THE EFFECT OF PLASMA SPRAY VARIABLES ON THE DEVELOPMENT OF CERAMIC COATINGS

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JANUARY 2008

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By

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**Thesis submitted in fulfilment of the requirements
for the degree of
Master of Science**

JANUARY 2008

ACKNOWLEDGEMENTS

This thesis represents a total of almost twenty four months of effort; it could not have been written and produced without the help of many colleagues and former students. It gives me great pleasure to acknowledge the assistance of the following in the completion and preparation of this MSc thesis:

I am very grateful and thankful to my supervisor, Associate Professor Dr. Luay Bakir Hussain for his enthusiastic support, for his guideline throughout the whole of academic semesters, and for his direct and indirect supervision in completing this thesis. Many thanks as well to my co. supervisor Dr. Fazilah Fazan in guiding and advising any matters occurred in the research study.

Special thank to Dr. Mohd Radzi Hj. Mohd Toff and Dr. Talib Ria Jaafar in allowing me using the Praxair Plasma Spray System at SIRIM Berhad, Kulim Kedah. Many thank to Pn Siti Mariam, Mohd Zakuan Abdullah and Mohd Hazri in operating Praxair air Plasma Spray Equipment and CSEM Tribometer Equipment.

I gratefully acknowledge my Head at Plastics Ceramics Programme, SIRIM Berhad, Shah Alam, Dr. Ahmad Fuad Md. Yusuf, my Coordinator Dr. Teng Wan Dung, my colleagues Rafindde Ramli, Zarina Abdul Wahid, Zalena Saem, Zaini Rahmat and Azura Ruhan in supporting the experiment done at the Ceramics Technology Group.

Students at the Faculty of Mechanical Engineering, Mara University of Technology, Shah Alam, Hasanul Ariff Che Jawias and Muhamad Yusup Hj. Kamis for their assistance in the early stage of my research with REMAKO, Klang.

Finally, to my beloved wife, Nor Saad for sharing her knowledge and giving the constructive criticisms and suggestion in completing this thesis.

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LIST OF SYMBOLS

T_q : Temperature of plasma beam
N_q : Output of plasma beam
I : Arc current
L : Arc length
C_p : Latent heat of gas
Q : Gas flow rate
d : Nozzle diameter
A_x : Coefficient of thermal conductivity from plasma to nozzle
$\bar{E}$: Gradient along the arc column axis
V : Plasma beam velocity
Q_o : Volume of gas flow rate
T : Gas temperature
d : Nozzle diameter
A : Constant
M : Molecular weight of gas
σ : Adhesion Strength
F : Maximum load
A : Cross sectional area
HV : Vickers hardness
F_1 : Testing load
S_1 : Surface area of indentation
d_1 : Average of the diagonal length of identation
θ : Facing plane angle of the diamond pyramid
μ : Friction coefficient
σ : Sigma
P : Porosity
W : Saturated weight
D : Dry weight
S : Suspended weight

LIST OF ABBREVIATION

DC	: Direct Current
HVOF	: High Velocity Oxy-Fuel
XRD	: X-Ray Diffraction
SEM	: Scanning Electron Microscopy
RF plasma	: Radio Frequency plasma
DC plasma	: Direct Current plasma
APS	: Air Plasma Spray
RPM	: Revolution Per Minute
TBC	: Thermal Barrier Coating
MSDS	: Material Specification Data Sheet
ASTM	: International American Standard
Ar	: Argon
He	: Helium
N_2	: Nitrogen
H_2	: Hydrogen
SLM	: Standard Litre per Minute
PSI	: Pound per Square Inches
Amdry 962	: Nickel base powder
Metco 204NS	: Yttria Stabilised Zirconia
YSZ	: Yttria Stabilised Zirconia
ALO-105	: Aluminium Oxide 3%wt Titanium Oxide
NI-109	: Aluminium 5% Nickel
SiC	: Silicone Carbide
POD	: Pin-On-Disc
m	: Monoclinic
t	: Tetragonal
c	: Cubic
ZrO_2	: Zirconium Oxide
α-Al_2O_3	: Alpha alumina phase
γ-Al_2O_3	: Gamma alumina phase
TiO_2	: Titanium Oxide
Al_2O_3	: Aluminium Oxide

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LIST OF PUBLICATIONS & SEMINARS

1.1 Development of Plasma Spray Ceramic Coating for Industrial Application, Malaysian Science and Technology Congress 2004 (MSTC 2004), Selangor, Malaysia, pp. 5 – 7 October 2004.

1.2 The Performance of Plasma Sprayed Ceramic Coatings: With And Without Bond Coat, *Proceedings:* APSIM 2005, Advanced Processes and Systems in Manufacturing (Bangi, Malaysia), ISBN: 983-2975-40-9, pp. 121 – 129, 17 – 18 May 2005.

1.3 Mechanical Properties Investigation - Plasma Sprayed Ceramic Coatings, Proceedings of National Conference on Advances in Mechanical Engineering, Malaysia, ISBN: 967-958-177-2, pp 743 - 750, 18 – 20 May 2005.

1.4 The Effects of Spraying Distance in Formation of Plasma Sprayed Alumina 3%wt Titania Coating onto Metal Substrate, Proceedings Techpos'06, 16-17 May, 2006.

1.5 Plasma Spray Ceramic Coating and Measurement of Developed Coating Behaviour, ICOMAST 2006, 28-30 August, 2006, (In Press).

KESAN PEMBOLEHUBAH-PEMBOLEHUBAH SEMBURAN PLASMA DALAM MENGHASILKAN SALUTAN SERAMIK

ABSTRAK

Semburan plasma adalah salah satu sistem semburan panas yang boleh meleburkan sebarang bahan untuk menghasilkan salutan. Suhu yang tinggi yang di hasilkan oleh api plasma membenarkan bahan seramik seperti ‘zirconia’ dan ‘alumina’ dilebur dan disembur kepada permukaan bahan asas untuk menghasilkan salutan. Pada peringkat permulaan, prestasi ciri-ciri mekanikal (kekuatan ikatan dan kekerasan) salutan ‘Yttria Stabilised Zirconia’ (Metco 204NS) pada besi bahan asas yang disalut dengan salutan ikatan dan tanpa salutan ikatan telah diuji dan disiasat kekuatannya. Keputusan menunjukkan penggunaan salutan ikatan (serbuk utama nikel) membantu menambah prestasi ciri-ciri mekanikal salutan. Kemudian, Al_2O_3 3%wt TiO_2 (ALO-105) disembur kepada besi bahan asas yang disalut dengan Ni 5%wt Al (NI-109) sebagai salutan ikatan dengan menggunakan sistem semburan plasma ‘praxair’. Salutan-salutan itu dihasilkan dengan melaraskan parameter-parameter pembolehubah salutan seperti kadar aliran serbuk, karan elektrik dan jarak semburan untuk kegunaan seperti tahan haus dan tahan panas. Struktur salutan telah di analisa dengan ‘X-ray Diffraction’ (XRD) dan ‘scanning electron microscope’ (SEM). Salutan itu juga telah di uji dengan ciri-ciri mekanikal (kekuatan ikatan dan kekerasan), rintangan haus (POD) dan rintangan panas (ujikaji kitaran panas).

