МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ

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SPECIAL TECHNOLOGIES FOR PRODUCT LIFE INCREASING

Textbook

СПЕЦІАЛЬНІ ТЕХНОЛОГІЇ ДЛЯ ПІДВИЩЕННЯ ДОВГОВІЧНОСТІ ВИРОБІВ

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We consider modern special resistant coatings technologies raising durability of products. We carry out the analysis of advantages and lacks of existing technologies. We give the recommendations at the choice of coating methods and used materials.

The textbook was elaborated on the basis of original sources.

For students of mechanical specialties.

Рассмотрены современные технологии нанесения специальных защитных покрытий, повышающих долговечность изделий. Проведен анализ преимуществ и недостатков существующих технологий, даны рекомендации по выбору методов получения покрытий и применяемых материалов.

Для студентов механических специальностей.

Розглянуто сучасні технології нанесення спеціальних захисних покрить, що підвищують довговічність виробів. Проведено аналіз переваг і недоліків існуючих технологій, дані рекомендації з вибору методів одержання покрить і матеріалів, що застосовуються.

Для студентів механічних спеціальностей.

Fig. 77. Tables 7. Bibliogr.: 19 titles.

Рис. 77. Табл. 7. Бібліогр.: 19 найм.

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INTRODUCTION

The role of coatings in modern equipment applications is increasingly important. Higher operating temperatures, new alloys and component life requirements all drive the need for more durable systems. A component designer is more and more using new coatings systems to help provide the environmental protection needed for these more stringent demands.

Producing solid ceramic components is not always the best approach to solving a wear or corrosion problems. In many cases, taking the original metallic part and applying a coating can be the best solution.

Coatings can vary from few microns to few millimeters and be deposited by different means.

The coating, its thickness and means of deposition will depend on the final use of the components and the environment it has to resist.

It is a fact of life that many components are deemed to be worn out when their surfaces have degraded beyond a predetermined limit. This limit may vary from the appearance of minor pitting or scoring marks in bearing surfaces to the removal of several millimetres of material from the bucket of an excavating tool.

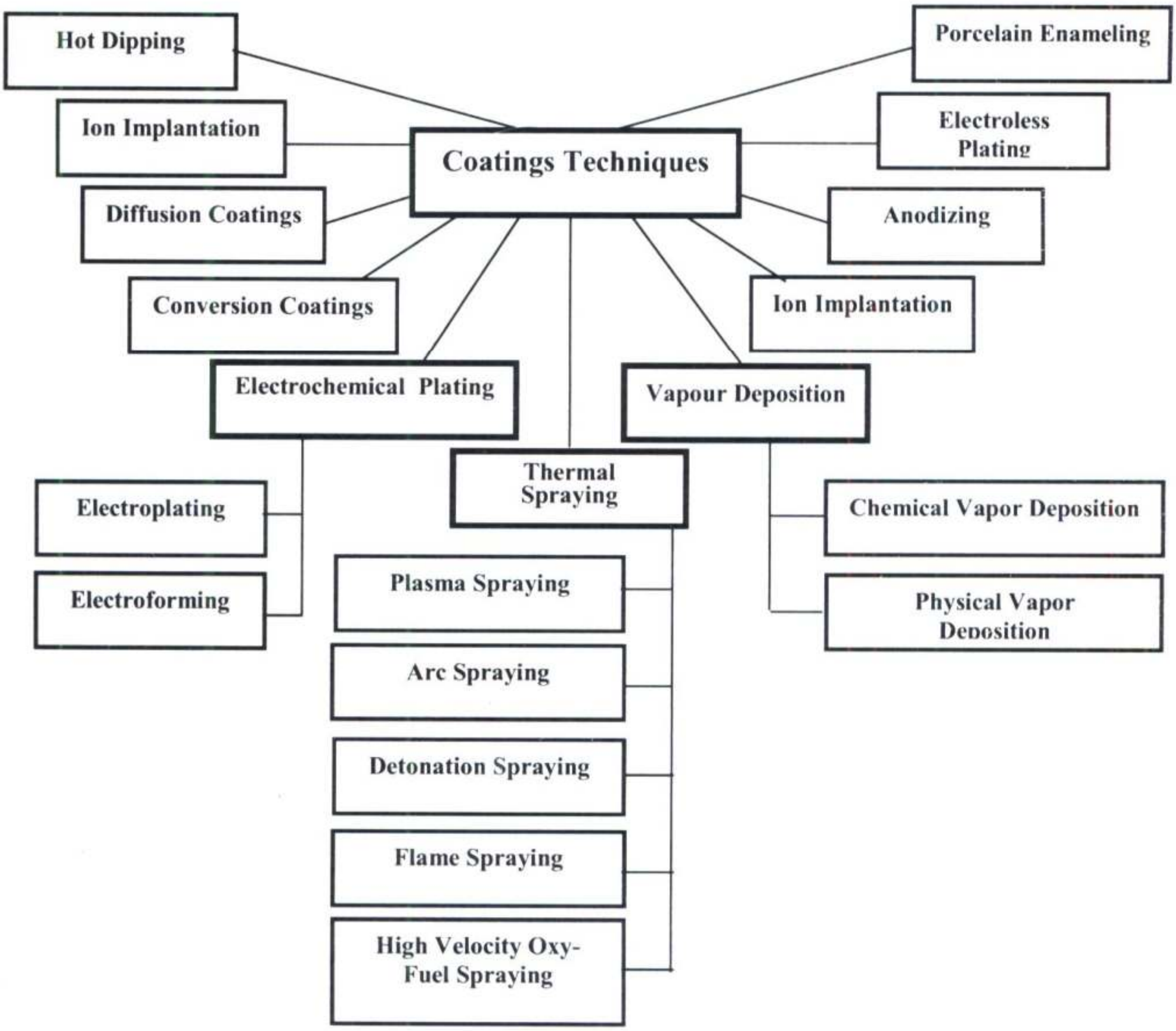

Fig.1. Schematic Diagram of the Coatings Techniques

However, the useful life of many components, which are unsuitable to be made from advanced ceramics, may be extended by coating with a material tailored to resist the particular environment in which the component is working. These include thermal barrier coatings as used in gas turbines and on piston crowns in large diesel engines; low friction and anti-seizure coatings as used in lubricant free bearings; wear resistant or "hard-facing" coatings as used for the treatment of valves in internal combustion engines and finally corrosion resistant coatings as used in the chemicals industry.

Coatings may be applied by many different techniques with coating thickness' varying from several microns to several millimetres. Thin coatings are usually applied by Physical (PVD), Chemical Vapour Deposition (CVD) and Chemically Formed Processes (CFP) with other techniques e.g. High Velocity Oxy-Fuel (HVOF), plasma and flame spraying together with Plasma Transferred Arc (PTA), weld over-laying and laser cladding, being used to deposit thicker coatings [1].

Selection of the best coating for an application is not often straight forward. Selection based on hardness or from standard wear testing would indicate coatings like HVOF tungsten carbide/cobalt, plasma sprayed chromium oxide ceramic or fused coatings as giving the ultimate performance. Indeed, these coatings do provide the best solution to many applications, but they are certainly not universally suited to all applications. Other factors must be considered:

- Cost
- Life expectancy
- Corrosion
- Counter surface
- Effect of process on substrate material
- Surface finish or profile
- Temperature
- Lubrication
- Abrasives
- Loads and speeds
- Impact, shock or fatigue
- Ability to work harden
- Severity and angle of attack
- Coefficient of friction
- Porosity
- Other specific coating properties may be required
  - Thermal barrier or conductor
  - Electrical insulator or conductor
  - Non-magnetic
  - Special surface profiles
  - Abradable (requiring erosion resistance, but sacrificial to counter surface)
  - Abrasive (required to abrade or grip counter surface)
  - Very low coefficient of friction or non-stick properties

Table 1. Typical Coatings Functions [2, 3]

FUNCTION	COATINGS
Reduce wear	Titanium carbide, nitride
Reduce friction	PTFE, molybdenum disulfide
Increase friction	Titanium, bonded abrasives
Improve lubrication	Copper, lead
Increase temperature or load capacity	Electroless nickel
Prevent adhesion	Silver/gold plate
Imbed particles	Indium, lead
Reduce corrosive wear	Chromium plate or diffusion
Retain fluid lubricants	Phosphating, nylon
Rebuild surface	Steel hard surfacing
Reduce surface roughness	Silver plate
Prevent drop erosion	Polyurethane, neoprene
Prevent particle erosion	Cobalt alloy, molybdenum

Table 2. Surface Treatment For Various Materials [2, 3]

METAL	TREATMENT
Aluminum	Chrome plate; anodic coating, phosphate; chromate conversion coating
Beryllium	Anodic coating; chromate conversion coating
Cadmium	Phosphate; chromate conversion coating
Die steels	Boronizing; ion nitriding; liquid nitriding
High-temperature steels	Diffusion
Magnesium	Anodic coating; chromate conversion coating
Mild steel	Boronizing; phosphate; carburizing; liquid nitriding; carbonitriding; cyaniding
Molybdenum	Chrome plate
Nickel- and cobalt-base alloys	Boronizing; diffusion
Refractory metals	Boronizing
Stainless steel	Vapor deposition; ion nitriding; diffusion; liquid nitriding; nitriding
Steel	Vapor deposition; chrome plate; phosphate; ion nitriding; induction hardening; flame hardening; liquid nitriding
Titanium	Chrome plate; anodic coating; ion nitriding
Tool steel	Boronizing; ion nitriding; diffusion; nitriding; liquid nitriding
Zinc	Vapor deposition; anodic coating; phosphate; chromate chemical conversion coating

1. COATINGS TECHNIQUES

1.1. THERMAL SPRAY PROCESS

The demands for engineering coatings are becoming more and more stringent. Environmental concerns are also being considered as an integral part of the design process.

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. Thermal spray coating techniques such as flame spraying, wire arc spraying and plasma spraying, allow many problems of wear, corrosion and thermal degradation to be resolved by engineering the surface with tailor-made coatings.

Compared to traditional surface modification processes, thermal spraying offers greater thickness capability, no part size restrictions, it produces minimal noxious waste. High processing temperatures allow deposition of many high melting point materials onto a relatively cold substrate.

Thermal spray technology allows parts to be made from less expensive, lighter or weaker base materials while providing the performance of a metallic, carbide, ceramic or cermet material. Rather than crafting the entire part from a premium, robust material, a thermal spray coating can yield the same, or better, performance for a significantly lower investment.

Principles of Thermal Spraying

The Basics

All thermal spraying processes rely on the same principle of heating a feed stock, (Powder or Wire) and accelerating it to a high velocity and then allowing the particles to strike the substrate. The particles will then deform and freeze onto the substrate.

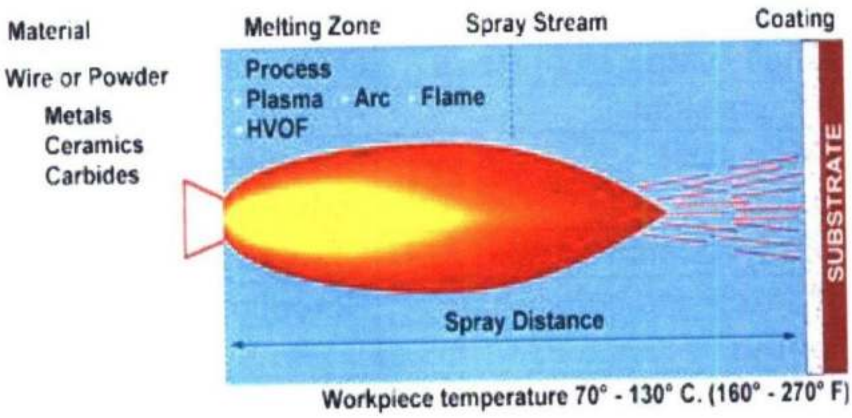

Fig.1.1. Thermal Spraying Process
(Source: Plasma & Thermal Coatings Ltd.)

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.

The Process

1. The first step of any coating process is surface activation. This is done by cleaning and grit blasting the surface to be coated. Masking techniques are normally adopted for components that only need specific areas coated.

2. The second step is to melt the material, this is done by introducing the feed stock material into the hot gas stream. The hot gas stream is produced by either chemical reaction (Combustion) or by physical reaction (Plasma).
3. Thirdly the particles are then accelerated to the substrate by the gas stream and deform on impact to form a coating.
4. Finally the coatings are inspected and assessed for quality by either mechanical or microstructural evaluation.

Nature of Thermal Spray Coatings

A common feature of all thermal spray coatings is their lenticular or lamellar grain structure resulting from the rapid solidification of small globules, flattened from striking a cold surface at high velocities [1].

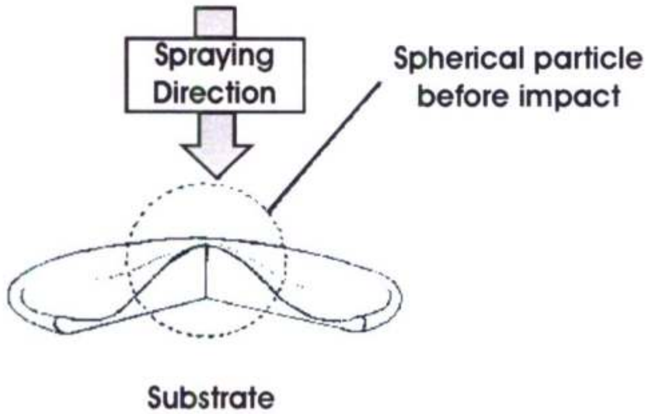

Fig.1.2. Schematic diagram of thermally sprayed spherical particle impinged onto a flat substrate (Source: Gordon England)

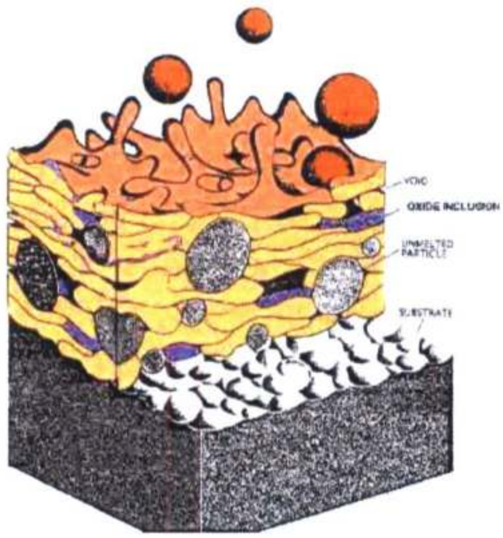

Fig.1.3. Schematic Diagram of Thermal Spray Metal Coating *(Source: Gordon England)*

Bonding

The bonding mechanisms at the thermal spray coating/substrate interface and between the particles making up the thermal spray coating is an area which in many cases is still subject to speculation. It generally suffices to state that both mechanical interlocking and diffusion bonding occur.

Thermal Spray Coating Bonding Mechanisms:

- Mechanical keying or interlocking.
- Diffusion bonding or Metallurgical bonding.
- Other adhesive, chemical and physical bonding mechanisms - oxide films, Van der Waals forces etc.

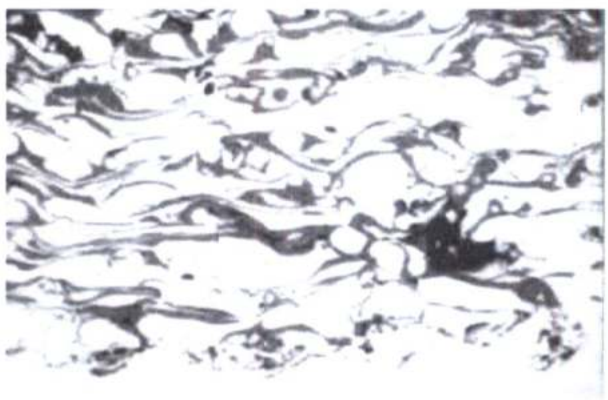

Fig.1.4. A typical microstructure of a metallic thermally sprayed coating. The lamellar structure is interspersed with oxide inclusions and porosity *(Source: Gordon England)*

Factors effecting bonding and subsequent build up of the coating:

- Cleanliness
- Surface area
- Surface topography or profile
- Temperature (thermal energy)
- Time (reaction rates & cooling rates etc.)
- Velocity (kinetic energy)
- Physical & chemical properties
- Physical & chemical reactions

Cleaning and grit blasting are important for substrate preparation. This provides a more chemically and physically active surface needed for good bonding. The surface area is increased which will increase the coating bond strength. The rough surface profile will promote mechanical keying.

Individual particle cooling rates on impact can be of the order of 1 million ° C per second ($10^6 Ks^{-1}$) [1]. Thermal interaction is obviously very limited. Important with regard to diffusion bonding (temperature and time dependent).

Increase in thermal and kinetic energy increases chances of metallurgical bonding (temperature, velocity, enthalpy, mass, density and specific heat content etc.). Thermal spray materials like Molybdenum, Tungsten, and Aluminum / metal composites produce so called "self bonding" coatings. These materials have comparatively high bond strengths (increased metallurgical or diffusion bonding) and can bond to clean polished substrates.

Higher preheat temperatures for the substrate increase diffusion bonding activities but will also increase oxidation of the substrate which could defeat the objective of higher bond strengths.

High kinetic energy thermal spraying using HEP, HVOF and cold spray produce high bond strengths due to the energy liberated from high velocity impacts. The high density tungsten carbide/cobalt and cold spray coatings are good examples.

Metallurgical or diffusion bonding occurs on a limited scale and to a very limited thickness (0.5 μm max. with heat effected zone 25μm) with the above type coatings.

Fused coatings are different. These are remelted and completely metallurgically bonded with the substrate and its self.

1.1.1. COMBUSTION SPRAYING

1.1.1.1. Combustion Wire Thermal Spray Process (Metal Spraying)
(also known previously as Flame Spray, Metallizing, and Metal Spray Processes)

The Combustion Wire Thermal Spray Process formerly known as Metallizing, Flame Spray and Metal Spray Processes was first invented in 1910 by Schoop in Switzerland [1].

The flame spray process is basically the spraying of molten metal (ceramics and cermets can be used in rod or composite wire form) onto a surface to provide a coating. Material in wire form is melted in a flame (oxy-acetylene flame most common and this heat source creates a gas stream with a temperature in excess of 3,000°C with correctly balanced conditions between oxygen and acetylene [5]) and atomised using compressed air to form a fine spray.

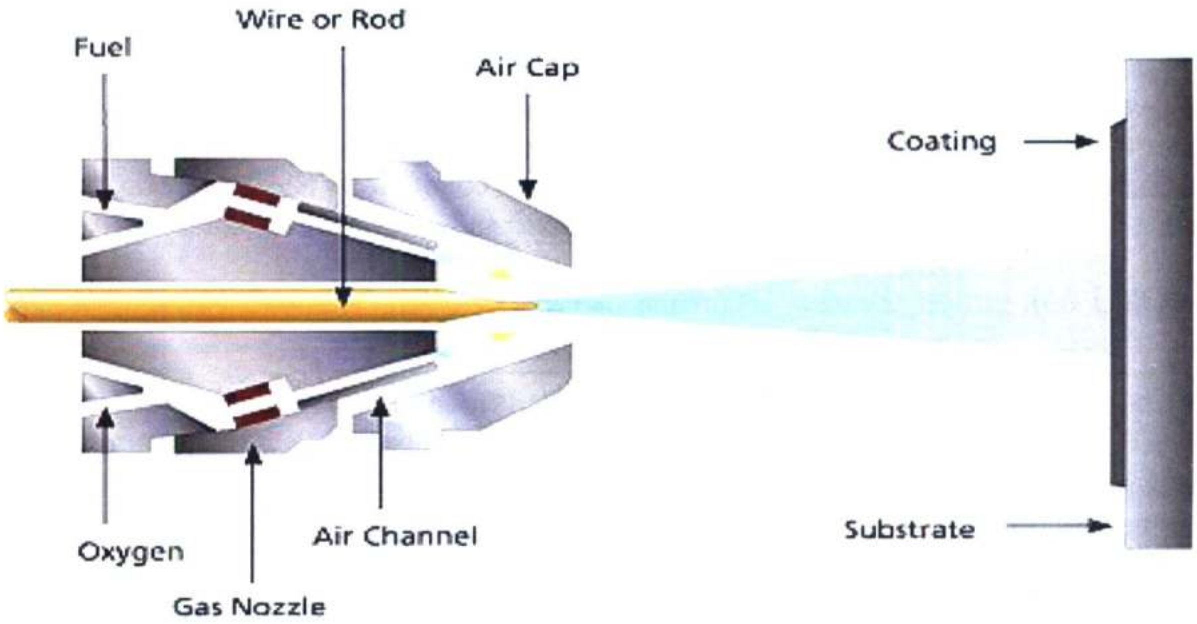

Fig.1.5. Schematic Diagram of The Combustion Wire Thermal Spray Process *(Source: Plasma & Thermal Coatings Ltd.)*

When the spray contacts the prepared surface of a substrate material, the fine molten droplets rapidly solidify forming a coating. This flame spray process carried out correctly is called a "cold process" (relative to the substrate material being coated) as the substrate temperature can be kept low during processing avoiding damage, metallurgical changes and distortion to the substrate material.

Fig.1.6. Recent Gun Spraying 13% Chromium Steel *(Source:Metco Ltd.)*

This flame spray process has been extensively used in the past and today for machine element work and anti-corrosion coatings.

Common materials Sprayed:

- Zinc and aluminium for anti-corrosion cathodic coatings on steel
- Nickel/aluminium composite wire for bond coats and self-bonding coatings
- Molybdenum for bond coats
- Molybdenum for hard bearing applications, excellent resistance to adhesive wear, used on piston rings, syncromesh cones and journals
- High Chromium steel for many applications requiring hard and wear resistant coating
- Bronzes, babbitt for bearing applications

- Stainless steels, nickel and monel for anti-corrosion and wear
- Aluminium, nickel/aluminium for heat and oxidation resistance

Table 1.1. The Combustion Wire Thermal Spray Coatings
Source: Plasma Group Science

Coating	Characteristics	Typical Applications
Copper/silicon Carbide (HIPAC) Ask for the separate Data Sheet for more details	High thermal conductivity, five times greater than cast iron. Good electrical conductivity. High wear resistance High energy absorbance and heat dissipation	Used on components subjected to high friction wear and heat build up cauded by rotating machine parts. Major uses are for brake and clutch components particularly on racing cars, bikes and other forms of transport.
13% Chrome Steel	Macrohardness - Rc 33 Tensile bond strength - 28 MPa (4000 p.s.i.) High Strength	Used extensively as a build up material. It can be ground finished to tight tolerances to reclaim shafts, hydraulic rams, pistons, bearings, plungers and other general engineering components.
Aluminium	Macrohardness - RH 80 Tensile bond strength - 10 MPa (1450 p.s.i.) High resistance to corrosion: • atmospheric • heat • chemical	With appropriate sealing of the coating aluminium can be used as an all purpose coating to prevent atmospheric corrosion and sea water attack on steel structures.
Aluminium Bronze	Macrohardness - RB 80 Wear resistant. Machines to excellent finish	It can be used for repairing defects in bronze castings. Also for build up of worn areas on bushings, bearings and other bronze or brass items.

There are a number of other wires available. These are detailed below with possible applications.

Coating	Typical Applications
Tin/Antimony/Copper (Babbit)	For heavy duty bearings
Zinc	For general corrosion resistance for similiar applications to aluminium
Molybdenum	For high wear areas such as wire capstans, brake drums and machine knives

Process Advantages:

- Low capital investment
- Simple to operate
- Wire form cheaper than powder
- Deposit efficiency very high

- Possibly still best for applying pure molybdenum coatings for wear resistance
- Portable system
- Preheating facility built in, unlike arc spraying
- Possible to use system in areas without electricity supply

Process Disadvantages:
- Limited to spraying materials supplied in wire or rod form
- Not capable of the low oxide, high density and high strength coatings of plasma and HVOF

1.1.1.2. Combustion Powder Thermal Spray Process
(Flame Spray Process) (also known as Powder Flame Spraying and LVOF (Low Velocity Oxygen Fuel Process)

This process is basically the spraying of molten material onto a surface to provide a coating. Material in powder form is melted in a flame (oxy-acetylene or hydrogen most common) to form a fine spray. When the spray contacts the prepared surface of a substrate material, the fine molten droplets rapidly solidify forming a coating.

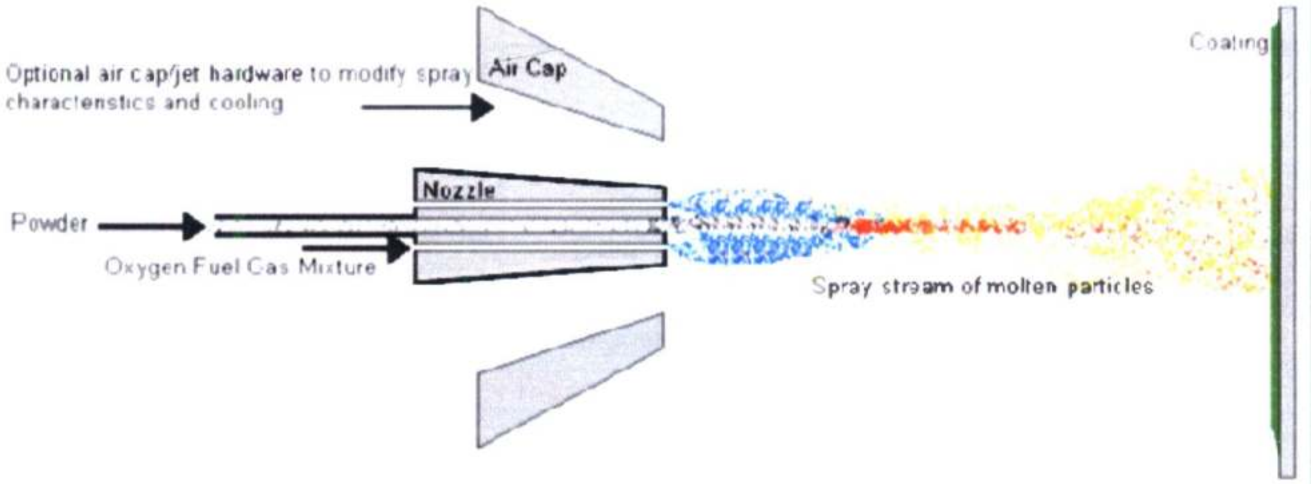

Fig.1.7. Schematic Diagram of Combustion Powder Thermal Spray Process
(Source:Gordon England)

Fig.1.8. Combustion Powder Sprayed Copper Aluminium Composite (aluminium bronze) Coating *(Source: Gordon England)*

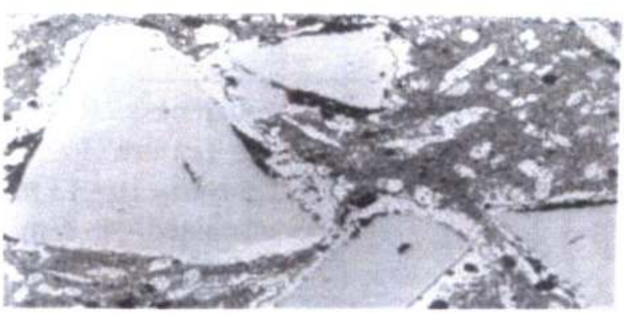

Fig.1.9. Combustion sprayed WC/NiCrBSi
(Source: Gordon England)

This flame spray process carried out correctly is called a "cold process" (relative to the substrate material being coated) as the substrate temperature can be kept low during processing avoiding damage, metallurgical changes and distortion to the substrate material.

Table 1.2. The Combustion Powder Thermal Spray Coatings
Source: Plasma Group Science

Fused Coatings		
Coating	**Characteristics**	**Typical Applications**
Nickel 70%,Chromium 17%, Iron, silicon, boron, carbon	Macrohardness - Rc 55 - 60 Surface Texture - as fused - 5 - 7.5 microns - as ground - 0.25 microns	This coating can be used in a wide range of applications. These include steel mill rolls, forging tools, exhaust fans, pumps and other components subject to wear.
Nickel 46%, Chromium 11%,Tungsten carbide/nickel 35%,Iron, silicon, boron, carbon	Macrohardness - Rc 58 - 60 Microhardness - KHN50 950 Surface Texture - as fused - 2-4 microns - as ground - 0.3 - 0.5 microns	This coating can be used where wear resistance is severe. It can be used on pump components, rolls, shafts, exhaust fans and other components subject to severe wear.
Cobalt 40% Nickel 27% Chromium 18% Molybdenum 6% Silicon, boron and iron	Macrohardness - Rc 50 Surface Texture - as fused - 6 - 7.5 microns - as ground - 0.35 microns	This coating is useful where cobalt base wear coatings are required and the substrate is a low shrink material. The possible applications are similiar to the other fused coatings.
Abradable Coatings		
Coating	**Characteristics**	**Typical Applications**
Nickel 75% Graphite 25%	Macrohardness - R15Y 30 - 50 Surface Texture - as sprayed - 25 - 33 microns - as machined - 4 - 6 microns	This coating is used in compressors on jet engines or in other machinery requiring close tolerance clearances in seal areas. It can be used as a low friction coating in the glass industry.
Aluminium 61%, Graphite 23%, Silicon 8%	Macrohardness - R15Y 50 - 70 Surface Texture - as sprayed - 10 - 13 microns - as machined - 4 - 6 microns	This coating is a lower cost alternative to the coating above. It is generally more erosion resistant at elevated temperatures and is used in similiar areas.

The main advantage of this flame spray process over the similar Combustion wire spray process is that a much wider range of materials can be easily processed into powder form giving a larger choice of coatings. The flame spray process is only limited by materials with higher melting temperatures than the flame can provide or if the material decomposes on heating.

