in Table 4.16 underlined that the CD variant satisfactorily meets all the system constraints. The rectangular, square, circular and elliptical nozzles were evaluated in Table 4.17 to obtain the preferable nozzle cross-section alternative. In view of the results from this table, the circular variant was found to adequately satisfy the evaluation criteria. Therefore, a circular nozzle cross-section will be utilised for the supersonic nozzle. Moreover, the nozzle will be non-stepped as this minimises nozzle erosion (Ajdelsztajn et al., 2005) and also requires less complex technologies for production compared to stepped nozzles.

Chosen sub-system variants (from respective evaluation matrixes) that best performs LPCGDS sub-functions were then assembled into an overall system in Figure 4.35. This portable system (see Appendix H4) is utilised in either manual or automatic applications. The chapter also looked into the additional equipment that completes the spray process. This consists of the spraying chamber (Figure 4.39), a gas and particle recovery system, the DACS and coating quality measurement equipment (section 4.10.4). Diagnostics such as electron microscopy and metallography are used for evaluating the quality of deposits obtained in the LPCGDS process. Lastly, a BOQ (Table 4.18) for the complete system showing components sizes and their costs was compiled.

5.3 Achievements of the Research

Requirements lists for both the overall LPCGDS system and its sub-systems were developed. These illustrate the demands and wishes that the overall system and the sub-systems must meet and, amongst these requirements is the need for the spray system to have a radial injection of powder into the nozzle, utilise low pressure gas (<10 bars) and achieve supersonic gas-particle velocities (of ~ 300 - 600 m/s). The requirements were then utilised in the construction of the spray system structure (Figure 4.1). After establishing the system structure, suitable technical and economic solutions to fulfil the respective sub-system's functions were generated. These were generated by variation of their physical structures, surfaces, motion and material make-up.

Through use of screening matrixes, the number of each sub-system's variants proposals created was reduced from a large number to a more convenient number for further elaboration and evaluation. This screening process was done to prevent going ahead with developing unviable variants. Selected variants from the screening process were then further analysed and evaluated through evaluation matrixes. The evaluation process determined strengths of sub-system's variants with respect to their requirements lists and that of the whole system. It assessed how well the variants satisfied the technical, economic, safety and environmental constraints imposed by the LPCGDS process.

Resultantly, an optimal conceptual design of a LPCGDS system was assembled from the chosen best sub-system variants (Figure 4.35). This optimum system has; a stable nozzle assembly operation with prolonged service life, reduced power consumption for maintaining the air temperature at the supersonic nozzle inlet and increased operational safety. The system was assembled in a modularised configuration (see Appendix H4, Figure H15) to enable the gun to be attached to robots and as such automate the system. This automation makes certain the production of high quality and reproducible coating structures. Such a modular system is also portable allowing it to be easily moved from place to place and be utilised in spraying confined areas. Because of the use of the non-pressurised (rotary air lock) feeder, the system has a reduced weight and a controllable and reproducible powder feeder feed-rate which make it achieve sound deposits. Also, since the feeder is not pressurised operating below 10 bars, this is a low cost feeder which makes the

spray costs low. Moreover, a BOQ of the complete LPCGDS system was compiled indicating that it costs approximately ZAR 486 158.75.

Lastly, other facilities that include the spraying chamber, a gas and particle recycling system, and the DACS were established and analysed. Techniques utilised to characterise the obtained deposits were also described. These include the; EDS or a HRTEM, triple-lug shear test method, Vickers microhardness test, salt spray corrosion test, an abrasion tester, and a collinear 4-probe tester.

5.4 Research Limitations

LPCGDS system components variants were generated, selected and evaluated to obtain optimum and viable combinations. However, only a theoretical assessment of the variant's technical, safety, environmental and economic values against the demands of the respective sub-system's requirements list was carried out. Assessment of the exact practical performance of the components in operation was not done due to the unavailability of resources. Accordingly, the perceived theoretical performances might not be the actual ones in operation and as a result, the chosen variants might not be the best for the sub-functions. As such, there is need to actually evaluate the physical components in operation, with measurable and quantifiable data.

Given that LPCGDS technology is a very wide research area, not all aspects of it were covered in detail in this research study. The research did not;

- Design the system components in detail.
- Analyse the gas-particle mixture flow inside and outside the nozzle.
- Look into the DE and adiabatic shear instability based mechanism for particles/substrate bonding.
- Analyse the effect of the standoff distance, spray angle and shock wave formation on DE.
- Characterise the resultant sprayed coatings.

5.5 Future Research

Future research of the LPCGDS technology requires a study of improving its efficiency and, in view of the research limitations mentioned in section 5.4, it is thus necessary to carry out a detailed research (theoretically or practically) in the following areas;

- Optimal design of a LPCGDS CD, circular un-stepped nozzle; rotary air lock feeder and coil heater.
- Modelling of the LPCGDS system.
- Effect of gas, particle and substrate parameters on the deposition characteristics for the spray process.
- Adiabatic shear instability based mechanism for particles/substrate bonding.
- Effect of the standoff distance, spray angle and shock wave formation on DE.
- Characterisation of LPCGDS coatings using techniques such as; microstructural analysis, hardness tests, tensile tests, fatigue and bend tests.

In order to obtain an optimal spray system efficiency, the following must also be studied; development of the boundary layer on the nozzle walls, the structure and stability of the supersonic jet, interaction of the jet with the substrate including the structure and time evolution of the high-pressure zone ahead of the substrate, and heat transfer between the jet and the substrate.

Since quality of LPCGDS coatings is enhanced by a number of variables (such as gas and particle parameters, stand-off distance, spray angle), use of a computer model (e.g. Computational Fluid Dynamic algorithm) to simulate the process during its design is required in order to optimise the variables. These simulations will clearly define the behavior of particles under varied spray process dynamic conditions.

Further, as LPCGDS is an additive manufacturing technology, combining it with traditional subtractive and formative fabrication techniques such as milling and forging is vital to explore the benefits of such a manufacturing arrangement. As a result, after establishing a LPCGDS system in the laboratory, it can be considered to have such a combination.

Consequently, there is need to construct and experimentally validate the whole system in order to maximise the spraying process.

5.6 Conclusion

This chapter discusses what the previous chapters achieved, the limitations of the dissertation and recommends work to be done in the future. It shows that in some applications, LPCGDS is preferred over traditional TS processes because of its ability to spray coatings that retain the initial properties of the particle material. The research methodology was explained whereby a system structure is established first, facilitating the search for sub-systems alternatives and their screening. An evaluation matrix in conjunction with the Guideline VDI 2225 is then used to evaluate these variants to obtain the favourable spray system.

Air was chosen for use as the propellant gas, the rotary air lock feeder for feeding the powder particles and the coil heater for pre-heating air. A powder particle size range of 10-50 μm was selected for the feedstock material. Additionally, these particles will have a granular structure to obtain superior quality coatings. A CD nozzle with a circular cross-section that's un-stepped will be employed for projecting the powder particle to the much needed critical velocity to achieve deposition. Supporting equipment that complements the spray system such as the spray booth, recycling system, the DACS and coating quality measurement equipment was also established.

An optimal conceptual design of a LPCGDS system was developed in this research. However, in order to better understand the spray process, further work is needed to establish the effects of process parameters on the resultant deposit. Hence there is need to develop a physical system in the laboratory, do the tests and assess the mechanical and chemical properties of the deposited material.

The developed LPCGDS system will not only benefit engineering applications but will also provide the scientific community with the opportunity to investigate the mechanical and chemical behavior of LPCGDS products (such as large bulk nanocrystalline (10 to 30 nm) materials) using standard testing methods (Ajdelosztajn et al., 2005).

REFERENCES

- Ajdelsztajn L., Zuñiga A., Jodoin B. and Lavernia E.J., (2006), Cold gas dynamic spraying of a high temperature Al alloy; *Surface & Coatings Technology* 201, Elsevier B.V, pp 2109 - 2116
- Ajdelsztajn L., Jodoin B, Kim G. E., and Schoenung J. M., (2005), Cold Spray Deposition of Nanocrystalline Aluminum Alloys; *Metallurgical And Materials Transactions A*, 658-Volume 36a, pp 657 - 666
- Alkhimov A.P., Kosarev V.F. and Klinkov S.V., (2001), The Features of Cold Spray Nozzle Design; Institute of Theoretical and Applied Mechanics SB RAS, Novosibirsk, Russia, *Journal of Thermal Spray Technology* Volume 10(2), ASM International, pp 375
- Assadi H., Gärtner F., Stoltenhoff T., Kreye H., (2003), Bonding mechanism in cold gas spraying; *Acta Materialia* 51, Elsevier Ltd., pp 4379 - 4394
- Balani K., Agarwal A., Seal S., Karthikeyan J., (2005a), Transmission electron microscopy of cold sprayed 1100 aluminum coating , *Scripta Materialia* 53, Elsevier Ltd., pp 845 - 850
- Balani K., Laha T., Agarwal A., Karthikeyan J., and Munroe N., (2005b), Effect of carrier gases on microstructural and electrochemical behavior of cold-sprayed 1100 aluminum coating; *Surface & Coatings Technology* 195, Elsevier B.V., pp 272 - 279
- Borissova A., Fairweather M. and Goltz G.E., (2006), An option generation and selection methodology for process equipment selection; *Research in Engineering Design* 17, Springer-Verlag London Limited, pp 13 - 26
- Bray M, Cockburn A, O'Neill W, (2008), Recent Developments of the Laser-assisted Cold Spray Process and Deposit Characterisation; Centre for Industrial Photonics, University of Cambridge Engineering Department, pp 1- 6

Cadney S., Brochu M., Richer P. and Jodoin B., (2008), Cold gas dynamic spraying as a method for freeforming and joining materials; *Surface & Coatings Technology* 202, Elsevier B.V., pp 2801 - 2806

Campbell M.I., Cagan J and Kotovsky K., (2002), The A-Design approach to managing automated design synthesis; *Research in Engineering Design* 14, Springer-Verlag, pp 12 - 24

Champagne V.K., (2007), Cold Spray: An Emerging Technology; The ASM Thermal Spray Society Workshop on Cold Spray Technology, Army Research Laboratory, pp 1 - 38

Champagne V., Helfrich D., Leyman P., Lempicki R. and Grendahl S, (2005a), The effects of gas and metal characteristics on sprayed metal coatings, *Modelling Simul. Mater. Sci. Eng.* 13, US Army Research Laboratory, Aberdeen, USA, IOP, pp 1119 - 1128

Champagne V.K., Helfrich D. Jr., Leyman P, Grendahl S, and Klotz B, (2005b), Interface material mixing formed by the Deposition of Copper on Aluminum by Means of the cold spray process; *Journal of Thermal Spray Technology* Volume 14(3), ASM International, pp 330 - 334

Crawmer D.E., (2004), *Handbook of Thermal Spray Technology*; ASM International and the Thermal Spray Society, pp 85 - 102

DeForce B., Eden T. and Potter J., (2006), Application of Aluminium coatings for the corrosion protection of magnesium by cold spray; Applied Research Laboratory, The Pennsylvania University, pp 1 - 23

Donsi G., Ferrari G. and Poletto M., (1997), Distribution of gas pressure inside a hopper discharging fine powders; *Chemical Engineering Science*, Vol 52, No. 23, Pergamon Press Ltd, pp 4291 - 4302

Dvorak M., (2006), A New Powder Feeder for the Transport of Ultrafine Powders; Firmennummer: CH-092.1.001.918-6, pp 1 - 5

Fukanuma H., Ohno N., Sun B. and Huang R., (2006), In-flight particle velocity measurements with DPV-2000 in cold spray; *Surface & Coatings Technology* 201, Elsevier B.V., pp 1935 - 1941

Gärtner F., Schmidt T., Stoltenhoff T., and Kreye H., (2006a), Recent Developments and Potential Applications of Cold Spraying, Helmut Schmidt University, Hamburg, Germany, ASM International, pp 1 - 9

Gärtner F., Stoltenhoff T., Voyer J., Kreye H., Riekehr S. and Koçak M., (2006b), Mechanical properties of cold-sprayed and thermally sprayed copper coatings; *Surface & Coatings Technology* 200, Elsevier B.V., pp 6770 - 6782

Gedzevicius I. and Valiulis A.V., (2006), Analysis of wire arc spraying process variables on coatings properties; *Journal of Materials Processing Technology* 175, Elsevier B.V., pp 206 - 211

Gilmore D.L., Dykhuizen R.C., Neiser R.A., Roemer T.J. and Smith M.F. (1998), Particle velocity and deposition efficiency in the cold spray process; Sandia National Laboratories, Albuquerque, NM 87185 - 1130, pp 1 - 29

Grujicic M., Zhao C. L., Tong C., DeRosset W. S. and Helfritsch D., (2004) Analysis of the impact velocity of powder particles in the cold-gas dynamic-spray process; *Materials Science and Engineering A368*, Elsevier B.V., pp 222 - 230

Grujicic M., Tong C., DeRosset W. S., and Helfritsch D., (2003), Flow analysis and nozzle-shape optimisation for the cold-gas dynamic-spray process; Department of Mechanical Engineering, Clemson University, Clemson, USA, IMechE, pp 1603 - 1613

Gulati P., Katti V. and Prabhu S.V., (2009), Influence of the shape of the nozzle on local heat transfer distribution between smooth flat surface and impinging air jet; *International Journal of Thermal Sciences* 48, Elsevier Masson SAS, pp 602 - 617

Guo X., Zhang G., Li W., Gao Y., Liao H. and Coddet C., (2009), Investigation of the microstructure and tribological behavior of cold-sprayed tin-bronze-based composite coatings; *Applied Surface Science* 255, Elsevier B.V., pp 3822 - 3828

Guo X., Zhang G., Li W.-Y., Dembinski L., Gao Y., Liao H. and Coddet C., (2007), Microstructure, microhardness and dry friction behavior of cold-sprayed tin bronze coatings; *Applied Surface Science* 254, Elsevier B.V., pp 1482 - 1488