Keputusan menunjukkan semua salutan ALO-105 membentuk γ-Al_2O_3 walaupun serbuk asalnya adalah α-Al_2O_3. Salutan-salutan yang padat dan ketebalan salutan yang berbeza telah dihasilkan dengan purata poros salutan ialah 7.7%. Kekuatan ikatan, kekerasan dan sifat haus salutan akan bertambah dengan pertambahan kadar aliran serbuk (22.5 g/min kepada 26 g/min) dan karan elektrik (22.5 g/min kepada 26 g/min). Kekuatan ikatan yang tinggi didapati pada jarak

semburan 75mm dan kekerasan yang tinggi pula didapati pada jarak semburan 90mm. Di dalam analisa rintangan panas, salutan telah membentuk retak-retak mikro dan terkopek daripada permukaan bahan asas selepas melalui beberapa ujikaji kitaran panas. Rintangan panas salutan yang paling tinggi diperolehi pada salutan yang mempunyai ketebalan yang rendah.

THE EFFECT OF PLASMA SPRAY VARIABLES ON THE DEVELOPMENT OF CERAMIC COATINGS

ABSTRACT

Plasma spray is one of the thermal spray systems which are able to melt any material for coating. The high temperatures of the plasma flame permit ceramic materials such as zirconia and alumina powders to be melted and sprayed toward substrate in producing a coating. At the first stage, Yttria Stabilised Zirconia (Metco 204NS) coating over metal substrate with and without coating bond coat (nickel base powder) was investigated for the mechanical properties performance (adhesion strength and hardness). The results showed that applying bond coat coating (nickel base powder) increased the performance of mechanical properties of ceramic coating. Then, Al_2O_3 3%wt TiO_2 (ALO-105) was deposited over metal substrate with Ni 5%wt Al (NI-109) as a bond coat by the Praxair Plasma Spray System. The coatings were produced and analysed for different variable coating parameters such as powder flow rate, electric current and stand-off-distance. The ALO-105 coatings structure were analysed by X-ray diffraction (XRD) and scanning electron microscopy (SEM). The coatings also were tested for the mechanical properties (adhesion strength and hardness), wear behaviour (POD) and thermal resistance (thermal cycling test).

The results revealed that all ALO-105 coating contained γ-Al_2O_3 although the original powder was α-Al_2O_3. Dense and different thickness of coating was produced, with low porosity level at the average of 7.7%. The adhesion strength, hardness and wear behaviour of coating were improved when powder flow rate (22.5 g/min to 26 g/min) and electric current (550A to 650A) were increased. The high adhesion strength (11.4 MPa) and high hardness of coating (772.7 Hv) were identified at stand-off-distance 75mm and 90mm setting. In thermal resistance analysis, the ALO-105 coating developed micro cracks and peeled off from substrate surface after a number of

thermal cycles test. The highest thermal resistant of coating was identified at the lowest thickness of the coating.

CHAPTER 1
INTRODUCTION

1.1 Surface Engineering

Surface engineering is an enabling technology applicable to a wide range of industrial sector activities. It encompasses techniques and process capable of creating and/or modifying surface to provide enhanced performance such as wear, corrosion and fatigue resistance and biocompatibility [Burnell & Datta, 1996]. Surface engineering now recognized as an enabling technology of major importance in the successful, most effective and efficient exploitation of material in engineering practice [Strafford et al., 1995]. Surface engineering enables the design and manufacture of metallic, ceramic, polymeric and composite material. Most metals, alloys, ceramics and some intermetallic compounds can be applied as coating either individually or as mixtures [Grainger & Blunt, 1998]. Any surface engineering technique and process has an advantage and limitation, which must be evaluated for a specific application. In general surface technology is used to reduce the cost of component in service by providing such as:

- Acceptable service life/ reduce downtime costs
- Wear and corrosion resistance on selected surface
- Repair a worn part surface

1.2 Thermal Spray Coating

Thermal Spraying is one of the advance hard facing technologies for surface preparation and protection [Knotek, 2001]. The technology has been used seriously as a remedy to combat wear, corrosion, heat, oxidation and other problems occurring across the whole spectrum of the manufacturing and engineering industries [Harrison, 1996]. The diversity of thermal spraying processes used for hard coating is due to the variety of applications and the required properties, as well as consideration of economic aspects [Grainger & Blunt, 1998]. Basically, thermal spray coatings are produced by melting and projecting a powder material and building up a surface coating at the substrate [Berndt, 1980]. The different coating microstructures and properties are dependent on the spray technique, powder properties and spray parameters of the coating [Li et al., 2004]. Microstructure and properties of coating should be examined in order to obtain good coating bonding. The coating condition such as porosity, closed pores and un-melted particles are always the cause of defects in coatings. There are advanced tests or performance tests techniques of plasma sprayed ceramic coatings in order to determine the coating properties such as mechanical tests, chemical tests and thermal tests [Herman et al., 1993].

1.3 Ceramic Coating and Application

Plasma spray technique is currently the primary method used commercially to produce thick coating for ceramic materials. The ceramic coating basically is used to extend product life, increase performance and reduce production maintenance costs. The applications involve wear, heat and corrosion resistance, surface restoration and others basically required in aircraft, automobile, power plant and oil and gas industries [Reeve, 2001].

Alumina and zirconia ceramics are the most popular material used in plasma spray coating. The selection of the material depends on the application of coating. Alumina is mostly used on mating surface to resist abrasive wear, adhesive wear and corrosion resistant. Zirconia is being increasingly used as thermal barrier coating especially for gas turbine and diesel engine [Sulzer Metco Inc., 1998]. Effective ceramic coating should exhibit low thermal diffusivity, strong adherent to the substrate, phase stability and thermal shock resistance during thermal cycling and provide oxidation wear and corrosion protection to the substrate [Herman et al., 1993].

1.4 Objective of The Study

In this study air plasma spray system is used for the ceramic coating. Ceramic and bond coating (Nickel base) powders and three variables parameters (current, powder flow rate and stand off distance) are investigated in order to develop a coating surface onto low carbon steel substrate. To achieve high-quality coating, it is necessary to understand the plasma system variables such as plasma spraying process and coating parameters. The study is focused on the new machine, Praxair Plasma Spray System with SG-100 gun. Mainly, there are two objectives:

1. To produce ceramic (Al_2O_3 3%wt TiO_2) coatings onto metal substrate with selected three variables parameters (current, powder flow rate and stand-off-distance) using Praxair Plasma Spray System.
2. To analyse the relationship of current, powder flow rate and stand-off-distance parameters of the coated samples for wear and thermal resistance performance.