1.1.2. HIGH VELOCITY OXY FUEL (HVOF)

Introduction

HVOF spraying has been developed principally to produce high quality metal and carbide coatings equivalent to the D - Gun process and with superior properties to conventional flame spray processes.

Process Description

HVOF is a thermal spray system utilising the combustion of gases, such as Hydrogen or a liquid fuel such as kerosene. Fuel and oxygen mix and atomise within the combustion area under conditions that monitor the correct combustion mode and pressure. Mixing of the gases occurs inside the gun and the externally ignited flame reaches a temperature of about 2700°C. Powder material is injected through the flame and the molten particles projected at velocities approaching 2000 metres per seconds on to the workpiece [5]. One of the basic rules of spraying is that high combustion pressure = high gas velocity, high particle velocity and resulting high coating quality.

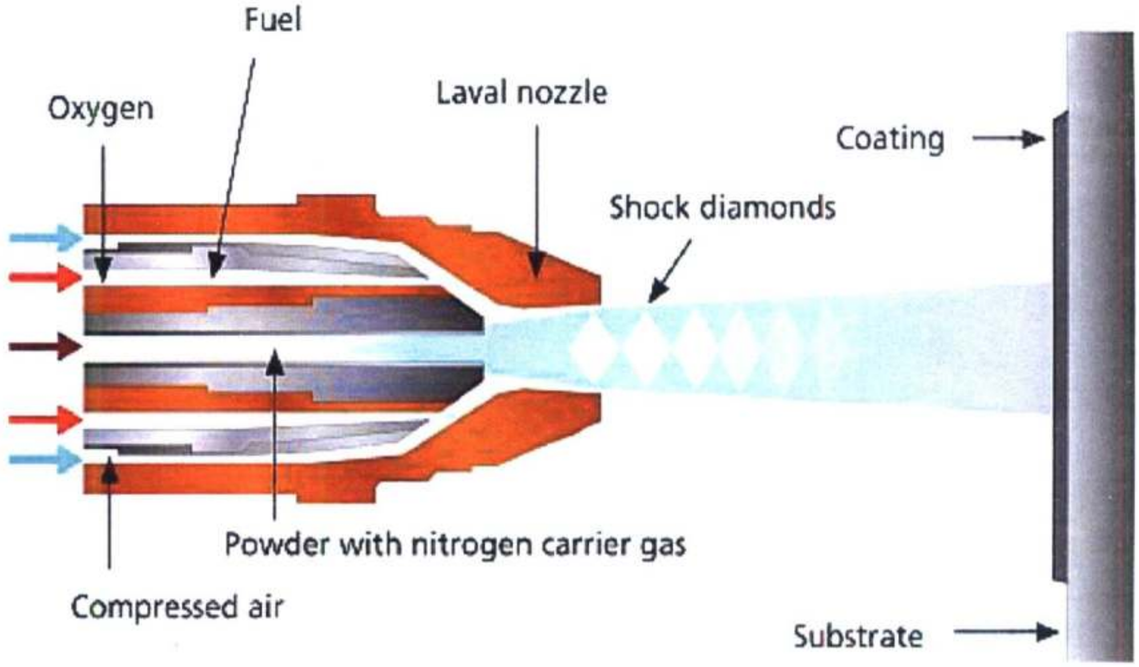

Fig.1.10. Schematic Diagram of the HVOF Process
(Source: Plasma & Thermal Coatings Ltd.)

Precise control of all spraying parameters and powder feed rates, and the use of a robot to precisely position the gun, enables high quality coatings to be repeated on a large variety of different components [7].

One of the key benefits of this system's high velocity is the extremely high coating density and low oxide content. The low oxides are due partly to the speed of the particles spending less time within the heat source and partly due to the lower flame temperature of the heat source compared with alternative processes.

Fig.1.11. The HVOF Process Robot *(Source: AP&C Advanced Powders & Coatings Inc.)*

Main Applications:

- Rotary knife blades
- Aero engine parts
- Gate valves
- Pistons
- Shafts.

General Coating Characteristics:

- high bond strength (83 MPa - 12000 p.s.i.);
- high density, low porosity;
- low oxide;
- high hardness (DPH 500 1000 - 1300 for WC/Co);
- fine as sprayed texture, able to be ground or lapped to a fine finish (0.1-0.2 microns);
- excellent resistance to wear by abrasion, erosion or fretting.

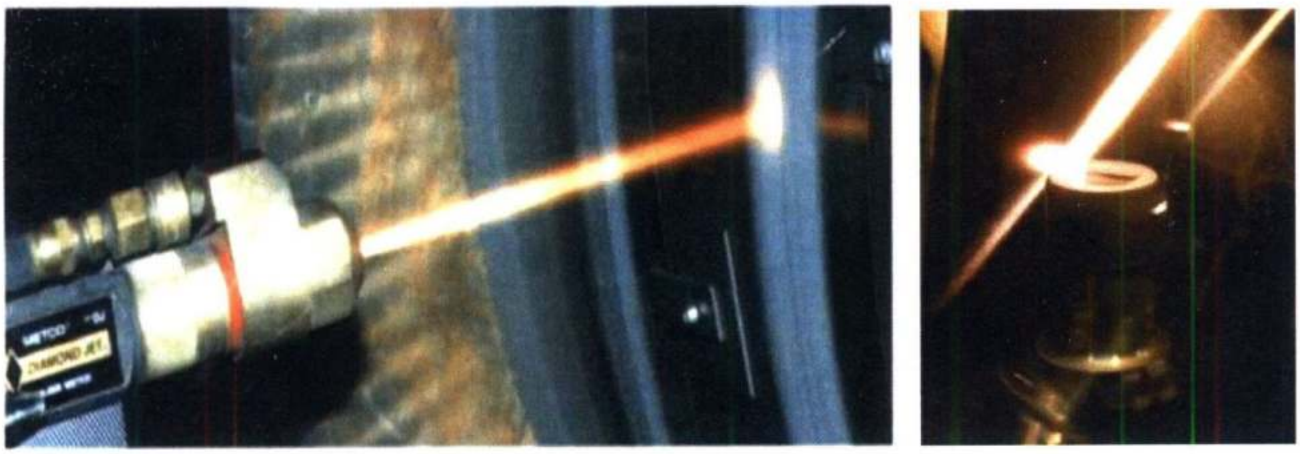

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Fig.1.12. The HVOF Process

Available Coatings

At present these consist mainly of coatings based upon Tungsten Carbide/Cobalt and Chrome Carbide/Nickel, as well as Stainless Steel, Aluminium Bronze and others.

Table 1.3. The HVOF Coatings
Source: Plasma Group Science

Coating	Characteristics	Typical Applications
Tungsten Carbide / Cobalt (88/12)	Macrohardness - Rc 64 - 66 Microhardness - DPH300 1015 -1300 Tensile Bond Strength - 83MPa(12000psi) Surface Texture - as sprayed - 2.5 - 4 microns - as ground - 0.05 - 0.1 microns	Shafts and pistons in high abrasive wear environments. Rotary cutting knives to improve edge life and cutting performance.
Chromium Carbide/Nickel Chrome (93/7)	Macrohardness - Rc 53 - 57 Microhardness - DPH300 600 - 650 Tensile Bond Strength - 73MPa(10500psi) Surface Texture - as sprayed - 5 - 6 microns - as ground - 0.2 - 0.3 microns	Used in temperature range 540 - 910°C where resistance to wear by fretting or particle erosion is required. Possible applications include piston guides, expansion joints and compressor seals.
Chromium Carbide/Nickel Chrome (75/25)	Macrohardness - Rc 55 Microhardness - DPH300 700 - 800 Tensile Bond Strength - 83MPa(12000psi) Surface Texture - as sprayed - 5 - 9 microns - as ground - 0.4 - 0.5 microns	Recommended to resist high wear by fretting or particle erosion at temperatures in the range 540 - 815°C. Possible applications include turbine seal rings, fuel rod mandrels and hot crushing rolls.
Cobalt/Molybdenum/ Chromium (62,28,8)	Macrohardness - RC 53 - 57 Microhardness - DPH300 500 - 700 Oxide Content - 10% Tensile Bond Strength - 68MPa(10000psi) Surface Texture - as sprayed - 5 - 9 microns - as ground - 0.1 - 0.2 microns	Used up to 700°C to resist corrosion and oxidation. Also has excellent resistance to galling and wear by rubbing. Possible applications in engine components where fretting or poor lubrication is a problem. For example, aft and forward seals in low pressure nozzles or valve seats.
Iron/Molybdenum/ Carbon (95,3,2)	Macrohardness - RC 48 - 52 Microhardness - DPH300 625 - 725 Oxide Content - 20% Tensile Bond Strength - 59MPa(8500psi) Surface Texture - as sprayed - 5 - 9 microns - as ground - 0.1 - 0.2 microns	For use below 340°C as a hard bearing surface where resistance to wear by hard surfaces or abrasive grains is required. Possible applications include bearing journals.

Fig.1.13. HVOF Sprayed Tungsten Carbide/12% Cobalt Coating [8]

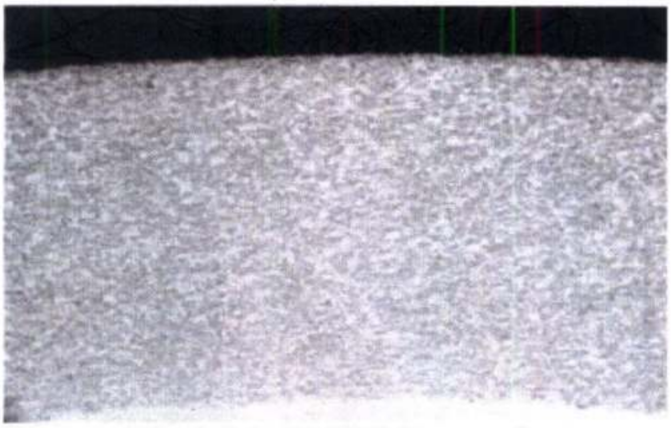


Fig.1.14. HVOF Sprayed WC/Co/NiCrBSi and Fused [8]

1.1.3. ARC WIRE

This form of thermal spraying uses wire material as a feed stock. An electric arc is used to provide the heat source by utilizing two current carrying wires (also called twin wire arc). As the wires are fed towards each other the electric current short circuits between the wires creating a temperature of around 4,000°C [5]. This process is an economical thermal spray technique for the application of metallic coatings that are high in internal porosity (10-15%).

This temperature causes the tips of the wire to melt and once molten, compressed air or inert gas is used to atomize and accelerate the feed metal towards the substrate.

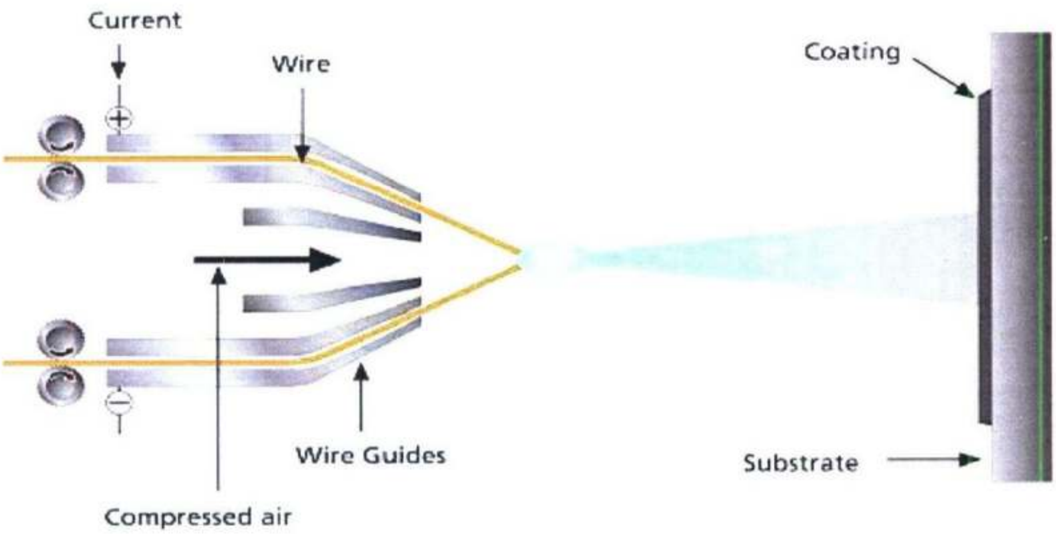


Fig.1.15. Schematic Diagram of the Electric Arc Wire Thermal Spray Process *(Source: Plasma & Thermal Coatings Ltd.)*

Electric arc spray coatings are normally denser and stronger than their equivalent combustion spray coatings. Low running costs, high spray rates and efficiency make it a good tool for spraying large areas and high production rates.

One of the ***advantages*** of this system is that two different wires can be used simultaneously to produce a pseudo alloy. Cored wires are also available producing coatings with unique properties.

Disadvantages of the electric arc spray process are that only electrically conductive wires can be sprayed and if substrate preheating is required, a separate heating source is needed.

The process is often used when applying to large areas such as corrosion resistance on large components or for the building up of worn components.

Fig.1.16. Arc Wire Sprayed 13Cr Steel Coating (*Source: Gordon England)*

Commonly applied materials include aluminum, copper, nickel, zinc, and stainless steel. Coating thickness can be upwards of 0.25", depending on the desired performance characteristics.

1.1.4. PLASMA SPRAYING

Introduction

The plasma spraying process involves the latent heat of ionized inert gas (Plasma) being used to create the heat source. The most common gas used to create the plasma is argon, this is referred to as the primary gas.

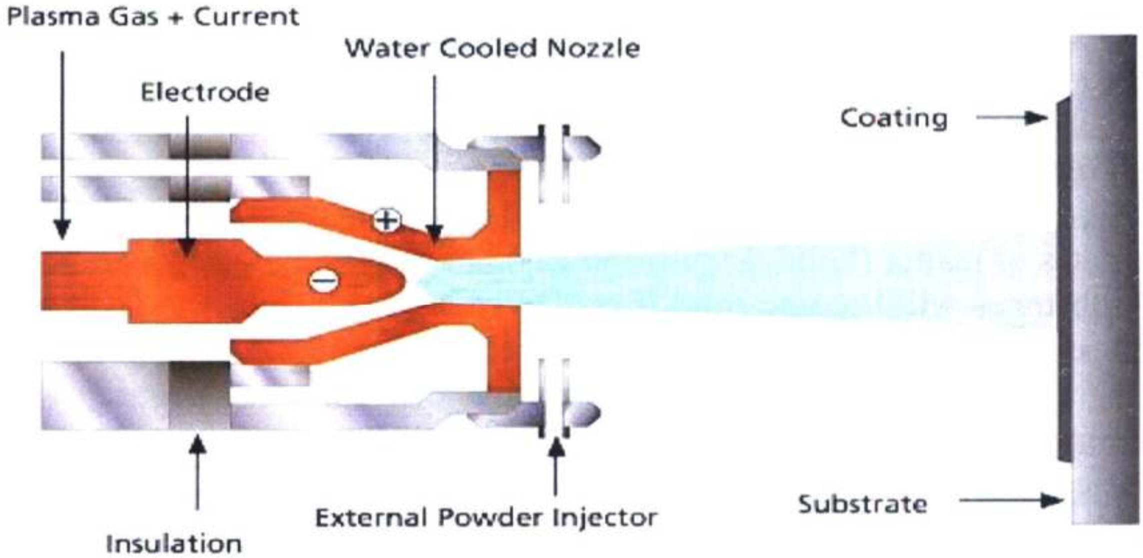


Fig.1.17. Schematic Diagram of the Plasma Process
(Source: Plasma & Thermal Coatings Ltd.)

Process Description

Argon flows between the electrode and nozzle. A high frequency or high voltage alternating electric arc is struck between the nozzle and the electrode, which ionizes the gas stream. By increasing the arc current, the arc thickens and increases the degree of ionization. This has the effect of increasing the power and also, due to the expansion of gas, an increase in the velocity of gas stream.

With a plasma created by argon only it requires a very large arc current (Typically 800 to 1,000amps) to create sufficient power to melt most materials.

With this level of arc current the velocity may be too high to allow materials with a high melting point to be made molten. Therefore, to increase the power to a level sufficiently enough to melt ceramic materials it is necessary to change the thermal and electrical properties of the gas stream. This is generally done by adding a secondary gas to the plasma gas stream (Usually Hydrogen).

Once the appropriate gas stream has been established for the material being sprayed, the feed stock (Material in various powder forms) is injected into the gas stream.

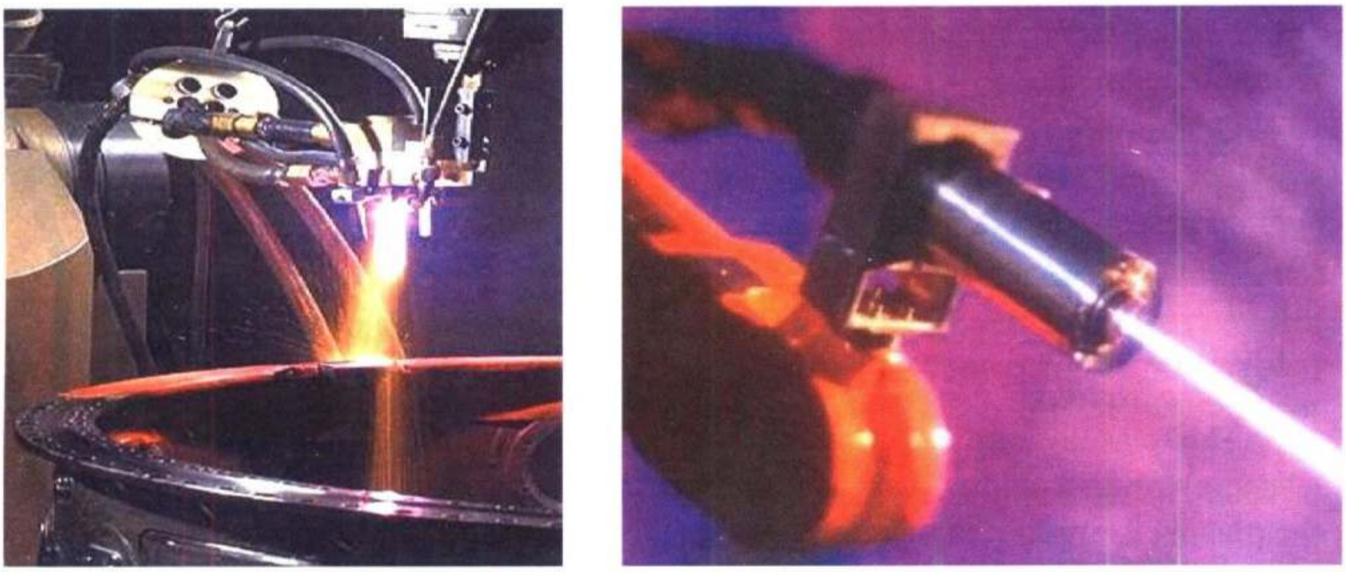


Fig.1.18. The Plasma Spraying Process
(Source: Plasma Group Science)

What is Plasma

Plasma is often referred to as the fourth state of matter. Plasma, like the other three states of matter (Solid, Liquid and gas) has its own unique properties. Just as most substrates will become solid if cooled enough, any substance will become a plasma if heated enough. In a plasma the electrons are stripped from the atoms creating a substance that resembles a gas but that conducts electricity. Plasmas occur naturally on the earth in flames, electrical discharges, lightning bolts and the aurora borealis (Northern Lights).

The Solar Winds

A naturally occurring Plasma phenomenon where the earth is protected by its magnetic field.

The Plasmas created by this phenomena are called solar winds, most of which we are protected from by the earth's magnetic field.

Process Energy

Flame Spray Technologies (FST) use this energy when creating a plasma by passing an electric current through a gas such as argon or nitrogen.

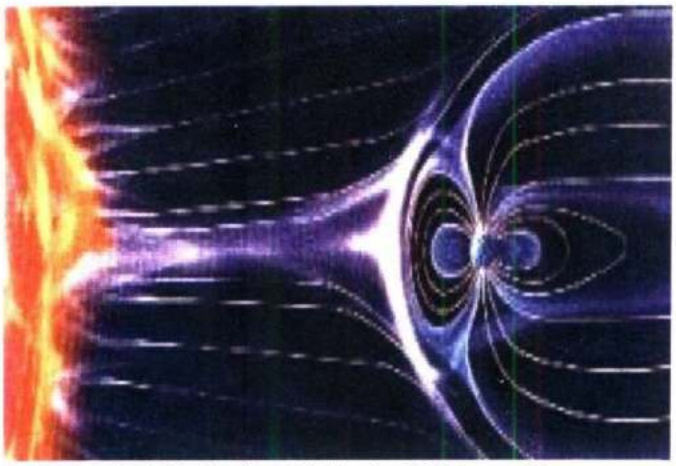


Fig.1.19. Solar Winds Effect *(Source: Plasma & Thermal Coatings Ltd.)*

This provides an energy heat source of around 15,000 °C under high pressure which heats and propels the coating material onto the substrate.

Plasma Flame Theory

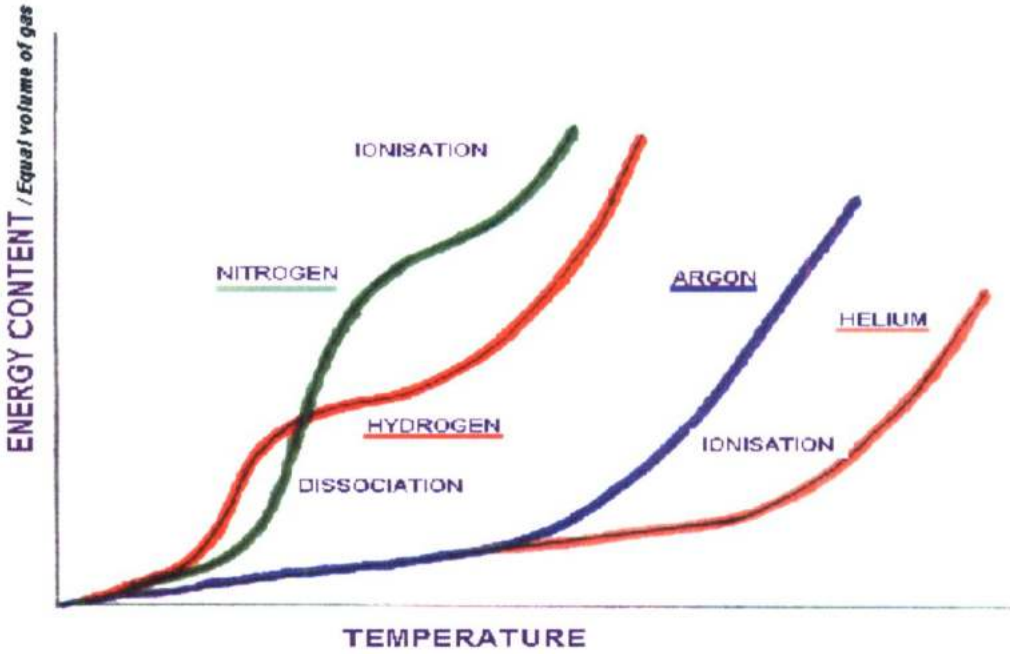


Fig.1.20. Schematic Diagram of the Plasma Process Sources
(Source: Gordon England)

A 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 ionized producing a plasma containing electrically charged particles - ions and electrons.

The plasma generated for plasma spraying usually incorporates one or a mixture of the following gases:

- Argon
- Helium
- Nitrogen
- Hydrogen

Plasma flames for thermal spraying can produce temperatures around 7,000 to 20,000K far above the melting temperature (and vapour temperature) of any known material. The extreme temperature of the plasma is not the only reason for the effective heating properties. If for example helium gas is heated to around 13,000K without a plasma forming, it would have insufficient energy for normal plasma spraying. Nitrogen on the other hand heated to 10,000K going through dissociation and ionization forming a plasma is an effective heating media for thermal spraying, being able to supply about six times more energy than an equal volume of helium at 13,000K. The plasma is able to supply large amounts of energy due to the energy changes associated with dissociating molecular gases to atomic gases and ionization which occur with little change in temperature.

- $\mathbf{N_2 + E = 2N}$
- Diatomic molecule of nitrogen + energy gives 2 free atoms of nitrogen
- $\mathbf{2N + E = 2N^+ + 2e^-}$

- 2 free atoms of nitrogen + energy gives 2 nitrogen ions and 2 electrons

The reverse process provides most of the energy for heating the spray material without a dramatic drop in temperature:

- $\mathbf{2N^+ + 2e^- = 2N + E}$
- $\mathbf{2N = N_2 + E}$

Nitrogen and hydrogen are diatomic gases (two atoms to every molecule). These plasmas have higher energy contents for a given temperature than the atomic gases of argon and helium because of the energy associated with dissociation of molecules.

Argon and Helium are monatomic gases (the atoms don't combine to form molecules). These plasmas are relatively lower in energy content and higher in temperature than the plasmas from diatomic gases.

Nitrogen is a general purpose primary gas used alone or with hydrogen secondary gas.

Nitrogen also benefits from being the cheapest plasma gas. Nitrogen tends to be inert to most spray material except materials like titanium.

Argon is probably the most favoured primary plasma gas and is usually used with a secondary plasma gas (hydrogen, helium and nitrogen) to increase its energy. Argon is the easiest of these gases to form a plasma and tends to be less aggressive towards electrode and nozzle hardware. Most plasmas are started up using pure argon. Argon is a noble gas and is completely inert to all spray materials.

Hydrogen is mainly used as a secondary gas, it dramatically effects heat transfer properties and acts as anti-oxidant. Small amounts of hydrogen added to the other plasma gases dramatically alters the plasma characteristics and energy levels and is thus used as one control for setting plasma voltage and energy.

Helium is mainly used as a secondary gas with argon. Helium is a noble gas and is completely inert to all spray materials and is used when hydrogen or nitrogen secondary gases have deleterious effects. Helium imparts good heat transfer properties and gives high sensitivity for control of plasma energy. It is commonly used for high velocity plasma spraying of high quality carbide coatings where process conditions are critical.

Diverse uses include

- aerospace
- petrochemicals
- mining
- textiles
- biomedical and other industrial environments.

General Coating Characteristics

- high bond strength (55 MPa / 8000 p.s.i. or higher)
- high density, low porosity
- able to be ground or lapped to a fine finish (0.1-0.2 microns).

Due to the range of materials that can be sprayed it is difficult to generalize on coating characteristics, but with the correct choice of material plasma coatings can:

- perform better than chrome plating.
- be more cost effective than solid sintered carbide.
- resist wear better than the same material in cast or wrought form.

Atmospheric Plasma Spraying – APS

This technology uses plasma under atmospheric pressure to melt and project the powder used for the coating. The heat generated in APS surpasses 10 000 °C, which allows the melting of virtually any material.

Applications:

- Wear resistance
- Corrosion resistance
- Thermal Barrier Coating (TBC)
- Component restoration
- Others

Materials:

- Ceramics (ex. Al_2O_3, TiO_2, Cr_2O_3, ZrO_2)
- Metals (ex. Co, Ni, Mo) Alloys (ex. Fe-based)

Fig.1.21. The Atmospheric Plasma Spraying Process *(Source: AP&C Advanced Powders & Coatings Inc.)*

Vacuum Plasma Spraying – VPS

This technology uses plasma under low pressure (aprox. 0.1 atm), inert conditions to melt and project the powder used for the coating.

The heat generated in VPS surpasses 10 000 °C, which allows the melting of virtually any material. This operation is performed in a controlled, inert environment, resulting in a high quality coating with low porosity, less oxidation, and a superior adhesion (see photo below).

Applications:

- Wear resistance
- Corrosion resistance
- Thermal Barrier Coating (TBC)
- Net-shape forming
- Others

Materials:

- Ceramics (ex: Al_2O_3 TiO_2, Cr_2O_3)
- Metals (ex: Ta, Ti, Co, Ni, Cu, W) Alloys (ex: Ti-based, Fe-based)

Fig.1.22. The Vacuum Plasma Spraying Process *(Source: AP&C Advanced Powders & Coatings Inc.)*

Available Coatings

The table below gives typical coating properties and applications for a variety of materials. It is by no means an exhaustive list, rather, it is a guide to the diversity of coatings that can be offered.

Table 1.4. The HVOF Coatings
Source: Plasma Group Science

Coating	Characteristics	Typical Applications
Tungsten Carbide / Cobalt (83/17)	Macrohardness - Rc 50-55 Microhardness - DPH300 750-950 Tensile Bond Strength - 62MPa(9000psi) Surface Texture - as sprayed - 6 - 9 microns - as ground - 0.25 - 0.5 microns	Used in low temperature environments below 500°C on parts subject to fretting and abrasive wear. Many aero engine applications including brackets and mounts. Industrial applications include pump shafts, piston and wire drawing capstans.
Chrome Oxide	Macrohardness - Rc 70-72 Microhardness - DPH300 900-1300 Tensile Bond Strength - 41MPa(6000psi) Surface Texture - as sprayed - 6 - 7.5 microns - as ground - 0.4 - 0.5 microns	Used extensively in high wear areas on pump seals, impellers and sleeves where resistance to corrosion by acids, alkalis and alcohols is important. Also used in the textile and paper industries on parts subject to wear by thread or paper products.
Yttrium stabilized Zirconium	Macrohardness - Rc 30-35 Surface Texture - as sprayed - 9 - 12 microns	Used as a thermal barrier coating where resistance to high temperature corrosion and thermal shock is important. Components coated with this material include gas turbine parts, cylinder liners, exhaust ports and other engine parts subject to temperatures above 850°C.
Nickel/Chromium (80/20) + 6% Aluminum	Macrohardness - RB 90 Microhardness - 215(Knoop50) Tensile Bond Strength - 28MPa(4000psi) Surface Texture - as sprayed - 7 - 11 microns - as ground - 0.25 - 0.5 microns	Used to produce heat resistant coatings to minimize oxidation and corrosion of carbon steels up to 980°C. Applications include turbine engine components and heat treating fixtures.
Cobalt / Chromium / Nickel / Tungsten	Macrohardness - Rc 59 Surface Texture - as sprayed - 9 - 11 microns - as ground - 0.25 - 0.5 microns	Able to be used at temperatures between 540 - 840°C, this material resists wear by particle erosion or fretting. Typical applications include exhaust valves, seats, and seals and hot crushing rolls.
Aluminum / Polyester	Macrohardness - R15Y 60 - 80 Surface Texture - as sprayed - 15 - 18 microns - as ground - 1.75 - 2.5 microns	Used as an abradable coating below 345°C as an air or oil seal in both high and low pressure compressors.