Helfritsch D. and Champagne V., (2006) A model study of powder particle size effects in cold spray deposition; U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, pp 1 - 5

Jen T.-C., Pan L., Li L., Chen Q. and Cui W., (2006), The acceleration of charged nanoparticles in gas stream of supersonic de-Laval-type nozzle coupled with static electric field; *Applied Thermal Engineering* 26, Elsevier Ltd, pp 613 - 621

Jen T.-C., Li L., Cui W., Chen Q. and Zhang X., (2005), Numerical investigations on cold gas dynamic spray process with nano and micro size particles; *International Journal of Heat and Mass Transfer*, Elsevier Ltd., pp 4384 - 4396

Jing S. and Li H., (1999), Study on the flow of fine powders from hoppers connected to a moving-bed standpipe with a negative pressure gradient; *Powder Technology* 101, Elsevier Science S.A., pp 266 - 278

Jodoin B., Raletz F., Vardelle M., (2006), Cold spray modeling and validation using an optical diagnostic method, *Surface & Coatings Technology* 200, Elsevier B.V., pp 4424 - 4432

Johnson K., (2005); *Kinetic Spray Metal Deposition Technologies for Corrosion Protection*, Solidica, pp 1 - 27

Jones J.C., (1970), *Design methods*; John Wiley and Sons Ltd

Karthikeyan J., (2007), *Development of Oxidation Resistant Coatings on GRCop-84 Substrates by Cold Spray Process*; Barberton, Ohio; ASB Industries, Inc., pp 1 - 16

Karthikeyan J., (2004), *Cold Spray Technology: International Status and USA Efforts*, Barberton, Ohio; ASB Industries Inc, pp 1 - 14

Kashirin A.I., Klyuev O.F. and Buzdygar T.V., (2002), Apparatus for gas-dynamic coating; United States Patent, US 6 402 050 B1, pp 1 - 4

Khandani S., (2005), ENGINEERING DESIGN PROCESS; Education Transfer Plan, IISME/Solelectron, pp 1 - 24

Khazaei J., Massah J. and Mansouri G.H., (2008), Effect of some parameters of air-jet on pneumatic extraction of citrus juice and juice sacs; Journal of Food Engineering 88, Elsevier Ltd., pp 388 - 398

Kim H.-J., Lee C.-H. and Hwang S.-Y., (2005), Superhard nano WC–12%Co coating by cold spray deposition; Materials Science and Engineering A 391 (2005), Elsevier B.V., pp 243 - 248

King P.C., Zahiri S.H. and Jahedi M., (2008), Focused ion beam micro-dissection of cold-sprayed particles; Acta Materialia 56, Elsevier Ltd., pp 5617 - 5626

Klinkov S.V., Kosarev V.F. and Rein M., (2005), Cold spray deposition: Significance of particle impact phenomena; Aerospace Science and Technology 9, Elsevier SAS., pp 582 - 591

Kreeger K., (1994), Application variables for powder coating systems; Nordson Corporation, pp 1 - 8

Kreye H., Schmidt T., Gärtner F. and Stoltenhoff T., (2006), The Cold Spray Process and its Optimisation; Helmut Schmidt University, University of the Federal Armed Forces, Hamburg, Germany, pp 1 - 8

Krishnakumar K. and Venkatarathnam G., (2003), Transient testing of perforated plate matrix heat exchangers; Cryogenics 43, Elsevier Science Ltd., pp 101 - 109

Kumar S., Bae G., Kang K., Yoon S. and Lee C., (2009), Effect of powder state on the deposition behaviour and coating development in kinetic spray process; Journal Of Physics D: Applied Physics, IOP Publishing Ltd, pp 1 - 8

Langston P. A., Tozon U. and Heyes D. M., (1996), Distinct element simulation of interstitial air effects in axially symmetric granular flows in hoppers; *Chemical Engineering Science*, Vol 51, No. 6, Pergamon Press Ltd, pp 873 - 891

Lee H., Lee S., Shin H. and Ko K., (2009), Mechanical matching and microstructural evolution at the coating/substrate interfaces of cold-sprayed Ni, Al coatings; *Journal of Alloys and Compounds*, Elsevier B.V., pp 1 - 6

Lee H., Shin H., Lee S. and Ko K., (2008), Effect of gas pressure on Al coatings by cold gas dynamic spray; *Materials Letters* 62, Elsevier B.V., pp 1579 - 1581

Lee J. C., Kang H. J., Chu W. S., and Ahn S. H., (2007), Repair of Damaged Mold Surface by Cold-Spray Method; *Annals of the CIRP* Vol. 56/1, pp 577 - 580

Li W.-Y., Zhang C., Guo X.P., Zhang G., Liao H. L., Li C.-J., and Coddet C., (2008), Effect of standoff distance on coating deposition characteristics in cold spraying; *Materials and Design* 29, Elsevier Ltd., 297 - 304

Li W., Liao H., Douchy G and Coddet C., (2007), Optimal design of a cold spray nozzle by numerical analysis of particle velocity and experimental validation with 316L stainless steel powder; *Materials and Design* 28, Elsevier Ltd., pp 2129 - 2137

Li W.-Y., Liao H., Wang H.-T., Li C.-J., Zhang G. and Coddet C., (2006), Optimal design of a convergent-barrel cold spray nozzle by numerical method; *Applied Surface Science* 253, Elsevier B.V., pp 708 - 713

Li C.-J., Li W.-Y., Wang Y.-Y., Yang G.-J. and Fukanuma H., (2005), A theoretical model for prediction of deposition efficiency in cold spraying; *Thin Solid Films* 489, Elsevier B.V., pp 79 - 85

Li C.-J., Li W.-Y. and Wang Y.-Y., (2004), Formation of metastable phases in cold-sprayed soft metallic deposit; Elsevier B.V.

Li C.-J. and Li W.-Y., (2003), Deposition characteristics of titanium coating in cold spraying; *Surface and Coatings Technology* 167, Elsevier Science B.V., pp 278 - 283

Lima R.S., Kucuk A. and Berndt C.C., (2002), Deposition efficiency, mechanical properties and coating roughness in cold-sprayed titanium; Department of Materials Science and Engineering, State University of New York at Stony Brook, Stony Brook, USA, Kluwer Academic Publishers, pp 1 - 3

Maev R. Gr. and Leshchynsky V., (2008), Introduction to Low Pressure Gas Dynamic Spray, Physics and Technology, Weinheim: Wiley-VCH.

Maier J.R.A. and Fadel G.M., (2009), Affordance-based design methods for innovative design, redesign and reverse engineering; Res Eng Design, Springer-Verlag London Limited, pp 1 - 15

Marcus R.D., Leung L.S., Klinzing G.E. and Rizk F., (1990), Pneumatic conveying of solids; A theoretical and practical approach, Chapman and Hall

Marot G., Lesage J., Démarécaux Ph., Hadad M., Siegmann St. and Staia M.H., (2006), Interfacial indentation and shear tests to determine the adhesion of thermal spray coatings; Surface & Coatings Technology 201, Elsevier B.V., pp 2080 - 2085

Masuda H., Higashitani K. and Yoshida H., (2006), Powder Technology; Handling operations, Process Instrumentation, and Working Hazards, CRC Press, pp 61 - 216

McCune R.C., Donlon W.T., Popoola O.O., and Cartwright E.L., (2000), Characterization of Copper Layers Produced by Cold Gas-Dynamic Spraying, Volume 9(1) March 2000-73, ASM International

Morks M.F. and Kobayashi A., (2006), Influence of gas flow rate on the microstructure and mechanical properties of hydroxyapatite coatings fabricated by gas tunnel type plasma spraying; Surface & Coatings Technology 201, Elsevier B.V., pp 2560 - 2566

Morgan R., Fox P., Pattison J., Sutcliffe C. and O'Neill W., (2004), Analysis of cold gas dynamically sprayed aluminium deposits; Materials Letters 58, Elsevier B.V., pp 1317 - 1320

Novoselova T., Fox P., Morgan R. and O'Neill W., (2006), Experimental study of titanium/aluminium deposits produced by cold gas dynamic spray; *Surface & Coatings Technology* 200, Elsevier B.V., pp 2775 - 2783

Ning X.-J., Kim J.-H., Kim H.-J., and Lee C., (2009), Characteristics and heat treatment of cold-sprayed Al–Sn binary alloy coatings; *Applied Surface Science* 255, Elsevier B.V., pp 3933 - 3939

Ning X.J., Jang J.-H and Kim H.-J, (2007), The effects of powder properties on in-flight particle velocity and deposition process during low pressure cold spray process; *Applied Surface Science* 253, Elsevier B.V., pp 7449 - 7455

Pahl G. and Beitz W., (1996) *Engineering Design: A systematic approach*; Great Britain, Springer-Verlag London Limited

Papyrin A., Kosarev V., Klinkov S., Alkhimov A. and Fomin V., (2007), *Cold Spray Technology*; Khristianovich Institute of Theoretical and Applied Mechanical of Russian Academy of Science in Novosibirsk, Russia; London : Elsevier.

Papyrin A.N., (2006), *Cold Spray: State of the art and applications*; Cold Spray Technology, Albuquerque, NM, USA, pp 1 - 21

Pattison J., Celotto S., Morgan R., Khan A. and O'Neill W., (2007a), Standoff distance and bow shock phenomena in the Cold Spray process, *Surface & Coatings Technology*, pp 1 - 12

Pattison J., Celotto S., Morgan R., Bray M and O'Neill W., (2007b), Cold gas dynamic manufacturing: A non-thermal approach to freeform fabrication; *International Journal of Machine Tools & Manufacture* 47, Elsevier Ltd, pp 627 - 634

Raletz F., Vardelle M. and Ezo'o G, (2006), Critical particle velocity under cold spray conditions; *Surface & Coatings Technology* 201 (2006) Elsevier B.V., pp 1942 - 1947

Rhodes M., (2001), *Introduction to particle technology*; John Wiley and Sons Ltd, West Sussex, England

Ruder J.A. and Sobek D.K. II, (2007), Experiment on a system-level design tool; Journal of Engineering Design, Vol. 18, No. 4, Taylor & Francis, pp 327 - 342

Schmidt T., Gärtner F., Assadi H. and Kreye H., (2006), Development of a generalized parameter window for cold spray deposition; Acta Materialia 54; Elsevier Ltd, pp 729 - 742

Shin S., Yoon S., Kim Y. and Lee C., (2006); Effect of particle parameters on the deposition characteristics of a hard/soft-particles composite in kinetic spraying; Surface & Coatings Technology 201, Elsevier B.V., pp 3457 - 3461

Smith M.F., (1999), Overview of Cold Spray; Sandia National Laboratories, Albuquerque, NM, pp 1 - 20

Stoltenhoff T., Borchers C., Gärtner F. and Kreye H., (2006), Microstructures and key properties of cold-sprayed and thermally sprayed copper coatings; Surface & Coatings Technology 200, Elsevier B.V., pp 4947 - 4960

Tsymbalov G.M. and Koshelev V.S., (1971), Solution of the steady-state heat-conduction problem for thin filament heaters of arbitrary geometry; Scientific-Research Institute of Mechanics and Physics, Saratov, pp 1301 - 1305

Ulrich K.T. and Eppinger S.D., (2008), Product Design and Development; 4th edition, Engineering Design I - Concept Selection, Irwin McGraw-Hill, pp 1 - 26

Van Steenkiste T.H., Smith J.R., Teets R.E., Moleski J.J., Gorkiewicz D.W., Tison R.P., Marantz D.R., Kowalsky K.A., Riggs W.L., Zajchowski P.H., Pilsner B., McCune R.C. and Barnett K.J., (1999), Kinetic spray coatings; Surface and Coatings Technology 111, Elsevier Science S.A., pp 62 - 71

Wang L., Shen W., Xie H., Neelamkavil J. and Pardasani A., (2002), Collaborative conceptual design - state of the art and future trends; Computer Aided Design 34, Elsevier Science Ltd, pp 981 - 986

Whittles D. N., Kingman S., Lowndes I. S. and Griffiths R., (2005), An investigation into the parameters affecting mass flow rate of ore material through a microwave continuous

feed system; VSP and Society of Powder Technology, Advanced Powder Technol., Vol. 16, No. 6, pp. 585 - 609

Wu J., Fang H., Yoon S., Kim H. and Lee C., (2005), Measurement of particle velocity and characterization of deposition in aluminum alloy kinetic spraying process; Applied Surface Science 252, Elsevier B.V., pp 1368 - 1377

Wu C.-Y., Dihoru I. and Cocks A. C. F., (2003), The flow of powder into simple and stepped dies; Powder Technology 134, Elsevier B.V., pp 24 - 39

Xu Y. and Hutchings I.M., (2006), Cold spray deposition of thermoplastic powder; Surface & Coatings Technology 201, Elsevier B.V., pp 3044 - 3050

Yandouzi M., Ajdelsztajn L. and Jodoin B., (2008), WC-based composite coatings prepared by the pulsed gas dynamic spraying process: Effect of the feedstock powders, Surface & Coatings Technology 202, Elsevier B.V., pp 3866 - 3877

Yandouzi M., Sansoucy E., Ajdelsztajn L. and Jodoin B., (2007), WC-based cermet coatings produced by cold gas dynamic and pulsed gas dynamic spraying processes; Surface & Coatings Technology 202, Elsevier B.V., pp 382 - 390

Yu Y. and Arnold P.C., (1996), The Influence of Screw Feeders on Bin Flow Patterns; Powder technology 88, pp 81 - 87

Zahiri S.H., Antonio C.I. and Jahedi M., (2009), Elimination of porosity in directly fabricated titanium via cold gas dynamic spraying; Journal of materials processing technology 209, Elsevier B.V., pp 922 - 929

Zhang D., Harris S.J., McCartney D.G., (2003), Microstructure formation and corrosion behaviour in HVOF-sprayed Inconel 625 coatings; Materials Science and Engineering A344, Elsevier Science B.V., pp 45 - 56

Zou H., Zhang H. and Wang G., (2008), A Flexible Synchronous Powder Feeder for Electromagnetism Compress Digital Manufacturing of FGM Metal Component; Huazhong University of Science and Technology, PIERS ONLINE, VOL. 4, NO. 8, 881, pp 881 - 885

BIBLIOGRAPHY

Champagne V.K., (2007), The cold spray materials deposition process: fundamentals and applications; Cambridge, England, Woodhead Publishing Limited

Fang J.C., Xu W.J., Zhao Z.Y. and Zeng H.P., (2007) Inflight behaviors of ZrO₂ particle in plasma spraying; Surface & Coatings Technology 201, Elsevier B.V., pp 5671 - 5675

Feng S.C. and Song E.Y., (2000), Information Modeling of Conceptual Design Integrated with Process Planning; Manufacturing Engineering Laboratory National Institute of Standards and Technology Gaithersburg, MD 20899, pp 1 - 8

Gärtner F., Stoltenhoff T., Schmidt T., and Kreye H., (2006), The Cold Spray Process and Its Potential for Industrial Applications; Helmut Schmidt University, Hamburg, Germany, ASM International, pp 1

Hardface Alloys, Inc. INTERNET.