1.5 Significance of The Research

Plasma spray coating is a unique process. It uses high direct current (DC) and voltage according to power range to produce plasma flame for melting high temperature of material [Dobler, 2003] such as ceramics. During process, the molten powder accelerates towards the substrate, cools and anchors together to form a strongly adhered coating with the principle technique of mechanical bonding adhesion. Understanding the plasma system and coating process are the most important to develop and improve the adherent bonding and quality of coating. Selected ceramic coating material for specific application such as for wear and thermal resistance application, type of metal substrate to reduce the constraint to manufacture components from very high cost bulk material, surface preparation for the strong adherence bonding between coating material and metal substrate and processing plasma spraying parameters are related to each other in achieving the high performance and high quality of coating. Selection and application of bond coating layered between ceramic and metal substrate are also important in order to improve high adherence coating bonding.

The analysis of phases exist and microstructures of coated samples are important in order to determine the coating behaviour, coating structure and condition of powder particles after plasma spray coating process. Measurement of mechanical properties (hardness and adhesion strength) thickness and porosity of coating relates to the coating performance such as in wear resistance and thermal resistance application.

1.6 Scope of The Study

In developing high quality plasma spray ceramic coating, the first important consideration is the selection of spraying process parameters and different type of coating materials. In addition, substrate preparation and application of bond coating are also considered in order to produce high strength and dense coating. In this study, the coating samples were produced based on three variables which are current, stand-off-distance and powder flow rate in order to obtain the best processing parameters in term of coating performance in the wear resistance and thermal resistance application. The coated samples were analysed for the phase, microstructure and the mechanical properties (adhesion strength and hardness) and porosity. Finally the coated sample were tested and analysed for the wear and thermal resistance application.

Overview and literature review of the plasma, thermal spraying, spraying process and plasma spray system, coating materials and properties, substrate and surface preparation, coating structure and properties and coating application are highlighted in Chapter 2. This chapter emphasises more on plasma spray system and ceramic coating.

Chapter 3 emphasises on air plasma spray system, Praxair Technology with SG-100 Gun which is used in the study. The system such as plasma gun, system controller, powder feeder, gasses system, cooling system and power system are highlighted. The important parameters and some initial parameters setting related to robotic arm (transverse speed, step distance and stand of distance) and powder flow rate are discussed. Chapter 3 also discusses the selection of ceramic and bond coat powders, bonding mechanism and the stressed of coating.

The analysis of the selected ceramic and bond coating powders such as chemical compositions, particle sizes, phase present and microstructure are highlighted in Chapter 4. The metal substrate preparation, experimental of coating samples, coating methodology (parameters setting) and testing methodology (adhesion strength, hardness, bending, thermal resistance, wear resistance and porosity) which were carried out in this study are presented in Chapter 4.

Result and discussion are presented in Chapter 5. Phases present in the ceramic coating powders and coated samples were analysed by X-Ray Diffraction (XRD) equipment. Profile and cross section of the ceramic coated samples were analysed and examined by Scanning Electron Microscopy (SEM). Results of the test such as mechanical test (adhesion strength, hardness), wear resistance, thermal resistance and porosity are investigated. Chapter 5 emphasises the relation of coating performances (adhesion strength, hardness, wear and thermal resistance) and the thickness of coating according to the selected variable parameters (current, powder flow rate and stand-off-distance).

Conclusions and future recommendation of the overall study are discussed in Chapter 6.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Plasma is an ionised gas. When gas is heated enough, the atoms collide with each other and knocking their electrons off in the process and this will form a plasma flame. In other definition, plasma is also known as 'fourth state of matter [Seoul National University, 2002]. Figure 2.1 shows the state of matters how plasma deforms from solid, liquid and gas state when heat is added. Plasma is an electrically conductive gas containing charged particles. When atoms of a gas are excited to high energy levels, the atoms loose hold of some of their electrons and become ionised thus producing a plasma containing electrically charged particles (ions and electrons) [Matejka & Benko, 1989].

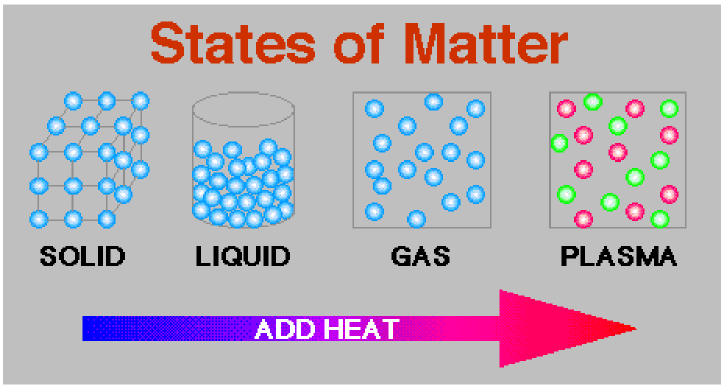

Figure 2.1: Plasma flame or 'fourth state of matter' was formed when heat added [Seoul National University, 2002].

Basically in plasma spray process, an electrical arc is struck between cathode and anode of the plasma torch. When the plasma gas flows through the arc it gets ignited. The plasma is initiated when electrons are accelerated from the cathode to the anode. As the electrons speed towards the anode they collide with, excite and ionise the atoms or molecules in the gas. The additional electrons freed by the ionisation are also accelerated causing further ionisation. These collisions transfer the kinetic energy of the electrons to the other species and raise the temperature of the gas. The ignited gases come out of the nozzle in the form of a plasma jet of temperature above 15,000 K [Alex et al., 2000]. Figure 2.2 shows the temperature distribution and geometry of plasma jet during ignition.

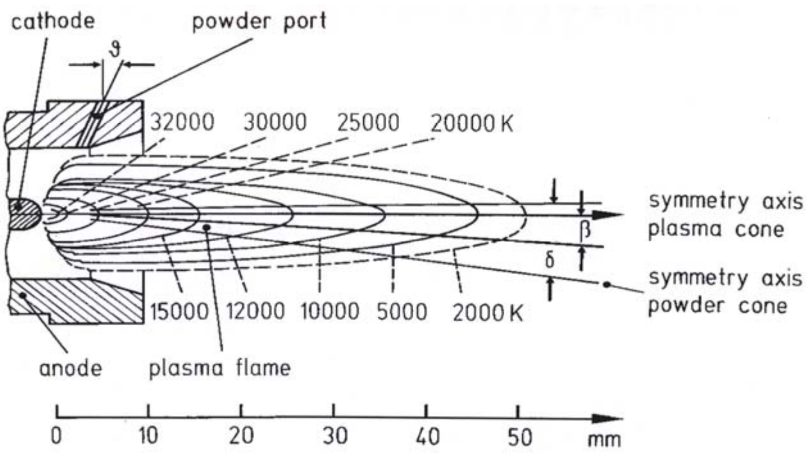

Figure 2.2: Temperature distribution and geometry of plasma jet [Knotek, 2001].