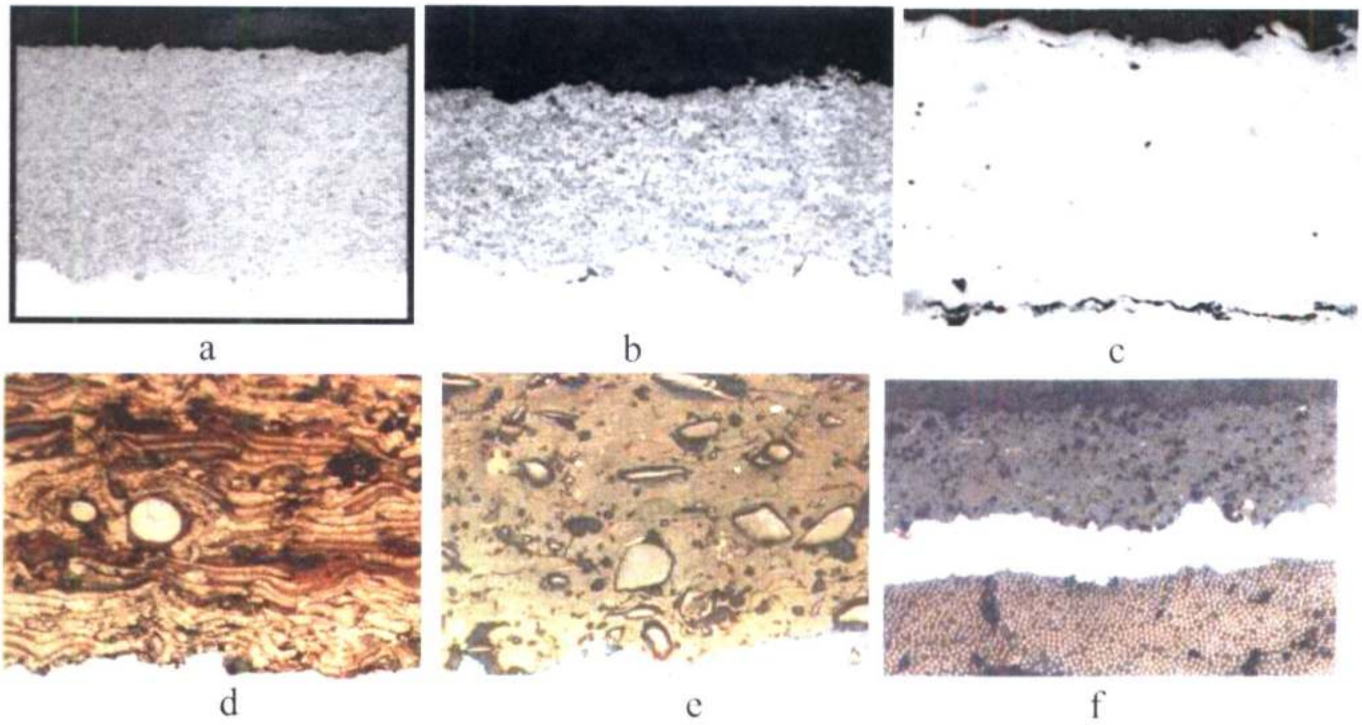


Fig.1.23. Plasma Spray Coating Photomicrographs [9]

a - Cr_2O_3; b - WC-17Co x200; c - NiCrBSi x200; d - Molybdenum coating;

e - Grey alumina (aluminium oxide) coating showing unmelted particles;

f - Ceramic Coating on Carbon Fibre Reinforced Composite

1.1.5. THE VACCUM PLASMA SPRAY FORMING (VPSF)

Introduction

Many high performance components are extremely difficult and costly to fabricate using conventional manufacturing technologies. Such components often require the use of exotic materials, composite structures, and functional coatings to satisfy the exacting requirements set forth by design engineers for the intended applications. Other components may require castings or forgings that are expensive, risky and have very long procurement lead-times.

Finally, many materials have properties (such as high reactivity to ambient oxygen or low ductility) that make them difficult or impossible to fabricate using such conventional technologies, hence limiting their widespread application.

Mired in the conundrum of the "unobtainium", design engineers often have to compromise in choosing the materials and structures based on the limitations of fabrication technologies.

Process Description

The Vaccum Plasma Spray Forming (VPSF) technology offers unique capabilities for the fabrication of parts using metal-matrix composites, laminated and functionally graded materials, metals, and ceramics [7]. Materials once thought to be unusable can now be employed using the VPSF process. The VPSF process is a single-step, rapid-prototyping manufacturing technology that is very sensitive to rapid changes in both design and materials, thus, offering the potential for "just-in-time" and reduced design to fabrication lead times.

Depending on the application, these characteristics enable the VPSF technology to be the most cost-effective method for the manufacturing of high performance components.

VPSF technology consists of the fabrication of a specially designed and treated mandrel that is sprayed using a plasma torch with molten or heat-softened materials engineered to achieve the desired properties. The hot material impacts on the target and rapidly cools to form a stable structure. Once the spray-formed structure is allowed to cool, the mandrel is removed to reveal the component, as shown on the left.

The component is then heat treated to obtain the desired microstructure and mechanical properties and can be machined to the final dimensions. Vacuum Plasma Spraying (VPS) is the plasma spray process performed under low-pressure conditions.

The absence of oxygen in such an application prevents the oxidation of the coating material. This process greatly enhances the sprayed structure's mechanical physical properties. Traditionally, thermal spraying techniques are used to apply protective coatings on actual components.

Fig.1.26. 3 components fabricated using VPSF: a military helmet, a combustion liner, and an eductor *(Source: AP&C Advanced Powders & Coatings Inc.)*

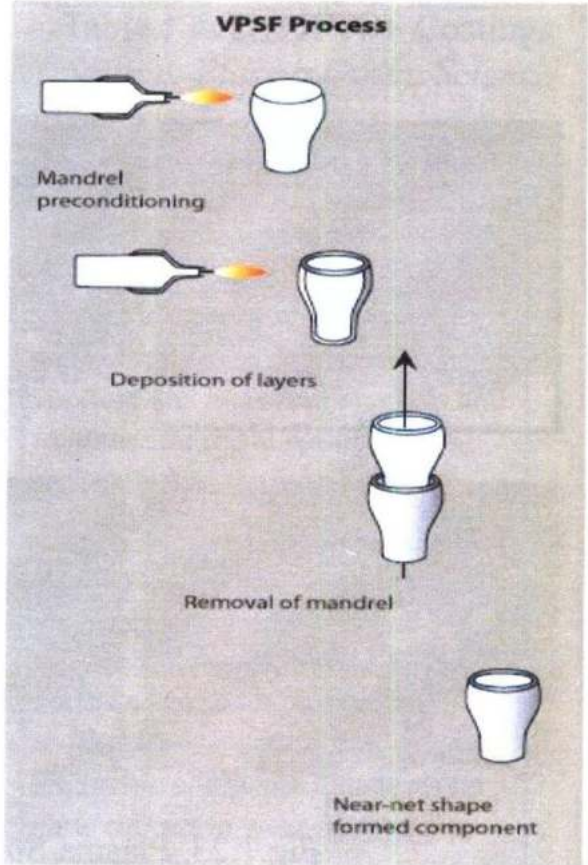


Fig.1.24. Schematic Diagram of the VPS Process *(Source: AP&C Advanced Powders & Coatings Inc.)*

Fig.1.25. The HVOF Process *(Source: AP&C Advanced Powders & Coatings Inc.)*

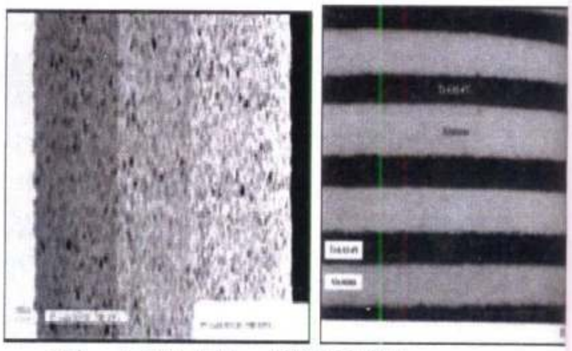


Fig.1.27. The HVOF Layers *(Source: AP&C Advanced Powders & Coatings Inc.)*

1.1.6. DETONATION THERMAL SPRAYING PROCESS

The Detonation Thermal Spray Process coating process efficiently uses high kinetic energy and temperature of detonation wave and controlled thermal output to produce dense, very low porosity coatings that exhibit very high bond strengths (some exceeding 350 MPa) [2]. The coatings have low residual fully controlled internal stresses and can be sprayed to thicknesses not normally associated with dense, thermal sprayed coatings.

The Detonation gun basically consists of a long water cooled barrel with inlet valves for gases and powder. Oxygen and fuel (acetylene most common) is fed into the barrel along with a charge of powder. A spark is used to ignite the gas mixture and the resulting detonation heats and accelerates the powder to supersonic velocity down the barrel. A pulse of nitrogen is used to purge the barrel after each detonation. This process is repeated many times a second.

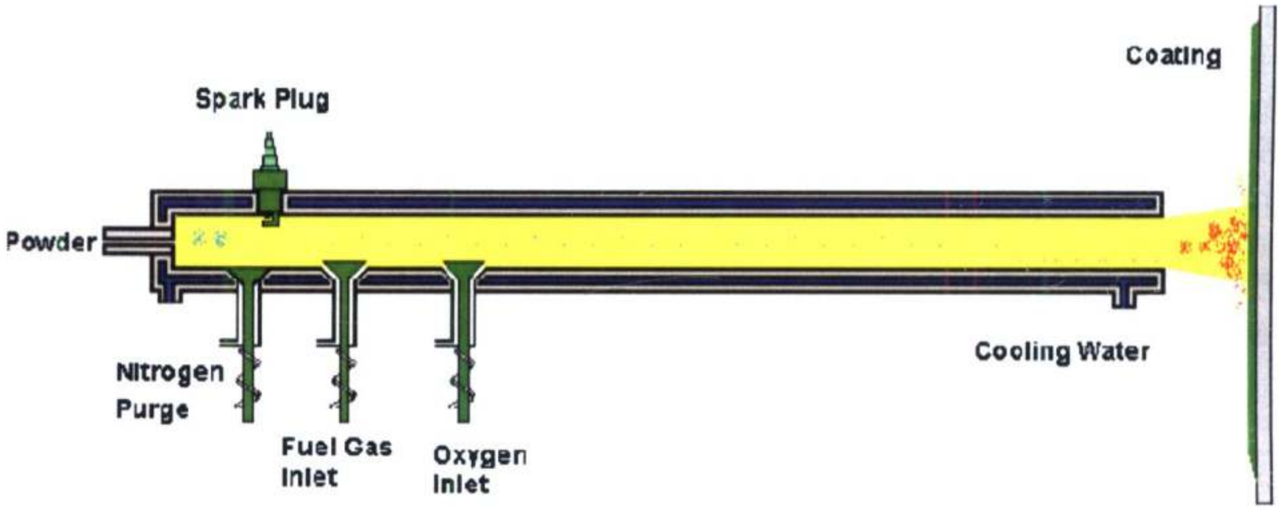


Fig.1.28. Schematic Diagram of the Detonation Thermal Spray Process
(*Source:Gordon England)*

The very high kinetic energy transferred to the particles by the detonation process (some exceeding 1200 mps) [2,3], the coating material generally does not need to be fully melted. Instead, the powder particles are in a molten state and flatten plasticly as they impact the workpiece surface. The result are coatings with more predictable chemistries that are very homogeneous with a fine granular structure. This method uses for parts, which work in super-heavy modes and aggressive media.

Fig.1.29. The Detonation Gun [4]

The Benefits of Detonation Coatings: Very high coating thickness

- Low porosity
- Excellent adhesion
- Optimized microhardnesses
- Low oxide metallic coatings
- Pre-loaded properties of layer

Typical Applications: Rebuild and Salvage Operations

- Abrasion or Erosion Resistance
- Sliding Wear Resistance
- Resistance to Fretting, Galling or Adhesive Wear
- Resistance to Chemical Attack

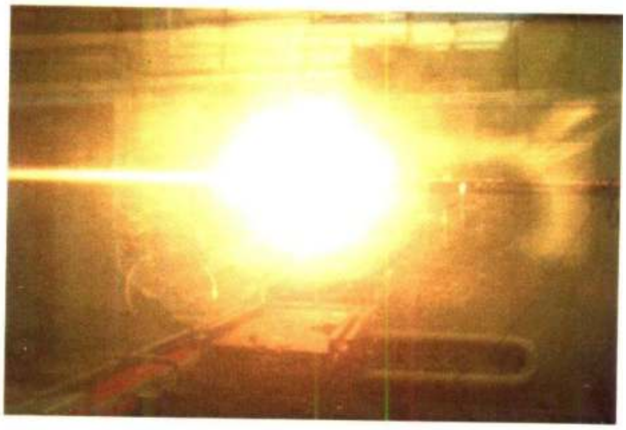


Fig.1.30. The Detonation Thermal Spray Process [4]

1.2. COLD SPRAY COATING PROCESS

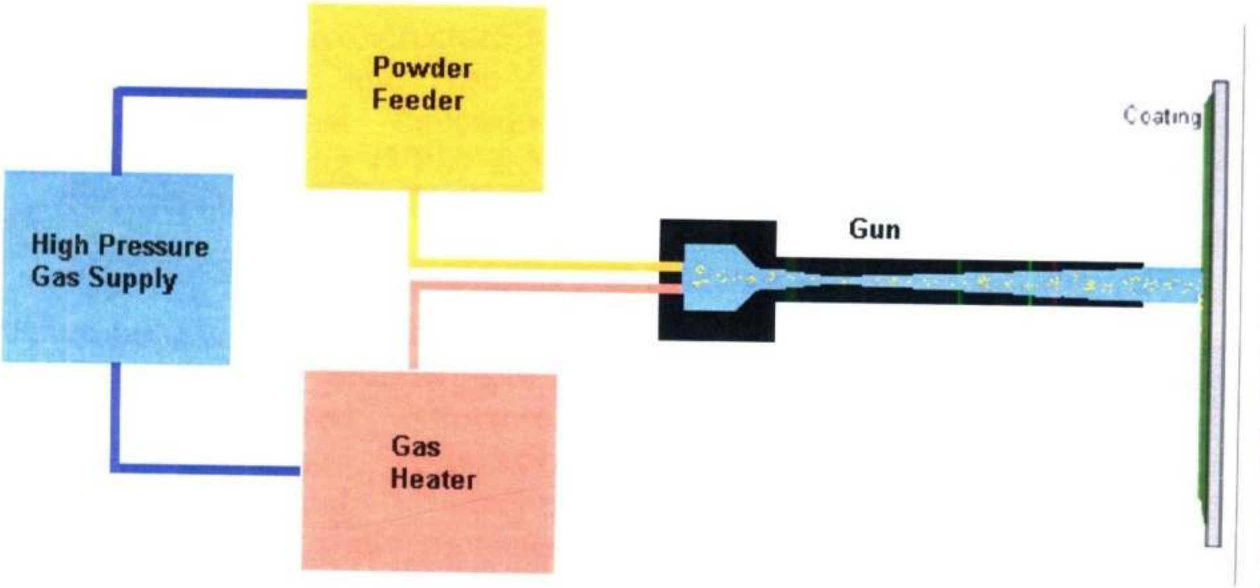


Fig.1.31. Schematic Diagram of Cold Spray Process
(Source: Gordon England)

Dr Antolli Papyrin and colleagues at the Russian Academy of Sciences were the first to demonstrate the cold spray process in the mid-1980s.

The Cold Spray or cold gas-dynamic spraying process is the next progressive step in the development of high kinetic energy coating processes. Similar in principle to the other thermal spray methods, it follows the trend of increasing particle spray velocity and reducing particle temperature as with the HVOF/HVAF processes, but to a more extreme level that it could be asked whether the process fits under the description of thermal spray.

The Cold Spray process basically uses the energy stored in high pressure compressed gas to propel fine powder particles at very high velocities (500 - 1500 m/s). Compressed gas (usually helium) is fed via a heating unit to the gun where the gas exits through a specially designed nozzle (laval type mostly) at very high velocity. Compressed gas is also fed via a high pressure powder feeder to introduce powder material into the high velocity gas jet. The powder particles are accelerated and moderately heated to a certain velocity and temperature where on impact with a substrate they deform and bond to form a coating. As with the other processes a fine balance between particle size, density, temperature and velocity are important criteria to achieve the desired coating.

The particles remain in the solid state and are relatively cold, so the bulk reaction on impact is solid state only. The process imparts little to no oxidation to the spray material, so surfaces stay clean which aids bonding. No melting and relatively low temperatures result in very low shrinkage on cooling, plus with the high strain induced on impact, the coatings tend to be stressed in compression and not in tension like liquid/solid state reactions of most of the other thermal spray processes. Low temperatures also aid in retaining the original powder chemistry and phases in the coating, with only changes due deformation and cold working.

Bonding relies on sufficient energy to cause significant plastic deformation of the particle and substrate. Under the high impact stresses and stains, interaction of the particle and substrate surfaces probably cause disruption of oxide films promoting contact of chemically clean surfaces and high friction generating very high localized heating promoting bonding similar to friction or explosive welding.

Coatings at present are limited to ductile materials like aluminium, stainless steel, copper, titanium and alloys. Hard and brittle materials like ceramics can not be sprayed in the pure form, but may be applied as composites with a ductile matrix phase. Substrate materials are also limited to those that can withstand the aggressive action of the spray particles. Soft or friable substrates will erode rather than be coated.

The cold spray process is still primarily in the research and development stage and only now becoming commercially available.

Cold Spray Process Advantages:

- Low temperature process, no bulk paticle melting
    - retains composition/phases of initial particles
    - very little oxidation
    - high hardness, cold worked microstructure
    - eliminates solidification stresses, enables thicker coatings
    - low defect coatings
    - lower heat input to work piece reduces cooling requirement
    - possible elimination of grit blast substrate preparation
- No fuel gases or extreme electical heating required
- Reduce need for masking

Cold Spray Process Disadvantages:

- Hard brittle materials like ceramics can not be sprayed without using ductile binders
- Not all substrate materials will accept coating
- High gas flows, high gas consumption. Helium very expensive unless recycled
- Still mainly in reasearch and development stage, little coating performance/history data

Possible Uses for Cold Spray Coatings:

- Corrosion protection, where the absence of process-induced oxidation may offer improved performance
- Electrical and thermal, where the absence of process-induced oxidation may offer improved conductivity
- Pre-placement of solders and coatings where purity is important

1.3. VAPOR DEPOSITION

Vapor deposition is a process in which the substrate (workpiece surface) is subjected to chemical reactions by gases that contain chemical compounds of the materials to be deposited. The coating thickness is usually a few μm, which is much less than the thicknesses provided by other techniques. The deposited materials may consist of metals, alloys, carbides, nitrides, borides, ceramics, or various oxides [10]. The substrate may be metal, plastic, glass, or paper. *Typical applications* are coating cutting tools, drills, reamers, milling cutters, punches, dies, and wear surfaces.

There are two major deposition processes: physical vapor deposition and chemical vapor deposition. These techniques allow effective control of coating composition, thickness, and porosity.

1.3.1. PHYSICAL VAPOR DEPOSITION (PVD)

The three basic types of *physical vapor deposition* (PVD) processes are vacuum or arc evaporation (PV/ARC), sputtering, and ion plating. These processes are carried out in a high vacuum at temperatures in the range of 200-500 °C (400-900 °F) [10]. In physical vapor deposition, the particles to be deposited are carried physically to the workpiece, rather than by chemical reactions as in chemical vapor deposition.

Vacuum evaporation. In vacuum evaporation, the metal to be deposited is evaporated at high temperatures in a vacuum and is deposited on the substrate, which is usually at room temperature or slightly higher. Uniform coatings can be obtained on complex shapes.

In PV/ARC, which was developed recently, the coating material (cathode) is evaporated by a number of arc evaporators (three are shown in Fig. 1.32) [10], using highly localized electric arcs. The arcs produce a highly reactive plasma consisting of ionized vapor of the coating material. The vapor condenses on the substrate (anode) and coats it.

Applications for this process may be functional (oxidation-resistant coatings for high temperature applications, electronics, and optics) or decorative (hardware, appliances, and jewelry).

Figure 1.33 shows a schematic of the process. Titanium Nitride (TiN), for example, is deposited in partial vacuum by feeding ionized titanium into a plasma of ionized argon and nitrogen. The operation occurs at a temperature of between 350 and 450°C with the resultant TiN growing on the surface of the work piece [5].

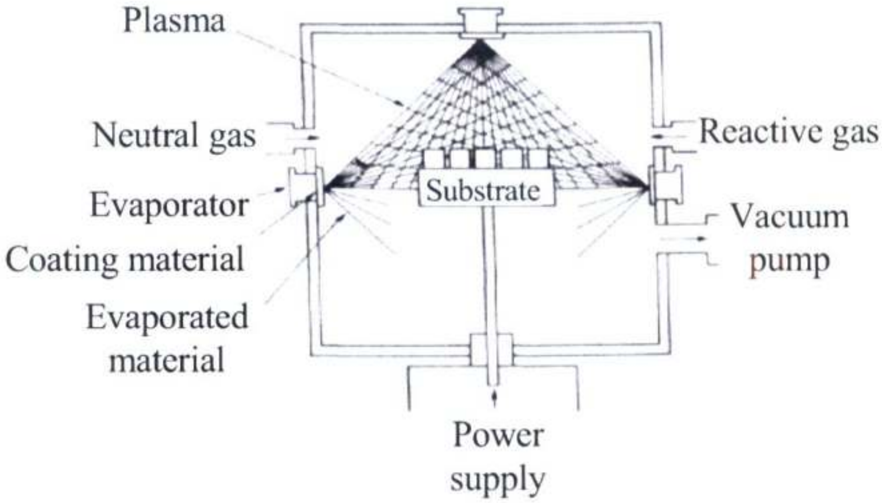


Fig.1.32. Schematic Diagram of The Physical Deposition Process *(Source: Cutting Tool Engineering)*

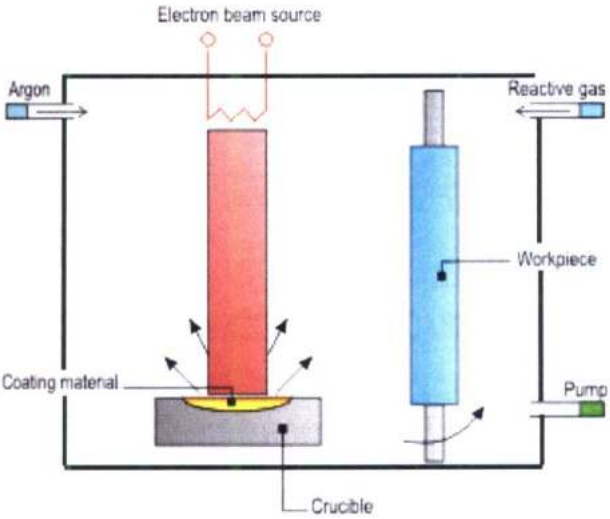


Fig.1.33. Physical Vapor Deposition Process *(Source: AP&C Advanced Powders & Coatings Inc.)*

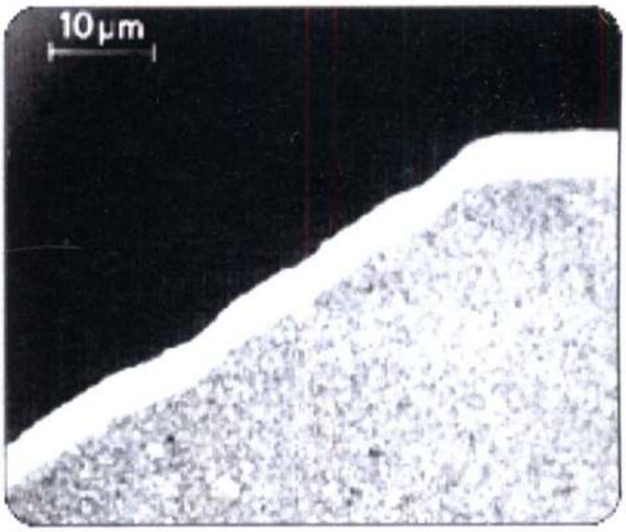


Fig.1.34. Section Through PVD Coating *(Source: AP&C Advanced Powders & Coatings Inc.)*

Materials such as Titanium Carbo Nitride, Chromium Nitride and Tungsten Carbide/Carbon can be produced by changing the material in the crucible and the reactive gases. Figure 1.34 shows a section through a PVD coating, from which it can be seen that the coating is thin, it is well bonded to the substance and that it contours accurately the original surface.

Because the process is carried out in a vacuum chamber there are issues of size limitation of the work piece. In addition the process is effectively line of sight so deep holes and bores can not easily be coated.

Sputtering. In sputtering, an electric field ionizes an inert gas (usually argon). The positive ions bombard the coating material (cathode) and cause sputtering (ejecting) of its atoms.

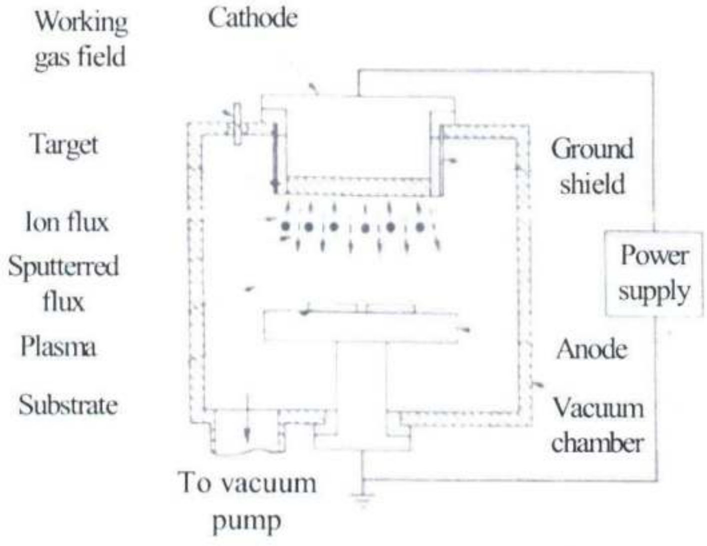


Fig.1.35. Schematic Diagram of The Sputtering Process *(Source: ASM International)*

These atoms then condense on the workpiece, which is heated to improve bonding (Fig. 1.35) [10].

In reactive sputtering, the inert gas is replaced by a reactive gas, such as oxygen, in which case the atoms are oxidized and the oxides are deposited. Carbides and nitrides are also deposited by reactive sputtering. Very thin polymer coatings can be deposited on metal and polymeric substrates with a reactive gas, causing polymerization of the plasma.

Radio-frequency (RF) sputtering is used for nonconductive materials such as electrical insulators and semiconductor devices.

Ion plating. Ion plating is a generic term describing the combined processes of sputtering and vacuum evaporation. An electric field causes a glow discharge, generating a plasma (Fig.1.36) [10]. The vaporized atoms in this process are only partially ionized.

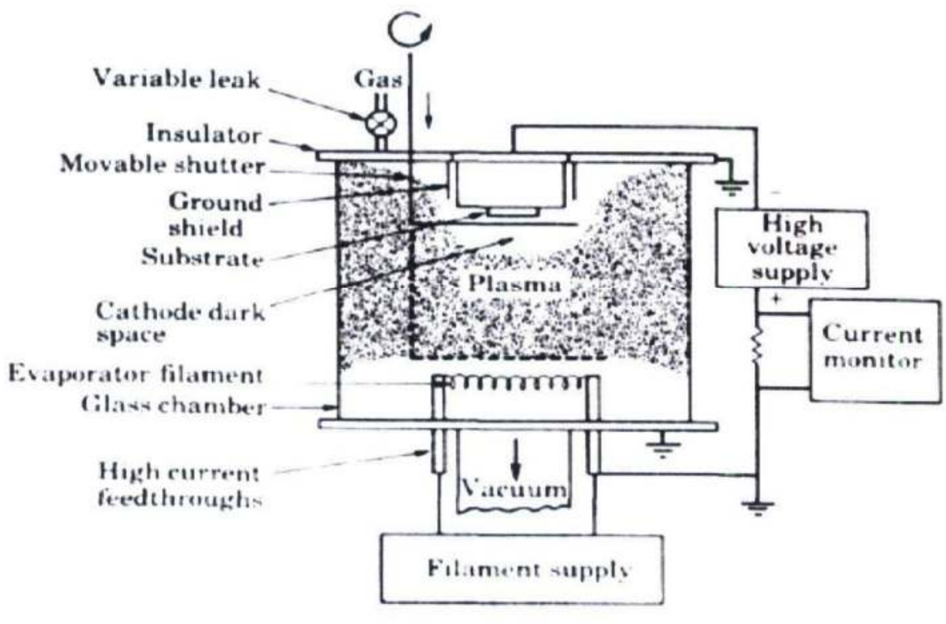


Fig.1.36. Schematic Diagram of The Sputtering Process *(Source: ASM International)*

1.3.2. CHEMICAL VAPOR DEPOSITION

Chemical vapor deposition (CVD) is a thermochemical process (Fig. 1.37) [10]. In a typical application, such as for coating cutting tools with titanium nitride (TiN), the tools are placed on a graphite tray and heated to 950-1050 °C (1740-1920 °F) [10] at atmospheric pressure in an inert atmosphere.