<http://www.hardfacealloys.com>, accessed on 17 March 2009

K-Tron Process Group. INTERNET.

<http://www.ktron.com/products/>, accessed on 4 of February 2009

Li W-Y., Li C-J., Wang H-T., Li C-X. and Bang H-S., (2006), Measurement and Numerical Simulation of Particle Velocity in Cold Spraying; Journal of Thermal Spray Technology, Vol 15(4), ASM International, pp 559 - 562

Lima R.S., Karthikeyan J., Kay C.M., Lindemann J. and Berndt C.C., (2002), Microstructural characteristics of cold-sprayed nanostructured WC-Co coatings; Thin Solid Films 416, Elsevier Science B.V., pp 129 - 135

Lima R. S., Kucuk A and Berndt C. C., (2002), Deposition efficiency, mechanical properties and coating roughness in cold-sprayed titanium; Department of Materials Science and Engineering, State University of New York at Stony Brook, Stony Brook, USA, Kluwer Academic Publishers, pp 1 - 3

Livshits M. I. and Kharlamov Y. A., (1980), Metering of fine powders in detonation-gas spray-deposition; Plenum Publishing Corporation, pp 402 - 404

Rus Sonic Technology, Inc. INTERNET.

<http://www.rusonic.com/equip.htm>, accessed on 21 August 2009

Supersonic Spray Technologies. INTERNET.

http://supersonicspray.com/applications_design.htm, accessed on 10 September 2008

Supersonic Spray Technologies. INTERNET.

http://www.supersonicspray.com/product_powders.htm, accessed on 19 November 2008

Supersonic Spray Technologies. INTERNET.

http://www.supersonicspray.com/product_portable.htm, accessed on 17 June 2009

Supersonic Spray Technologies. INTERNET.

http://www.supersonicspray.com/product_robotic.htm, accessed on 17 June 2009

Supersonic Spray Technologies. INTERNET.

http://www.supersonicspray.com/product_components_feeders.htm, accessed on 7 October 2009

Van Steenkiste T.H., Smith J.R. and Teets R.E., (2002), Aluminum coatings via kinetic spray with relatively large powder particles; Surface and Coatings Technology 154, Elsevier Science B.V., pp 237 - 252

Venkatarathnam G. and Sarangi S., (1989), Matrix heat exchangers and their application in cryogenic systems; Butterworth-Heinemann Ltd, Cryogenics Vol. 30, pp 907- 918

Vergheze T. M. and Nedderman R. M., (1995), The Discharge Of Fine Sands From Conical Hoppers; Chemical Engineering Science, Vol. 50 No. 19, Elsevier Science Ltd, pp 3143 - 3153

World International Property Organisation. INTERNET

<http://www.wipo.int/pctdb/images/PCT->

[IMAGES/19062008/US2006047965_19062008_gz_en.x4-b.jpg](http://www.wipo.int/pctdb/images/PCT-IMAGES/19062008/US2006047965_19062008_gz_en.x4-b.jpg), accessed on 3 June 2009

Zhu J.-X., Li G.-Z., Qin S.-Z., Li F.-Y., Zhang H. and Yang Y.-L., (2001), Direct measurements of particle velocities in gas–solids suspension flow using a novel five-fiber optical probe; Powder Technology 115, Elsevier Science B.V., pp 184 - 192

APPENDICES

Appendix A - Glossary

Adiabatic - no heat loss or transfer occurs (between the gas-particle mixture and the substrate)

Auxiliary - Additional

Cold gas dynamic spraying - processes wherein particles are deposited in solid state to form a coating

Conceptual design - that part of the design process in which, by the identification of the essential problems through abstraction, by the establishment of a system structure and by the search for appropriate working principles and their combination, the basic solution path is laid down through the elaboration of a solution principle (Pahl et al., 1996)

Constraints - limitations that the design must conform to

Criteria - performance specifications that the design must meet

Decision matrix - a mathematical tool used to derive a number that specifies and justifies the best decision

Demands - requirements that must be met under all circumstances, without whose fulfilment the design is not acceptable

Deposition efficiency (DE) - the weight percentage of particles that are deposited on the substrate to the particles that are accelerated towards it

Flowability - the powder particles ability to flow evenly, by means of gravity and other forces, from the top to the bottom of a hopper

Guideline VDI 2225 - a combined technical and economic evaluation technique

Hydrodynamic resistance - pressure loss

Incubation time - time needed to activate the substrate surface during which erosion instead of deposition takes place

Isentropic - adiabatic and frictionless

Mach number - velocity of the gas divided by the local speed of sound

Nanostructured - a structure with particles that's a few hundred nano-meters in size

Nozzle - a manifold designed to accelerate a gas to high velocity

One dimensional flow - the flow velocity, pressure and density are uniform across any cross section normal to the nozzle axis

Propellant - a gas used to accelerate or drive powder particles

Quality - all data involving permissible variations or special requirements

Quantity - all data involving numbers and magnitudes

Screening matrix - a mathematical tool used to trim down variants from a large number to a more manageable number

Sonic - Mach number = 1

Stand-off distance - distance between the tip of the nozzle and substrate

Stagnation temperature and pressure - gas quantities before nozzle entry

Sub-sonic - Mach number < 1

Substrate - the material, work piece or substance on which a coating is deposited

Subsystems - components that make up the complete system set-up

Supersonic - Mach number > 1

System structure (function structure) - a design configuration of a system

Thermal spraying - processes wherein particles are deposited in a molten or semi-molten condition to form a coating

Throat - smallest cross-sectional area of the nozzle

Two phase flow - feedstock powder particles suspended in a carrier gas

Variant - a subsystem alternative

Wishes - requirements that should be taken into consideration whenever possible

Appendix B - The CGDS Process

Appendix B1 - The solid state nature of CGDS

XRD patterns of Cu and W powder particles and coatings with and without preheating are shown in Figure B1. Although Cu powder is sensitive to oxidation at high temperatures, peaks for the coatings with room temperature particles and preheated particles are almost the same as that of the starting powder. Only the crystalline phases of Cu and W are detected in (d) and no evidence of any interactions is observed. This is because particle temperature in CGDS is lower enough to avoid the particle phase transformations and consequently, the crystalline structure of the powders is completely retained in the coatings. The lack of other phases is strong evidence supporting that the deposition mechanism of CGDS is primarily a solid state process (Shin et al., 2006).

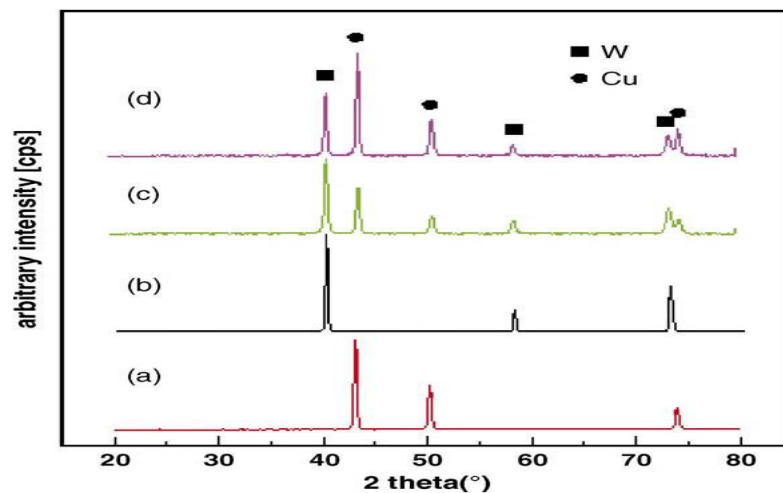


Figure B1: XRD patterns of (a) Cu powder, (b) W powder, (c) coating using room temperature feedstock, (d) coating using preheated feedstock (Shin et al., 2006)

Appendix B2 - Applications of CGDS

The solid state nature of CGDS lends itself to the deposition of metals onto composites and polymers. Given that the substrate does not have to be metallic, or have a very flat surface, the process is conducive to embedding devices within the deposited material. Provided the device is sufficiently hard so as to resist particle bombardment, sensors such as thermocouples and optical fibres can be easily sprayed upon. In doing so, components can

be created in a single step without the need for complex lithographic techniques. Figure B2(a) shows three-sheathed thermocouples embedded within a Ti part without loss of functionality. A first layer of material is deposited, and then a second one is laid down that contains three grooves; the transmitters are placed into the grooves and clamped in position; a third and final layer is added to complete the structure. After that, the component is machined to net shape (Pattison et al., 2007b).

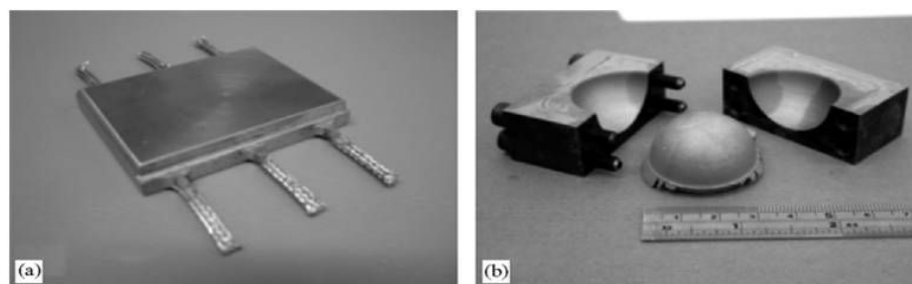


Figure B2: Photographs showing (a) three sheathed thermocouples embedded within a Ti part and (b) a Ti hemisphere formed by a mould tool (Pattison et al., 2007b)

Since the CGDS process can deposit fully dense material, it is possible to create mould forms that can be heat treated without shrinkage and hence without the need for hot isostatic pressing (HIPing). Figure B2(b) shows a hemispherical mould form created by spraying Ti into a hardened tool steel mould and removed via a sacrificial layer of Al (Pattison et al., 2007b).

CGDS technology is also a viable means of producing both nanocrystalline coatings and bulk nanostructured materials for engineering applications. Figure B3 shows complex geometries capable by CGDS. In Figure B3(a) is a near-net shape block composed of 80W-20Cu wt% and in Figure B3(b) is a cone.

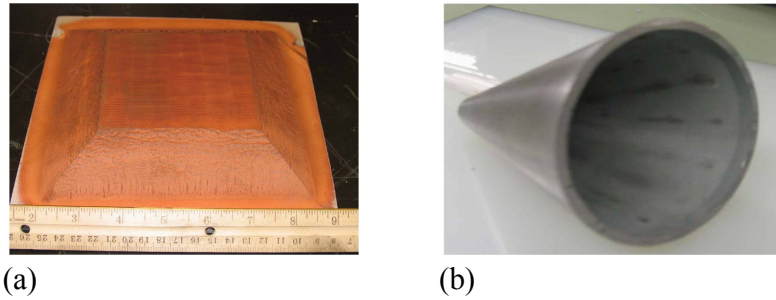


Figure B3: Near-net shape forming by CGDS (a) 80W-20Cu wt% block (b) cone (Champagne et al., 2007)

Illustrated in Figure B4 is a helicopter-ring groove that was repaired using CGDS. Figure B4(a) shows an area that was damaged and the material removed, Figure B4(b) the area is filled with CGDS and; Figure B4(c) shows a re-machined ring groove.

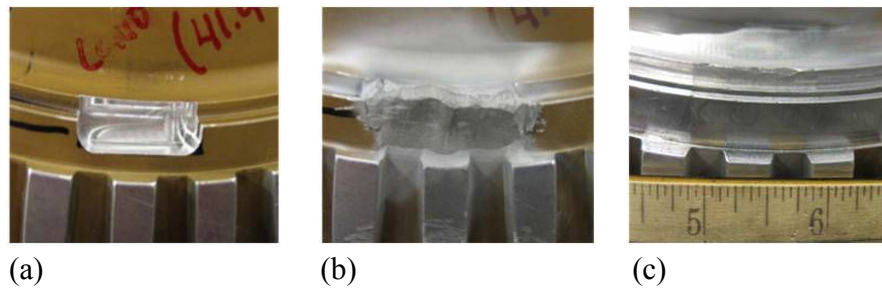


Figure B4: Helicopter-ring groove repair (a) metal removed from ring groove (b) area filled with CGDS (c) re-machined ring groove (Champagne et al., 2007)

Appendix B3 - Cross-section of a CGDS joined section

Figure B5(a) presents an optical micrograph of the cross-section of a section joined by CGDS, with both sides of the weldment successfully filled by the sprayed particles. Figure B5(b) shows a magnified micrograph corresponding to the contact point between the two Al substrates. The substrates are not in contact and are slightly misaligned; nevertheless, the sprayed particles were able to deform and fill the area between the two substrates, leaving no porous region at the point of contact. The micrographs also portray the defect-free adhesion between the sprayed particles and surfaces of the substrates, which shows that a CGDS deposit can be obtained on a slightly angled surface, so long as the normal

component of the particle impact velocity reaches the material dependant critical velocity (Cadney et al., 2008).