2.2 Thermal Spraying System

According to the literature, thermal spraying started in early 1900s by Swiss engineer, M.U. At the time, lead and tin wires were melted using welding torch by the energy of an acetylene/ oxygen flame. The wire-arc spraying process was patented in 1908 by Schoop for various metals feedstock [Knotek, 2001]. Development of spraying techniques and equipment progressed slowly during 20s and 30s. Late 50s and early 60s the thermal spraying technology was expanded due to the increasing demand of high temperature and wear resistant materials and coating systems [Burnell & Datta, 1996]. At present time, thermal spray processing is highly demanding in surface engineering technology. Thermal spray coatings for ceramic, metallic and carbide help to improve surface properties of parts such as in wear and corrosion resistance [Reeve, 2001]. The principle characteristics of thermal spraying coating process are as follows [Grainger & Blunt, 1998]:

- The strength of the bond between coating and substrate is dependent on the materials and process used.
- Able to apply any coating materials to the substrate that are unsuited compared to welding process.
- Able to deposit coating material from thinner to thicker layer of coating.
- Almost all material compositions may be deposited such as metals, ceramics, carbides, polymers or any combination.
- Most processes are cold compared to welding process.
- The process can be operated in air with great flexibility.

Thermal spraying is a generic term used to describe a group of processes. Thermal spraying is an attractive coating technique as it offers a wide choice of materials and processes that have a reduced impact on the environment when compared to conventional plating processes. Figure 2.3 shows the group of thermal spraying coating in various applications.

Basically there are 4 types of thermal spraying system, including flame spraying, high velocity oxy-fuel, arc spraying and plasma spraying. All thermal spraying processes rely on the same principle of heating a feedstock, (powder or wire) and accelerating it to a high velocity and then allowing the particles to strike the substrate. The particles will then form and freeze onto the substrate. The coating is formed when millions of particles are deposited on top of each other. These particles are bonded by the substrate by either mechanical or metallurgical bonding [Dobler, 2003].

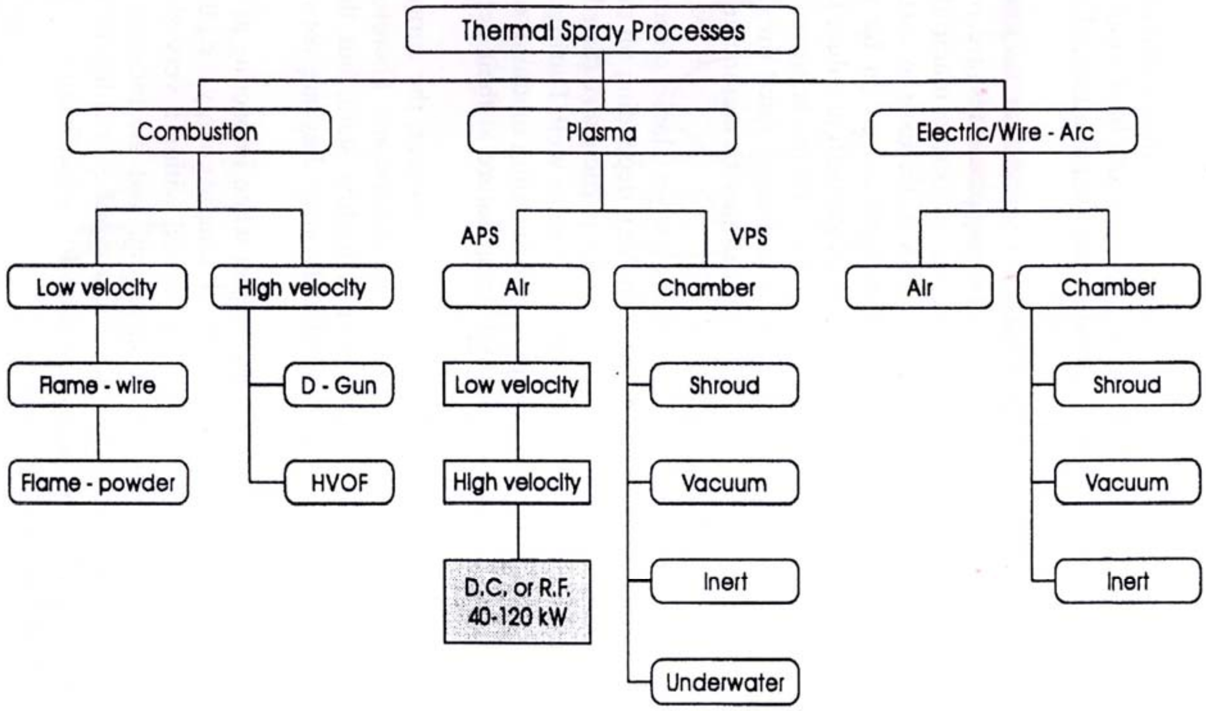

Figure 2.3: Group of thermal spraying process [Knotek, 2001].

2.2.1 Flame Spraying

Flame spraying is a low cost process compared to other thermal spraying processes. Flame spraying does not produce distortion or effect of heat treated on the part during spraying process due to the temperature of flame produced at the nozzle tip which is only 3,000^{o}C. The flame spraying can be used for any metal, ceramic and plastic substrate for coating process. The process produces thicker, contains high levels of oxides and porous coating together with the option of achieving a rough surface finish than other thermal spraying process [Knotek, 2001]. The process relies on carefully control of chemical reaction between oxygen and a fuel (acetylene) to produce heat with temperatures varying up to 3,000^{o}C. In flame spraying process, feedstock material is fed onto the flame in the form of wire or powder and compressed air is used to atomise the molten metal and accelerate the particles onto the substrate to produce a coating [Dobler, 2003]. Mostly spray coating is used for corrosion resistance applications. Figure 2.4 shows a typically gun design and flame spraying coating process.

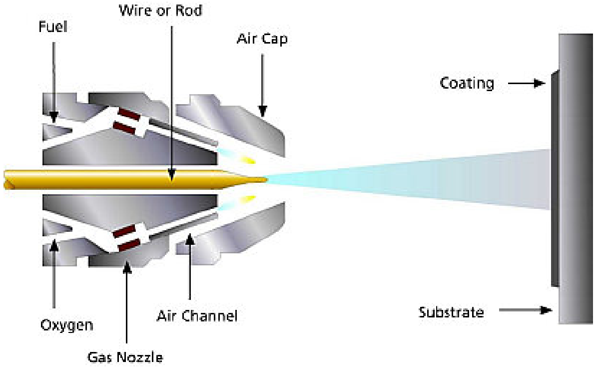

Figure 2.4: Gun design and flame spraying coating was sprayed onto substrate [Plasma & Thermal Coatings Applied Surface Technology Ltd, 2005].