Titanium tetrachloride (a vapor), hydrogen, and nitrogen are then introduced into the chamber. The chemical reactions form titanium nitride on the tool surfaces. For coating with titanium carbide, methane is substituted for the gases.

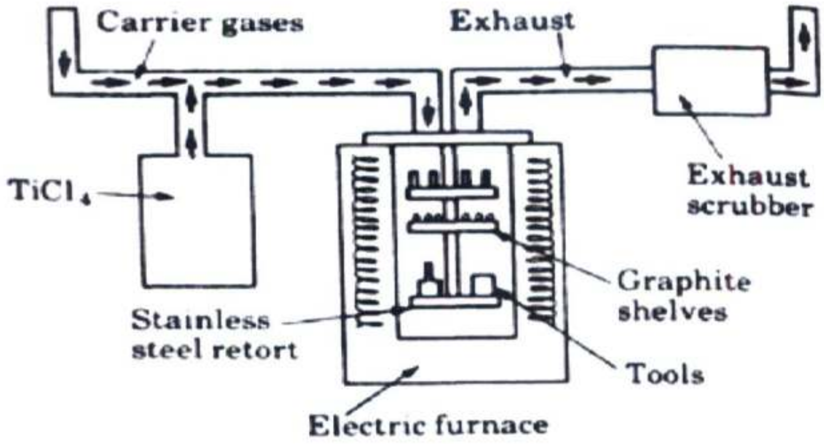


Fig.1.37. Schematic illustration of the chemical vapor deposition process

Chemical vapor deposition coatings are usually thicker than those obtained from PVD. A typical cycle for CVD is long, consisting of 3 hours of heating, 4 hours of coating, and 6-8 hours of cooling to room temperature [10]. The thickness of the CVD coating depends on the flow rates of the gases used, time, and temperature.

1.4. ION IMPLANTATION

In ion implantation, ions are introduced into the surface of the workpiece material. The ions are accelerated in a vacuum to such an extent that they penetrate the substrate to a depth of a few μm [10].

Ion implantation (not to be confused with ion plating) modifies surface properties by increasing surface hardness and improving friction, wear, and corrosion resistance. This process can be controlled accurately, and the surface can be masked to prevent ion implantation in unwanted places. When used in specific applications, such as semiconductors, this process is called doping (meaning alloying with small amounts of various elements).

1.5. DIFFUSION COATING

Diffusion coating is a process in which an alloying element is diffused into the surface of the substrate, thus altering its properties. Such elements can be supplied in solid, liquid, or gaseous states. This process acquires different names, depending on the diffused element, which describes diffusion processes such as carburizing, nitriding, and boronizing [10].

1.6. ELECTROCHEMICAL PLATING

Electrodeposition as an industrial activity has been practiced for over 150 years, one of the first applications having been the electroforming of printing plates. Subsequently, electroplating gained major importance as a cheap and versatile surface finishing process for decorative applications and for corrosion and wear protection. Typical examples include chromium plated automobile trimmings, gold plated brass jewelry, nickel-plated steel, gold plated electrical contacts or hard chromium plated bearings [12].

Traditionally, the automotive industry has been a big user of electroplating. While this industry used large integrated plating facilities, much of the plating for other applications was performed by specialized shops of relatively small size. Indeed, a characteristic of the traditional plating industry has been its fragmentation to which several factors may have contributed. On one hand, before strict environmental regulations came into effect, the investment needed to start a commercial.

1.6.1. ELECTROPLATING

In *electroplating,* the workpiece (cathode) is plated with a different metal (anode), while both are suspended in a bath containing a water-base electrolyte solution. Although the plating process involves a number of reactions, basically the metal ions from the anode are discharged under the potential from the external source of electricity, combine with the ions in the solution, and are deposited on the cathode.

All metals can be electroplated, with thicknesses ranging from a few atomic layers to a maximum of about 0.05 mm (0.002 in.) [10]. Complex shapes may have varying plating thicknesses.

Chemical cleaning and degreasing and thorough rinsing of the workpiece prior to plating are essential. The parts are placed on racks or in a barrel (bulk plating) and lowered into the plating bath.

Common plating materials are chromium, nickel, cadmium, copper, zinc, and tin. Chromium plating is carried out by first plating the metal with copper, then with nickel, and finally with chromium.

Hard chromium plating is done directly on the base metal and has a hardness up to 70 HRC. This method is used to improve wear and corrosion resistance of tools, valve stems, hydraulic shafts, and diesel- and aircraft-engine cylinder liners and also for rebuilding worn parts.

Brush Electroplating Processes

Brush or selective plating is a method of electroplating from concentrated plating solutions on selected area without immersion tanks. The solution is held in absorbent material wrapped around an anode. Electrical contact is made by brushing or swabbing the part (cathode) with the anode. It is also called brush plating. Faraday's laws of electrolysis applies to selective plating.

Brush Plating Equipment (selective) [13]:

1. DC Power Supply (Brush Plating Machines)
2. Anode and Anode Holder (Selective plating supplies)
3. Solutions or Chemicals (Selective plating chemicals)
4. Containing and Transferring

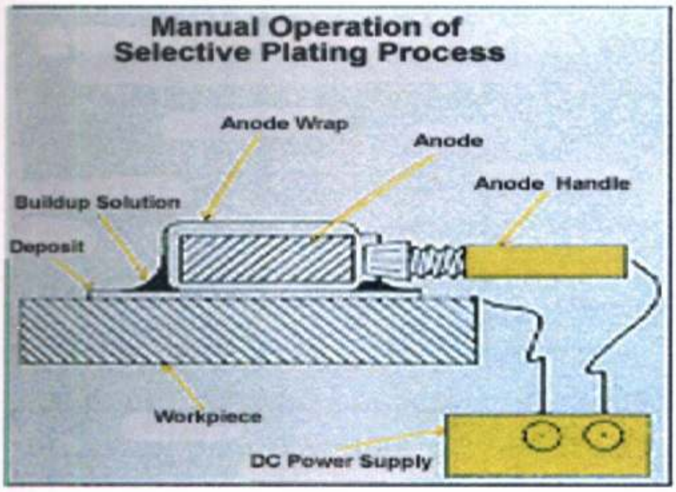


Fig.1.38. Brush Electroplating Process *(Source: Brooktronics Engineering Corporation)*

Benefits of Brush Plating (Selective Electroplating):

1. Prevent or minimize disassembly of workpiece
2. Portable equipment allows on-site work
3. Plate large parts or other parts not easily tank-plated
4. Supplement tank plating, minimize masking
5. Restore worn, corroded or mis-machined parts
6. Improve solderability, EMI shielding, conductivity in select areas

Fig.1.39. Portable Electroplater *(Source: Brooktronics Engineering Corporation)*

Compare to Tank Electroplating:

1. Same electrochemical process as tank electroplating but a different method of application
2. Brush plating chemicals are more concentrated
3. Brush plating uses higher current densities - faster build-up of metal deposit
4. The brush-plated deposit can be more dense, less porous
5. Precision build-up easier with brush plating
6. Brush plating equipment is portable. Click to view our Photo Gallery.

Brush Plating Machines

The basic features are a voltmeter, ammeter, variac, polarity switch, and circuit breaker. Additional features are an amp-hour meters and dual operating ranges.

Anode Assembly

An anode assembly consists of a handheld anode holder, an anode and anode wrapping. Various anode handles are available to accommodate specific applications. Anodes are usually made from a material inert to the plating solution. Materials such as graphite, stainless steel and 90%platinum/10%iridium are commonly used. Anode wrappings are used to hold the solution about the anode and provide insulation between the anode and cathode(workpiece). Common wrapping materials are cotton, dacron and scotchbrite. Sometimes sleeves of a similar material are placed over the anode wrapping.

Chemicals and Purpose:

1. Cleaning - remove surface contaminants.
2. Activating - activate or etch base material.
3. Anodizing or chromate coating - optional surface treatment for aluminum, zinc and cadmium only.
4. Pre-plating - deposit a pre-plate which increases adhesion or prevents intermetallic diffusion between build-up plate and the base material. Often nickel or copper pre-plates are used on aluminum, steel or brass.
5. Finish or build-up - deposit a final plate which imparts certain functional or decorative qualities to the base metal. Metals that may be deposited are cadmium, copper, gold, lead, nickel, silver, tin, zinc, rhodium, platinum and palladium. Alloys such as tin-lead, tin-zinc, nickel-zinc and babbitt may also be deposited in varying alloy compositions.
6. Blackening - surface treatment for steel, copper, nickel, silver and tin. Click here for info Blackening.

Containing, Transferring, Disposal

Usually trays, beakers, polypropylene bottles are used to contain chemicals during storage and use. Laboratory wash bottles are used for rinsing workpieces. Chemicals are considered hazardous materials and should be disposed of in compliance with all local, state, and federal requirements. Persons using solutions should wear personal safety equipment such as eye safety glasses or goggles, rubber or nitrile gloves, and a rubber apron if necessary.

Typical Applications

Typical electroplating applications are copper plating aluminum wire and phenolic boards for printed circuits, chrome plating hardware, tin plating copper electrical terminals for ease of soldering, and components requiring resistance to wear and corrosion and good appearance. Because they do not develop oxide films, noble metals (such as gold, silver, and platinum) are important electroplating materials for the electronics and jewelry industries.

Plastics such as ABS, polypropylene, polysulfone, polycarbonate, polyester, nylon also can be electroplated. Because they are not electrically conductive, plastics must be preplated by such processes as electroless nickel plating. Parts to be coated may be simple or complex, and size is not a limitation.

Electrodeposited Materials:

Alloys for magnetic applications:

- permalloy (Ni-Fe alloy containing 19 % Fe);
- CoNiFe.

Materials for corrosion and wear protection:

- Al, Cu;
- Zn;
- Zn-Ni (with about 15 to 20% Ni).

Electrodeposited semiconductor materials:

- ZnSe, CdSe, PbSe, CuSe, In_2Se_3, ZnS, CdS, ZnTe;
- Cd(Hg)Te, (CdZn)S, $CuInSe_2$, and $CuInTe_2$.

Fig.1.40. Shows the damper piston thread before plating, after cadmium and after the Type II coating *(Source: Brooktronics Engineering Corporation)*

Fig.1.41. Nickel plating clutch assemblies for the Space Station after the gear has been sealed in *(Source: Brooktronics Engineering Corporation)*

1.6.2. ELECTROFORMING

A variation of electroplating is *electroforming,* which actually is a metal fabricating process. Metal is electrodeposited on a mandrel (also called mold or matrix), which is then removed. Thus the coating itself becomes the product. Simple and complex shapes can be produced by electroforming, with wall thicknesses as small as 0.025 mm (0.001 in.). Parts may weigh from a few grams to as much as 270 kg (600 Ib) [10].

Mandrels are made from a variety of metallic (such as zinc or aluminum) or nonmetallic materials, which can be made electrically conductive with proper coatings. Mandrels should be physically removable without damaging the electroformed part. They may also be made of low-melting alloys, wax, or plastics, which can be melted away or dissolved with suitable chemicals.

The electroforming process is particularly suitable for low production quantities or intricate parts (such as molds, dies, waveguides, nozzles, and bellows) made of nickel, copper, gold, and silver. It is also suitable for aerospace, electronics, and electrooptics applications. Production rates can be increased with multiple mandrels.

1.7. ELECTROLESS PLATING

Electroless plating is carried out by chemical reactions, without the use of an external source of electricity. The most common application utilizes nickel, although copper is also used. In electroless nickel plating, nickel chloride (a metallic salt) is reduced—with sodium hypophosphite as the reducing agent—to nickel metal, which is then deposited on the workpiece. The hardness of nickel plating ranges between 425 HV and 575 HV [10], and can be heat treated to

1000 HV. The coating has excellent wear and corrosion resistance. Cavities, recesses, and the inner surface of tubes can be plated successfully. This process can also be used with nonconductive materials, such as plastics and ceramics. Electroless plating is more expensive than electroplating. However, unlike electroplating, the coating thickness in electroless plating is uniform.

1.8. ANODIZING

Anodizing is an oxidation process *(anodic oxidation)* in which the workpiece surfaces are converted to a hard and porous oxide layer that provides corrosion resistance and a decorative finish. The workpiece is the anode in an electrolytic cell immersed in an acid bath, resulting in chemical adsorption of oxygen from the bath. Organic dyes of various colors (typically black, red, bronze, gold, gray) can be used to produce stable, durable surface films [10].

Typical applications for anodizing are aluminum furniture and utensils, architectural shapes, automobile trim, picture frames, keys, and sporting goods. Anodized surfaces also serve as a good base for painting, especially for aluminum, which otherwise is difficult to paint.

1.9. CONVERSION COATING

Conversion coating, also called *chemical reaction priming,* is a coating that forms on metal surfaces as a result of chemical or electrochemical reactions. Various metals, particularly steel, aluminum, and zinc, can be conversion coated. Oxides that naturally form on their surfaces are a form of conversion coating. Phosphates, chromates, and oxalates are used to produce conversion coatings. These coatings arc for purposes such as corrosion protection, prepainting, and decorative finish. An important application is in conversion coating of workpieces as a lubricant carrier in cold forming operations. The two common methods of coating are immersion and spraying. The equipment involved depends on the method of application, the type of product, and considerations of quality.

As the name implies, *coloring* involves processes that alter the color of metals, alloys, and ceramics. It is caused by the conversion of surfaces (by chemical, electrochemical, or thermal processes) into chemical compounds, such as oxides, chromates, and phosphates. Note, for example, how the color of iron and steel changes as it oxidizes (rust color).

1.10. HOT DIPPING

In hot dipping, the workpiece, usually steel or iron, is dipped into a bath of molten metal, such as zinc (for galvanized-steel sheet and plumbing supplies), tin (for tinplate and tin cans for food containers), aluminum (aluminizing), and terne (lead alloyed with 10-20 percent tin). Hot-dipped coatings on discrete parts or sheet metal provide long-term corrosion resistance to galvanized pipe, plumbing supplit and many other products.

The rolled sheet is first cleaned electrolytically and scrubbed by brushing. The sheet is then annealed in a continuous furnace with controlled atmosphere and temperature and dipped in molten zinc at about 450 °C (840 °F). The thickness of the zinc coating is controlled by a wiping action from a stream of air or steam, called *air knife* (similar to air-drying cars in car washes). The coating thickness is usually given in terms of coating weight per unit surface area of the sheet, typically 150-900 g/m^2 (0.5-3 oz/ft^2). Service life depends on the thickness of the zinc coating and the environment to which it is exposed [10]. Various precoated sheet steels are used extensively in automobile bodies. Proper draining to remove excess coating materials is an important consideration.

1.11. PORCELAIN ENAMELING

Metals may be coated with a variety of glassy (vitreous) coatings to provide corrosion and electrical resistance and for service at elevated temperatures. These coatings are usually classified as porcelain enamels and generally include enamels and ceramics. The word *enamel* is also used for glossy paints, indicating a smooth, hard coating.

Porcelain enamels are glassy inorganic coatings consisting of various metal oxides. A fully developed art by the Middle Ages, enameling involves fusing the coating material on the substrate by heating them both to 425-1000 °C (800-1800 °F) [10] to liquefy the oxides. Depending on their composition, enamels have varying resistances to alkali, acids, detergents, cleansers, and water and come in different colors.

Typical applications for porcelain enameling are household appliances, plumbing fixtures, chemical processing equipment, signs, cookware, and jewelry. Porcelain enamels are also used as protective coatings on jet-engine components. The coating may be applied by dipping, spraying, or electrodeposition, and thicknesses are usually 0.05-0.6 mm (0.002-0.025 in.). Metals that are coated are typically steels, cast iron, and aluminum. Glasses are used as lining for chemical resistat and the thickness is much greater than in enameling. Glazing is the application glassy coatings on ceramic wares to give them decorative finishes and to make them impervious to moisture.

Ceramic coatings such as aluminum oxide or zirconium oxide are applied, with the use of binders, to the substrate at room temperature. Such coatings have been used in hot extrusion dies to extend their life.

1.12. PAINTING

Because of its decorative and functional properties (such as environmental protection), low cost, relative ease of application, and the range of available colors, paint is widely used as a surface coating. Engineering applications of painting range from all types of machinery to automobile bodies. Paints are classified as enamels, which produce a smooth coat and dry with a glossy or semiglossy appearance; *lacquers,* which form a film by evaporation of a solvent; and *water-base paints* which are easily applied, but have a porous surface, absorb water, and are not as easily cleaned as other paints. Paints are now available with good resistance to abrasion, fading, and temperature extremes; they are easy to apply and dry quickly.

Selection of a particular paint depends on specific requirements. Among these are resistance to mechanical actions (abrasion, marring, impact, and flexing) or to chemical actions (acids, solvents, detergents, alkalis, fuels, staining, and general environmental attack).

Common methods of applying paint are dipping, brushing, and spraying (Fig.1.42) [10].

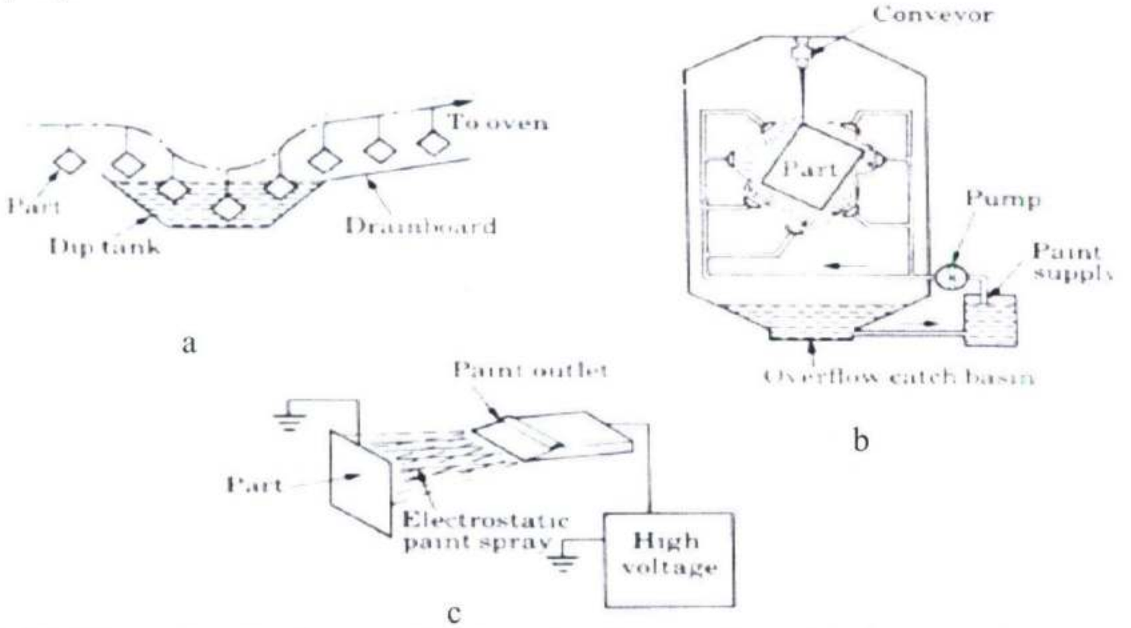


Fig.1.42. Methods of paint application: (a) dip coating, (b) flow coating, and (c) electrostatic spraying

2. COATINGS TYPES

2.1. THERMAL BARRIER COATINGS

Fig.2.1. Application of Thermal Barrier Coating to the inside surface of land based gas turbine combustor. (Process - Plasma Spray Coating system - CoNiCrAlY. Zirconia) *(Source: AP&C Advanced Powders & Coatings Inc.)*

A range of coatings designed to enable components to work within elevated or reduced temperatures. Thermal Barriers are often used on materials that work in temperatures above their melting point. The coatings also protect against oxidation, spalling and other associated heat induced effects.

Thermal Barrier Coatings (TBC's) are used to reduce the operating temperature of a metallic component which in turn leads to extended working life. High energy, reliability and longer maintenance intervals are demanded from today's TBC's to reduce surface temperatures in environments of over 14,000°C [5].

Components suffering from oxidation at high temperatures can be protected by using MCrAlY materials. The 'M' factor (Ni,Co,Fe or a combination thereof) will depend on the requirements of the application. TBC's are then applied to the surface of this material providing excellent reliability and long life.

Thermal Barrier Features

- Oxidation & Corrosion Resistance
- Low Thermal Conductivity
- Enhanced Erosion Resistance
- Longer Duty Cycle & Increased Part Life
- Reduction of substrate operating temperature - lower thermal & creep stresses
- Protection against 'hot spots'
- Enhanced operation temperature resulting in increased thermal efficiency
- Reduction of No_x emissions
- Reduction in cooling requirement
- Improved efficiency and fuel economy

Typical Applications:

- Diesel Engines - Piston Crowns, Valves etc.
- Land Based Turbines - Transistion Ducts,
Vanes, Combustors etc.
- Aero Engines - Discharge nozzle, combustors etc.

Processes:

- Plasma Spray
- HVOF

Typical Materials:

Top Coat:

- Yttria Stabilised Zirconia
- Ceria Stabilised Zirconia (CeSZ)
- Magnesia stabilised Zirconia

Bond Coat:

- CoNiCrAlY
- NiCrAlY

The efficiency of gas turbine engines is dictated by the maximum temperature that the turbine rotors can sustain during continuous operation. Such a limitation is usually imposed by the mechanical properties, particularly the creep resistance of the turbine blade material. Improvements to the composition of the superalloy series, internal air cooling, and in the extreme case, directionally solidified blades and single crystal blades have all been employed to extend the technology of the metal turbine blade to its limit. Ceramic blades have been manufactured, but are brittle and liable to failure by mechanical and thermal shock arising out of the extreme operating conditions. However, if a thin coating of ceramic can be applied to a metal blade, the engine temperature may be increased by 50-200°C without the metal temperature increasing; the ceramic acting as a thermal insulating barrier [11]. In this manner the efficiency of an engine may be increased by ~ 6-12% thereby saving $250,000 per year in fuel costs on a large aircraft engine [11]. The economic inducement to find a successful coating is therefore high.

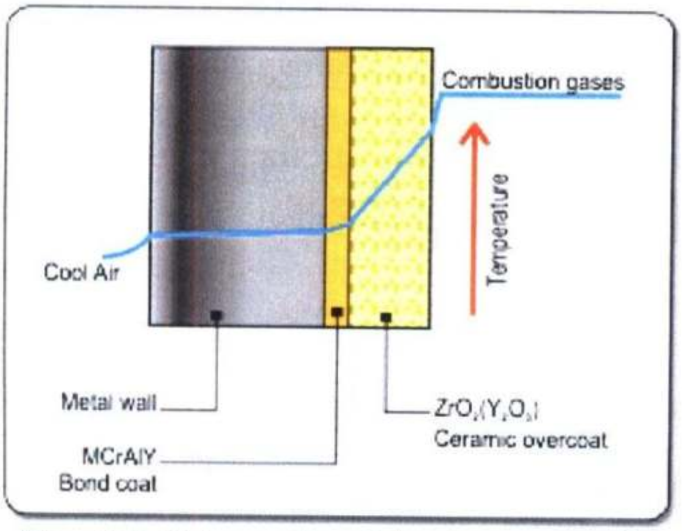


Fig. 2.2. Schematic of the structure of a two layer thermal barrier coating on a turbine blade surface together with a temperature profile *(Source: AP&C Advanced Powders & Coatings Inc.)*

At present, coatings are applied as a duplex structure, shown schematically in the diagram, figure 2.2.

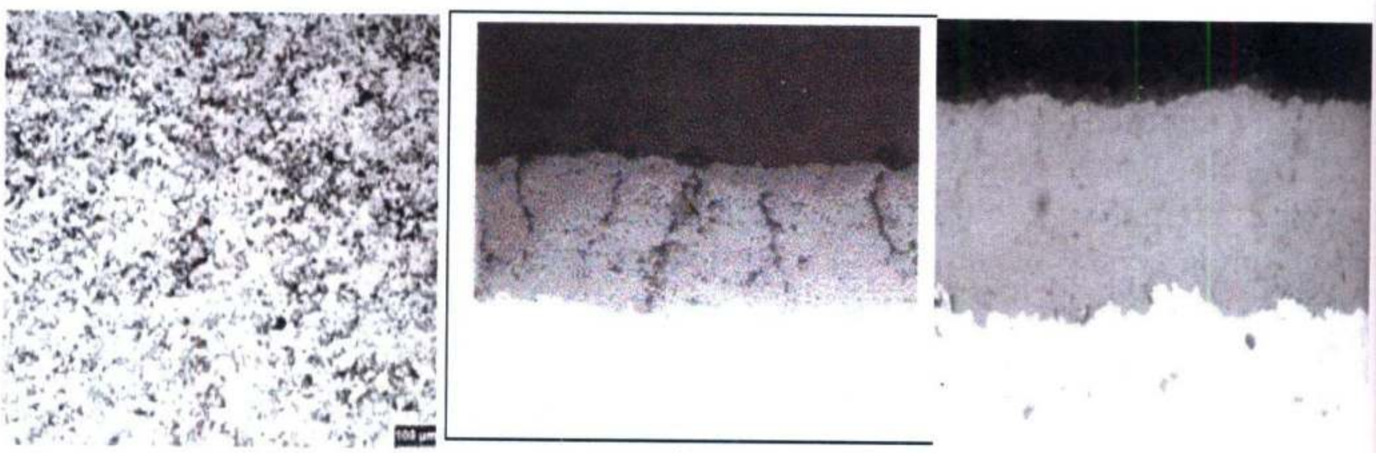
The thermal barrier is made up of plasma spayed ceramic layer, up to 0.6mm thick, over an intermediate layer, up to 0.7mm thick, which usually consists of a metallic bonding coat, or of a graded composition ceramic layer designed to minimise thermal mismatch of the adjacent layers [11].

Desirable properties of the ceramic barrier coating include a high thermal expansion coefficient, low thermal conductivity, chemical stability in the gas turbine environment and thermal shock resistance.

Plasma sprayed zirconia compositions have been investigated and the most suitable composition was found to be ZrO_2-6 to 8wt% Y_2O_3, which formed an adherent layer with the Ni, Cr, Al, Y, bond coat [11].

The most durable coatings were found to be formed from a partially stabilised zirconia composition. Investigation of the structure of the plasma sprayed coating has been undertaken. As would be expected from the rapid cooling rates, the structure is non-equilibrium and extremely fine.

Furthermore the structure varies considerably over short distances, indicating considerable fine scale inhomogeneity within the thermal barrier coating. X-ray diffraction studies indicate that both the partially stabilized composition (ZrO_2-8 wt % Y_2O_3) and the fully stabilised but inhomogeneous ceramic coating (ZrO_2-20 wt % Y_2O_3) consist of tetragonal and cubic phases with minor quantities of monoclinic present in the lower Y_2O_3 material [11].



a b c

Fig.2.3. Thermal Barrier Coatings: a – Porosity 25%, Thickness - 1500μm; b – Vertically Micro-Cracked TBC; c – Dence TBC, Porosity – 1% *(Source: Gordon England)*

2.2. ABRADABLE COATINGS

Derived from aero engine gas turbine compressors, these abradable and rub tolerant coatings are now applied to automotive engine turbochargers, pumps and compressors to provide clearance control. A turbocharger rotor spins at high speed within its housing. As its rotational speed increases, and to some extent the operating temperature, the outside diameter of the rotor also increases.

If the clearances between the rotor blade tips and its housing were designed for optimal aerodynamic performance, this growth would cause the rotor blade trips to touch the bore of the housing. These clearances are therefore larger than desirable due to mechanical considerations.

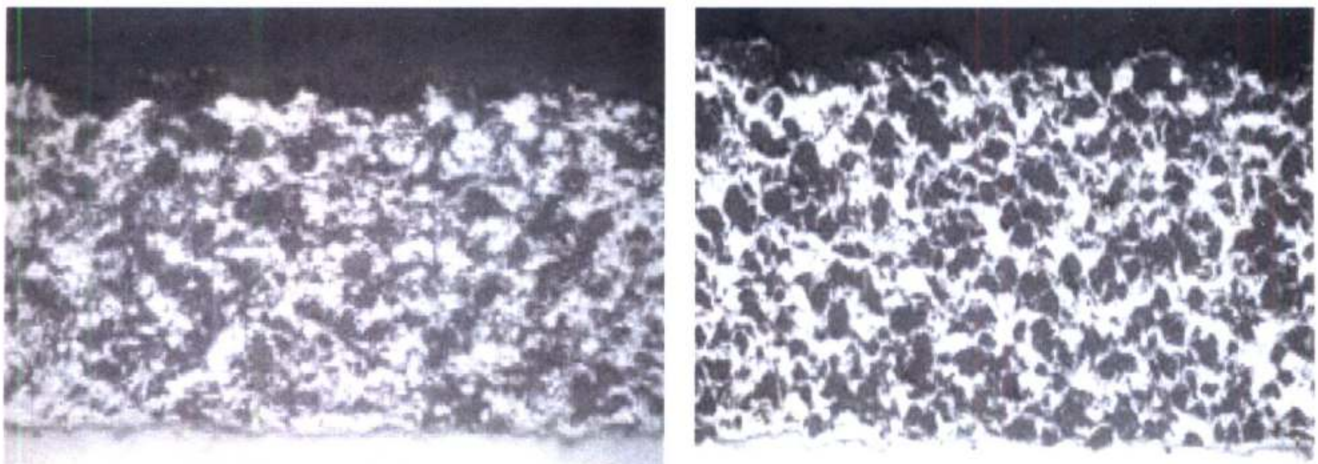
The thermal spray coating solution for this problem is to apply a soft abradable coating to the housing bore that can be rubbed away by the rotor blades without causing material loss from the rotor.