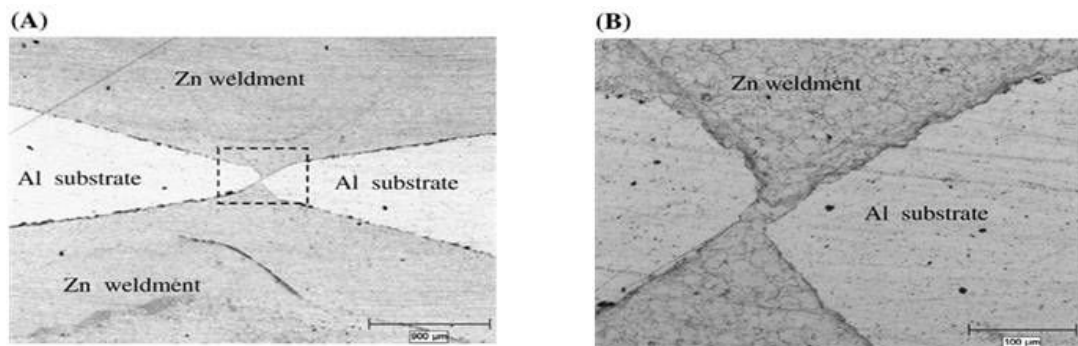


Figure B5: Optical micrograph of intersecting regions of a CGDS weld (Cadney et al., 2008)

Appendix C - Other Forms of CGDS

a) Pulsed Gas Dynamic Spraying

Pulsed gas dynamic spraying (PGDS) process, Figure C1 allows the feedstock particles to be accelerated to high impact velocities similar to those found in HPCGDS and LPCGDS. Particles are heated to intermediate temperatures in a non-reacting gas, thus enabling the production of dense coatings that exhibit the chemical and microstructural composition of the feedstock particles (Yandouzi et al., 2007).

The spray process consists of a long smooth wall pipe, divided in two compartments separated by a valve ($V_{H/L}$). The first compartment of the tube, the shock generator, is initially kept at high pressure P_{int} by being connected to a high-pressure gas supply. The second compartment, the spraying gun, is opened at the end and kept at atmospheric pressure (P_{at}). The initial pressure ratio of the system (P_{int}/P_{at}) is set to generate the required driving shock wave in the driven section. When $V_{H/L}$ is rapidly opened for a short period of time, a shock wave is generated and propagates into the spraying gun, accelerating and heating the powder present in the gun. Particles then impact the substrate and deform plastically to produce a coating. This operation is repeated at a set frequency. During each cycle (pulse), a controlled quantity of the feedstock powder is dropped down from the feeder to the tube by opening the feeder valve (V_F), and closing it prior to the passage of the shock wave. The system is equipped with electrical heaters, allowing preheating of both the gas and the powder (Yandouzi et al., 2007).

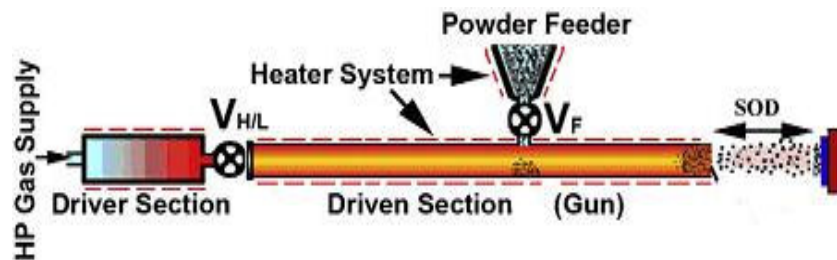


Figure C1: Schematic of the PGDS process (Yandouzi et al., 2008)

Due to the unsteady nature of the flow generated in the spray gun, the PGDS technique allows reaching a higher particle impact temperature. The propellant gas does not

experience the rapid drop of temperature found during gas expansion in the HPCGDS and LPCGDS processes.

b) Laser-assisted Cold Spray

Laser-assisted Cold Spray (LCS) process, Figure C2 combines the supersonic powder beam found in LPCGDS with laser heating of the deposition zone. LCS retains the advantages of LPCGDS while reducing operating costs by removing the need to use gas heating and helium as the process gas (Bray et al., 2008).

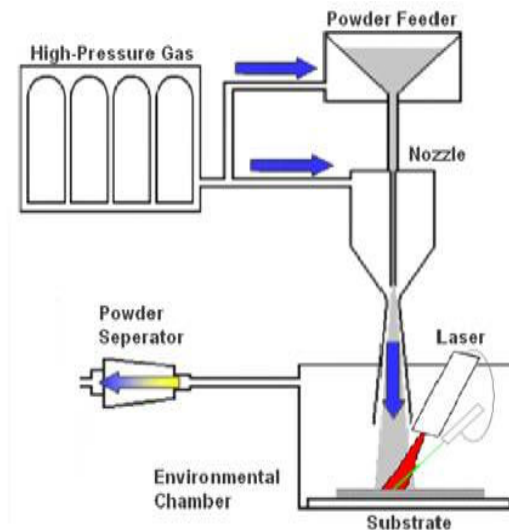


Figure C2: Layout of a Laser assisted Cold Spray system (Bray et al., 2008)

c) Electrostatic force assisted Cold Gas Dynamic Spray

Electrostatic force assisted cold gas dynamic spray (ECGDS), Figure C3 consists of; (1) carrier gas, (2) positively charged particles, (3) de-Laval-type nozzle, (4) tube for particle acceleration, (5) high-speed carrier gas with particles, and (6) substrate with a negative voltage. The substrate is connected to a high voltage generator to establish a negative potential around it (Jen et al., 2006).

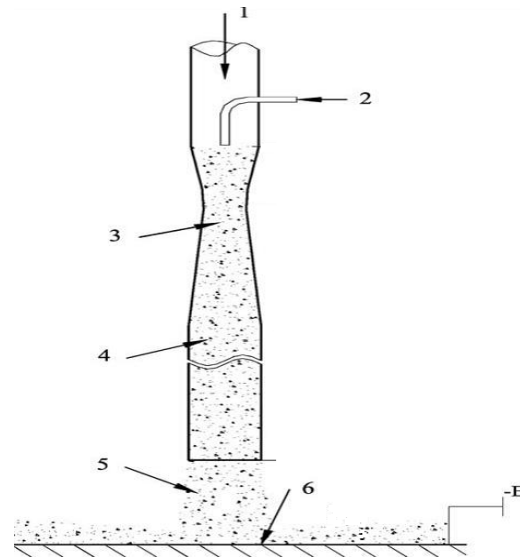


Figure C3: Configuration of ECGDS (Jen et al., 2006)

The carrier gas enters the nozzle to carry positively charged particles from the particle-feed pipe at the inlet of the convergent section. Outside the nozzle, there exists bow shock near the substrate, which causes steep pressure increase across the shock. When the gas flow penetrates the bow shock and approaches the substrate, the carrier gas speed decreases to nearly zero. Electrostatic force is used to assist the charged particles to achieve high velocity upon impact on the substrate. The higher particle charge densities lead to higher particle impact velocities; and the closer the particles approach the substrate, the stronger the electrostatic forces act on particles (Jen et al., 2006).

Appendix D - Gas Flow Outside the Nozzle

Appendix D1 - The shock wave stand-off position

As the supersonic flow exits the nozzle, shock diamonds are formed due to the pressure difference between the supersonic flow and the ambient atmosphere. The adjustment of supersonic flow to the atmospheric pressure is through shock waves; these are initially either oblique shocks (lip shock) or expansion fans (barrel shock), which correspond to over-expanded or under-expanded jets respectively. As the waves reflect from the edges of the jet, they change polarity, that is an expansion fan reflects as a compression wave and a compression shock reflects as an expansion fan. Thus, both types of shocks are simultaneously present. Figure D1(a, b) depict the under-expanded flow situations for N_2 and He respectively. Barrel shock appears outside the nozzle first because the flow static pressure at the exit is higher than the back pressure, so the flow must be expanded to eventually reach the back pressure. Outside of the jet core the densely spaced contour levels indicate the shear layers developing at the jet boundary. Flow at this region entrains the gas outside the shear layers, therefore, the shear layer grows and it penetrates into the jet core (Jen et al., 2005).

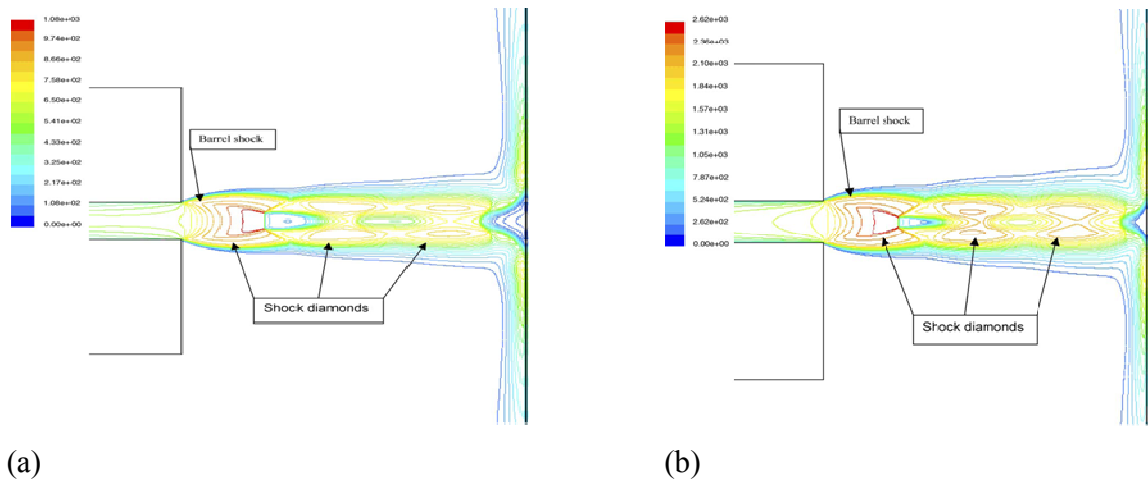


Figure D1: Velocity contours outside the nozzle of (a) N_2 and (b) He (Jen et al., 2005)

Flow between the nozzle exit and the shock wave upstream of the substrate is assumed to be constant, and equal to the conditions at the nozzle exit. The stand-off position of the

shock wave relative to the substrate is given by Billig's approximation (Helfrich et al., 2006) as:

$$\Delta = 0.143d_e \left[\exp \left(3.24/M_e^2 \right) \right]$$

where;

d_e = nozzle exit diameter (m)

M_e = Mach number at the nozzle exit

The Mach number immediately behind the shock wave is given by the normal shock relationship:

$$M^2 = \frac{\left[M_e^2 + \frac{2}{\gamma-1} \right]}{\left[\left(\frac{2\gamma}{\gamma-1} \right) M_e^2 - 1 \right]} \quad (d1)$$

Downstream of the shock wave, the Mach number is assumed to linearly decrease from the value given by Equation d1 to zero at the substrate surface. When the gas jet impinges on the substrate, a high pressure region is formed directly above the substrate, resulting in a bow shock wave opposing the flow from the nozzle, Figure D2. The particles have to penetrate the bow shock before impacting on the base material. While the larger particles have sufficient momentum to maintain the critical velocity, the smaller lighter particles are decelerated to the point where they will no longer undergo deformation on impact. The bow shock effect can be reduced by increasing the nozzle standoff distance or by providing increased velocity to the particles. While an increase in gas pressure will achieve this, it is subject to significant diminishing returns (Morgan et al., 2004).

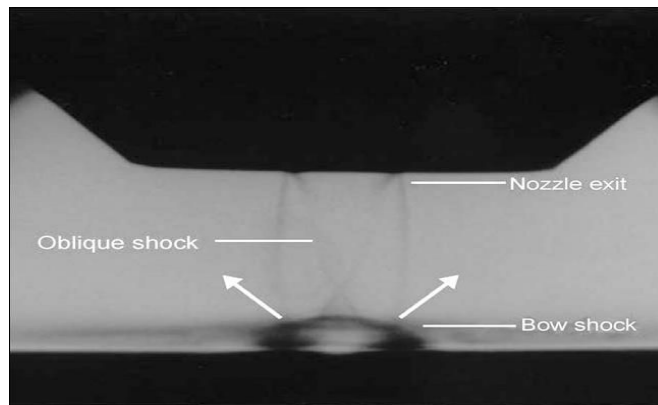


Figure D2: Bow shock formation above the substrate (Morgan et al., 2004)

For all supersonic flow impacting an object, the flow correction is made by this shock wave which instantly reduces gas velocity to subsonic and increases gas pressure and temperature. Particle velocity and temperature are not instantly affected by the shock wave, but continue to be affected by gas velocity and temperature through drag and heat transfer. Gas velocity decreases linearly downstream of the shock to zero at the substrate surface. Accordingly, particle velocity also decreases and is at a value lower than that at the nozzle exit when it strikes the substrate (Helfrich et al., 2006).

Appendix D2 - Variation of particle velocity with standoff distance

The variation of mean particle velocities with the standoff distance (z-axis) is shown in Figure D3. With air as the driving gas, particles accelerate to their peak velocity, just under 400 m/s by the time they exit the nozzle. They maintain this velocity almost constant out to a distance of 50 mm from the exit plane of the nozzle, past which point the velocity decreases linearly, diminishing by about 3% over the next 50mm. With He, the particles are still accelerating out to a distance of about 30mm (Gilmore et al., 1998).