2.2.2 High Velocity Oxy-Fuel (HVOF)

The high velocity oxy-fuel (HVOF) has extended the range of thermal spray applications. HVOF utilizes the combustion of gases, such as hydrogen or a liquid fuel such as kerosene. A mixture of process gases is injected into the combustion chamber of a torch at high pressure and ignited to produce the flame. The process creates a very high velocity which is used to propel the particles at near supersonic speeds before impacting onto the substrate and producing a coating. HVOF is designed to give high levels of coating density and adhesion to a substrate [Grainger & Blunt, 1998].

Since the temperature of the flame is about 3,000^{o}C, HVOF thermal spraying is preferred for spraying tungsten carbide and/or corrosion-resistant carbides, alloy of hastelloy, triballoy and inconel [Knotek, 2001]. Due to high kinetic energy and low thermal energy of hydrogen, HVOF can produce high bond strengths, extremely high coating density (less than 1% porosity) and low oxide content (less time speed of particle spending within the heat source) [Grainger & Blunt, 1998; Knotek, 2001]. Figure 2.5 shows a typical gun design and HVOF coating onto substrate.

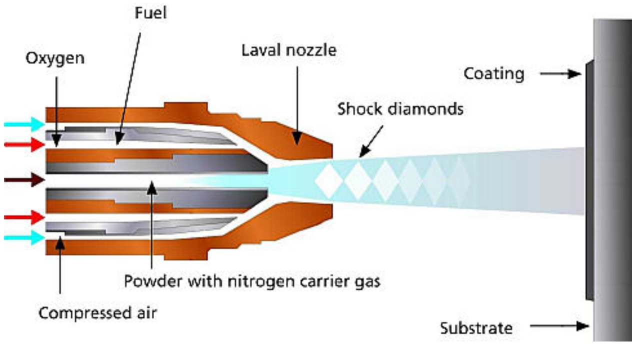

Figure 2.5: Gun design and HVOF coating was sprayed onto substrate [Plasma & Thermal Coatings Applied Surface Technology Ltd, 2005].

2.2.3 Arc Spraying

In arc spraying process, feedstock in the form of two wires is simultaneously brought into contact with each other at a nozzle. The two wires with electric arc are used to provide the heat source. As the wires are fed towards each other at a nozzle, as it is touched, the electrical load placed on the wires causes the tips of the wires to melt and to create a flame temperature around 4,000^{o}C. An atomizing gas such as air or nitrogen is used to strip the molten material from the wires and transport it to the substrate [Dobler, 2003].

Arc spraying is among the lowest cost running process compared to the other thermal spray systems. The materials applied by arc spraying are only for electrically conductive wires such as stainless steel, hattelloy, nickel aluminides, zinc, aluminium, and bronze. Arc spraying has the highest deposition rate of thermal spraying process. It can be used to spray large areas or large numbers of components on repetitive production line operation such as bridges and offshore fabrication with zinc and aluminium coating to give corrosion protection on the structure. Other coating applications are worn engineering components such as bearing and shaft with steel and bronze alloys coating. [Knotek, 2001; Grainger & Blunt, 1998]. Figure 2.6 shows a typical gun and coating process of wire arc system onto substrate.

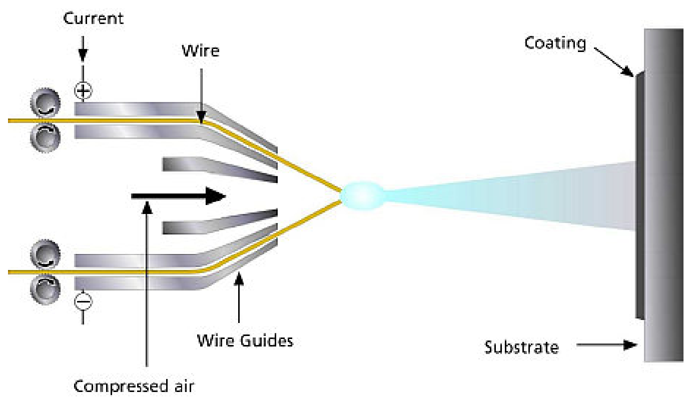

Figure 2.6: Gun design and wire arc spraying coating was sprayed onto substrate [Plasma & Thermal Coatings Applied Surface Technology Ltd, 2005].

2.2.4 Plasma Spray

Plasma spray is regarded as the most versatile of all the thermal spray processes e.g. flame spraying, arc spraying and HVOF. The plasma spraying process involves the latent heat of ionised inert gas being used to create the heat source. The most common gas used to create the plasma is argon as the primary gas and hydrogen or helium as the secondary gas [Knotek, 2001]. However the gas usage depends on the type of material to be sprayed and coating application.

Plasma spray is able to use and melt any variety of ceramic materials [Gansert, 2002]. The plasma spray system consists of an electronically controlled power supply, a PLC-based operator control station, a gas mass flow system, a closed-loop water chilling system, a powder feeder and a plasma gun. A primary inert gas, such as argon is injected between two water-cooled electrodes (anode and cathode) in the gun, where it is ionised to form a plasma jet when ignited. Any powders is injected into the plasma flame will melt and subsequently deposited onto the component to form a coating [Berndt et al. 1979].

Most of the ceramic materials used in plasma spray coatings are chromium oxide, zirconium oxide and aluminium oxide [Knotek, 2001]. The particle velocities of plasma spraying are higher than for those flame and arc spraying which produce denser coatings and finer surface roughness [Dobler, 2003 & Fazan, 1997]. Figure 2.7 shows a typical gun and plasma spray coating process.

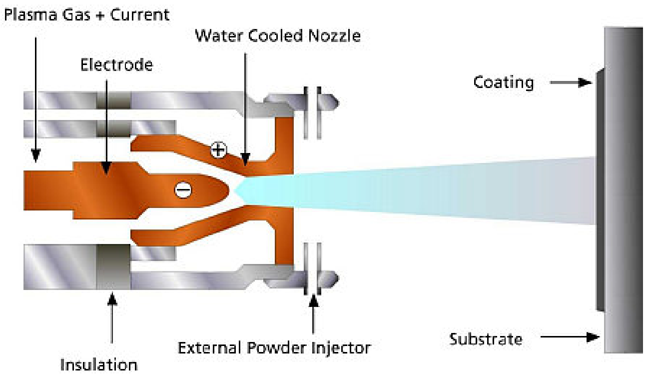

Figure 2.7: Gun design and plasma spray coating was sprayed onto substrate [Plasma & Thermal Coatings Applied Surface Technology Ltd, 2005].