These coatings reduce the risk of blade damage and at the same time improve the efficiency and performance of the turbocharger by managing the rotor path tip clearance.

Abradable Coating Features/Benefits

- Raise Levels of Reliability
- Lower Cost of Overhaul
- Increase fuel Efficiency
- Increase Performance
- Low Material Transfer
- Coating Wear without Surface Deformation
- Low Adhesive Transfer
- Low Turbine/Rotor Wear

Fig.2.4. Abradable clearance control coating applied to rotor path of turbocharger *(Source: AP&C Advanced Powders & Coatings Inc.)*



a b

Fig.2.5. Abradable Coatings: a – Aluminum Silicon Boron Nitrate (Spray Rate: 80-100 g/min, Deposition Efficiency: 68%, Hardness R15Y: 60-75); b – Aluminum Silicon Polyester (Spray Rate: 80-150 g/min, Deposition Efficiency: 90%, Hardness R15Y: 65-75) *(Source: Gordon England)*

Typical Applications:

- Turbochargers
- Land Based Turbines
- Aerospace Power Units
- Compressors
- Pumps

Typical Materials:

- Aluminium-Polymer
- Nickel Graphite
- CoNiCrAlY-BN-Polymer

Processes:

- Plasma
- Combustion

2.3. CAVITATION RESISTANT

This is the term used to describe the phenomenon of liquid to gas, and gas to liquid phase changes that occur when the local fluid dynamic pressure in areas of accelerated flow drop below the vapor pressure of the local fluid.

Fig.2.6. Pump Impeller - Plasma sprayed Alumina Titania to protect against cavitation *(Source: AP&C Advanced Powders & Coatings Inc.)*

The gas to liquid phase change is akin to the boiling of water, except that it occurs at ambient temperatures.

Typical Applications

Cavitation often occurs in hydro-electric turbines and is often a major consideration within the Marine industry [5]:

- Turbines
- Guide Vanes
- Wicket gates
- Turbine runner
- Draft tube
- Pumps
- Impellers
- Propellers

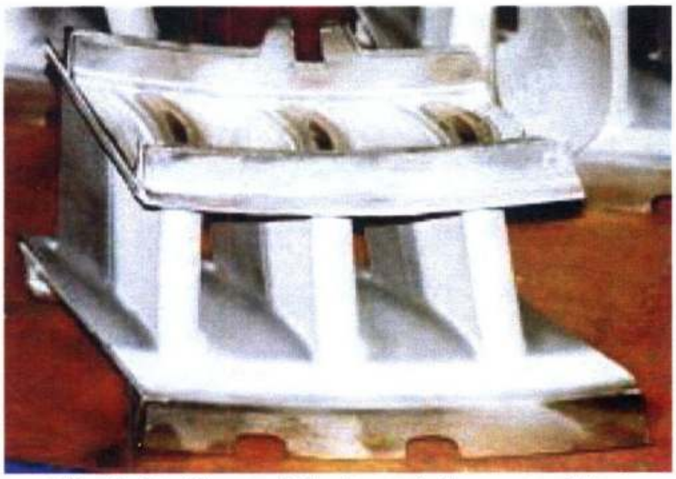


Fig.2.7. Coated Industrial gas turbine nozzle guide vanes *(Source: AP&C Advanced Powders & Coatings Inc.)*

Typical Materials:

- Tribaloy T-800
- WC - 17 Co
- Cr_3C_2 - 25NiCr
- Cr_2O_3
- Alumina/Titania

Typical Processes:

- HVOF
- Plasma
  - Atmospheric Plasma Spraying – APS
  - Vacuum Plasma Spraying – VPS

2.4. CORROSION & CHEMICAL RESISTANT

Corrosion and chemical resistant coatings have traditionally been deposited by either welding or electroplating. Welding applications are limited due to the problem associated with the heat affected zone (HAZ) and the dilution of weld material with the substrate. Electroplating is becoming an environmental concern due the nature of its' effluent. Thermally applied coatings are rapidly becoming the preferred choice. Non-porous HVOF coatings can be applied with hardnesses in excess of 1,200 Hv which can also be superfinished [5]. Other materials deposited by Plasma or Arc Wire can be "sealed" to enhance their corrosion resistance.

The coatings enable the utilization of low cost or lightweight materials without suffering poor performance or short life due to corrosive action on the surface.

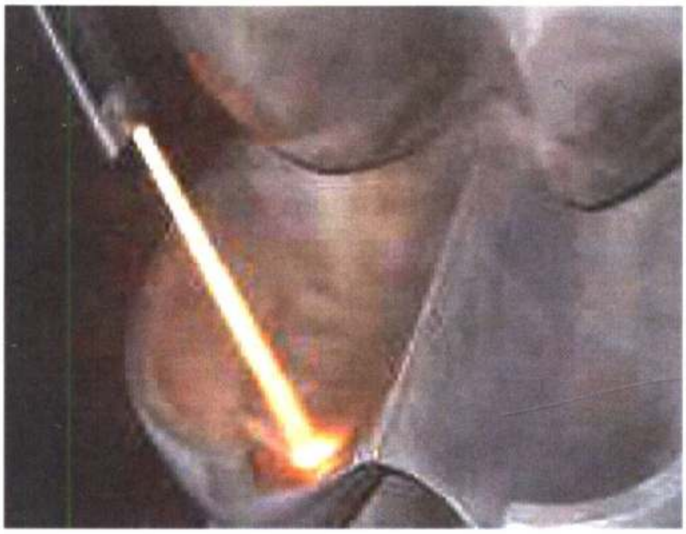


Fig.2.8. Pelton Wheel After Special WC coatings lasts 200+ days *(Source: AP&C Advanced Powders & Coatings Inc.)*

Typical Applications:

- Off Shore structures - Zinc
- Petrochemical - process vessels
- Pumps

Typical Processes:

- HVOF
- Plasma
- Arc Wire

Typical Materials:

- Zinc
- Ni/Cr
- Stainless Steels
- Tantalum
- Nickel
- WC/Ni

2.5. ELECTRICALLY CONDUCTIVE/INSULATING

As most thermal spray processors utilize powders as "feedstock" materials, and almost every material is now accessible in powder form, there is a near infinite number of coatings and coating composites available. The benefits of thermal spraying, to the electronic and electrical industries are now becoming exploited. Components can be coated to provide the exact level of electrical conductivity required.

Applications can be broken down into two areas.

- **Conductive workings.** Typically these may be copper, aluminium and zinc etc. Precise conductive paths can be created using masking techniques. These conductive coatings can be deposited onto a wide variety of substrates such as carbon fibre, glass reinforced plastics and numerous other polymeric materials.
- **Insulative Coatings.** Typically these may be pure ceramics, such as

Alumina or Titania. As with the conductive coatings, deposits can be laid down accurately to customer specifications. Conductive and Insulative coatings can also be used together to produce a composite insulated component with an integral electrical path.

2.6. EROSION RESISTANT

Erosion is a result of the impact of sharp particles on to a surface. Solid particles transported in a gas or liquid flow can cause severe damage to industrial components, leading to expensive repair or replacement. Thermally applied coatings offer excellent resistance to erosion at high and low service temperatures, due to the way they are formed. Large particles of Carbide (typically tungsten carbide) are sprayed with a matrix bonding material (typically cobalt). The cobalt is melted and bonds the solid carbides to the substrate and to each other, producing a dense carbide protective surface.

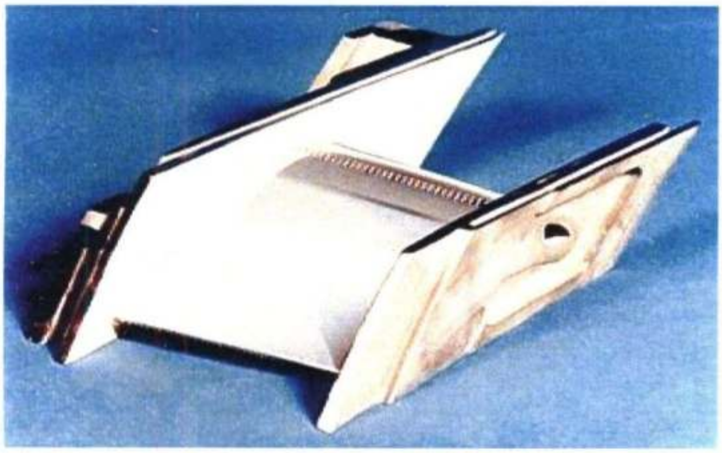


Fig.2.9. Industrial Gas Turbine Row 1 Vane - High temperature erosion-resistant coating on all gas washed surfaces *(Source: AP&C Advanced Powders & Coatings Inc.)*

Typical Applications:

- Fans - pulverized coal and cement etc.
- Centrifugal Compressors
- Centrifugal Pumps

Typical Materials:

- Carbide/Nickel Chrome (High Temp.)
- High Carbon Steels
- Nr, Cr, Si, B
- Aluminium Titania

Processes:

- Plasma
- HVOF
- Arc

2.7. THERMAL SPRAY COATINGS FOR RESISTANCE TO EROSION

The selection of coating for erosive wear is dependant on the severity and type of erosion. For solid impingement erosion at a shallow angle of attack where the wear is similar to that of abrasion, high hardness coatings are required. For solid impingement angles near 90 coating toughness becomes more important. For cavitation and liquid impingement generally, a coating with good surface fatigue resistance is needed. The following coatings are commonly used:

- Cermet coatings like tungsten carbide/cobalt
- Chromium carbide/nickel chromium (particularly for high temperatures above 540 °C)
- Fused self fluxing alloys
- Non ferrous alloys, aluminium bronze, monel
- Oxide ceramics like chromium oxide and alumina
- Various alloys of iron, nickel, chromium or cobalt

2.8. ABRASION RESISTANT

The abrasive wear mechanism similar to machining, grinding, polishing or lapping used for shaping materials. Two body abrasive wear occurs when one surface (usually harder than the second) cuts material away from the second. This mechanism very often changes to three body abrasion as the wear debris then acts as an abrasive between the two surfaces. Abrasives can act as in grinding where the abrasive is fixed relative to one surface; or as in lapping where the abrasive tumbles, producing a series of indentations as apposed to a scratch. There is a large range of thermally sprayed coatings designed to protect against abrasion. These can be grouped as Metallics, Ceramics, Carbides and self-fused, self-fluxing Alloys. Coatings are designed to operate at high temperatures or within aggressive environments.

Typical Applications:

- Ball valve
- Gate valves
- Bearing Journals

Materials:

- Tungsten Carbide
- Chrome Carbide

Processes:

- HVOF
- PLASMA
- ARC

Thermal Spray Coatings for Resistance to Abrasion

Ideally, the material should have a hardness that is in excess of that of the mating surface or abrasive particles. The following coatings are commonly used:

- Cermet coatings like tungsten carbide/cobalt
- Chromium carbide/nickel chromium (particularly for high temperatures above 540 °C)
- Oxide ceramics like chromium oxide and alumina
- Fused self fluxing alloys (NiCrSiB)
- Various hard alloys of iron, nickel, chromium or cobalt

2.9. COATINGS FOR RESISTANCE TO FRETTING AND SURFACE FATIGUE

Coatings resistant to wear caused by repeated sliding, rolling, impacting or vibration. Generally coatings with good toughness and low residual tensile stress are best. The following coatings are commonly used:

- Cermet coatings like tungsten carbide/cobalt
- Chromium carbide/nickel chromium (particularly for high temperatures above 540 °C)
- Fused self fluxing alloys
- Aluminium bronze
- Copper nickel indium
- Various alloys of iron, nickel, chromium or cobalt

2.10. COATINGS FOR LOW FRICTION AND NON-STICK PROPERTIES

PTFE polymer type materials have extremely low coefficient of friction and are "non-stick" to most materials. These particular properties are very useful, but these materials have very low strength and very poor wear resistance. Combination coatings, where thermal spray coatings are used to provide the mechanical support and keying for the polymer and to provide the wear resistance, make for an extremely effective compromise.

Table 2.1. Coatings Properties and Applications
(Source: Ellison Surface Technologies Inc.)

Material composition	Hardness	Tensile bond strength	As-sprayed finish	Properties and applications
Silicon Aluminum	15T 65 Min	2,500 PSI, Min	500-750 Ra	Salvage and build-up of parts made of Aluminum, Magnesium and alloys, good machine finish
Aluminum	15T 65 Min	3,000 PSI, Min	450-750 Ra	Corrosion resistant in coastal and industrial atmospheric conditions, good electrical and thermal conductivity, relatively soft and ductile, non-magnetic
Silicon Aluminum Alloy, Aromatic Polyester	15Y 65-75	800-3,500 PSI	600-900 Ra	High quality abradable coatings, have a temp. operating range of 315-425 °C (600-800 °F), suitable for operating temps. to 325 °C (617 ° F).
Aluminum Oxide	15N 90 Min	2,000 PSI	250-350 Ra	Dense coatings which resist wear by fibers and threads and also resist erosion in high temps. ranging from 840-1,650 °C (1,550-3,000 ° F)
Titanium Dioxide, Aluminum Oxide	15N 85 Min	2,500 PSI	500 Ra	Good resistance to abrasive wear, sliding wear, friction and oxidation up to approx. 1,100 °C (2,040 °F), coatings are particularly suitable for applications in the textile or synthetic fiber manufacturing industries, where surface resistance is required on parts used for the guiding and handling of thread, can be used in many environments including most acids and alkalies
Titanium Dioxide, Aluminum Oxide		4,100 PSI	200-300 Ra	Can be used for applications similar to Al_2O_3 + 3% TiO_2 coatings, but have a lower dielectric strength and are less resistant to chemical attack, 550 °C (1,020 °F) max. service temp.

Table 2.1. Coatings Properties and Applications
(Source: Ellison Surface Technologies Inc.)

Material composition	Hardness	Tensile bond strength	As-sprayed finish	Properties and applications
Chromium, Nickel, Tungsten, Cobalt	15N 78-80	4,500 PSI, Min	250-375 Ra	Resists wear by abrasive grains, hard surfaces, fretting and particle erosion in high temp. environments between 540-840 °C (1,000-1,550 ° F)
Chromium, Nickel, Tungsten, Cobalt	15N 78-79	5,000 PSI, Min	350-500 Ra	Resists wear by abrasive grains, hard surfaces, fretting and particle erosion in high temp. environments between 540-840 °C (1,000-1,550 ° F)
Molybdenum, Chromium, Silicon, Cobalt	15N 80 Min	7,000 PSI, Min	200-250 Ra	Coatings perform well in reducing environments such as hydrochloric, formic and sulfuric acids; oxidizing environments, such as ferric chloride non-oxidizing environments, such as phosphoric and acetic acid and salt water, particularly suitable where lubrication is low or non-existent, excellent sliding wear resistance and moderate oxidation resistance, at temps. up to approx. 800° C (1,470° F)
Molybdenum, Chromium, Silicon, Cobalt	15N 83 Min	6,500 PSI, Min.	200-350 Ra	Coatings perform well in reducing environments such as hydrochloric, formic and sulfuric acids; oxidizing environments, such as ferric chloride and nitric and non-oxidizing environments, such as phosphoric and acetic acid and salt water, particularly suitable where lubrication is low or non-existent, excellent sliding wear resistance combined with good hot corrosion resistance and moderate oxidation resistance, at temps. up to approx. 800 °C (1,470 ° F)
Chromium Carbide, Nickel Chromium Alloy	15N 83 Min	5,000 PSI, Min	250-350 Ra	Good abrasion, particle erosion, cavitation, and fretting resistance up to 815 °C (1,500 °F), good corrosion resistance, good hot gas corrosion resistance, particularly in sulfurous gases, oxidation and erosion resistant up to approx. 900 °C (1,650 °F), applications: fuel rod mandrels and hot forming dies, hydraulic valves, tooling, machine parts, pump housing and wear protection of aluminum parts

Table 2.1. Coatings Properties and Applications
(Source: Ellison Surface Technologies Inc.)

Material composition	Hardness	Tensile bond strength	As-sprayed finish	Properties and applications
Chromium Carbide, Nickel Chromium Alloy	15N 78 Min	3,500 PSI, Min	400-500 Ra	Good abrasion, particle erosion, cavitation and fretting resistance up to 815 °C (1,500 °F), good corrosion resistance, good hot gas corrosion resistance, particularly in sulfurous gases, applications: fuel rod mandrels and hot forming dies, hydraulic valves, tooling, machine parts, pump housing and wear protection of aluminum parts
Silicon, Titanium, Chromium	15N 94-95	5,500 PSI	200-300 Ra	High wear and corrosion resistance tough finish resists mechanical shock better than other ceramics, good low friction characteristics
Nickel, Indium, Copper	15T 85 Min	3,500 PSI, Min	250-350 Ra	Produces dense coatings with good resistance and galling and fretting, melting temp. 1,150° C (2,100° F) Applications: jet engine parts such as turbine blade roots
Nickel, Indium, Copper	15T 85 Min	3,500 PSI, Min	350-550 Ra	Produces dense coatings with good resistance and galling and fretting, melting temp. 1,150 °C (2,100 °F) Applications: jet engine parts such as turbine blade roots
Nickel, Copper	15T 85	3,500 PSI, Min	350-550 Ra	Coatings are very dense with low porosity and oxide content
Aluminum, Iron, Copper	15T 85 Min	3,500 PSI, Min	250-350 Ra	Typical parts which may be coated are pumps (cavitation resistance), piston guides (soft bearing surfaces), shifter forks and compressor air seals, moderate oxidation, wear and fretting resistance at low temps., good emergency dry running properties, can be used for build-up and repair of copper base alloy parts, easily machined, melting temp. 1,040 °C (1,900 °F)
Aluminum, Iron, Copper	15T 85 Min	3,000 PSI, Min	350-550 Ra	Typical parts which may be coated are pumps (cavitation resistance), piston guides (soft bearing surfaces), shifter forks and compressor air seals, moderate oxidation, wear and fretting resistance at low temps., good emergency dry running properties,

Table 2.1. Coatings Properties and Applications
(Source: Ellison Surface Technologies Inc.)

Material composition	Hardness	Tensile bond strength	As-sprayed finish	Properties and applications
				can be used for build-up and repair of copper base alloy parts, easily machined, melting temp. 1,040 °C (1,900 °F)
Molybdenum	15N 75-80	3,000 PSI, Min	350-550 Ra	Tough and hard, with excellent sliding properties and galling resistance; good emergency running properties, fret resistance, resistant to electric, erosion high density coatings are possible, in oxidizing or atmospheric conditions, should not be used above 340 °C (650 °F), used for pump parts, diesel engine fuel injectors, piston rings, synchro-nizing, ring press fits, valves, gears, cam followers and similar applications, bonds well to steel
Aluminum, Nickel	15T 80-85	3,000 PSI, Min	450-550 Ra	Coatings are dense and resistant to oxidation and abrasion, recommended for use as oxidation resistant bond coats which can be used up to 800 °C (1470 °F). This coating is self-bonding and undergoes an exothermic reaction during spraying, resulting in excellent bonding to the substrate, Applications: salvage and build-up on machinable carbon and corrosion resistant steels, particle erosion resistance for exhaust valve seats, oxidation resistance for exhaust mufflers and heat treating fixtures
Aluminum, Nickel Chromium Alloy	15T 85-90	2,750 PSI, Min	400-700 Ra	Plasma sprayed coatings are self-bonding, recommended for resistance to oxidation and corrosion in high temps., recommended for salvage and build-up of worn or mis-machined nickel, nickel alloy or machinable corrosion resistant steel parts. Coatings can also be used as undercoats for ceramics, thermospray coatings are not self-bonding but can be used as abradable coatings, undercoats for ceramics or to resist oxidation and corrosion.

Table 2.1. Coatings Properties and Applications
(Source: Ellison Surface Technologies Inc.)

Material composition	Hardness	Tensile bond strength	As-sprayed finish	Properties and applications
Nickel, Carbon	15Y 40+- 20	1.200 PSI, Min	1,000- 1,000 Ra	High quality abradable coatings for use in the compressor section of jet engines, operating temps. up to approx. 480 °C (900 °F), self-lubricating, can be used for friction reducing bearings
Chromium, Aluminum, Yttrium, Nickel	15T 73	3,000 PSI	350-500 Ra	Coatings are usually used in aerospace applications and subsequently heat treated, used as protective coatings in hot corrosive or oxidizing environments at high temp. (e.g. to protect gas turbine blades or valve systems)
Aluminum, Chromium, Iron, Molybdenum, Niobium, Titanium, Nickel	15T 90	4,000 PSI, Min	350-650 Ra	Oxidation and corrosion resistant up to approx. 1,000° C (1,850° F) designed for use on super alloys, especially Inconel 713 and 718
Aluminum, Molybdenum, Nickel	15T 75-80	2,750 PSI, Min	450-750 Ra	General purpose material for producing medium hard coatings for hard bearing and wear resistance applications, coatings are self-binding, extremely tough and capable of exhibiting good erosion and impact resistance, can be used to protect parts such as machine elements bearing seats and valves
Cobalt, Tungsten Carbide	15N 85 Min	8,000 PSI	200-300 Ra	Resistant to abrasion and erosion, good sliding wear resistance, will produce superior coatings for abrasion and erosion resistance, do not use above 500 °C (930 °F) or in corrosive media, coatings are hard and dense with good bond strength, good fretting resistance, used for machine parts, pump housing, etc.
Carbide, Cobalt, Tungsten	15N 86-88	9,000 PSI	200-300 Ra	Higher toughness and fretting resistance than 12% Co coatings due to higher cobalt levels, for protection against sliding wear, hammer wear, abrasion and fretting, do not use above 500 °C

Table 2.1. Coatings Properties and Applications
(Source: Ellison Surface Technologies Inc.)

Material composition	Hardness	Tensile bond strength	As-sprayed finish	Properties and applications
				(930 °F) or in corrosive media. This material is suitable for hard chrome replacement. Applications: mid-span stiffeners (gas turbine engine blades), aircraft flap tracts, sucker rod couplings, extrusion dies and exhaust fans
Magnesium Oxide, Zirconium Dioxide	15N 75-80	1,500 PSI	200-400 Ra	Primarily used for thermal barrier coatings recommended for combustion applications, abrasive wear resistant up to approx. 900 °C (1650 °F) coatings resist wetting and corrosive effects of molten metal. Applications: diesel engine pistons, valves, cylinder heads and coatings for casting molds and troughs
Yttrium Oxide, Zirconium Dioxide	15N 77-80	3,500 PSI	550-600 Ra	Designed to produce coatings that are stable at high temps., recommended for resistance to erosion at temps. above 845 °C (1550 °F). This coating is flame stabilized Yttria Zirconia. Applications: thermal barrier coatings in rocket and jet engines
Yttrium Oxide, Zirconium Dioxide	15N 75-80	3,5400 PSI	400-600 Ra	Powders are spheroidal with excellent flow ability, chemical homogeneity structural stability and high purity, coatings have excellent thermal shock and insulating features, primarily used as thermal barrier coatings on turbine combustion components and airfoils

3. SURFACE COATINGS TECHNOLOGIES APPLICATIONS

3.1. AEROSPACE

As one of the first industries to fully adopt thermally sprayed coatings into the design of precision engineered components, aerospace applications have been at the focus of the companies activities. There are over 100 key thermally sprayed applications within aerospace turbine engines, without these coating today turbine engines would not operate to the required standards. These functional coatings are used throughout the engine including the high temperature environments.

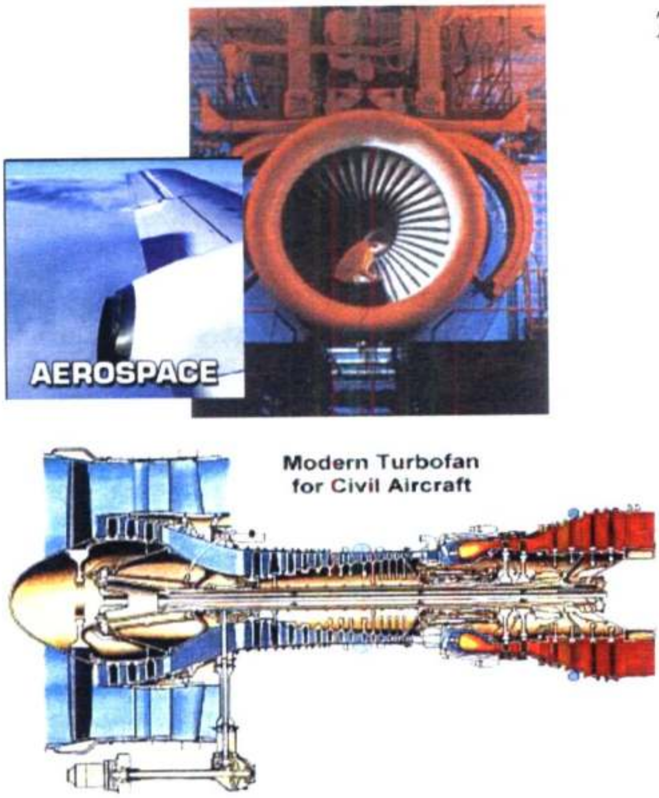


Fig.3.1. Aerospace applications *(Source: Plasma & Thermal Coatings Ltd., Ellison Surface Technologies)*

Typical applications include:

- Wear control (fretting, sliding, impact etc)
- Corrosion control
- Thermal barrier / Thermal efficiency
- Oxidation / Sulfidation
- Clearance control / tipping
- Restoration / Salvage

Fig.3.2. RB199 Multivane with Abradable coating for clearance control *(Source: Plasma & Thermal Coatings Ltd.)*

3.2. AUTOMOTIVE

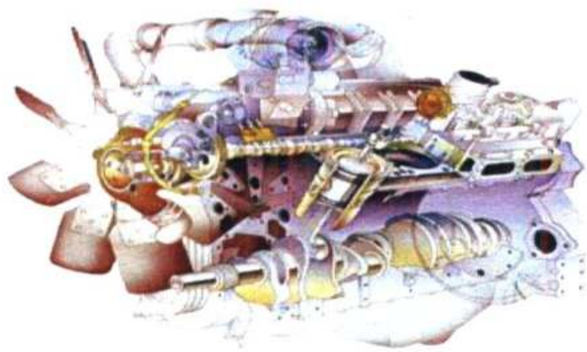


Fig.3.3. Resistant Coatings applications *(Source: Plasma & Thermal Coatings Ltd.)*

A Dynamic industry continually seeking performance improvements and value engineering. From, Formula One and Indy car racing engines to new generation electrically powered vehicles more and more designers of automotive components are towards thermally applied surface engineering to enhance performance and reduce costs.

Utilizing the latest mechanical materials handling and system robotics, high volume production at low unit cost is readily achievable.

TurboChargers

Initially derived from aerospace, abradable coatings give excellent clearance control resulting in improved efficiency and performance.

Brake Discs

Ceramic coating developed as a thermal barrier and friction couple to protect this new lightweight alloy from the heat generated during braking.

Fig.3.4. TurboCharges with abradable coatings *(Source: Plasma & Thermal Coatings Ltd.)*

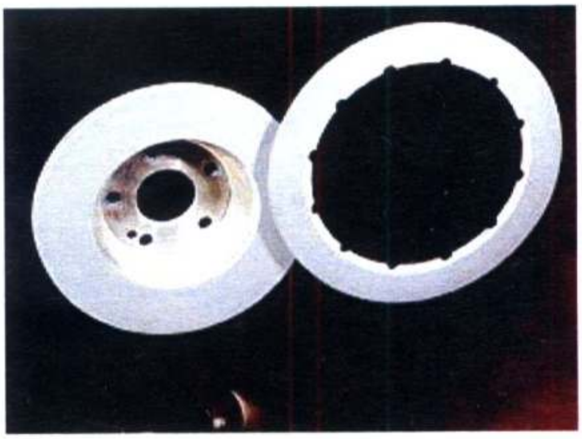


Fig.3.5. Ceramic coatings application *(Source: Plasma & Thermal Coatings Ltd.)*

Heavy Duty Diesel Engines

Fig.3.6. Heavy duty diesel Valves *(Source: Plasma & Thermal Coatings Ltd.)*

Heavy duty diesel engines suffer from high levels of erosion and wear. This is due to a combination of causes such as high combustion temperatures, poor quality fuel and the variable heavy loads the engines are subjected to. Heavy duty diesel engines such as those used in locomotives, marine and earth moving equipment are increasing their use of functional coatings to improve performance and reliability.

3.3. BIOMEDICAL

The Thermal spray process and particularly Plasma Spray offers a system by which Bioactive and Bio-friendly coatings can be produced. Typical deposits used in this industry include Titanium alloys, Cobalt Chrome and Hydroxyapatite (HA). Plasma sprayed metallics allow a bond to be created between the implant and related tissue. The addition of a Bioactive material such as HA actually promotes bone growth at an accelerated rate.