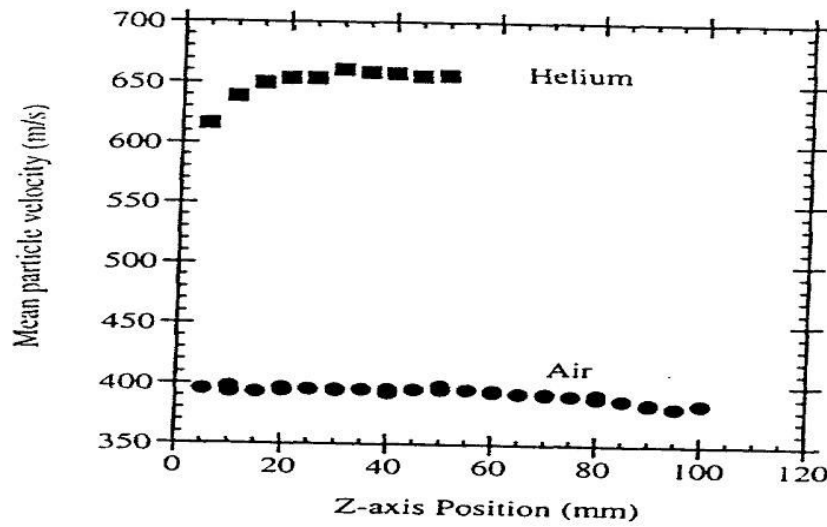


Figure D3: Mean particle velocity versus z-axis position (Gilmore et al., 1998)

Due to the lower density of He, the drag force on the particles is lower than for air at a given gas velocity relative to the particles. Therefore the distance required for the particles to reach a given fraction of the velocity of the driving gas (which is the limiting velocity) will be greater for He than for air. Theoretical calculations for the condition shown in Figure D3 indicate that at the gun exit, the particles have reached 42% of the gas velocity when He is used and 62% of the gas velocity when air is used. However, since He velocity is 2.5 times that of air, higher particle velocities are still observed with He as the driving gas (Gilmore et al., 1998).

Appendix D3 - Variation of porosity with particle velocity

The volume fraction of porosity in cold sprayed deposits is controlled through CGDS parameters such as gas temperature, gas pressure, powder feeding rate, stand-off, average powder size and deposition gas, all of which affect particle velocity. An increase in this particle velocity leads to a decrease in volume fraction of pores in the coatings (Zahiri et al., 2009). Figure D4 represents a decline in volume fraction of porosity to 12% at 635 m/s and 10% at 700m/s. However, an increase in velocity from 700 to 730 m/s is not large enough to decrease volume fraction of porosity significantly resulting in 9.5% porosity in the material (Zahiri et al., 2009).

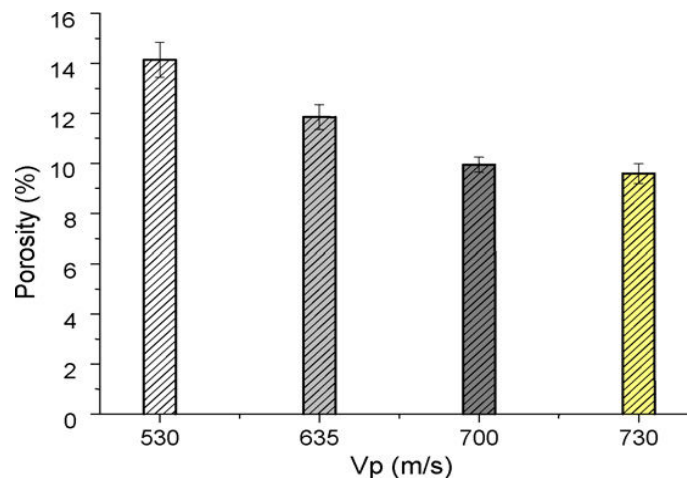


Figure D4: Volume fraction of porosity as a function of particle velocity (Zahiri et al., 2009)

Appendix E - The Bonding Process

Appendix E1 - Regions characteristic of particle impact phenomena

Particles impinging onto a substrate can reflect off the surface, stick to the surface or penetrate into the material. Often, the impact of particles on a surface causes a deformation or destruction of both the particles and the solid body. Regions characteristic of certain impact phenomena are displayed in Figure E1. Impacts of small ductile particles on surfaces of ductile and brittle materials at velocities of approximately 300-1200 m/s correspond to the region denoted cold spray (Klinkov et. al., 2005).

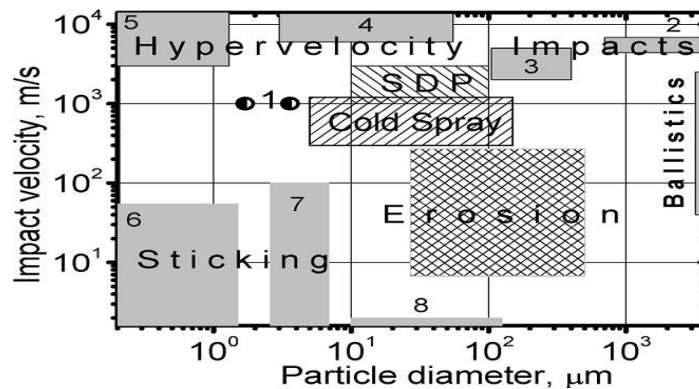


Figure E1: Regions characteristic of impact phenomena (Klinkov et. al., 2005)

Appendix E2 - Formation of interfacial jets

Figure E2(a-d) shows the collision between an Al particle and a Cu substrate at four times; 5, 20, 35 and 50 ns respectively. As the particle/substrate contact time increases, the particle (height to-width) aspect ratio decreases while the substrate crater depth and width increase. At the same time, an interfacial jet composed of both the particle material and the substrate material is formed at the particle/substrate contact surface. When this jet reaches the free surface, it forms a lip which points away from the flattened particle. Formation of such jets and their role in removing the contaminated material from the particle and substrate surfaces is a major (necessary) condition controlling the strength of particle/substrate bonding (Grujicic et al., 2003).

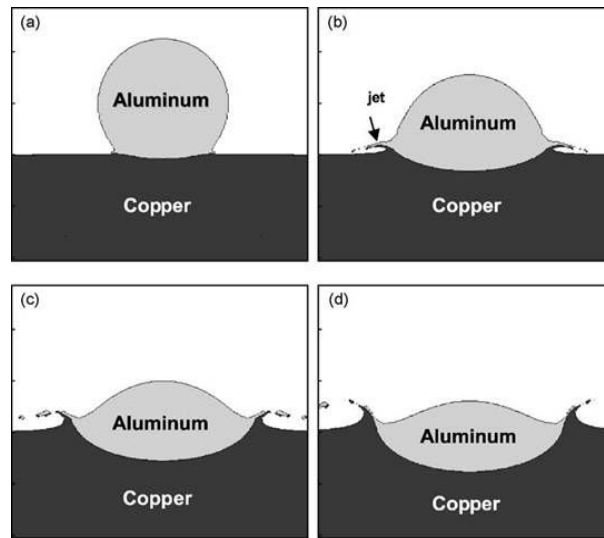


Figure E2: The evolutions of shapes of an Al feed-powder particle and a Cu substrate at the times: (a) 5 ns, (b) 20 ns, (c) 35 ns and (d) 50 ns (Grujicic et al., 2003)

Figure E3 shows micrographs of impacted particles of Cu on a Cu substrate. Overviews at low magnifications, Figure E3(a) demonstrate that more than 80% of the impacting particles adhere to the substrate. The close-up view in Figure E3(b) illustrates a view of a single impact of a Cu particle on a flat Cu substrate, demonstrating the localised, more viscous flow of material, resulting in consolidated material jets at the outer rim of impact crater. The micrographs also show that the deformation of secondary particles is influenced by the morphology created by primary impacts (Assadi et al., 2003).

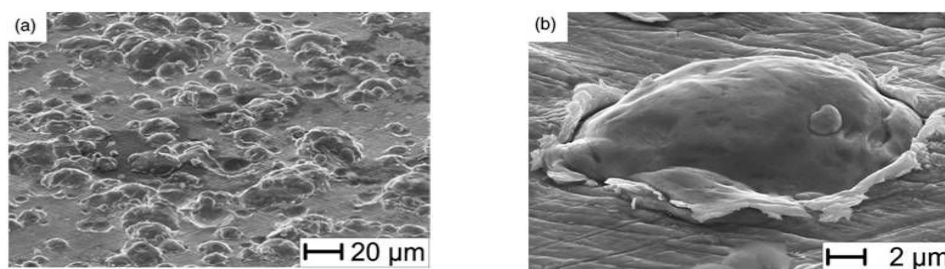


Figure E3: SEM of wipe test samples of Cu particles on a Cu substrate, showing (a) an overview and (b) a close-up image (Assadi et al., 2003)

Displayed in Figure E4 is the temperature field obtained 15 ns after initial contact of a Cu particle impinging with a velocity of 500 m/s on a Cu substrate. The deformation and heating of particle and substrate is highest in the interface region and decreases with

increasing distance. The highly non-uniform stress conditions and in consequence temperature distributions result in jet-like features aside the impacting particle (Gärtner et al., 2006a).

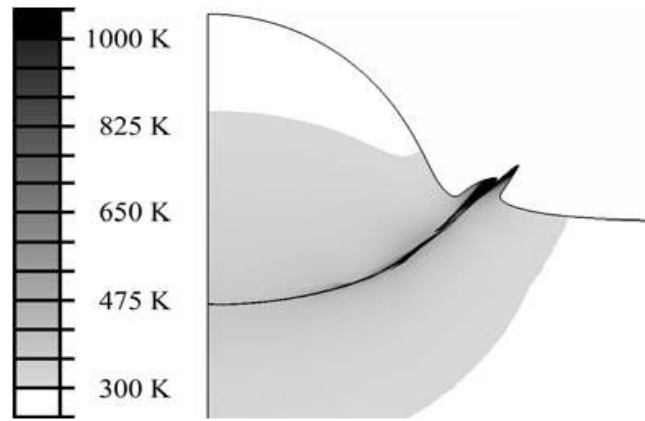


Figure E4: Temperature distribution in the particle-substrate interface for a Cu particle impacting on a Cu substrate (Gärtner et al., 2006a)

Appendix E3 - Formation of interfacial instabilities

Interfacial instabilities occur when two fluids in contact are moving at different velocities in a direction parallel to their interface and, the interface is subjected to a perturbation or curvature. As one fluid flows around the other, a centrifugal force is generated. A change in pressure is observed and promotes amplification of the interfacial perturbation. Figure E5 is a backscattered image illustrating interface instabilities of cold-sprayed Ni powder onto an Al substrate. The bright region is Ni and the darker region is the Al substrate (Ajdelsztajn et al., 2005).

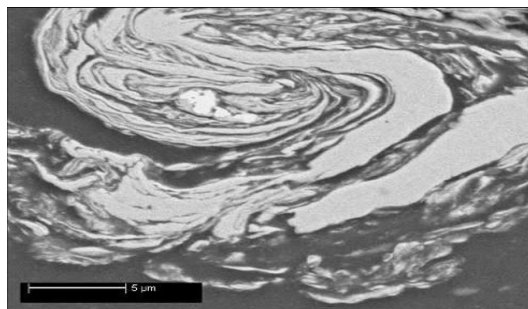


Figure E5: Backscattered image of interface instabilities of cold-sprayed Ni powder onto an Al substrate (Ajdelsztajn et al., 2005)

Appendix F - Effects of CGDS parameters

Appendix F1 - Effects of gas type on particle velocity

Particle exit velocity from the nozzle is shown as a function of particle diameter in Figure F1 for N₂ and He gases (Champagne et al., 2005a). For the same particle diameter, different particle velocities are achieved with these different gases because of their different properties. Use of high weight gases (N₂) decreases the capability of the carrier gas in accelerating the spray particle due to its heavier mass (Balani et al., 2005b). Hence, deposits obtained when using low molecular weight gases (He) display higher hardness in contrast to those obtained with high molecular weight gases.

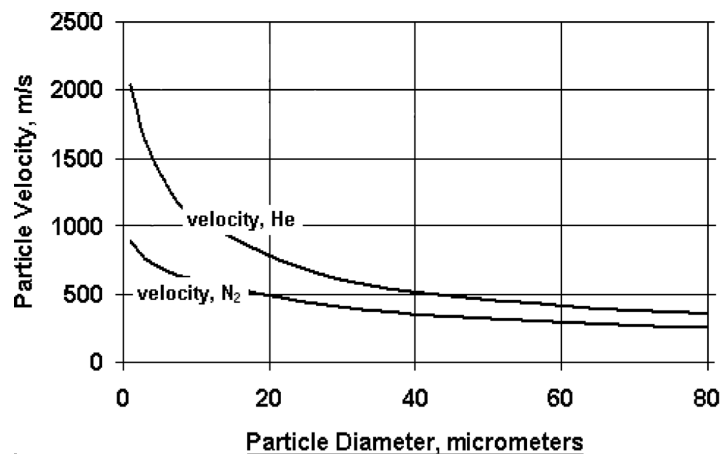


Figure F1: Particle velocity vs. diameter for N₂ and He gases (Champagne et al., 2005a)

Figure F2(a) shows an SEM micrograph of 1100 Al coating cold sprayed with 100 vol. % He and Figure F2(b) He - 20 vol. % N₂. Use of He alone, Figure F2(a) provides tamping of powder particles onto substrates due to its low carrier gas density (0.1785 kg/m³) and higher specific heat ratio. Heavy plastic deformation and reconsolidation into dense coating structures is distinct in this coating. Most of the particles exceed the critical velocity and get deposited onto the substrate.

The coating processed with He - 20 vol. % N₂, (Figure F2(b)) displays a relatively higher degree of porosity portraying low carrying capability of accelerating gas. This behavior is due to the increase in density of the carrier gas (N₂ density is 1.2506 kg/m³), and thereby reduced degree of plastic deformation of the spray particles for the coating. The features of

Figure F2(b) indicate a layer that is impacted by particles that are not actually getting deposited (similar to shot blasting) because of not being able to acquire the critical velocity required for the deposition (Balani et al., 2005b).