The versatility of plasma spray has been widely recognised in many numbers of industries. The unique features that characterise plasma spray processing are listed below [Herman et al., 1993]:

- It can be used to deposit a wide range of ceramics and metals and any combinations of the materials.
- It is able to develop homogeneous coating without composition change with coating thickness.
- High deposition rates are possible without extreme investments in capital equipment.
- Plasma spray can be applied at any environment conditions (air, vacuum and underwater).

2.3 Plasma Spray System

Plasma system can be classified into RF plasma and DC Plasma. The processes are described as below:-

- RF plasma – The gas is passed through a radio frequency field so that electrical coupling occurs and energy is transferred to the gas.
- DC plasma – The gas is used as a medium in which a direct current arc is established between two or more electrodes.

In RF plasma, no electrode is necessary to produce the flame, no contamination of the working gas or materials injected into plasma occur during coating process [Berndt, 1980].

Air plasma spray system used for the study is classified as DC plasma. The air plasma spray consist of several principle components to form a complete system in order to generate plasma flame, bring coating material to the plasma flame and produce a coating onto a substrate. In general, the air plasma system consists of:

- Plasma torch
- DC power supply
- Control and instrumentation system
- Cooling water system
- Gas supply system
- Material feeder system

The principle components of the plasma spray system are arranged and linked together in an optimum way in order to ensure maximum efficiency at minimum power, pressure and space. Figure 2.8 shows a flow diagram of plasma spray operation.

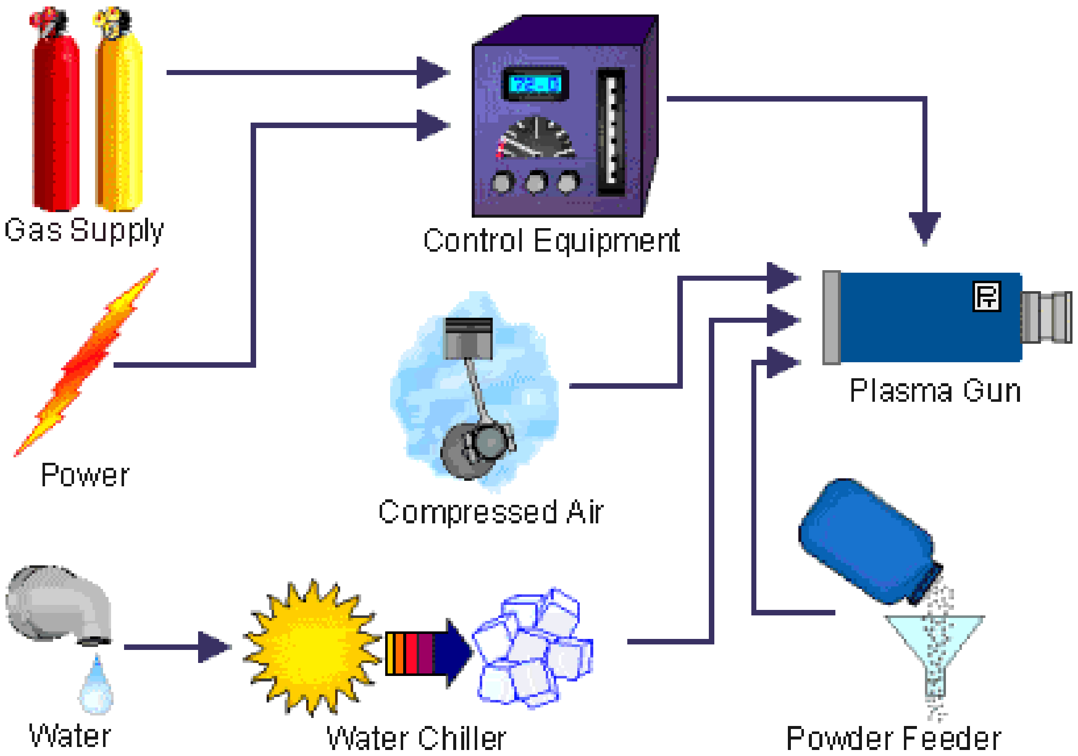

Figure 2.8: Basic system (gases, power, cooling, controller, feeder and plasma torch) of the plasma spray equipment [Gordon England, 2004].

2.3.1 Plasma Torch System

Plasma torch is one of the most important systems of the plasma spray technology [Matejka & Benko, 1989]. Plasma torch is designed purposely to produce plasma flame jet at high velocity, high temperature, able to melt any coating material and stable in operation [Herman & et al., 1993]. Basically plasma torch components of the DC plasma torch are summarised as below:

- The cathode is usually made of tungsten enriched by 2% ThO_2 (Thorium Oxide). Basically tungsten serves to lower electron emission threshold from 4.52 eV to 2.63

eV, allowing an arc to be established at a lower voltage gradient [Herman et al., 1993] and hindering cathode wear due to impurities in the plasma gases. The oxygen and humidity present in the impurities gases will oxidise cathode rapidly at high temperatures and reduce the electrode life.

- The nozzle which acts as anode is subjected to considerable heat effect and must transfer several kW of output per each square centimetre. Basically anode is made from high purity copper with high thermal conductivity and water cooled directly [Matejka & Benko, 1989]. Normally the anode incorporates the nozzle or anode throat [Herman et al., 1993].
- An insulating medium between cathode and anode – normally Teflon or ceramic are used as insulating medium.
- A torch body is used to join and align the cathode, anode and insulating medium into an integral assembly.
- Attachments for water lines and power cables.

Nowadays, there are two types of cathode design use in the plasma torch. These are solid cathode tip and hollow cathode tip. Matjeka [1989] had pointed that the use of solid cathode tip is much more better instead of the use of hollow cathode tip due to cooling water could approach the tip surface. The tip shapes (e.g. acute, blunt or hemispherical) depend on the loading and the plasma gas used. The nozzle profile normally designed in cylindrical and conical shape [Berndt et al., 1979]]. A simplified diagram of the plasma torch configuration for a DC plasma torch is shown in Figure 2.9.

The plasma arc is produced between two electrodes (i.e. cathode and anode) when the gas flowed through the electric arc, ignited and transformed into ions of high temperature. The anode and cathode have a limited life from 20 to 200 hours depending on the operating power level of plasma torch. The anode and cathode have to be replaced when it wears. Water leakages have to be avoided within cooling circuit at plasma torch where it will lead to rapid erosion of the anode and cathode [Herman et al., 1993].

Recently, the modern plasma torch design uses different combination of plasma gases (Ar, N_2, Ar + H_2, N_2 + H_2, Ar + He) such as Torches 7 MB or 9 MB from Metco cooperation. The principle of plasma torch designed is similar compared to the oldest design. The different mainly are the shape of electrodes, the supply of plasma gas between electrodes, the method of powder injection into plasma beam and geometry design of the torch [Berndt, 1980].