Implants that have been successfully coated with a Plasma deposit include:

- Femural stems
- Asceptabulor cups
- Knee joints
- Dental implants

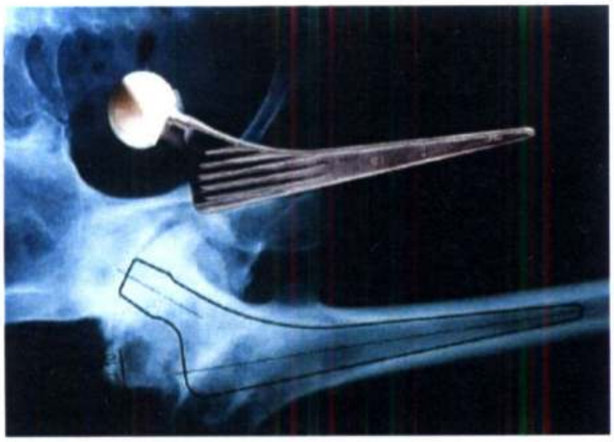


Fig.3.6. Implant coated with a Plasma deposit *(Source: Plasma & Thermal Coatings Ltd.)*

Fig.3.7. Thermal-spray Coated Implant *(Source: Plasma & Thermal Coatings Ltd.)*

Protheses

Porous titanium hydroxyapatite coating used on medical implants to increase bio-computability and/or bio-activity, thereby improving fixation without the need of acrylic cements.

3.4. ELECTRONIC & ELECTRICAL

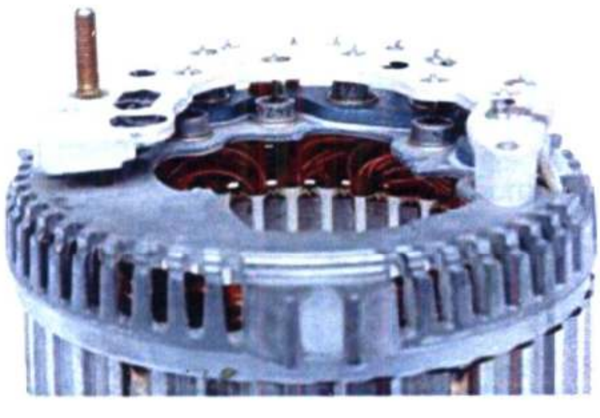


Fig.3.8. Conductive Coatings Application *(Source: Plasma & Thermal Coatings Ltd.)*

As most thermal spray processors utilise powders as "feedstock" materials, and almost every material is now accessible in powder form, there is a near infinite number of coatings and coating composites available. The benefits of thermal spraying, to the electronic and electrical industries are now becoming exploited. Components can be coated to provide the exact level of electrical conductivity required.

Applications can be broken down into two areas.

- **Conductive workings.** Typically these may be copper, aluminium and zinc etc. Precise conductive paths can be created using masking techniques. These conductive coatings can be deposited onto a wide variety of substrates such as carbon fibre, glass reinforced plastics and numerous other polymeric materials.
- **Insulative Coatings.** Typically these may be pure ceramics, such as Alumina or Titania. As with the conductive coatings, deposits can be laid down accurately to customer specifications. Conductive and Insulative coatings can also be used together to produce a composite insulated component with an integral electrical path.

3.5. OIL & GAS

With productivity improvements a constant target; long life, reliability and reduced "down time" are key issues. Many companies have worked closely with exploration, drilling and processing companies to provide tailored solutions for applications as diverse as valves, drilling heads, pumps, compressor rods and hydraulic components. This technically demanding field requires the highest quality engineering coatings.

Fig.3.9. Drilling Head Application *(Source: Plasma & Thermal Coatings Ltd.)*

Fig.3.10. Ball Valve: Selection of Ball valves awaiting processing *(Source: Plasma & Thermal Coatings Ltd.)*

Typically HVOF coatings are employed, these high density well bonded deposits can operate in the most extreme environments (high pressure, erosion, corrosion, abrasion etc). These coatings can be finished machined to the highest standards in accordance with application specifications.

3.6. CHEMICAL PROCESSION INDUSTRY

Components within the chemical industry are generally exposed to many difficult, strongly interacting wear mechanisms: Corrosion, Erosion etc. Although corrosion attacks can be kept within limits by a suitable choice of base materials (ie special alloy), erosion caused by a solid particle suspended in a medium (gas or liquid) can be a serious problem.

Typical parts that suffer from wear in this, often highly aggressive environment are shafts and pumps. By identifying the media that is being pumped, Plasma & Thermal Coatings Ltd are able to select a coating that will ensure high component protection. Coatings can be polished to provide a suitable surface for a seal. Reclaimation work is often carried out on high value components in addition to the application of coatings onto new components.

Chemical processing vessels are often subjected to chemical corrosion. The costs associated with manufacture of these large vessels from chemical resistant material can be significant. Thermally applied coatings are for more cost effective and with the vast range of materials now available it is viable to spray the vessel with a sealed coating that will give excellent resistance to the chemicals contained within.

3.7. POWER GENERATION

Fig.3.11. Transition Ducts - Thermal Barrier Coating applied to complex internal surface *(Source: Plasma & Thermal Coatings Ltd.)*

Many of the applications found within power generation have been derived from aerospace. For example the HVOF process has been used to create thick oxidation-resistant coatings on large turbine blades and nozzle guide vanes.

As well as land based gas turbines, other methods of power generators create environments where components will endure high temperature corrosion and erosion, fine particular abrasion and general wear.

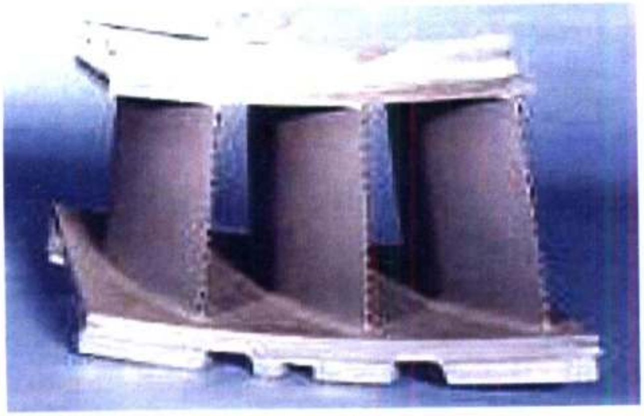


Fig.3.12. Land based gas turbine nozzle guide vane - HVOF aplied MCrAlY coating *(Source: Plasma & Thermal Coatings Ltd.)*

Typical applications include:

- Land based gas turbines
- Coal fired power stations
- Steam turbines
- Boiler tubes
- Fans / Cyclones
- High temperature applications

There have been several thermally sprayed coating systems developed to combat these issues such as, Plasma sprayed nickel chrome for fireside corrosion, Ceramic coatings for fine particulate abrasions, and carbide coatings for sliding and frictional wear.

3.8. PRINTING, PULP & PAPER

The fibrous nature of paper product can create problems of abrasion, this coupled with chemical additives can cause severe problems on many contact surfaces. Rolls are typically coated with wear resistant materials to combat this effect. As well as rolls, doctor blades, knives and guides all suffer from abrasion. Coatings are also used for ink retention, release qualities and to provide a friction drive.

Anilox rolls for example utilize the unique properties of plasma sprayed chrome oxide. The dark colour and high density of this deposit allows it to be laser engraved. The coating also improves the wear performance of the roll. Tungsten Carbide is used as an alternative to hard chrome due to its speed of deposition and it being kinder to the environment.

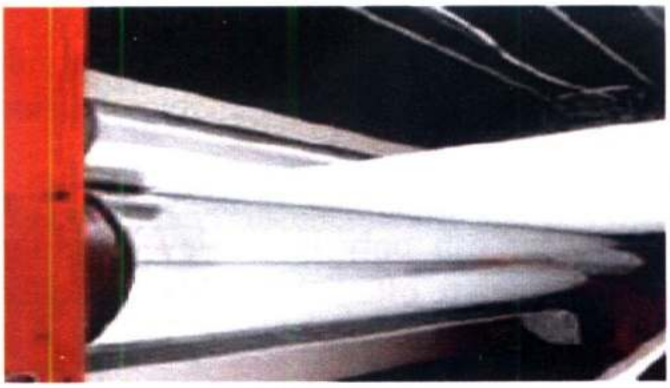


Fig.3.13. Tungsten Carbide roll ground to mirror finish *(Source: Plasma & Thermal Coatings Ltd.)*

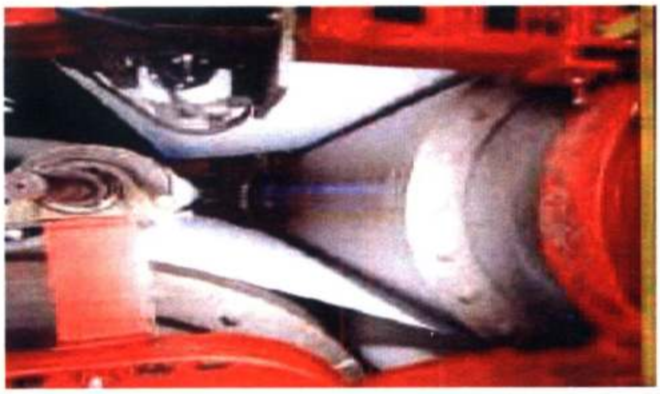


Fig.3.14. Printing process in operation *(Source: Plasma & Thermal Coatings Ltd.)*

3.9. STEEL INDUSTRY

Fig.3.15. Various Rolls coated with Tungsten Carbide for wear resistance *(Source: Plasma & Thermal Coatings Ltd.)*

The thermal spray process is suited to the coating of large surface areas. This wide range of functional coatings offers a cost effective, rapid solution to an increasing number of wear related issues within the industry.

Typical appliances include:

- Rolls (journals and faces)
- Guides
- Chutes
- Repair and Salvage
- High temperature / High wear

3.10. TEXTILES

Thermally sprayed coatings have been used successfully against wear on textile machinery for years. In particular plasma spraying is used to deposit ceramic coatings that can be matched to specific requirements and finished to required surface textures.

Fig.3.16. Grooved roller coated and finished with Alumina or Chrome Oxide *(Source: Plasma & Thermal Coatings Ltd.)*

Fig.3.17. Texturizing Rings *(Source: Plasma & Thermal Coatings Ltd.)*

Considerable abrasive wear is often the cause of worn components, for example, high rotational speed of grooved rollers results in considerable abrasion wear which is seen as an increase in the groove diameters.

Due to the very high rational speed, the roller has to be made from aluminium and therefore, the reduction in wear can only be achieved by the deposition of a coating. Alternatives such as plating are often unsuitable due to the smooth, non-structured surface leading to poor co-efficients of friction.

4. COATINGS' PROPERTIES

For quality control purposes, a test coupon can be coated with the part to ensure the accuracy and effectiveness of the coating application. A chip taken from the coupon is analyzed and tested for tensile strength, density, hardness, porosity and other properties. The coupon can also be pre-tested in the physical environment in which the part will function (e.g., the zinc bath of a galvanizing line).

Whether controlled by hand or computer-automated, coating application requires skill and experience. The careful selection of the right material, application process and control parameters is essential for optimal results.

The time-tested techniques of coatings are now used in a variety of industries to provide enhanced performance at a reasonable cost. This technology can be a competitive advantage in today's fast-moving global economy, serving as a solution to the challenges of better performance for a lower investment.

4.1. COATING'S STRUCTURE

High cooling rates or super cooling (10^6 Ks^{-1}) [1] of particles can cause the formation of unusual amorphous (glassy metals) microcrystaline and metastable phases not normally found in wrought or cast materials.

A large proportion of thermal spraying is conducted in air or uses air for atomization. Chemical interactions occur during spraying, notably oxidation. Metallic particles oxidize over their surface forming an oxide shell. This is evident in the coating microstructure as oxide inclusions outlining the grain or particle boundaries. Some materials (such as titanium) interact with or absorb other gases such as hydrogen and nitrogen.

Coatings show lamellar or flattened grains appearing to flow parallel to the substrate. The structure is not isotropic, with physical properties being different parallel to substrate (longitudinal) than across the coating thickness (transverse). Strength in the longitudinal direction can be 5 to 10 [1] times that of the transverse direction.

The coating structure is heterogeneous relative to wrought and cast materials. This is due to variations in the condition of the individual particles on impact. It is virtually impossible to ensure that all particles are the exact same size and achieve the same temperature and velocity.

All conventionally thermally sprayed coatings contain some porosity (0.025% to 50%) [1]. Porosity is caused by:

- Low impact energy (unmelted particles / low velocity)
- Shadowing effects (unmelted particles / spray angle)
- Shrinkage and stress relieve effects

The above interactions can make the coatings very different from their starting materials chemically and physically.

4.2. STRESSES

Cooling and solidification of most materials is accompanied by contraction or shrinkage. As particles strike they rapidly cool and solidify. This generates a tensile stress within the particle and a compressive stress within the surface of the substrate.

As the coating is built up, so are the tensile stresses in the coating. With a lot of coatings a thickness will be reached where the tensile stresses will exceed that of the bond strength or cohesive strength and coating failure will occur.

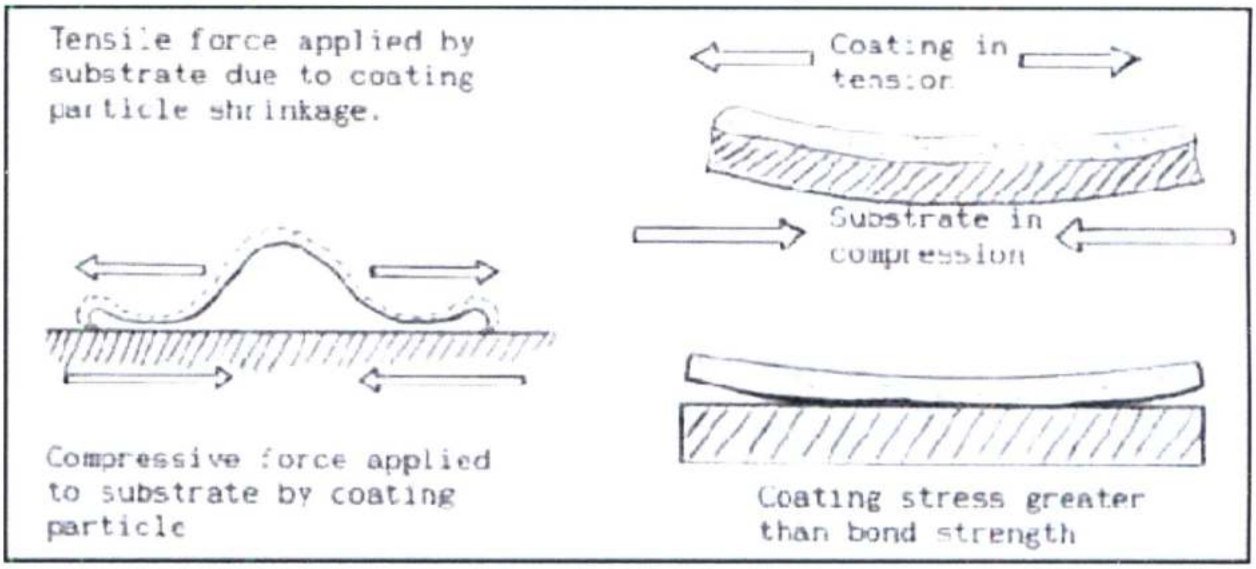


Fig.4.1. Schematic Diagram of Coatings' Stresses Influence
(Source: Gordon England)

High shrink materials like some austenitic stainless steels are prone to high levels of stress build up and thus have low thickness limitations. Look out for thickness limitation information on coating data sheets. Generally thin coatings are more durable than thick coatings.

Coating method and coating microstructure influence the level of stress build up in coatings. Dense coatings are generally more stressed than porous coatings. Notice that Combustion powder sprayed coatings generally have greater thickness limitations than plasma coatings.

Contrary to that just mentioned, the systems using very high kinetic energy and low thermal energy (HVOF, HEP, cold spray [1]) can produce relatively stress free coatings that are extremely dense. This is thought to be due to compressive stresses formed from mechanical deformation (similar to shot peening) during particle impact counteracting the tensile shrinkage stresses caused by solidification and cooling.

4.3. POROSITY

This is present in most thermally sprayed coatings (except VPS, post heat treated coatings or fused coatings). 1 to 25% porosity is normal [1] but can be further manipulated by changes in process and materials.

Porosity can be detrimental in coatings with respect to:

- Corrosion - (sealing of coatings advised).
- Machined finish.
- Strength, macrohardness and wear characteristics.

Porosity can be important with respect to:

- Lubrication - porosity acts as reservoir for lubricants.
- Increasing thermal barrier properties.
- Reducing stress levels and increasing thickness limitations.
- Increasing shock resisting properties.
- Abradability in clearance control coatings.
- Applications in prosthetic devices and nucleate boiling etc.

4.4. OXIDE

Most metallic coatings suffer oxidation during normal thermal spraying in air. The products of oxidation are usually included in the coating. Oxides are generally much harder than the parent metal. Coatings of high oxide content are usually harder and more wear resistant. Oxides in coatings can be detrimental towards corrosion, strength and machinability properties.

4.5. SURFACE TEXTURE

Generally the as-sprayed surface is rough and textured. The rough and high bond strength coatings are ideal for bond coats for less strongly bonding coatings. Many coatings have high friction surfaces as-sprayed and this property is made use of in many applications (rolling road drum surfaces for MOT brake testing [1]). Some plasma sprayed ceramic coatings produce smooth but textured coatings important in the textile industry. Other applications make use of the abrasive nature of some coating surfaces. Thermally sprayed coatings do not provide bright high finish coatings with out finishing like that of electroplated deposits.

4.6. STRENGTH

Coatings generally have poor strength, ductility and impact properties. These properties tend to be dictated by the "weakest link in the chain" which in coatings tends to be the particle or grain boundaries and coating/substrate interface. Coatings are limited to the load they can carry, and thus require a substrate for support, even then, coatings are poor when point loaded.

Internal tensile coating stresses generally adversely effect properties. Effective bond strength is reduced and can be destroyed by increasing levels of internal stress. This in turn effects coating thickness limits. Coatings on external diameters can be built up to greater thickness than that on internal diameters.

Surface properties such as wear resistance are usually good, but the properties are more specific to the material or materials used in the coating. The properties of a substrate need only to be strength, ease of fabrication and economic (like mild steel). The coating supplies the specific surface properties desired. For example, materials used for applications of thermal barrier and abradable clearance control by nature have poor strength and thus benefit from being applied as a coating onto a substrate which supplies the strength.

Some Properties Thermally Sprayed Coatings can Provide:

- Tribological (wear, resistance).
- Corrosion resistance.
- Heat resistance.
- Thermal barrier.
- Electrical conductivity or resistivity.
- Abradable or abrasive.
- Textured surfaces.
- Catalyst and prosthetic properties.
- Restoration of dimension.
- Copying of intricate surfaces.

5. COATINGS' TESTING

There are very few reliable non-destructive testing (NDT) methods available for coatings [1]. The majority of tests for coatings tends to be of a destructive nature, which, obviously can not be used on the actual coated part going into service and therefore, must be considered as a test for process control.

The main practical NDT methods used are:

- Dimensional measurements - micrometer, eddy current and magnetic thickness measuring devices etc.
- Machining tests - response of coating during machining operations is a good test for general integrity.
- Visual inspection - grit blast, spraying, coating/substrate, machined finish.
- Dye penetrant - used in limited applications, but natural coating porosity fogs flaw indications.
- Ultrasonic and magnetic particle flaw detection methods have proved to be poor with thermally sprayed coatings due to the very high number of particle boundaries giving flaw like responses and causing high levels of interference.
- Hardness testing is generally considered a destructive test for coatings unless made in a non-working area.
- Advanced techniques like thermography, thermal wave interferometry and acoustic emission are presently being researched and are still laboratory set-ups with limited practical use for industry.

The limited non-destructive testing should emphasise the need for a high standard of quality control over the process, to ensure a high level of confidence in the coated products.

Destructive testing such as hardness, bend, bond strength, metallography etc. are important to prove the process and coating integrity expected in the component.

5.1. ADHESION TESTING

Adhesive strength is the magnitude of attractive forces, generally physical in character, between a coating and substrate.

A Sebastian adhesion tester

This instrument uses a pin that is coated with an epoxy that is attached to a sample and heated to promote curing of the epoxy. After curing, the pin/sample combination is inserted into the Sebastian adhesion tester with a pulling load applied to the pin. A corresponding force measured in pounds is obtained when the pin breaks free from the sample.

An LSRH Revetest scratch tester

This unit uses a diamond that is dragged along the surface of a thin film coating. At a particular load the diamond will remove the coating from the substrate's surface causing adhesive and cohesive failures. The corresponding load where failure occurs is recorded in kg units.

Tensile Adhesive Strength Test

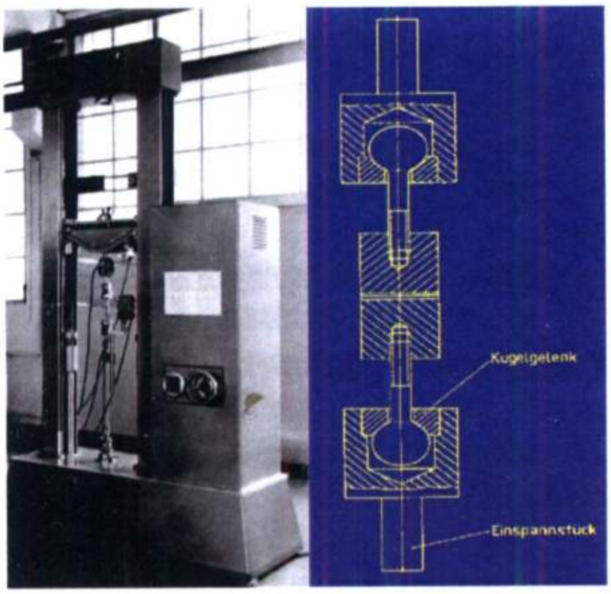


Fig.5.1. Tensile testing machine : Epprecht: 250 kN [14]
(Source: EMPA)

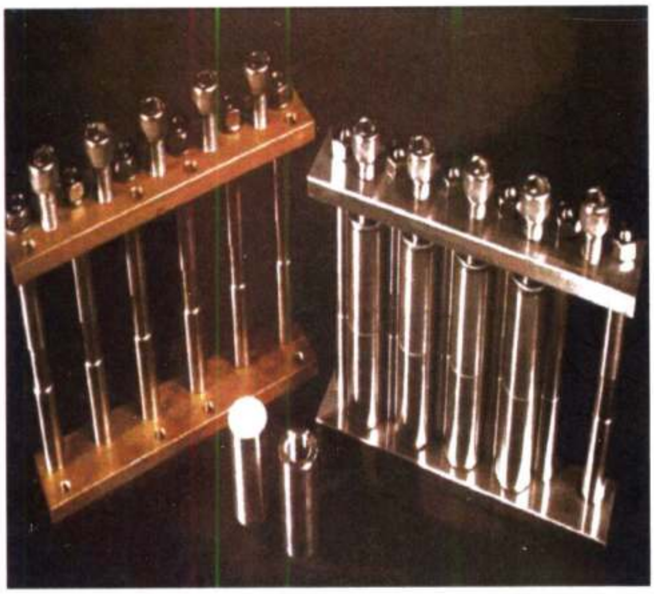


Fig.5.2. Frame for glueing 5 samples (left: empty, right: with samples)
(Source: EMPA)

5.2. STANDARD TEST METHOD FOR MEASURING ABRASION

This test method covers laboratory procedures for determining the resistance of metallic materials to scratching abrasion by means of the dry sand/rubber wheel test. It is the intent of this test method to produce data that will reproducibly rank materials in their resistance to scratching abrasion under a specified set of conditions [15].

Abrasion test results are reported as volume loss in cubic millimetres for the particular test procedure specified. Materials of higher abrasion resistance will have a lower volume loss.This test method covers four recommended procedures which are appropriate for specific degrees of wear resistance or thicknesses of the test material.

Fig.5.3. Abrasion testing machine *(Source: EMPA)*

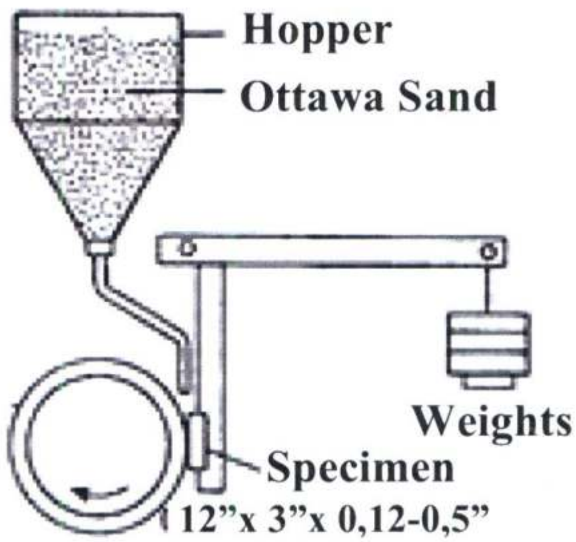


Fig.5.4. Schematic Diagram of Abrasion Testing Process *(Source: EMPA)*

1. Procedure A - This is a relatively severe test which will rank metallic materials on a wide volume loss scale from low to extreme abrasion resistance. It is particularly useful in ranking materials of medium to extreme abrasion resistance.

2. Procedure B - A short-term variation of Procedure A. It may be used for highly abrasive resistant materials but is particularly useful in the ranking of medium- and low-abrasive- resistant materials.

Procedure B should be used when the volume-loss values developed by Procedure A exceed 100 mm^3.

3. Procedure C - A short-term variation of Procedure A for use on thin coatings.

4. Procedure D - This is a lighter load variation of Procedure A which is particularly useful in ranking materials of low-abrasion resistance. It is also used in ranking materials of a specific generic type or materials which would be very close in the volume loss rates as developed by Procedure A.

5. Procedure E - A short-term variation of Procedure B that is useful in the ranking of materials with medium- or low-abrasion resistance. (Ref. ASTM)

Requirements and testing conditions [15]:

Sample geometry:	1″× 3″ × 0.12 - 0.5″
Abrasives:	300 ... 600 gr/min.
Feed rate:	20 ... 130 ... 250 N
Contact force:	1000...6000 U min^{-1}
Rotation speed:	718..4309 m, drying and
equivalent distance:	other materials than rubber on request e.g.
Wheels:	(St37, CK45, GG25, X155)

5.3. STANDARD TEST METHOD FOR DETERMINATION OF SLURRY ABRASIVITY

This test method covers a single laboratory procedure that can be used to develop data from which either the relative abrasivity of any slurry (Miller Number) or the response of different materials to the abrasivity of different slurries (SAR Number) can be determined [16].

The test data obtained by this procedure are used to calculate either a number related to the rate of mass loss of duplicate standard-shaped 27% chromium iron wear blocks when run for a period of time in the slurry of interest (Miller Number), or to calculate a number related to the rate of mass loss (converted to volume loss) of duplicate standard-shaped specimens of any material of interest when run for a period of time in any slurry of interest (SAR Number) [16].

The requirement for a finished flat wearing surface on the test specimen for a SAR Number test may preclude application of the procedure where thin (0.051 to 0.127-mm), hard, wear-resistant coatings will not allow for surface finishing. The 6 hours total duration of the SAR Number Test may not allow establishment of a consistent rate-of-mass-loss of the unfinished surface. (Ref. ASTM).