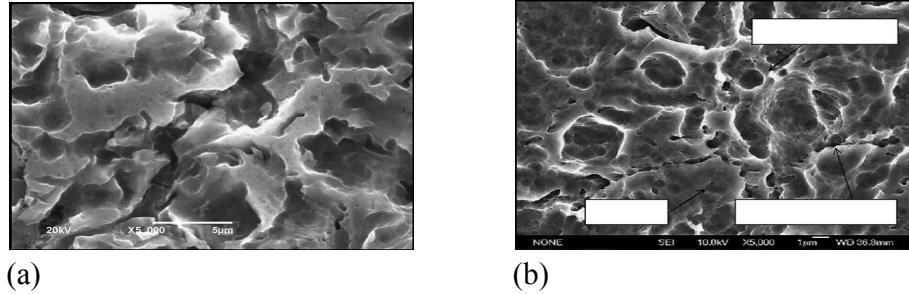


Figure F2: SEM micrograph of 1100 Al coating showing (a) smooth and dense coating, cold sprayed with 100 vol. % He; and (b) craters due to impact of un-deposited particles cold sprayed with He - 20 vol. % N₂ (Balani et al., 2005b)

Normally, the porosity observed on the top surface of deposited coatings is not actually the overall porosity of the deposits. Some of these pores keep getting impacted and filled by the next oncoming spray particles. Hence, the deposits are denser than they actually appear.

Appendix F2 - Effects of gas temperature on particle velocity

According to aerodynamics, an increase in gas temperature results in an increase of gas velocity and consequently the increase of the velocity of spray particles and the resultant DE. Figure F3 shows the effect of gas temperature on the relative DE. A critical temperature (~ 155 °C) is obtained below which no particle deposition occurs (Li et al., 2003). Above this temperature, with an increase in the gas temperature, the DE increases quickly, especially when the temperature becomes higher than 215 °C. At the critical temperature, particles are considered to have just reached the critical velocity.

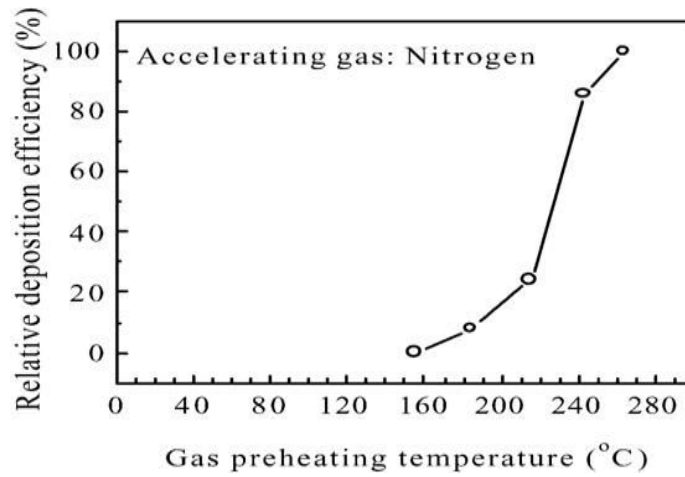


Figure F3: Effect of gas temperature on the relative DE (Li et al., 2003)

Appendix F3 - Effects of particle size and gas pressure on particle velocity

Particle velocity can be varied by changing the particle size and gas pressure in the gas-particle mixture flow. Figure F4 shows the variation of particle velocity for two sizes of polymer particles. The smaller particles experience a greater acceleration and achieve higher final velocities than the larger particles for the same air pressure.

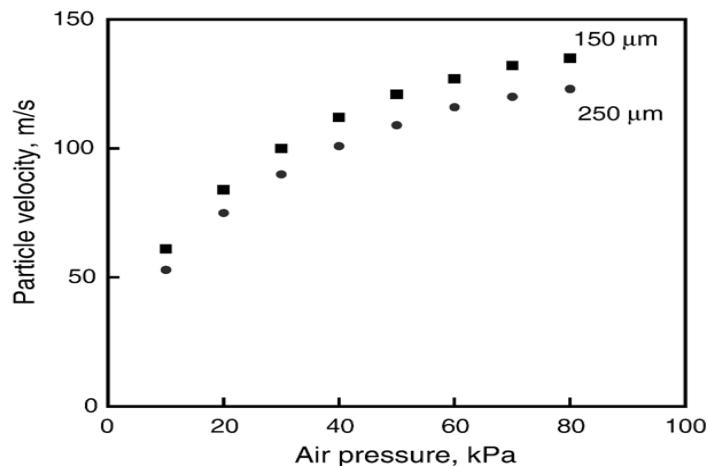


Figure F4: Nozzle exit velocity for 150 and 250 μm polyolefin particles as a function of air pressure (Xu et al., 2006)

The total mass of particles deposited is plotted in Figure F5 as a function of the mass of powder sprayed for the two different particle sizes and stand-off distances. A linear relationship is observed between the deposit mass and the amount of the input powder. For

the smaller particles, a greater deposit mass is obtained at the smaller stand-off distance of 15 mm. For the same stand-off distance and the same amount of input particles, the smaller particles give larger deposits than the larger particles because of their higher impact velocity (Xu et al., 2006).

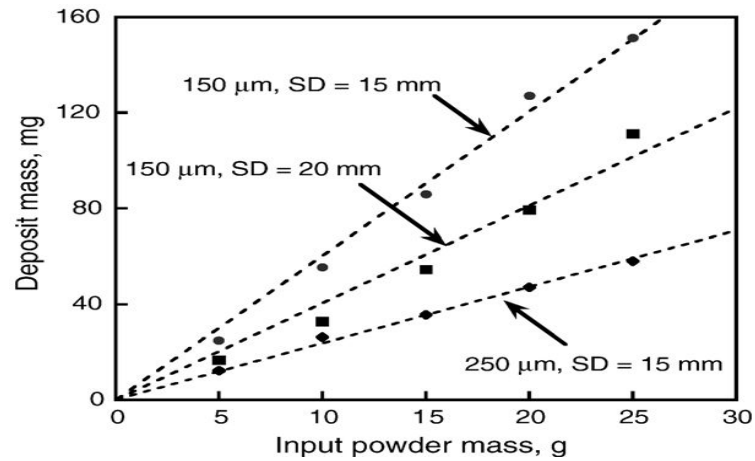


Figure F5: Deposited mass as a function of the input powder mass for different nozzle stand-off distances (SD) and different polymer particle sizes (Xu et al., 2006)

Appendix G - The Conceptual Design Process

Impacts or effects of design decisions are very high during the early stages of a design process, declining steeply as the design matures, Figure G1. The concept generated at this stage affects the basic shape generation and material selection of the product concerned. In the subsequent phase of detailed design, it becomes extremely difficult or even impossible to compensate or to correct the shortcomings of a poor design concept formulated at the conceptual design phase (Wang et al., 2002). Figure G1 also shows that at the early stages, no support tools (commercial or research) are available to address early design problems. However, as the design process proceeds, a number of design tools exist to support the design activities.

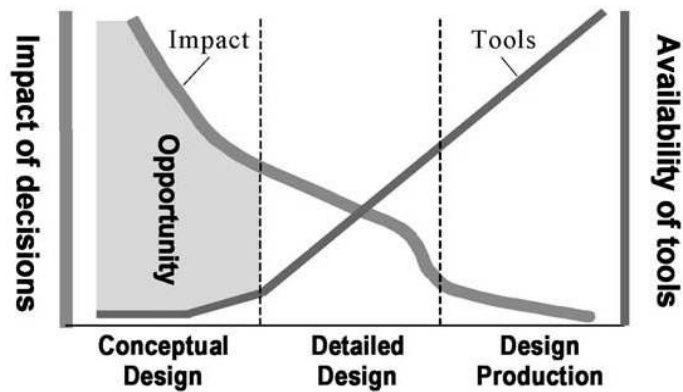


Figure G1: Opportunity in early design stage (Wang et al., 2002)

The majority of product costs are committed by the end of the conceptual design stage. All the life cycle concerns such as manufacturability, reliability marketing and distribution are taken into account at this early stage to achieve high return on investments (ROI) (Wang et al., 2002). The basic procedure in the conceptual design phase is divided into planning and clarifying the task, conceptual design on the system's level and the conceptual design on the module's level, Figure G2.

Planning and clarifying the task

This process step identifies the design task and the resulting requirements on the system which has to be developed will be worked out in here. The results are the list of

requirements, the environment model, the recommended product structure type and the design rules for this as well as the application scenarios.

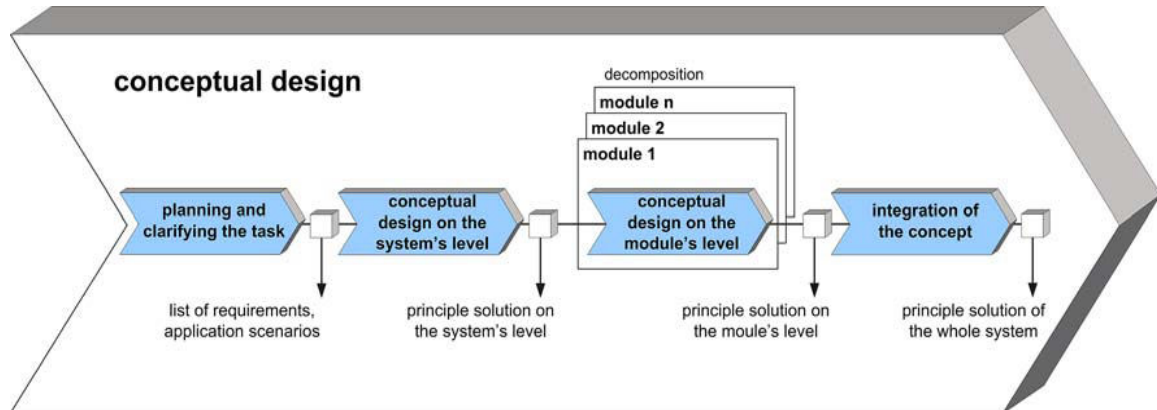


Figure G2: Process of conceptual design (Campbell et al., 2002)

Conceptual design on the system's level

Based on previously determined requirements on the system, solution variants will be developed for each application scenario. The best ones will be chosen and consolidated to a principle solution on the system's level. Afterwards, an analysis takes place which looks for contradictions within the principle solution of the system and which contradictions might be solved by self-optimization. The principle solution of a self-optimizing system on the system's level is the result of that phase (Campbell et al., 2002).

Conceptual design on the module's level

The principle solution on the system's level describes the whole system. It is necessary to have a closer look at the solution in order to give a statement on the technical and economical realisation of the principle solution. For that purpose, the system is modularised and a principle solution for each single module will be developed. The procedure corresponds to the conceptual design on the system's level, starting out with planning and clarifying the task. This phase's result is presented by the principle solutions on the module's level. The module's principle solutions will be integrated into a detailed principle solution of the whole system (Campbell et al., 2002).

After generating design alternatives, the solutions are evaluated to determine their individual worth. Evaluation can be done based on the A-Design that has the ability to adapt to changes in the design goals throughout the search process. This adaptive approach builds on traditional multi-objective methods like Pareto optimality.

An A-Design employs a unique strategy whereby candidates are divided into three separate populations labeled Pareto designs, good designs and poor designs, Figure G3. From this division, the Pareto and good candidates are preserved for use in the next iteration, while the remaining poor designs are discarded.

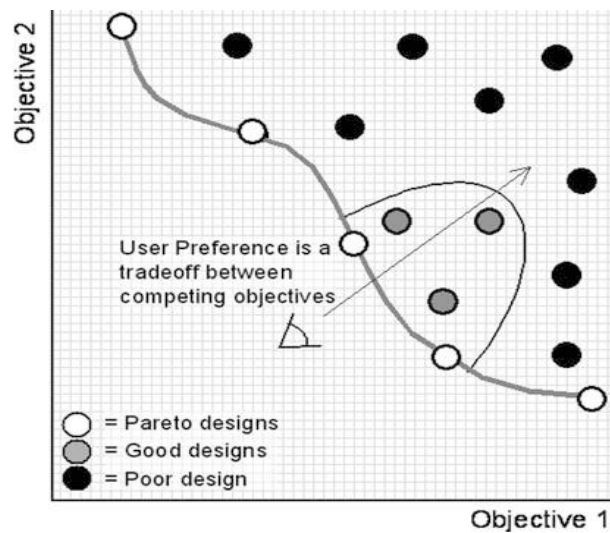


Figure G3: Design selection separating a population into three sets: Pareto designs, good designs, and poor designs (Campbell et al., 2002)

The orthogonal axes represent independent objectives that are to be minimised. The dots represent designs that are plotted by their objective values. In this division, Pareto designs are a mathematically determined set, which includes the designs that are clearly better than others without using a user preference to determine the proper tradeoff of the design objectives. This constantly updated front of Pareto designs is a conservative preservation of designs depicting a diversity of relative strengths in the objectives. Outside of Pareto-optimal designs, the system further divides solutions into good and poor designs. Some designs while not Pareto optimal might better meet user preference or better serve as a basis for modification than some of the outlying Pareto-optimal alternatives. These preferred but non-Pareto designs comprise the good population visualized as a set of solutions located

within a given radius of the intersection of current user preference and the Pareto set (Figure G3). In general, the good designs are the best designs (top 50% in the current implementation) of the non-Pareto designs that meet the current approximation of the user's utility function. By preserving this set of good designs, the design process concentrates on the current desired tradeoff in objectives; by preserving the Pareto designs, it maintains a diversity of design ideas to adapt to changes in the process.

Appendix H - CGDS Equipment

Appendix H1 - Gas heaters

There are various designs of tubular heaters. Figure H1(a, b) shows some of these heaters with the tube/element coiled into a spiral. These versatile resistance elements can also be bent into loopcoils or multileg configurations to meet specific applications requirements, Figure H1(c).

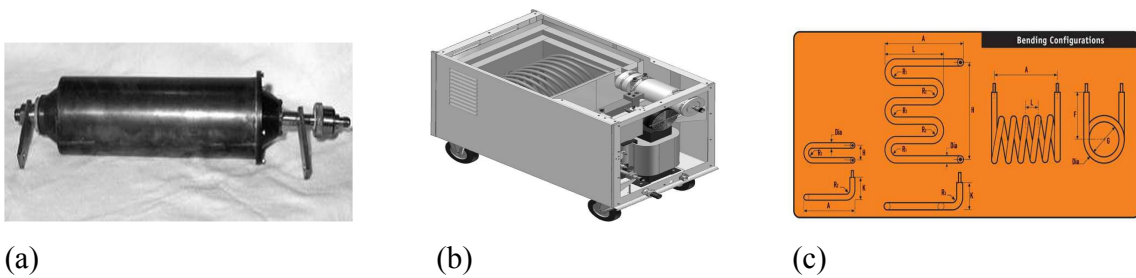


Figure H1: Ohmic heaters of the working gas (a, b) and (c) resistance elements (Papyrin et al., 2007)

Appendix H2 - Powder feeders

Screw feeder

Figure H2 represents different types of screws that are utilised in screw type powder feeders. In Figure H2(a) is an auger, Figure H2(b) a spiral and Figure H2(c) a concave type.