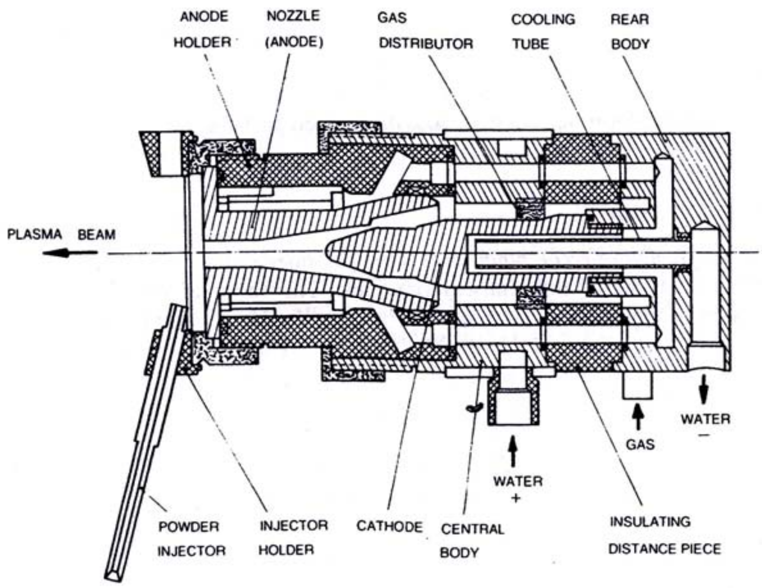

Figure 2.9: Schematic of plasma torch type F4 produced by Plasmatechnik Co. [Matejka & Benko, 1989]

The plasma beam temperature of plasma torch depends mainly on the ionisation degree, type of plasma gas and working parameters. Figure 2.10 shows the temperature comparison of argon (a) and nitrogen (b) gasses of plasma beams which has been done by Jehn [1992]. The experiment used similar type of plasma torch (6mm diameter of nozzle) and gas flow rate setting. The figure illustrates that the temperatures measured in the nitrogen gas is substantially lower than argon gas. The temperature of plasma beam e.g. 10,500 K of nitrogen and argon gasses are archived at distance of 15mm and 20mm from the tip of plasma torch [Matjeka & Benko, 1989].

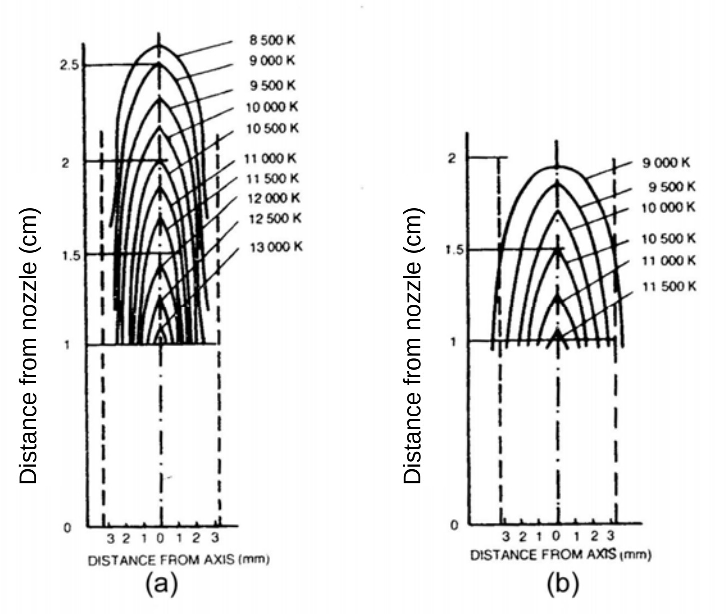

Figure 2.10: Temperature distribution of plasma beam (a) for argon gas and (b) for nitrogen gas [Matejka & Benko, 1989].

Figure 2.11 show how the change in gas flow rate, current, nozzle diameter and arc length affect the temperature and output of plasma beam. If the current is increased, the arc temperature and output of beam is increased. If the gas flow rate increased, the arc temperature decreased and beam output increased [Matjeka & Benko, 1989].

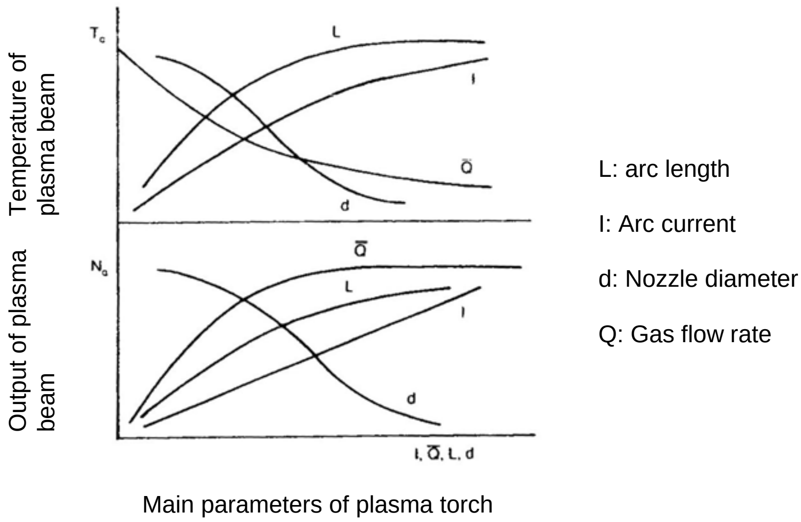

Figure 2.11: Effect of plasma torch parameters on temperature characteristics of plasma beam (temperature and output of plasma beam) [Matjeka & Benko, 1998].

Plasma beam velocity also plays an important role in plasma spray coating. The velocity of a plasma beam can be calculated in terms of the plasma beam output, gas volume and its properties and the nozzle diameter based on the relationship below [Matjeka & Benko, 1989]:

$$V = A.\ (Q_o / d^2)\ .\ (T/M) \qquad (1)$$

Where;

V - Plasma beam velocity ($m.s^{-1}$)

Q_o - Volume of gas flow rate ($m^3.s^{-1}$)

T - Gas temperature (K)

d - Nozzle diameter (m)

A - Constant

M - Molecular weight of gas

Referring to equation (1), plasma beam velocity is directly proportional to the gas flow rate and indirectly proportional to the square of nozzle diameter. This indicates that increasing gas flow rate will decrease the plasma temperature [Matjeka & Benko, 1989].