Requirements and testing conditions (Liquid Impingement Erosion Testing with or without particles) [16]:

Sample geometry:	25.4×12.7×4.6-7.0 mm (sharp edges removed at front and back side by 150)
Load:	22.24 N
Medium:	distilled water; changes in pH values on request size
Abrasives:	Corundum Al_2O_3
Particle distribution:	F 220 (0.045 - 0.075 mm)
Testing intervals:	after every 2 hours: cleaning, drying and weighing
Total testing time:	6 hours

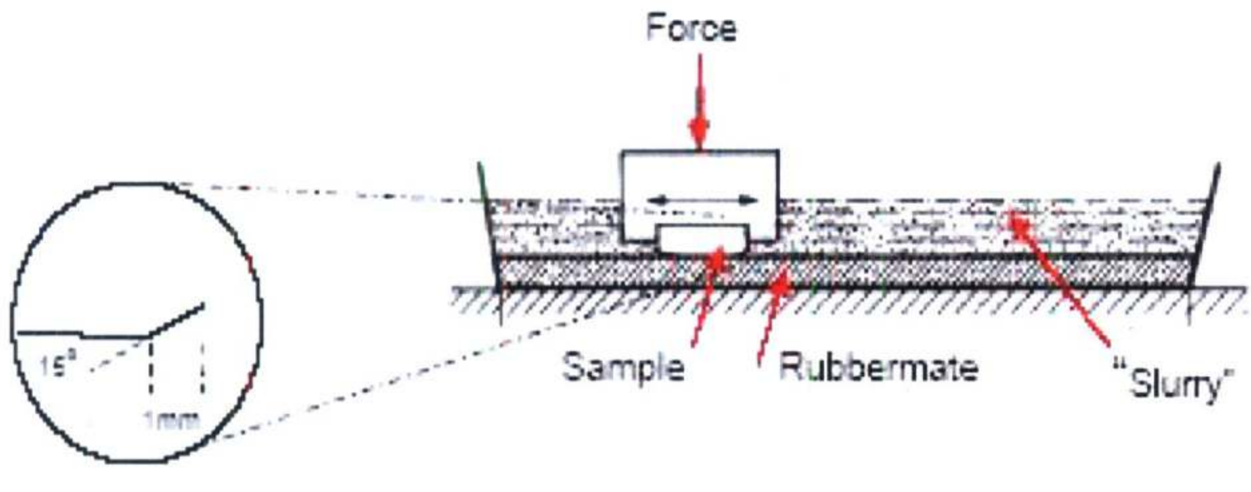


Fig.5.5. Schematic Diagram of the Slurry Abrasivity Testing Process
(Source: EMPA)

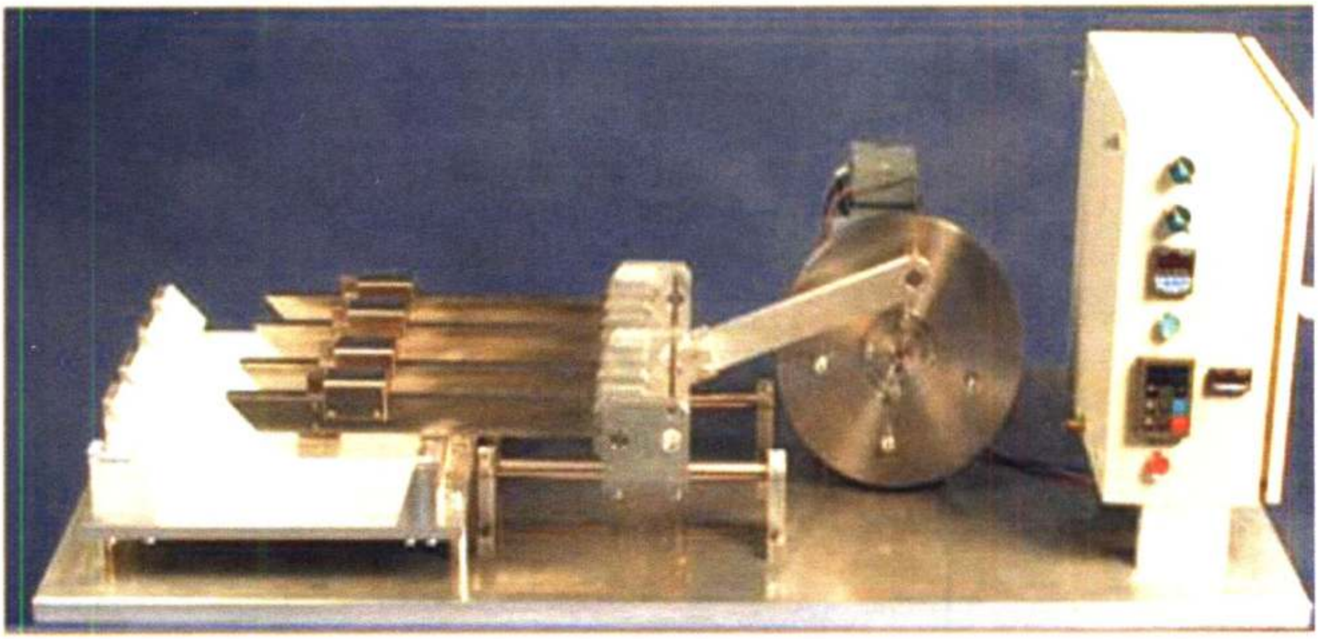


Fig.5.6. Slurry abrasivity testing machine *(Source: EMPA)*

5.4. STANDARD TEST METHOD FOR CAVITATION EROSION USING VIBRATORY APPARATUS

This test method produces cavitation damage on the face of a specimen vibrated at high frequency (20 kHz) [17] while immersed in a liquid. The vibration induces the formation and collapse of cavities in the liquid, and the collapsing cavities produce the damage to and erosion (material loss) of the specimen. Although the mechanism for generating fluid cavitation in this method differs from that occurring in flowing systems and hydraulic machines, the nature of the material damage mechanism is believed to be basically similar.

The method therefore offers a small-scale, relatively simple and controllable test that can be used to compare the cavitation erosion resistance of different materials, to study in detail the nature and progress of damage in a given material, or -by varying some of the test conditions- to study the effect of test variables on the damage produced.

It permits deviations from some of these conditions if properly documented, that may be appropriate for some purposes. (Ref. ASTM).

Requirements and testing conditions [17]:

Testing frequency:	20 ± 0.2 kHz
Amplitude:	50 μm ± 5%
Liquid media:	distilled water
Temperature:	22 ± 1 °C
Testing intervals:	after every 2 hours: cleaning, drying and weighing
Total (cumulative) time:	(different conditions upon request) up to 10 hours

Fig.5.7. Sample after testing *(Source: EMPA)*

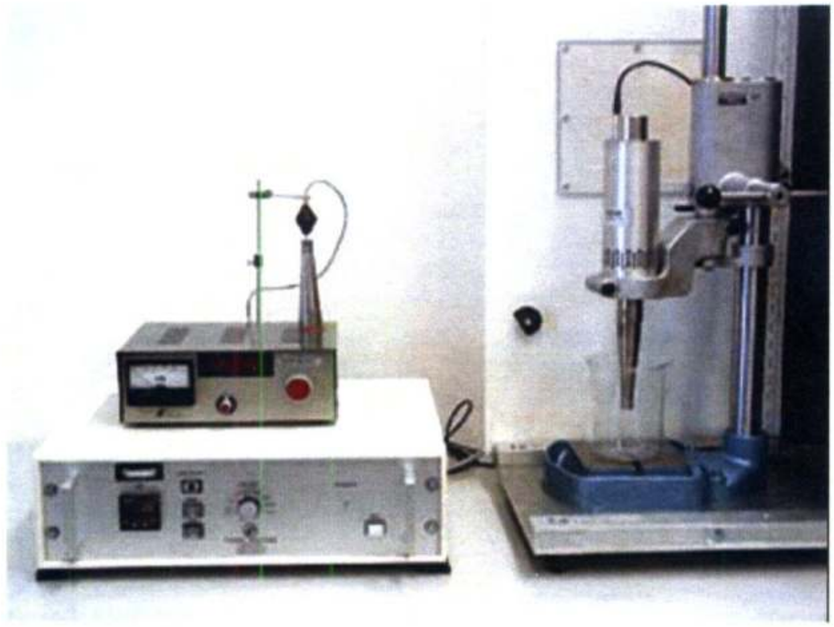


Fig.5.8. The Cavitation Erosion Testing Machine *(Source: EMPA)*

5.5. STANDARD TEST METHOD FOR WEAR TESTING

Fig.5.9. The Wear Testing Machine *(Source: EMPA)*

This test method describes a laboratory procedure for determining the wear of materials during sliding using a pin-on-disk apparatus. Materials are tested in pairs under nominally non-abrasive conditions. The principal areas of experimental attention in using this type of apparatus to measure wear are described. The coefficient of friction may also be determined. (Ref. ASTM)

Requirements and testing conditions [18]:

Rotation speed:	0.03 to 500 Rpm
Force rage:	1 to 60 N
Standard forces:	1, 2, 5, 10 N
Sample dimensions:	ø = 60 mm, h = 15 mm

5.6. STANDARD PRACTICE FOR LIQUID IMPINGEMENT EROSION TESTING

This practice concerns tests in which solid specimens are eroded or otherwise damaged by repeated discrete impacts of liquid drops or jets. Among the collateral forms of damage considered are degradation of optical properties of window materials, and penetration, separation, or destruction of coatings. The objective of the tests may be to determine the resistance to erosion or other damage of the materials or coatings under test, or to investigate the damage mechanisms and the effect of test variables. Because of the specialized nature of these tests and the desire in many cases to simulate to some degree the expected service environment, the promulgation of a method is not deemed practicable. (Ref. ASTM)

Fig.5.10. The Wear Testing Machine *(Source: EMPA)*

Requirements and testing conditions (Liquid Impingement Erosion Testing with or without particles) [19]:

Sample geometry (test inclusive tensile load):	140 × 40 × 4 mm
Sample geometry (test without tensile load):	40 × 40 × 4 mm
Fluid velocity:	65 up to 230 m/s
Particle concentrations:	0 – 10 wt.-%
Incident angle:	30° – 90°
Distance between nozzle exit and sample:	50 – 200 mm
Testing intervals:	10s – 3 min.
Total (cumulative) testing time:	30s – 10 min.

SUMMARY

Surface treatment is an important aspect of all manifacturing processes. It is used to impart certain physical and mechanical properties, such as appereance and corrosion, friction, wear and fatigue resistance.

Several techniques are availaible for modifying surfaces. They include mechanical working and coating surfaces, heat treatment, deposition, plating and coatings such as enamels, nonmetallic materials and paints. Resistant coatings help to provide the environmental protection for modern equipment life increasing.

A to Z of Terms related to the Thermal Spray Process and Surface Engineering

A

Abradable coatings

Coatings which are designed to be abraded by a mating surface to form a tight gas or air seal, while retaining good erosion resistance.

Abrasive

Material such as sand, crushed chilled cast iron, crushed steel grit, aluminum oxide, silicon carbide, flint, garnet, of crushed slag used for cleaning or surface roughening.

Abrasive blasting

A process for cleaning and roughening a surface by means of an abrasive directed at high velocity against the work piece.

Abrasive Wear

Wear due to hard particles or hard protuberances forced against and moving along a solid surface.

Absorb

To take in and engulf wholly.

Absorptive Lens (eye protection)

A filter lens designed to attenuate the effects of glare and reflected and stray light. See Filter Plate.

Acetylene C_2H_2 (ethyne)

Unsaturated aliphatic hydrocarbon gas. Used as a fuel gas in combustion thermal spray processes, welding and cutting. Acetylene has the highest flame temperature and requires the smallest amount of oxygen to form a neutral flame.

Acoustic emission

Acoustic emissions are sound or ultrasound pulses generated during crack initiation or propagation in materials and coatings as a result of being subjected to stress. Acoustic emissions can be detected by transducers.

Acoustical Room

A soundproof enclosure, containing thermal spraying and sometimes related auxiliary equipment.

Its design and construction prevent any unacceptable process noises from interfering with normal work in the environment surrounding the enclosure.

Adhesion

A binding force that holds together molecules of substances whose surfaces are in contact or near proximity.

Adhesive Strength

The magnitude of attractive forces, generally physical in character, between a coating and substrate.

Two principle interactions that contribute to the adhesion are van der Waals forces and permanent dipole bonds.

Adhesive Wear

Wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or the loss from either surface.

Adsorb

To take in on the surface.

Agglomerate

Several particles adhering together.

Agglomerated powder

A powder made up of agglomerates.

Air Cap

A device for forming, shaping and directing an air flow pattern for the atomization of wire or ceramic rod.

Air classification

The separation of powder into particle size fractions by means of an air stream of controlled velocity.

Air Cooler

See preferred term Workpiece Cooler.

Air Feed

A thermal spraying process variation in which an air stream carries the powdered surfacing material through the gun and into the heat source.

Air Filter

Mechanism for cleaning air of contaminants such as water, oil, and solid matter.

Alumina

A chemical compound (aluminum oxide); a ceramic used in powder or rod form in thermal spraying operations.

May also be a blasting medium.

Aluminising (gas)

High temperature (approx. 900°C) pack or gaseous diffusion of aluminium into the surface of a component to enhance high temperature corrosion and oxidation resistance.

Alkyd resin

A type of polyester resin used in paints and other surface coatings. The original alkyd resins were made by co-polimerising phathalic anhydride with glycerol, to give a brittle cross. Linked polymer.

Aluminising (hot dip)

An aluminium coating process based on submersion in liquid metal, usually with a strip steel product being continuously fed through the bath. Provide galvanic corrosion protection.

Aluminising (Thermal Spray Method)

Thermal sprayed coatings of aluminium usually on substrates of steel or nickel chromium alloys which are subsequently heat treated to aluminise the surface.

Aluminium Ion Plating

The deposition of aluminium by a vacuum evaporative process. Provides galvanic corrosion resistance. Normally given a passivation treatment.

Amorphous

Noncrystalline, or devoid of regular structure.

Anchoring

A supplemental method of locking the thermal spray deposit to the substrate by screw heads, studs, or similar means.

Anion

A negatively charged ion.

Anode

Positively charged electrode (nozzle in plasma gun) - the electrode of an electrolytic cell at which oxidation is the principle reaction. (Electrons flow away from the anode in the external circuit. It is usually the anode where corrosion occurs and metal ions enter solution).

Anodic coating

A coating that becomes the anode in an electrochemical cell with the substrate (cathode). The only metals in common use for thermal spraying which are anodic to iron and steel are zinc and aluminium.

Anodising

The production of an oxide layer on aluminium alloys. The process is electrolytic, a typical electrolyte being sulphuric acid. Treatment at room temperature produces thin, decorative layers with some corrosion protection. Treatment at $0^{o}C$ produces hard, thicker layers (up to 100μ) with wear resistance. They can be post sealed to give improved corrosion resistance.

Apparent density

The weight of a unit volume of powder or coating.

Apparent Density Ratio

The ratio of the measured density of an object to the absolute density of a perfectly solid material of the same composition, usually expressed as a percentage.

Apparent hardness

The value obtained by testing a coating or sintered material with standard indentation hardness equipment (See macrohardness). Since the reading reflects a composite of pores and solid material, (which may be particles relatively poorly bonded together) it is usually lower than that of an equivalent solid wrought or cast material. Not to be confused with particle hardness (See microhardness).

Arc

A luminous discharge of electrical current crossing the gap between two electrodes.

Arc Chamber

The confined space within the plasma thermal spraying gun enclosing the anode and cathode, in which the arc is struck.

Arc Force

The axial force developed by an arc plasma.

Arc Gas

The gas introduced into the arc chamber and ionized by the arc to form a plasma.

Are Gas

Primary. See preferred term Primary Gas.

Arc Gas

Secondary. See preferred term Secondary Gas. Arc Plasma.

A gas that has been heated by an electric arc to at least a partially ionized condition, enabling it to conduct an electric current.

Arc Wire Spraying

A thermal spray process where two electrically conducting wires are brought together to form an electric arc. Molten material formed in the arc is projected by a compressed gas stream towards the work piece to form a coating.

Argon (Ar)

Monatomic noble gas, atomic number 18, one of the most inert elements. Commonly used as a plasma gas for plasma spraying and providing inert environments for many processes.

Atomisation

The dispersion of a molten material into particles by a rapidly moving gas or liquid stream or by mechanical dispersion.

Atomised powder

A powder produced by the dispersion of a molten material into particles by a rapidly moving gas or liquid stream or by mechanical dispersion.

Autoclaving

The production of a stable, protective oxide on steel parts by treatment in a pressurized, high temperature steam containing atmosphere.

Auxiliary Cooler

A device used to direct compressed air to prevent overheating of the thermal spraying deposit or the substrate.

B

Backfire

The momentary recession of the flame into the spray gun, followed by immediate reappearance or complete extinction of the flame.

Base Material

See preferred term Substrate.

Base Metal

See preferred term Substrate.

Berry Formation

See preferred term Nozzle Accumulation.

Binder

A cementing medium used in producing composite or agglomerate powders.

Blasting

A pressurized stream of particlulates (ceramic, plastic, metal, etc.) applied on a surface to clean, peen or abrade.

Blended Powder

A powder consisting of two or more different powder materials thoroughly mixed.

Body Stress

Residual stresses within an individual sprayed particle.

Bond

This represents the state of adhesion between the coating and the substrate. Its strength will depend on the details of the spraying process and the materials used. Bonding mechanisms may be mechanical, physical, chemical or metallurgical or a combination of these.

Bond Cap (Bond Bar)

The test specimen on which a spray coating is applied for the purpose of determining adhesive-cohesive strength.

Bond coat

A coating applied as an intermediary between the main or top coating and the substrate in order to improve the bond strength and/or to provide a corrosion or oxidation barrier.

Bond strength

The strength of the adhesion between the coating and the substrate. A number of test methods are in use to measure the bond strength of coatings.

Bond Coat

A preliminary (or prime coat) of material that improves adherence of the subsequent spray deposit.

Bonding Force

The force that holds two atoms together; it results from a decrease in energy as two atoms are brought closer to one another.

Bond Line

The interface between a thermal spraying deposit and substrate, or between adhesive and adherent in an adhesive bonded joint.

Boronizing

The diffusion of boron into the surface of a component (usually steel) by a high temperature (approx. 900°C) gas or pack process. Produces hard phases within the surface (typically 100µm deep).

British Thermal Unit (BTU).

A unit of measure for heat (equal to 1055 J).

Buildup

A surfacing variation in which surfacing metal is deposited to achieve the required dimensions.

Burnoff Rate

A nonstandard term for melting rate.

C

Cadmium plating

The electrolytic deposition of cadmium to provide galvanic corrosion protection. Restricted by environmental considerations.

Cadmium ion plating

The deposition of cadmium by a vacuum process to provide galvanic corrosion protection.

Cap

See preferred term Nozzle or Air Cap.

Carbide

A chemical compound formed between carbon and a metal or metals; examples are tungsten carbide, tantalum carbide, titanium carbide, chromium carbide.

Carbonitriding

Similar to Carburising. Diffusion of carbon and nitrogen at about 900 °C (by pack, gas, salt bath or plasma process) into low carbon steel, followed by quenching and tempering to produce martensitic case (typically 1mm thick).

Carburizing (also called Case Hardening)

Diffusion of carbon at about 900°C (by pack, gas, salt bath or plasma process) into low carbon steel, followed by quenching and tempering to produce martensitic case (typically 1mm thick).

Carburizing Flame

A nonstandard term for reducing flame.

Carrier gas

Usually nitrogen or argon gas that carries powder into the thermal spray process.

Casehardening

See Carburizing.

Cast

The twist warp or curvature of a metal wire.

Cathode

Negatively charge electrode. Electrode of an electrolytic cell at which reduction is the principle reaction. (Electrons flow towards the cathode in the external circuit).

Cathodic coating

Coatings which become the cathode in an electrochemical cell with the substrate (anode). This type of coating protects the substrate from corrosion only by being a complete barrier. If the coating allows the environment to reach the substrate, accelerated corrosion of the substrate will occur.

Cathodic protection

A technique to reduce the corrosion rate of a metal by making it the cathode of an electrochemical cell. Thermal spray zinc and aluminium coatings provide this protection to steel substrates, the coating being the anode and the steel being the cathode.

Cation

A positively charged ion.

Cavitation

The formation and rapid collapse within a liquid of cavities or bubbles that contain vapour or gas or both.

Cavitation Erosion

A form of erosion causing material to be removed by the action of vapour bubbles in a very turbulent liquid.

Ceramic Rod Flame Spray Gun

A flame spraying device wherein an oxy-fuel gas flame provides the beat, and the surfacing material to be sprayed is in ceramic rod form.

Ceramic Rod Flame Spraying

A thermal spraying process variation in which the material to be sprayed is in ceramic rod form.

See Flame Spraying (FLSP).

Ceramic Rod Speed

The length of ceramic rod sprayed in a unit of time.

Cermet

A physical mixture of ceramics and metals; examples are alumina plus nickel and zirconia plus nickel.

Chemical conversion coating

A protective or decorative nonmetallic coating produced in situ by chemical reaction of a metal with a chosen environment. (It is often used to prepare the surface prior to the application of an organic coating).

Chemical Vapour Deposition (CVD)

The deposition of a coating by means of a chemical reaction in gases in a chamber producing components which deposit on and adhere to the substrate.

Chromating

Chromate conversion is a process which completely degreases and removes all traces of the oxide film, replacing it by immersion with a chromate coating which can then be painted. It is used as a post-treatment for cadmium, zinc and aluminium coatings.

Chromising

High temperature (approx. 900°C) pack or gaseous diffusion of chromium into the surface of a component to enhance high temperature corrosion and oxidation resistance.

Cladding

The application of a thick (generally above 1mm) coating which melts or diffuses into the substrate. Processes include weld cladding and plasma transferred arc (PTA).

Clad Metal

A laminar composite consisting of a metal, with a metal of different chemical composition applied to one or two sides.

Clad Powder

See preferred term Powder Clad.

Closed Loop Control

A method to continuously monitor and control thermal spray parameters to assure repeatability of the process and coatings.

Coalesce

To grow or come together; fuse; unite.

Coating

(1) The act of building a deposit on a substrate, (2) the spray deposit.

Coating Density

A nonstandard term for spray deposit density ratio.

Coating Strength

(1) A measure of the cohesive bond within a coating, as opposed to coating-

to-substrate bond (adhesive strength), (2) the tensile strength of a coating, usually expressed in kPa (psi).

Coating Stress

The stresses in a coating resulting from rapid cooling of molten material or semimolten particles as they impact the substrate.

Coating stresses are a combination of body and textural stresses.

Coefficient of Thermal Expansion

The ratio of the change in length per degree rise in temperature to the length at a standard temperature such as 200 °C (680 °F).

Cohesive Strength

See Coating Strength.

Cold welding

Cohesion between two surfaces of a metal, generally under the influence of externally applied pressure at room temperature.

Cold Spray

or cold gas-dynamic spraying process uses the energy stored in high pressure compressed gas to propel fine powder particles at very high velocities at a substrate to form a coating.

Collaring

Adding a shoulder to a shaft or similar component as a protective confining wall for the thermal spray deposit.

Combination Aftercooler/Dryer

A deliquescent desiccant dryer with an integral aftercooler.

Companion Panel

A small tab coated concurrently with the workpiece, used for inspection.

Composite

Mixture of two or more materials. Nearly all have a reinforcing material (metal, wood, glass, etc.), called filler, and a natural or artificial resin, called matrix to achieve specific characteristics and required properties.

Composite Coating

Mixture of two or more materials. Many thermal spray coatings could be considered as composites.

Composite Powder

A powder in which each particle consists of two or more distinct materials joined together. (Not the same as a powder blend).

Compressed Air Mask

A force feed type of face mask with a suitable regulator worn by the thermal spraying operator to provide a fresh air supply.

Cone

The conical part of an oxy-fuel gas flame next to the orifice of the tip.

Contact Tube

A device which transfers current to a continuous electrode.

Control Console

The instrumented unit from which the gun is operated and operating variables are monitored and controlled.

Controlled Atmosphere Chamber

An enclosure or cabinet either filled with an inert gas or evacuated to below atmospheric pressure in which thermal spraying can be performed to minimize, or prevent, oxidation of the coating or substrate.

Cooler

See preferred term Workpiece Cooler.

Cord

A plastic tube tilled with powder, and extruded to form a compact, flexible layer level wound wire-like "cord."

Copper plating

The electrolytic deposition of copper to provide either a corrosion barrier (often as an undercoat for hard chrome plate) or for reclamation of worn parts.

Corrosion

Chemical or electrochemical reaction between a material and its environment which results in deterioration in the properties of the material.

Corrosion fatigue

The process in which a metal fractures prematurely under conditions of simultaneous corrosion and repeated cyclic loading at lower stress levels or fewer cycles than would be required in the absence of the corrosive environment.

Corrosion potential

The potential of a corroding surface in an electrolyte relative to a reference electrode measured under open circuit conditions.

Corrosive wear

Wear in which chemical or electrochemical reaction with the environment is significant.

Cospray

Thermal spraying of two or more dissimilar materials through a single gun using multiple powder injection ports.

Crevice corrosion

Localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from the full exposure to the environment because of close proximity between the metal and the surface of another material.

Critical Resolved Shearing Stress

The shearing stress on the slip plane necessary to produce slip (threshold value).

Crushed powder

Powder formed from a solid which is then crushed to the appropriate size for spraying.

Cubicle

See preferred term Acoustical Room.

CVD

See Chemical Vapour Deposition.

Cylinder

See Gas Cylinder.

Cylinder Manifold

A multiple header for interconnection of gas or fluid sources with distribution points.

D

Defect

A discontinuity or discontinuities that by nature or accumulated effect (for example, total crack length) render a part or product unable to meet minimum applicable acceptance standards or specifications. See also Discontinuity and Haw.

Degreasing

The removal of grease and oil from a surface. Degreasing by immersion in liquid organic solvents or by solvent vapours condensing on the parts to be cleaned.

Deliquescent

The process of melting or becoming liquid by absorbing moisture from the air.

Deliquescent Desiccant Dryer

A pressure vessel containing a collection chamber and a drying desiccant.

It has no moving parts, and normally produces a 100 °C (500 °F) dewpoint or lower. Density.

The mass or quantity of matter of a substance per unit volume, expressed as grams per cubic centimeter, or pounds per cubic inch.

Density Ratio

See Apparent Density Ratio.

Deposit

A nonstandard term for thermal spraying deposit.

Deposit corrosion

Localized corrosion under or around a deposit or collection of material on a metal surface. (See also crevice corrosion.)

Deposition Efficiency

The ratio, usually expressed in percent, of the weight of spray deposit to the weight of the material sprayed.

Deposition Rate

The weight of material deposited in a unit of time.

Desiccant

A chemical used to attract and remove moisture from air or gas.

Detonation Flame Spraying

A thermal spray process in which the coating material is heated and accelerated to the workpiece by a series of detonations or explosions from oxy-fuel gas mixtures.

Dewpoint

Temperature at which moisture will condense from humid vapors into a liquid state.

Diamond-like Carbon

A thin carbon-based coating applied by either PVD or PACVD. It has high hardness and low friction.

Diffusion Coating

An alloy coating produced by applying heat to one or more coatings deposited on a basis metal.

Ductility

The ability of a material to deform plastically without fracturing.

Discontinuity

An interruption of the typical structure of a coating, such as a lack of homogeneity in the mechanical, metallurgical, or physical characteristics of the material.

A discontinuity is not necessarily a defect.

See also Defect and Flaw.

Dovetailing

A method of surface roughening involving angular undercutting to interlock the spray deposit.

Dwell Time

The length of time the spray material is exposed to the heat zone which produces and sustains a molten condition.

E

Ear Protection

OSHA or other safety agency approved devices for the reduction of sound audible to the outer ear.

Edge Effect

Loosening of the adhesional bond between the spray deposit and the substrate at the workpiece edges.

Edge Loss

Spray deposit lost as overspray resulting from spraying near the edge of the workpiece.

Elastic Modulus

The ratio of stress, within the proportional limit, to the corresponding strain.

Electric Arc Spraying

A nonstandard term for arc spraying.

Electric Bonding

A nonstandard term for surfacing.

Electrode

A component for the electrical circuit through which current is conducted to the arc.

See Anode and Cathode.

Electrochemical cell

An electrochemical system consisting of an anode and a cathode in metallic contact and immersed in an electrolyte. (The anode and cathode may be different metals or dissimilar areas on the same metal surface).

Electroless Nickel

The autocatalytic deposition of nickel/phosphorous and nickel/boron have many useful corrosion and tribo/corrosion applications. Unlike the electrolytic processes, they produce a deposit with completely uniform coverage. In the case of Ni P, deposits around 25 to 50 microns thick with a hardness of about 500Hv is obtained, but thermal ageing at temperatures around 400°C can develop hardness values in excess of 1000Hv.

Electrolyte

A conducting medium in which the flow of current is accompanied by movement of matter. A substance that is capable of forming a conducting liquid medium when dissolved or melted.

Electrolysis

Production of chemical changes of the electrolyte by the passage of current through an electrochemical cell.

Electromotive Force Series (EMF Series)

A list of elements arranged according to their standard electrode potentials, with "noble" metals such as gold being positive and "active" metals such as zinc being negative.

Elasticity

The property of certain materials that enables them to return to their original dimensions after an applied stress.

Electroplating

The electrodeposition of an adherent metallic coating upon an electrode for the purpose of securing a surface with properties or dimensions different from those of the substrate material.

Embrittlement

The severe loss of ductility or toughness or both, of a material, usually a metal or alloy.

Endothermic Compounds

Beads and tablets which absorb moisture from the air and are consumed in the process. The action is termed deliquescence. Beads used are inorganic with absorption capability to reduce dewpoints 5.5 °C (42 °F) at an inlet temperature of 38 °C (100 °F), and - 2.8 °C (27 °F) -at an inlet temperature of 21 °C (70 °F). Beads or tablets utilized are of two types: potassium carbonate and sodium chloride.

Erosion

Removal of material from a surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, or impinging liquid or solid particles.

Erosion-corrosion

Associated action involving corrosion and erosion in the presence of a corrosive substance.

Etch

A roughened surface produced by chemical, electrochemical or mechanical means. To dissolve unevenly a part of the surface of a material to highlight microstructure in metallography.

Exhaust Booth

A mechanically ventilated, semienclosed area in which air flow across the work area is used to remove fumes, gases, and solid particles.

Exfoliation

Corrosion that proceeds laterally from the sites of initiation along planes parallel to the surface, generally at grain boundaries or coating interfaces, forming corrosion products that force metal or coating away from the body of the material, giving rise to a layered appearance.

Exothermic reaction or material

Certain materials undergo chemical reactions when thermally sprayed and produce extra heating. This can be useful in improving adhesion of the coating to the substrate.

Eye Protection

Proper helmets, face masks, or goggles which are required to be used to protect the eyes from ultraviolet and infrared radiation during thermal spraying operations.

F

Fatigue

A cumulative effect causing a material to fail after repeated applications of stress none of which exceeds the ultimate tensile strength. The fatigue strength (or fatigue limits) is the stress that will cause failure after specified number cycles.

Face Shield (eye protection)

A device positioned in front of the eyes and over all or a portion of the face to protect the eyes and face. See also Hand Shield and Helmet.

Fatigue wear

Wear of a solid surface caused by fracture arising from material fatigue.

Feed Rate

A nonstandard term for spray rate.

Filter Glass

A nonstandard term for filter plate.

Filter Lens (eye protection)

A round filter plate.

Filter Plate (eye protection)

An optical material that protects the eyes against excessive ultraviolet, infrared, and visible radiation.

Fines

The portion of a powder composed of particles which are smaller than the specified size.

Flame hardening

The localized surface heating of a medium carbon steel by an impinging gas flame so that the temperature is raised above 900 °C. The part is quenched (or self-quenches by virtue of the remaining cool bulk of the component) and tempered to produce a hard martensitic structure at the surface.

Flame spraying

A thermal spraying process in which the particles are heated and accelerated in a flame (combustion flame, plasma flame). Old term for thermal spray process.

Flashback

A recession of the flame into or back of the mixing chamber of the thermal spraying gun.

Flashback Arrester

A device to limit damage from a flashback by preventing propagation of the flame front beyond the location of the arrester.

Flaw

An undesirable discontinuity.

See Defect.

Flow Meter

A device for indicating the rate of gas flow in a system.

Filler

A solid inert material added to a synthetic resin or rubber, either to change its physical properties or simply to dilute it for economy.