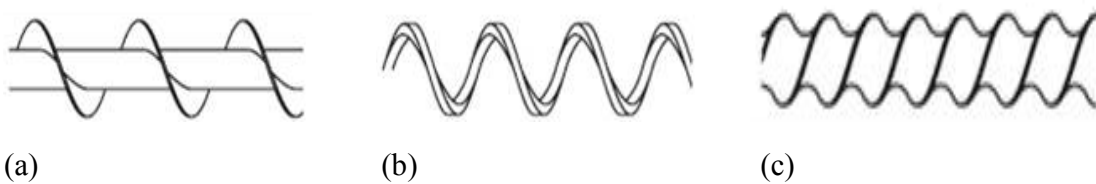


Figure H2: Different types of screws (a) auger, (b) spiral, and (c) concave (K-Tron Process Group)

Figure H3 illustrates the geometric variables of a screw feeder where $P(x)$ = pitch and $D(x)$ = outside diameter of the screw.

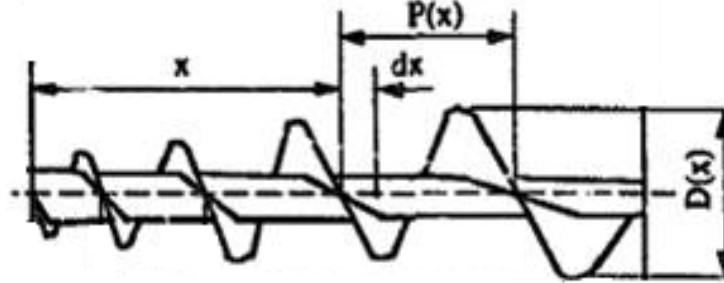


Figure H3: Schematic of a feeder screw (Yu et al., 1996)

The cross sectional area of the screw is given by;

$$A(x) = \frac{\pi}{4} \left(D(x)^2 - d(x)^2 \right)$$

In one revolution, the screw advances a distance equal to one pitch $P(x)$ and, the volume of material withdrawn by the screw from the hopper is (Yu et al., 1996);

$$V = A(x) \times P(x)$$

The screw feeder volume flow rate depends on two factors; the fullness factor and rotational factor. For slow driven screws the fullness factor is assumed to be 100%. The rotational factor depends on both the geometry of the screw and also on the coefficient of friction of the material on the flight face. As a result, a certain factor called the volumetric efficiency η_v is introduced into the flow rate and thus the actual volume of material withdrawn in one revolution is modified to be (Yu et al., 1996);

$$V_a = A(x) \times P(x) \times \eta_v$$

Figure H4 represents a screw feeder feedrate (GM/Min) against the speed of the screw (feed rate speed). As illustrated, feedrate is directly proportional to the feed screw speed. Also, indicated in the figure is that as the pitch of the screw increases, feed rate decreases.

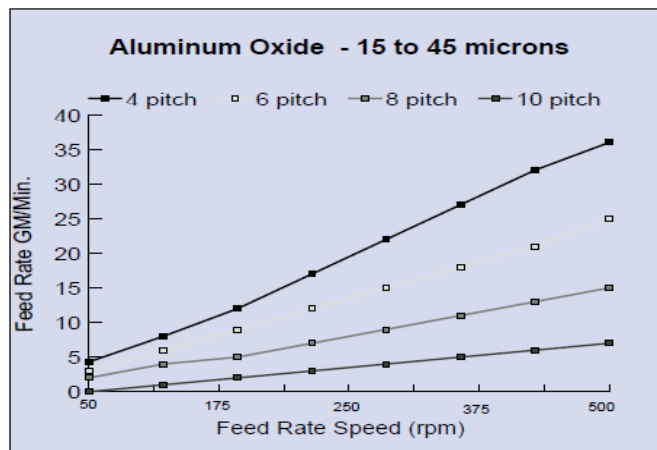


Figure H4: Feed rate against the speed of the screw (Hardface Alloys, Inc.)

Gravity feeder

Figure H5 illustrates a dual hopper powder feeding system that enables spraying of a mixture of powders. Powder particles flow under gravity into the hoppers from the powder containers. Pneumatic motors are utilised to impart mechanical vibrations to the hopper bodies. By vibrating the hoppers, sinusoidal oscillations are applied on the powder within, reducing powder agglomerations. The frequency and amplitude of these oscillations is controlled by adjusting the air supply to the motors. Particles then flow under gravity from the hopper to the powder supply line which connects to the nozzle.



Figure H5: Dual hopper powder feeding system (Supersonic Spray Technologies)

Pump feeder

The principle of pneumatic conveying is given in Figure H6 where Q_s is the mass flow rate of particles and Q_1 is the feeding gas flow rate. Powder particles are kept floating in a gas stream. Consequently, the feeding gas velocity determines the powder transport and; the feeding gas flow rate and velocity have to be adjusted accordingly to avoid plugging of the particles in the feeding line. This requires relative high gas flow rates to guarantee a continuous and pulse free powder transport (Dvorak, 2006).

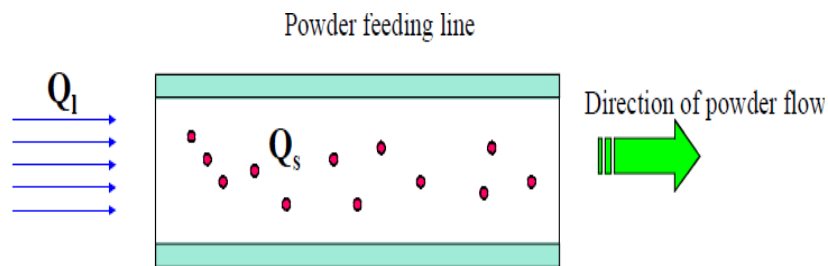


Figure H6: Pneumatic conveying of powder (Dvorak, 2006)

In the dense phase conveying mode of powders, Figure H7, not the flow rate of the feeding gas is responsible for feeding the powder. Instead, it's the pressure difference between the beginning and the end of the feeding line. As such, P_1 must be greater than P_2 to achieve powder conveyance in the direction of the (green) arrow (Dvorak, 2006).

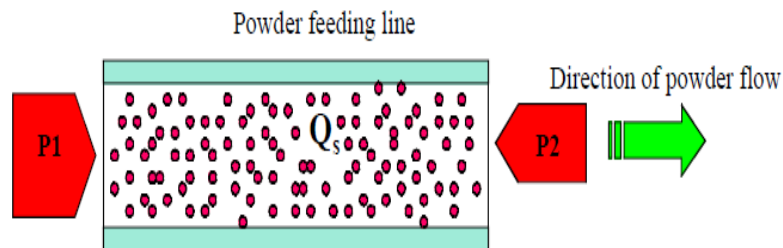


Figure H7: Dense phase conveying of powder (Dvorak, 2006)

Due to its basic principle, the powder pump feeder (Figure H8) need roughly by factor 3 to 10 lower powder feeding gas volume flow rates (compared to pneumatic feeders). Also, there are by the same factor reduced powder feeding speeds in the line. This allows nearly the independent control of the powder feeding gas rate and the powder mass flow. Powder

feeding rates range from 1g/hr to 100kg/hr and more can be realised, depending on the design of the system.

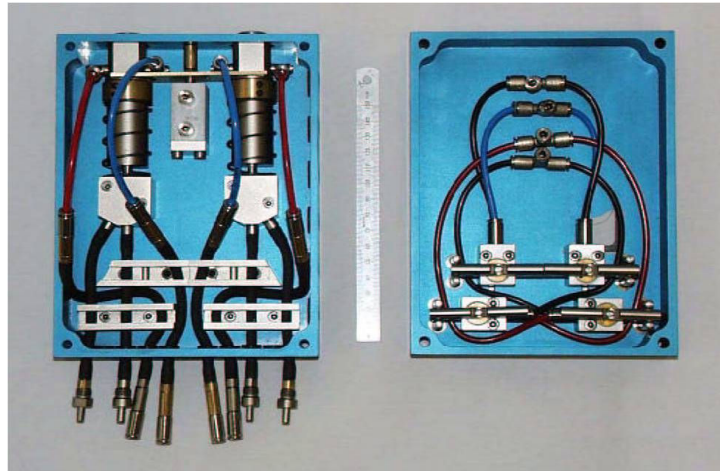


Figure H8: Body of a powder pump with two variable doses (Dvorak, 2006)

Feeding line lengths of 20 m or more are normally no problem. If pressure on the end of the line (gun) is less than 0.2 MPa or vacuum, the powder hopper can be under atmospheric pressure, meaning there are no limitations in the size of the hopper (Dvorak, 2006).

The flexible numerical control powder feeder

The flexible numerical control powder feeder unit, Figure H9 is based on the timing belt driving and pneumatic conveying principle. It consists of; a powder barrel, time belt, belt pulley, air vibrator, powder falling tube and it's adjust device, the powder feeder body, a carrying gas channel, the step-motor and the control electro circuit.

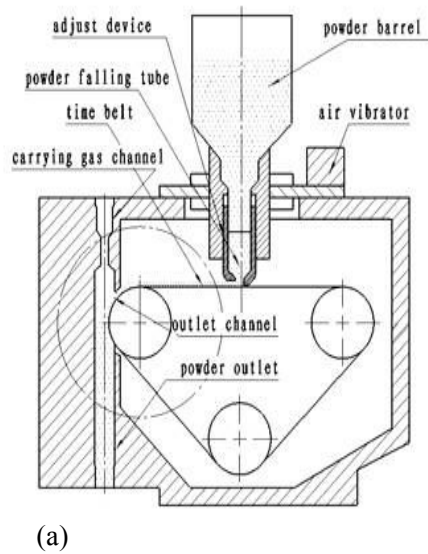


Figure H9: The flexible numerical control powder feeder unit, (a) Schematic drawing and (b) photograph (Zou et al., 2008)

During the powder delivering process, particles fall from the powder barrel onto the timing belt by the gravity. An air vibrator installed shakes the powder barrel. The high frequency vibration of the powder barrel enhances the flow ability of powders and avoids powders from blocking as well as bridging. The powder falling tube automatic adjust device eliminates the gap between the powder falling tube and time belt. As such, the quantity measurement of delivered powders is decided by the through hole size at the bottom of falling tube which guarantees delivering the powders with accurate quantity. The time belt driven by belt pulley carries the particles into the outlet channel at the one side of powder feeder body. The belt structure ensures that it sends the particles on it to the powder outlet channel completely. The accelerated powder carrying gas is sent into the powder outlet channel through the gas inlet hole on the top of the powder feeder body. By using accelerated powder carrying gas, the gas-particle mixture out of the feeder can keep good concentration after a long transportation distance (Zou et al., 2008).

Its particle mass flow rate is determined by the density of the powder, the radius of through hole and the rotational speed of the step motor. The mass quantity of delivered powder per minute is shown in the formula below (Zou et al., 2008);

$$m = \rho \times N \times \pi \times D \times \frac{1}{2} \times \pi \times r$$

where;

ρ = powder density (kg/m³)

N = deliver pulley rotational speed (rpm)

D = diameter of deliver pulley (m)

r = radius of the through hole at the bottom of powder falling tube (m)

Fluidised-bed powder feeder

Figure H10 shows a schematic of a fluidised-bed powder feeder consisting of; 1-gas supply, 2-pressure gauges, 3-powder particles and 4-fluidizing chamber. Gas supplied at the top of the hopper fluidises the particles in the fluidizing chamber, which are then drawn into the carrier gas as it passes the pick-up area creating a venturi effect.

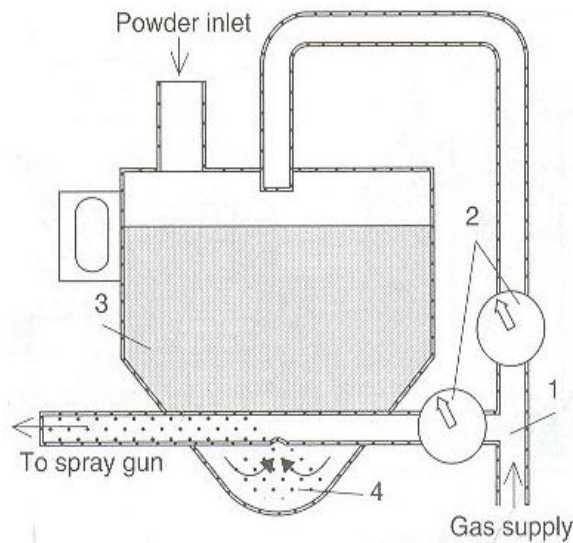


Figure H10: Fluidised-bed powder feeder (Maev et al., 2008)

Appendix H3 - Supersonic nozzles

Figure H11(a) illustrates a nozzle with a rectangular cross section of the supersonic part. The nozzle unit consist of a pre-chamber with a thermocouple for regulating the temperature of gas flowing through it.