2.3.2 DC Power Supply System

Power Supply is the main important component in plasma spraying system. It is designed to suit the specific voltage and current characteristic of the plasma torch. In order to produce superb plasma sprayed coatings using wide variety of materials, plasma equipment must perform consistently, whether the energy level is as low as 15 kW or over 200kW [Praxair Surface Technology Inc., 2001]. Basically thermal plasma spray technology used energy less than 100 kW [Herman et al., 1993]. An example in Praxair Technology Inc. [2001], the energy used for the plasma torches SG-100 and SG-200 is up to 80 kW and 40 kW. The power of DC circuit can be calculated from Joule relation (voltage x current). The operating characteristic of a torch are given by the voltage-current relationship and indicates the power level of the torch [Herman etc, 1993]. The arc characteristics and the power supply determine the stability of voltage and operating current. The plasma arc is produced steadily when the arc voltage equals to the voltage across the sources terminals at point A and B which is shown in Figure 2.12.

At point B, any decrease in the current will extinguish the arc since the voltage requirement of the torch cannot be supplied by the generator. If current increases then the arc voltage decreases and equilibrium point is reached at A. At this point any current change causes a voltage change which returns the current to point A. The torch resistance is given by the slope (V/I) of the straight line as shown in Figure 2.12. The maximum operating resistance of the torch is given by the tangent to the source characteristics at point C.

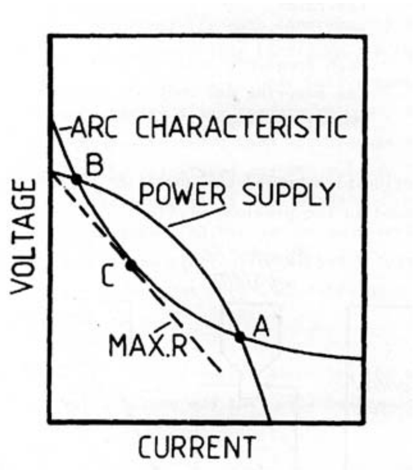

Figure 2.12: Voltage-current characteristics of a torch and power supply [Berndt, 1980].

2.3.3 Control and Instrumentation System

The control and instrumentation system is used for controlling the overall system efficiently during the operation of the system. All the switch systems such as gasses, ignition and feedstock feeding are contained in one control box. However the robotic arm control is separately from the control box system mentioned above. Figure 2.13 shows a typical example of a control unit which is used in a plasma spray system.

Figure 2.13: Control system 3710 of Praxair Technology [Praxair Surface Technologies, 2001]

2.3.4 Cooling Water System

Cooling system in plasma spray technology is used to cool the plasma torch. Many problems associated with the running of torch can be attributed to a poor cooling system and may result in overheating of anode, cathode and seals [Herman et al., 1993]. Normally water is used as the agent of the cooling system. The cool water is pumped to the torch in closed loop process from the cooling tower. The cool water flow rate is very important in order to ensure the plasma torch cooled sufficiently during spraying process. Otherwise, it may result wear of plasma torch component and need to be replaced frequently especially for the tungsten electrode.

2.3.5 Gas Supply System

Gas supply system is linked with ignition system in order to ignite the plasma arc. The gas will be injected to the plasma torch in order to produce plasma flame. The gas also supplied to material feeder unit in order to seal coating powder from any oxidation and assisted coating powder to be fed to the plasma torch. Basically plasma spray gasses are divided into primary and secondary, i.e. gases such as Ar and N_2 are normally used as primary gas whereas gasses such as He and H_2 are used as secondary gas. The plasma forming gas is selected on the basic of the desired temperature and velocity of plasma beam and the degree of inertness gas [Matejka & Benko, 1989].

Application of gas mixture such as Ar + He and Ar + H_2 with different properties normally is used in order to increase the enthalpy and velocity of the plasma arc. The temperature and enthalpy of gases can be controlled over a wide range by variation in electrical input, flow rate and composition of plasma gases in the plasma arc.

2.3.6 Material Feeder System

The material feeder system is used for feeding an adjustable, uniform and reproducible amount of powder to the plasma flame. Basically the feeder system is designed and developed suitable for any coating powders and provided maximum accuracy of the volume of powder fed to the plasma flame. The conventional feeder system was upgraded and designed to modern feeder system which employs inert carrying gas by which the powder supplied through a tube to the plasma gun. The modern material feeder system was designed with automatic system to feed the powder to plasma flame. The system normally includes powder container (in vacuum condition), heater (attached to the container to heat the powders) and controller unit (to feed powder to plasma gun). The velocity of the carrying gas is set in such a way that powder remains suspended during the transfer and injected to the plasma gun at the optimum kinetic energy [Matejka & Benko, 1989 & Praxair Technologies Inc, 1999].

2.4 Coating Material

Coating material is the main agent in order to develop a coating. The selection of coating material is dependent on application of the coating such as wear, thermal barrier, friction and the type of substrate material to be coated. In general most powders used in advance thermal spray depositions have particle sizes in the range of 5 to 60 microns [Tucker, 2001]. Coating materials require quality control during storage and handling to avoid outside contamination which will affect the coating quality [Herman et al., 1993].

2.4.1 Coating Material Properties

Basically in thermal spray coating, available coating materials in market are a spray-able form. The feedstock used in the thermal spray coating have to meet further requirement such as chemical homogeneity, density, flow behaviour, size and shape distribution of powders [Knotek, 2001]. For example, size and shape are particularly significant for meltability considerations, and the shape of the particles will determine the flowability of powder into the flame. Flake-shape powder will not flow smoothly, resulting in a discontinuous, pulsing feed of powder into the flame, leading to a non-uniform stream of molten particles and produce a poor coating. Spherical shape of the coating powder enables smooth flow, uniform feeding and deposit with continuous flow [Herman et al., 1993]. The techniques for producing powder materials are water and gas atomization, crushing and milling and chemical techniques such as sol-gel, agglomeration and spray drying [Knotek, 2001]. Now almost all material is available for spraying application such as metals and alloys, hard compound or hard metals and ceramics.

According to Herman [1993], the optimal particle size distribution of coating powders is between 10 and 44 micrometers. Most of the powder used for advanced thermal spray deposition falls between 5 and 60 microns in size [Tucker, 1994]. The specific coating powders size range is related to torch or detonation gun design and the heating characteristics of powder. To achieve uniform heating and acceleration of a single component powder, it is advisable to have the size distribution as narrow as possible [Tucker, 1994]. The coating sprayed using coarse powder produces very porous and laced with cracks [Herman et al., 1993]. Fine powders are accelerated and heated more rapidly, but they also tend to lose momentum more rapidly when spraying at longer stand off distance. The coating results are dense and highly stressed coatings [Tucker, 1994]. Coating powder specification such as chemical analysis, shape characterisation, size distribution and flowability should be identified for better coating produced. A wide variety of equipment is available for coating powder analyses, and selection of a specific technique or type of test will vary with the type of powder. The coating powder should be kept clean and dry. Contamination and moist