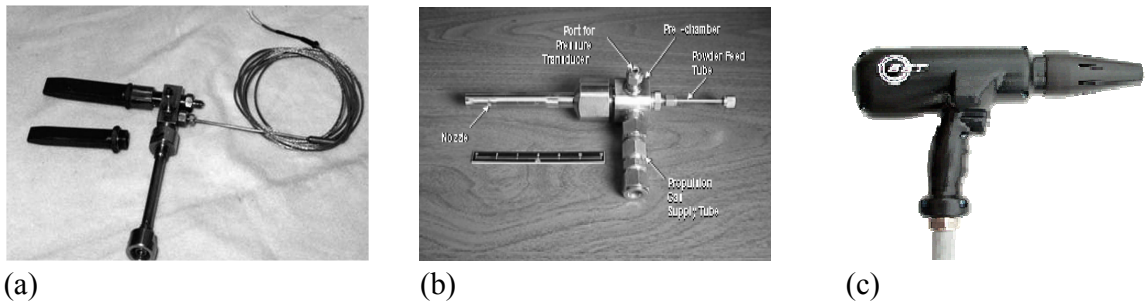


Figure H11: Nozzle units (a) rectangular, (b) circular cross section and, (c) manual gun (Papyrin et al., 2007)

The circular nozzle assembly shown in Figure H11(b) only weighs approximately 1.4 kg. The unit is designed to conveniently attach to the end effector of a motion control system for versatility. The pre-chamber too contains ports for a thermocouple and pressure transducer for monitoring the temperature and pressure respectively, of the propulsion gas within the chamber. The connection of the nozzle to the pre-chamber is by a conical flange, using a single large nut. Figure H11(c) then shows an example of a manual gun used in the spray operations (Papyrin et al., 2007).

Appendix H4 - Portable and Robotic systems

a) Portable systems

The most often acknowledged strength of the LPCGDS process is the portability of the equipment. Figure H12(a, b) presents a complete portable spray system (RSTI K-100 series) which is custom designed and tailored to meet customers specific requirements and have bigger spraying capacity. Besides surface's coating, it's also used to spray certain hard alloys (more like production type).



(a)



(b)

Figure H12: RSTI CGDS equipments (a) K-101 series portable gun and, (b) K-102 series gun with control unit (Rus Sonic Technology, Inc.)

Shown in Figure H13(a, b) is another portable CGDS configuration (RSTI K-200 series), which is standard equipment designed to handle soft/hard alloyed or blended powders, with a spraying capacity of small up to medium jobs. Both K-100 series and K-200 series equipments are all designed to perform as stationed and/or field service capable, which means that both are very user friendly and not only durable but also versatile.



(a)



(b)

Figure H13: Portable CGDS equipments (a) K-201 and (b) K-202 series (Johnson, 2005)

Both the K-100 and K-200 series systems operate with 80 psi up to 140psi and come with two powder feeders which are already installed and connected to a control unit. Also the heater is already installed in the gun.

Figure H14 illustrate compact portable CGDS systems (CenterLine). These units are ready to spray when connected to a supply of compressed air and electricity. Both machines provide a quick disconnect style fittings on the spray gun, gas and power supply lines. Also, their plug-n-play controls accept both manual and robotic gun styles.



Figure H14: CenterLine CGDS system models (a) SSM-P3800-001 and, (b) SSM-P3300-003 (Supersonic Spray Technologies)

The SSM-P3800-001 model is easy to maneuver for addressing air preparation and dust handling with external systems. The SSM-P3300-003 model incorporates air preparation and dust collection equipment so that only the supply of compressed air and electricity is needed to start spraying. The integrated air filtration equipment provides the necessary treatment of shop air. The explosion rated vacuum is provided for clean-up of powder and waste.

Illustrated in Figure H15 is a schematic of a portable LPCGDS system arrangement. The system components are in a modular configuration to facilitate convenience of installation at the spraying facility. The pre-chamber and nozzle assembly constitute a spray gun (20) perfect for line-of-sight operations. The gas heater is housed in the metal enclosure (18) and is supplied with pressurised air from a pressurised vessel (14) via a high-pressure hose (16). Both the air and powder supply lines together with the power and signal cables (to the gun) are enclosed in the cable assembly (22).

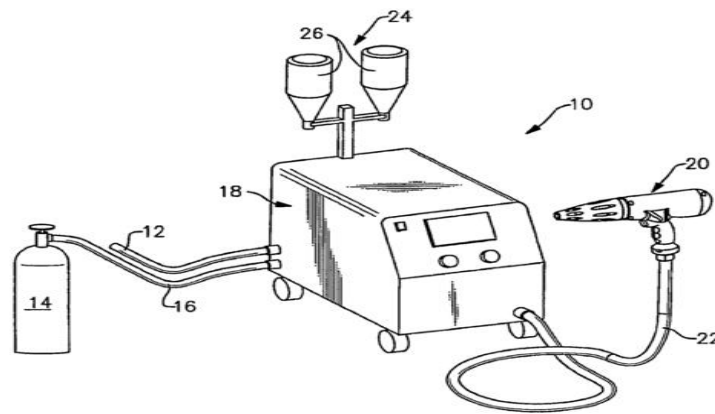
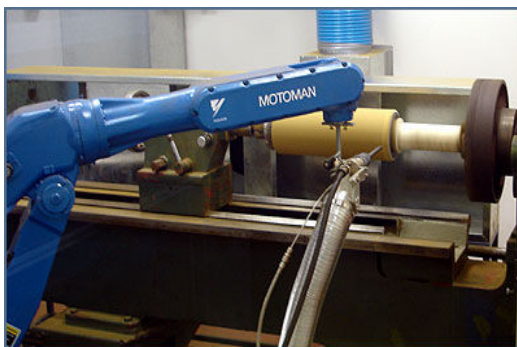


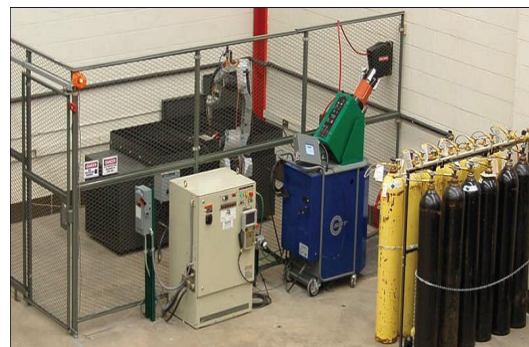
Figure H15: A portable LPCGDS system arrangement (World International Property Organisation)

b) Robotic systems

Robotic systems are configured for use in complex and repetitive spraying tasks. These systems provide consistent and repeatable coating characteristics. The gun unit is mounted on a robotic arm allowing for CAD controlled computer numerical control (CNC) input, with the substrate mounted and spun on a lathe machine, Figure H16(a). The robot gives transverse displacement to the gun and, the substrate is sprayed with precision. Both Cartesian and 6-axis robot systems are ideal for spraying normal to the substrate surface. Illustrated in Figure H16(b) is a cell where the actual spraying takes place (DeForce et al., 2006).



(a)



(b)

Figure H16: Illustration of a (a) gun unit mounted on a robot arm and, (b) robotized cell (DeForce et al., 2006)

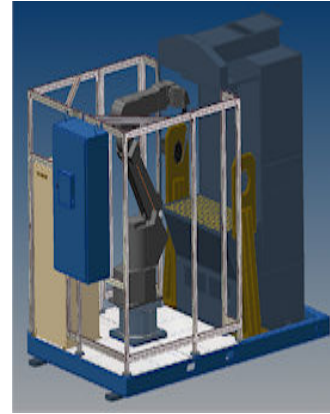
Spray chambers, Figure H17 are customized to suit equipment standards or specific production requirements. They have some perimeter guarding and door interlocks as safety measures.



(a)



(b)



(c)

Figure H17: Illustration of spray chambers (Supersonic Spray Technologies)

Appendix I - Coating Quality Measurement Techniques

Appendix I1 - Potentio-dynamic polarisation experiment

Electrochemical measurements in the form of potentio-dynamic polarization tests are performed on sprayed coatings. Samples having ground surfaces are mounted in non-conducting resin, with their edges protected with a lacquer to eliminate the possibility of edge effects or crevice corrosion. A three electrode cell is employed. The test solution comprises deaerated sulphuric acid (H_2SO_4) held at 25 °C with a platinum counter electrode and saturated calomel electrode (SCE) as a reference electrode. Following introduction into the solution the sample is allowed to stabilise at its rest potential, E_{corr} prior to initiating the potential scan. Using a potentiostat, the potential is then scanned and current flowing between the specimen and the counter electrode recorded (Zhang et al., 2003).

Appendix I2 - Tribological test

Dry sliding tribological tests are performed on a ball-on-disc CSM tribometer, Figure I1 in an ambient environment. Before the tests are conducted on the specimens, all coating surfaces are polished. A ball having a mirror finished surface, with a normal load being applied to it is slide over the coating. The radius of the worn trace and the wear rate are measured. Wear rate is defined as the worn volume per unit of normal load and sliding distance (Guo et al., 2009).

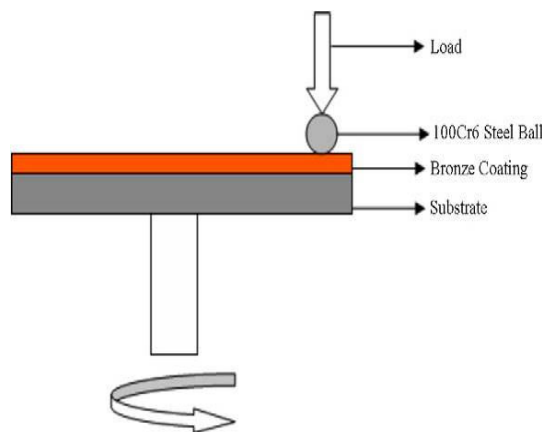


Figure I1: Schematic representation of a tribological test apparatus (Guo et al., 2009)

Figure I2 represents wear tests conducted to compare the wear properties of an original mold and repaired mold using a tribological test apparatus. A steel ball was used as the test ball. By measuring the amount of wear at the respective cross-sections, Figure I2(a) and by calculating wear volume, their coefficients of wear are obtained in Figure I2(b) (Lee et al., 2007). A deeper Al 6061-T6 valley in Figure I2(a) indicates a higher wear of material for the original mould. In addition, as shown in Figure I2(b), the repaired part is better in wear resistance because its coefficient of wear is lower than that of Al 6061-T6 (Lee et al., 2007).

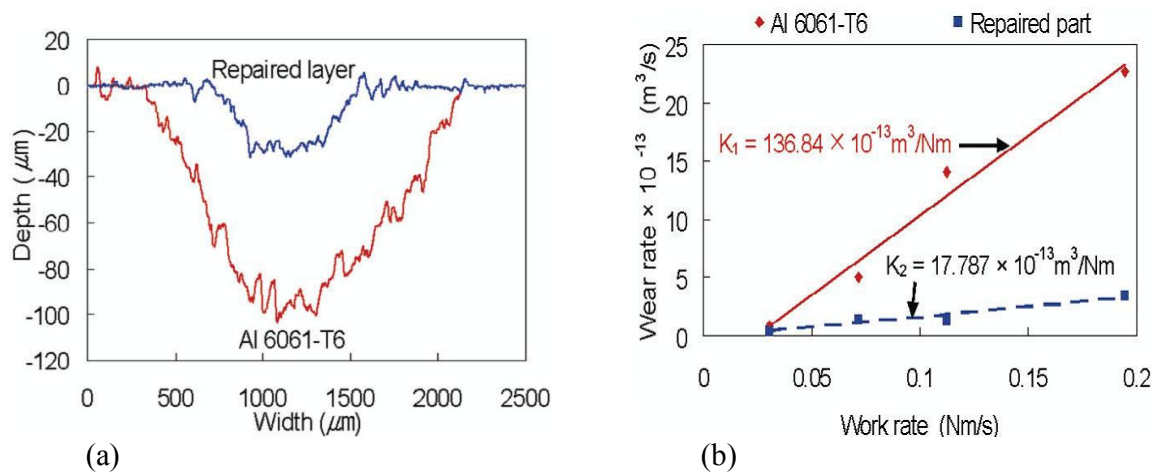


Figure I2: (a) Comparison of cross-sections from wear tests, (b) Wear coefficients of repaired specimen and original Al 6061-T6 (Lee et al., 2007)

Appendix J - Feedstock Powders

Table J1 gives a number of feedstock powders utilised for surface repair and fabrication, corrosion protection, sealing and cleaning applications. It describes the obtained coating characteristics, setup parameters and process considerations. The powder materials have the right combination of particle size, shape and purity. A number of safety considerations are taken during handling and use of the powders. These include; handling the powder with care wearing the recommended protective clothing, not ingesting or smelling the powder, storing the powder at room temperature in its original container and not using contaminated powder.

Table J1: Powder characteristics and preliminary set-up parameters (Supersonic Spray Technologies)

Powder material	Coating characteristics	Setup parameters	Other process considerations
Aluminum	Very good deposition, smooth coatings and good machinability. Good for repairing a variety of components like Al mold repairs. Hardness: 25-30 HRB	Air Temperature: 375 °C Max. Gun Pressure: 85-90 psi	Gas temperatures as low as 200 °C deposit particles and avoid nozzle clogging but the deposition will not be efficient. Temperatures approaching 375 °C causes premature nozzle clogging. A shorter nozzle is used to avoid nozzle clogging.
Aluminum Oxide	An excellent general blasting media, particularly for preparing most surfaces. This is not a high purity oxide and thus not suitable for applications with high sensitivity to purity (e.g.	Air Temperature: 0-500 °C Gun Pressure: 60-100 psi	

	corrosion protection coatings)		
Copper	Smooth, thick and highly conductive coatings are produced. Good machinability and good bonding. Hardness: 75-80 HRB	Air Temperature: 500 °C Gun Pressure: 85-90 psi	A rough surface emerges as the coating gets thicker. The material feed rate is reduced to avoid roughness.
Nickel	More durable coating. Built up to thick coatings with smooth spray finish. Recommended for cast iron repair. Hardness: up to 288 HRB	Air Temperature: 450-550 °C Gun Pressure: 90-145 psi	
Stainless Steel	Hardness is up to 3 times greater than a pure aluminum deposit. Hardness: 70-75 HRB	Air Temperature: 475 °C Max. Gun Pressure: 85-90 psi	Gas temperature is reduced to avoid nozzle clogging.
Zinc	Excellent deposition, very thick and smooth coatings are produced. It's used to repair kirkstite tools. Hardness: up to 65 HRB	Air Temperature: 450 °C Gun Pressure: 85-90 psi	Zinc tends to be very sticky and nozzle clogging could occur at excessive temperatures. Gas temperatures are reduced to avoid clogging.