Fretting

Small amplitude oscillatory motion, usually tangential, between two solid surfaces in contact.

Fretting corrosion

A form of fretting wear in which corrosion plays a significant role.

Fretting wear

Wear arising as a result of fretting (see fretting).

Friction

The reaction force resulting from surface interaction and adhesion during sliding. The friction coefficient is defined as the friction force divided by the load.

Fuel Gases

Gases such as acetylene, natural gas, hydrogen, propane, stabilized methylacetylene propadiene, and other fuels, and hydrocarbons, usually used with oxygen for heating.

Furnace Fusing

The melting together of the spray deposit and the substrate which results in coalescence.

The furnace offers the advantages of controlled heating, cooling, and protective atmosphere.

Fused coatings

A process in which the coating material is deposited by thermal spraying and then fused by post heat treatment. This can be done by flame, induction heating, furnace or by laser.

Fused and crushed powder

Powder formed from a fused solid mass which is then crushed to the appropriate size for spraying.

Fusion

The melting together of filler metal and metal (substrate), which results in coalescence.

Fusion Temperature

In thermal spraying, during the fusing of self-fluxing coatings, the narrow temperature range within which the coating surface exhibits a glassy or highly reflective appearance.

Galling

Damage to the surfaces of materials sliding in contact with each other, usually caused by the localized welding together of high spots. Common for materials like stainless steel, aluminium alloys and titanium.

Galvanic corrosion

Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

Galvanic Series

A list of metals and alloys arranged according to their relative corrosion potentials in a given environment.

Gas carburizing

See Carburizing.

Gas Cylinder

A portable container used for transportation and storage of a compressed gas.

Gas flow rate

The flow rate of gas (e.g. litres per minute) through the spraying torch.

Gas nitriding

See Nitriding.

Gas nitrocarburizing

See Nitrocarburizing.

Gas Pocket

A nonstandard term for porosity.

Gas Regulator

A device for controlling the delivery of gas at some substantially constant pressure.

Galvanising

A hot dip process for deposition of zinc for galvanic corrosion protection of steel.

Gold plating

The electrolytic deposition of gold for decorative or electrical applications.

Gradated Coating

A thermal spraying deposit composed of mixed materials in successive layers which progressively change in composition from the constituent material lot the substrate to the surface of the sprayed deposit.

Also referred to as graduated or graded coating.

Granular powder

Particles having approximately equidimensional nonspherical shapes.

Gravity Feed

A process by which powder is fed into a thermal spraying gun by gravity.

Grinding

The removal of material by the use of fixed abrasives like grinding wheels or emery paper.

Grit

See preferred term Abrasive.

Grit blasting

A pressurized stream of hard metal or oxide grit material used to clean and roughen surfaces prior to coating.

Grit Size

The particle size and distribution of abrasive blasting grains. Usually expressed by Society of Automotive Engineers numbers, such as SAE G25.

Groove and Rotary Roughening

A method of surface roughening in which grooves are made and the original surface is roughened and spread.

Gun

A nonstandard term for thermal spraying gun.

Gun Extension

The extension tube attached in front of the thermal spraying gun to permit spraying within confined areas or deep recesses.

H

Hand Shield

A protective device for shielding the eyes, face, and neck.

A hand shield is equipped with a filter plate and is designed to be held by hand.

Hard Chromium Plating

The electrolytic deposition of chromium to form a very hard (1000Hv), tough coating with good wear resistance. The structure is micro-cracked.

Hardfacing

The application of a cladding or coating of material designed to resist wear.

Hardness test

A test designed to assess the resistance to penetration from a load. The surface is indented under a defined load and the depth or area of penetration is measured.

Helium (He)

Monatomic noble gas, the most inert element, atomic number 2. Used as a plasma gas in plasma spraying.

Helmet

A device designed to be worn on the head to protect eyes, face, and neck from arc radiation, radiated heat, spatter, or other harmful matter.

High Velocity Oxy-fuel Spraying (HVOF)

A Thermal spray process. The spray powder particles are injected into a high velocity jet formed by the combustion of oxygen and fuel, heated and accelerated to the workpiece.

Hipping

The high temperature/high pressure consolidation of a powder metallurgy component or thermally sprayed coating. Density is greatly increased and metallurgical changes provide enhanced corrosion and wear properties.

Hot dip coating

A metallic coating obtained by dipping the substrate metal into a molten metal.

HVOF

See High Velocity Oxygen fuel spraying.

Hydrogen (H_2)

Diatomic gas, atomic number 1. The lightest element, very reactive and powerful reducing agent. Used as a secondary plasma gas in the plasma spraying process and as a fuel gas in combustion thermal spray processes (CWS, CPS and HVOF).

Hydrogen embrittlement

Hydrogen induced cracking or severe loss of ductility caused by the presence of hydrogen in the metal. Hydrogen absorption may occur during electroplating, pickling etc. (The use of hydrogen as a secondary gas in plasma spraying does not appear to effect substrates and the majority of coatings, one exception being titanium coatings).

Hydrophilic

Tending to absorb water.

Hydrophobic

Tending to repel water or lacking affinity for water

I

Impingement

A process resulting in a continuing succession of impacts between (liquid or solid) particles and a solid surface.

Impingement corrosion

A form of erosion-corrosion generally associated with the impingement of a high velocity, flowing liquid containing air bubbles against a solid surface.

Impregnation

A process of filling the pores of a coating with resin, wax or oil. (See sealer, vacuum impregnation).

Induction heating

The heating of a electrically conductive material by an induction coil producing alternating magnetic fields which induce alternating electric currents to flow in the material and cause heating by resistance. Used in many heating process (induction fusing, induction plasma, induction hardening etc.).

Induction hardening

The localized surface heating of a medium carbon steel by an induction coil so that the temperature is raised above 900°C. The part is quenched (or self-quenches by virtue of the remaining cool bulk of the component) and tempered to produce a hard martensitic structure at the surface.

Inert Gas

A gas which does not normally combine chemically with the substrate or the deposit.

Typical examples are argon and helium.

Injection Angle

Angle at which powder is injected into flame.

Powder injected at 0 (is injected perpendicular to the flame).

Positive angles indicate injection in direction of flame; negative angles in direction against flame.

Interface

The contact surface between the spray deposit and the substrate.

Interconnected porosity

A network of pores in and extending to the surface of a coating.

Interpass Temperature

In multiple pass thermal spraying, the temperature (minimum or maximum as specified) of the deposited spray coating before a subsequent pass is started.

Ion

An atom or group of atoms forming a molecule that carries a positive or negative charge as a result of having lost or gained one or more electrons.

Ion-Implantation

A process in which a beam of positive ions is projected towards and into the surface. It is carried out in partial vacuum and the ions diffuse into the surface layer of the substrate. Typically this is carried out with nitrogen giving a nitrided effect.

Ion nitriding

Also called plasma nitriding. A vacuum glow discharge technique of nitriding. See Nitriding.

Ion plating

A process in which positive ions produced in a glow discharge are attracted to the substrate which is connected as the cathode. The ions are typically made by evaporation.

Ionic Bond

A primary bond arising from the electrostatic attraction between two oppositely charged ions.

Irregular powder

Particles lacking symmetry.

Intergranular corrosion

Preferential corrosion at or adjacent to the grain boundaries of a metal or alloy.

Internal oxidation

The formation of isolated particles of corrosion products beneath the surface of the metal or coating. (This occurs as a result of preferential oxidation of certain alloy constituents by inward diffusion of oxygen, nitrogen, sulphur, etc).

K

Kerosene

Liquid fuel used in some HVOF thermal spray processes.

Keying

A nonstandard term for mechanical bond.

Knurling

See Groove and Rotary Roughening, Threading and Knurling.

L

Lamella

A thin layer, as in the overlayed particles in a thermal spray deposit.

Lamination
See preferred term Lamella.

Lapping
Rubbing two surfaces together, with or without abrasives, for the purpose obtaining extreme dimensional accuracy or superior surface finish.

Laser alloying
The application of a powder to a surface followed by fusing and alloying into the surface via the heat from an impinging laser.

Laser glazing
The melting and quenching of a surface to form a fine grained structure or "glaze".

Laser hardening
The localized surface heating of a medium carbon steel by an incident laser so that the temperature is raised above 900°C. The part is quenched (or self-quenches by virtue of the remaining cool bulk of the component) and tempered to produce a hard martensitic structure at the surface.

Lens
See Filter Lens.

Liquid impingement erosion
Progressive loss of material from a solid surface due to continue exposure to impacts by liquid drops or jets.

Localized corrosion
Corrosion at discrete sites, for example, pitting, crevice corrosion, and stress corrosion cracking.

Locked-up Stress
A nonstandard term for residual stress.

Low Pressure Plasma Spray
See preferred term Vacuum Plasma Deposition.

LPPS
See Vacuum or Low Pressure Plasma Spraying.

Lubricant
Any substance interposed between two surfaces for the purpose of reducing the friction or wear between them.

M

Macrohardness
The hardness of a coating as measured on a macroscopic scale, which shows the coatings bulk properties.

Magnetron sputtering
See Sputtering. In this PVD process, the sputtering action is enhanced by intense magnetic fields.

Manifold
See Cylinder Manifold.

Mask
A device for protecting a substrate surface from the effects of blasting or adherence of a spray deposit.

Matrix

The continuous phase of a material or coating in which separate particles of another constituent are embedded. (Like tungsten carbide particles in a cobalt matrix).

Mechanical bonding

Usually represented by mechanical interlocking of the deposited particles with the rough heights on the substrate surface produced during grit blasting.

Melting Rate

The weight or length of spray wire or rod melted in a unit of time.

Metallic Bond

The principal bond that holds metals together and is formed between base metals and filler metals in all processes.

This is a primary bond arising from the increased spatial extension of the valence electron wave functions when an aggregate of metal atoms is brought close together.

See also Bonding Force, and Ionic Bond.

Metallizing

See preferred term Thermal Spraying.

Metallurgical bonding

A nonstandard term for metallic bond.

Micrograph

A micrograph is produced when a section of the coating is taken, polished to show the particulate layers and then photographed through a microscope.

Microhardness

The hardness of a coating as measured on a microscopic scale. Can show the hardness of individual phases within the coating and avoid the effects of porosity.

Microinch

One millionth of an inch, 0.000001".

Micrometer (μm)

One millionth of a metre, 0.001mm.

Microtrack

A device for measuring powder particle size distributions.

Mil

One thousandth of an inch, 0.001" (Common in USA).

Minus sieve

The portion of a powder sample which passes through a standard sieve of specified number e.g. -140 mesh +325 mesh. (See plus sieve)

Molten Metal Flame Spraying

A thermal spraying process variation in which the metallic material to be sprayed is in the molten condition. See Flame Spraying (FLSP).

N

Neat

Unadulterated.

Neutral Flame

An oxy-fuel gas flame in which the portion used is neither oxidizing nor reducing.

See also Oxidizing Flame and Reducing Flame.

Nickel plating

The electrolytic deposition of nickel to form a corrosion barrier or to reclaim a worn part. Can also include hard ceramic particles to from a wear resistant composite coating.

Nitriding

The diffusion of nitrogen into alloy steel to form hard nitrides in the surface layer (typically 250μm). Performed at between 500 and 750°C from a gas, salt bath or plasma glow discharge.

Nitrocarburizing

The diffusion of nitrogen and carbon into alloy steel or mild steel to form hard nitrides in the surface layer (typically 250μ). Performed at between 500 and 750°C from a gas, salt bath or plasma glow discharge.

Nitrogen (N2)

Diatomic gas. Used as a primary and secondary gas in plasma spraying. Inert to most materials, with some exceptions like titanium.

Noble metal

A metal that does not readily tend to furnish ions, and therefore does not dissolve readily, nor easily enter into such reactions as oxidation, etc. The opposite of base metal.

Nodular powder

Irregular particles having knotted, rounded, or similar shapes.

Nontransferred Arc

An arc established between the electrode and the constricting nozzle.

The workpiece is not in the electrical circuit.

Nozzle

(1) A device which directs shielding media, (2) a device that atomizes air in an arc spray gun, (3) the anode in a plasma gun, (4) the gas burning jet in a rod or wire flame spray gun.

Nozzle Accumulation

Surfacing material deposited on the inner surface and on the exit end of the nozzle.

O

Open Circuit Voltage

The potential difference applied between the anode and cathode prior to initiating the arc.

Overspray

The excess spray material that is not deposited on the part being sprayed.

Oxide

A chemical compound, the combination of oxygen with a metal forming a ceramic; examples - aluminum oxide, zirconium oxide.

Oxidation

Loss of electrons by a constituent of a chemical reaction. (Also refers to the corrosion of a metal that is exposed to an oxidising gas at elevated temperatures).

Oxidizing Flame

An oxy-fuel gas flame having an oxidizing effect (excess oxygen).

Oxidizing

An environment or material which promotes oxidation.

Oxy-fuel Gas Spraying

A nonstandard term for flame spraying.

Oxygen (O_2)

Gas used to support combustion of fuel gases in combustion thermal spray processes. Achieves much higher flame temperatures than using air.

P

Pack carburizing

See Carburizing.

Painting

The application of organic based layers (acrylics, etc.) for corrosion protection and decorative purposes.

Parameter

A measurable factor relating to several variables; loosely used to mean a spraying variable, spraying condition, spray rate, spray distance, angle, gas pressure, gas flow, etc.

Parent Metal

A nonstandard term for substrate.

Particle chemistry

The elements contained within the particles of a spray powder.

Particle size

The controlling lineal dimension of an individual particle as determined by analysis with sieves or other suitable means.

Particle Size Range

See preferred term Particle Size Distribution.

Pass

A single progression of the thermal spray device across the surface of the substrate.

Particle size distribution

The percentage by weight, or by number, of each fraction into which a powder sample has been classified with respect to sieve number or microns.

Passivation

The process in metal corrosion by which metals become passive. (See passive)

Passivator

A type of inhibitor which appreciably changes the potential of a metal to a more noble (positive) value.

Passive

The state of a metal surface characterized by low corrosion rates in a potential region that is strongly oxidising for the metal.

Peening

Blasting process using spherical shaped beads or shot for cleaning and/or modifying surface properties.

Permeability

A property measured as a rate of passage of a liquid or gas through a coating.

Plus sieve

The portion of a powder sample retained on a sieve of specified number. (See minus sieve).

Physical Bond

See preferred term Metallic Bond.

Physical Vapour Deposition

A term covering all the vapour deposition processes including Ion plating. It does not include CVD as this is chemical not physical.

Phosphating

A conversion treatment to produce a thin phosphate-based layer on a steel surface, providing improved corrosion protection and good surface for painting.

Photo-thermal NDT

An NDT technique for spayed coatings. A repeated pulse of heat, from a laser source, flows through the coating and substrate. The thermal signature is detected and related to the input signal thereby indicating coating thickness.

Pistol

See preferred term Thermal Spraying Gun.

Pitting-tribology

A form of wear characterized by the presence of surface cavities the formation of which is attributed to processes such as fatigue, local adhesion, or cavitation.

Pitting-corrosion

Corrosion of a metal surface, cofined to a point or small area, that takes the form of cavities.

Plasma

See Arc Plasma.

Plasma Carburizing

See Carburizing.

Plasma Forming Gas

See preferred term Arc Gas. Plasma Metallizing. A nonstandard term for plasma spraying.

Plasma jet or plasma flame

A jet of highly ionized gas usually produced from a plasma torch. An electric arc is struck between a cathode and anode and is then blown through a nozzle to form the flame or jet.

Plasma Nitriding

Also called Ion Nitriding. See Nitriding.

Plasma Spraying

A thermal spraying process in which a nontransferred arc is utilized as the source of heat that ionizes a gas which melts and propels the coating material to the workpiece.

Plasma Transferred Arc (PTA)

Similar to the plasma spray process in that powder is sprayed through a plasma, but instead of being heated via a neutral plasma (carrying no electric current) the arc is transferred to the substrate (made to be the anode). This is a hot process and produces coatings similar to fused or weld hardfacing coatings.

Plenum Chamber

The space between the inside wall of constricting nozzle and the electrode.

Plowing

The formation of grooves by plastic deformation of the softer of two surfaces in relative motion.

Polishing

The smoothing of a material surface by means of the action of abrasive particles attached usually to a fabric cloth. The final mechanical step in metallographic preparation.

Polyester

A condensation polymer formed by the interaction of polyhydric alcohols and polybasic acids. They are used in some coatings and the manufacture of glass-fibres products. See Alkyd resin.

Polymer

Organic substance having large molecules consisting of repeated units. There are a number of natural polymers, such as polysaccharides synthetic polymer are extensively used in plastics.

Porosity

The presence of pores or voids in a coating, usually expressed as a percentage by volume.

Postflow Time

The time interval between plasma arc shutdown and electrode cooling, to inhibit oxidation of electrodes.

Postheating

The application of heat to an assembly after a thermal spraying operation.

Powder

Material manufactured into finely divided particles.

When explicitly blended for thermal spraying, powder falls within a specific mesh range, usually finer than 120 mesh (125 microns).

Fine powder is usually defined as having particles smaller than 325 mesh (44 microns).

Powder Alloy

Powder prepared from a homogeneous molten mixture of elements, and sometimes entrapped carbides or metal oxides.

All of the particles have approximately the same composition.

Powder Blend

A heterogeneous mixture of two or more alloy powders.

Powder Clad (Wire Clad)

Powder or wire wherein one alloy is encapsulated in another; a composite.

Powder coating

A polymeric coating deposited via electrostatic attraction

Powder Composite

Two or more independent materials, combined to form a single integrated unit.

May be either chemically clad or mechanically agglomerated.

Powder Feeder

A device for conveying powdered materials to thermal spraying equipment.

Powder Feed Gas

See preferred term Carrier Gas.

Powder Feed Rate

The quantity of powder introduced into the hot, gaseous stream per unit of time.

Powder Fame Spraying

A thermal spraying process variation in which the material to be sprayed is in powder form; all oxyfuel gas processes.

See Flame Spraying (FLSP).

Powder Injection

Feeding of a powder through a powder port into a thermal spray flame.

Powder injection angle

The angle from which the powder is injected into the plasma jet in plasma spraying.

Powder Metallizing

A nonstandard term for powder flame spraying.

Powder Port

Internal or external orifice through which powder is injected into flame or plasma.

Pre-alloyed powder

A powder composed of two or more elements which are alloyed in the powder manufacturing process and in which the particles are of the same nominal composition throughout.

Prenow Time

The time interval between start of shielding gas flow and arc or gas ignition.

Preheat

The heat applied to the base metal or substrate immediately before spraying.

Preheat Temperature

A specified temperature that the substrate is required to attain immediately before material deposition.

Primary Gas

The major constituent of the arc gas fed to the gun to produce the plasma; usually argon or nitrogen.

Procedure

The detailed elements of a process or method used to produce a specific result.

Propane (C_3H_8)

Aliphatic hydrocarbon gas used as a fuel gas in thermal spray processes.

Propylene (C_3H_6)

Hydrocarbon gas used as a fuel gas in thermal spray processes. Higher flame temperature than hydrogen and propane.

Protective Atmosphere

A gas envelope or vacuum surrounding the part to be thermally sprayed, with the gas composition controlled with respect to chemical composition; dewpoint, pressure, flow rate, etc.

Examples are inert gases, combusted fuel gases, hydrogen and vacuum.

Protective Barriers

Curtains or portable fireproof canvas shields, sometimes required to enclose work areas, when there is a possibility of the spray stream being misdirected, or where the glare of the arc or flame could injure unprotected eyes.

Protective Clothing

Leather or metal coated articles designed to prevent burns from ultraviolet radiation or misdirected particles.

Pull-out

Pull-out occurs when particles are plucked from the coating during machining or grinding. Also occurs during metallographic preparation. It is sometimes confused with porosity.

PVD

See Physical Vapour Deposition.

Q

Quality Control

All aspects of the control of the spraying process including the surface preparation, spraying, control of thickness deposited and the oxide and porosity levels, surface finish and NDE checks as specified.

R

Rate of Deposition

See Deposition Rate.

Reducing Agent

A substance that cases reduction, thereby itself becoming oxidized.

Reduction

A reaction in which electrons are added to the reactant. More specifically, the addition of hydrogen or the abstraction of oxygen.

Reducing Flame

A gas flame having a reducing effect (excess fuel gas).

Refrigerated Dryer

The application of a refrigeration cycle to physically lower the dewpoint.

Regenerative Dryer

A double column apparatus containing a drying medium for moisture absorption, which is automatically regenerated.

Regulator

See Gas Regulator.

Relative Density

See preferred term Apparent Density Ratio.

Residual Stress

Stress remaining in a structure or member as a result of thermal or mechanical treatment or both. See Coating Stress.

Resin

A synthetic or naturally occurring polymer.

Resonance Time

See preferred term Dwell Time.

RFI Shielding

Thermal spray coatings of electrically conductive metals such as zinc, aluminium and copper are used on non-conducting composite casing materials to shield sensitive electronic devices from radio frequency electromagnetic interference.

Rhodium plating

The electro-deposition of rhodium for oxidation resistance combined with surface hardness.

Root Mean Square (RMS)

A method of defining the average roughness of a surface.

It is the square root of the sum of all individual measurements divided by the number of measurements.

Rotary Roughening

A method of surface roughening in which are revolving roughening tool is pressed against the surface being prepared, while either the work or the tool, or both, move.

Rough Threading

A method of surface roughening which consists of cutting threads with the sides and tops of the threads jagged and torn.

S

Sacrificial coating

A coating that provides corrosion protection wherein the coating material corrodes in preference to the substrate, thereby protecting the latter from corrosion.

Salt Bath Carburizing

See Carburizing.

Salt Bath Nitriding

See Nitriding.

Salt Bath Nitrocarburizing

See Nitrocarburizing.

Saturated Air

To reach 690 kPa (100 psi) air at 100% humidity, it is necessary to compress approximately 0.23 ml (8 ft.') of free air, with its inherent moisture, into 0.028 ml (one cubic foot), since atmospheric humidity is usually more than 12.5% at ambient. All undried compresed air systems at 690 kPa (100 psi) and ambient temperatures are at 100% relative humidity.

Scoring

A severe form of wear characterized by the formation of extensive grooves and scratches in the direction of sliding.

Scratching

The mechanical removal or displacement, or both, of material from a surface by the action of abrasive particles or protuberances sliding across the surfaces.

Screen

One of a set of sieves, designated by the size of the openings, used to classify and sort powder to particle size.

Seal Coat

Material applied to infiltrate and close the pores of a thermal spraying deposit. Secondary Gas. The minor or second constituent of the arc gas fed to the gun to produce plasma.

Sealant, Sealer

A preparation of resin or wax type materials for sealing the porosity in coatings.

Sealing

A process which, by absorption of a sealer into thermal spray coatings, seals porosity and increases resistance to corrosion of the underlying substrate material.

Self-bonding coatings

A name given to thermal spray coatings that are capable of bonding to clean smooth surfaces. Bond and "one-step" coatings are normally in this group. These are paticularly important where grit blasting or surface roughening processes must be omitted.

Self-Fluxing Alloys

Surfacing materials that "wet" the substrate and coalesce when heated to their melting point, without the addition of an externally applied flux.
These alloys contain boron or silicon, or both, as fluxing agents.

Shadow Mask

A protective device that partially shields an area of the work, thus permitting some overspray to produce a feathering at the coating edge.

Shear Stress

The stress on the slip plane produced by external loads tending to slide adjacent planes with respect to each other in the direction parallel to the planes.

Shielding Gas

Protective gas used to prevent or minimize atmospheric contamination.
See also Protective Atmosphere.

Shrinkage

A decrease in dimensions of a coating during processing.

Shrinkage stress

The residual stress in a coating caused by shrinkage during processing.

Shot peening

The bombardment of a component surface with steel or ceramic shot. Produces a residual compressive stress in the surface and improves fatigue and stress corrosion performance.

Sieve

See preferred term Screen.

Sieve Analysis

A method of determining particle size distribution, usually expressed as the weight percentage retained upon each of a series of standard screens of decreasing mesh size.
See also Particle Size Distribution.

Sieve classification

That portion of a powder sample which passes through a standard sieve of specified number and is retained by some finer sieve of specified number.

Slick Up

Point at which a self-fluxing alloy begins to shine during the fusing operation.

Shroud

A gaseous and/or mechanical or physical barrier placed around the spraying process designed to reduce the ingress of air into the system and so reduce oxidation of the of the materials being sprayed.

Silver plating

The electro-deposition of silver for electrical, decorative or anti-fretting properties.

Size analysis

Analysis of the size of the particles being deposited by spraying processes.

Size distribution

The distribution of sizes within a size analysis. The distribution may be normal or skewed in some way due to the powder manufacturing process.

Solvent Degreasing

The removal of oil, grease, and other soluble contaminants from the surface of the workpiece by immersion in suitable cleaners.

Spalling

The lifting or detachment of a coating from the substrate.

Splat

A single thin flattened sprayed particle.

Splat Cooling

Extremely rapid, high rate of cooling, the effects of which can be observed in thermal spraying deposits leading to the formation of metastable phases and an amorphous microstructure.

Spray

A moving mass of dispersed liquid droplets or heat softened particles.

Spray Angle

The angle of particle impingement, measured from the surface of the substrate to the axis of the spraying nozzle.

Spray Booth

See preferred term Exhaust Booth.

Spray chamber

A chamber in which the spraying process is carried out. It may merely be an acoustic chamber for plasma spraying or a vacuum chamber for vacuum plasma spraying.

Spray Deposit

See thermal spraying deposit.

Spray Deposit Density Ratio

The ratio of the density of the spray deposit to the theoretical density of the surfacing material.

Usually expressed as percent of theoretical density.

Spray Distance

The distance maintained between the thermal spraying gun nozzle tip and the surface of the workpiece during spraying.

Spray dried powder

Powder formed by the spray drying process.

Spray Dry

A method for making thermal spray powder, especially ceramic powder, by spraying a slurry into a heated chamber and drying it to powder.

Spray-fused coatings

A process in which the coating material is deposited by flame spraying and then fused into the substrate by the addition of further heat. This can be applied by flame, induction heating or by laser.

Spray Rate

The rate at which surfacing material passes through the gun.

Spraying Sequence

The order in which different layers of similar or different materials are applied in a planned relationship, such as overlapped, superimposed, or at given angles.

Sputtering

This is a glow discharge process whereby bombardment of a cathode releases atoms from the surface which then deposit onto a nearby target surface to form a coating.

Stabilizing Gas

The arc gas, ionized to form the plasma, is usually introduced into the arc chamber tangentially.

The relatively cold gas chills the outer surface of the arc stream, tending to constrict the plasma, raise its temperature, and force it out of the anode (nozzle) in a steady, relatively unfluctuating stream.

Statistical Process Control (SPC)

To enhance, optimize and control coating properties influenced by parameter interaction.

Steam tempering

The production of a stable oxide on steel parts by treatment in steam at about 300°C. Improves corrosion performance and reduces friction.

Step Mounting

The intentional overlapping of several workpieces in order that one protects or masks its neighbor during the blasting or spraying process.

Strain

A measure of the extent to which a body is deformed when it is subjected to a stress.

Stress

The force per unit area on body that tends to cause it to deform. It is a measure of the internal forces in a body between particles of the material of which it consists as they resist separation, compression, or sliding.

Stress corrosion cracking

A cracking process that requires the simultaneous action of a corrodent and sustained tensile stress.

Substrate

The parent or base material to which the coating is applied.

Sulphidation

The reaction of a metal or alloy with a sulphur containing species to produce a sulphur compound that forms on or beneath the surface of the metal or alloy.

Superfines

Extra small, minute powder particles, usually less than five microns in size.

Superheat

The difference between the higher actual temperature at the evaporator outlet and the lower theoretical temperature of the refrigerant at pressure.

Surface preparation

Cleaning and roughening the surface to be sprayed, usually by grit blasting. This is to increase the adhesion of the coating to the substrate.

Surface Feet Per Minute (SFPM)

Linear velocity of the thermal spray gun as it traverses the length of the workpiece.

Also, the circumferential velocity of the substrate.

Surface Preparation

The operations necessary to produce a desired or specified surface condition.

Surface Roughening

A group of methods for producing irregularities on a surface.

See also Dovetailing, Groove and Rotary Roughening, Rotary Roughening, Rough Threading, and Threading and Knurling.

Surface topography

The geometrical detail of a surface, relating particularly to microscopic variations in height.

Surfacing

The application of a coating or cladding to a surface to impart a change in its surface behaviour.

Surfacing Material

The material that is applied to a substrate during surfacing.

Surfacing Metal

The metal that is applied to a substrate during surfacing.

T

Tensile strength

A measure of the resistance that a material offers to tensile stress. It is defined as the stress, expressed as the force per unit cross sectional area, required to break it.

Tensile stress

Axial forces per unit area applied to a body that tend to extend it.

Textural Stress

The accumulated stress within an entire coating.

Thermal barrier coating

A coating forming an insulating barrier to a heat source to protect the substrate.

Thermochemically formed coatings

A painted, dipped or sprayed chromium oxide based coating consolidated by repeated deposition and curing cycles (about 500°C).

Thermal spraying

A group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semimolten condition on a substrate to form a spray deposit.

The surfacing material may be in the form of powder, rod, cord, or wire.

See also Arc Spraying, Flame Spraying, and Plasma Spraying.

Thermal Spraying Deposit

The coating or layer of surfacing material applied by a thermal spraying process.

Thermal Spraying Gun

A device for heating and directing the flow of a surfacing material.

Thermal Stress

Stress resulting from nonuniform temperature distribution.

Thermography

An NDE technique in which the coating is flash heated and then viewed with an infra-red camera. "Hot spots" indicate areas of poor bonding or greater coating thickness.

Threading and Knurling

A method of surface roughening in which spiral threads are prepared, followed by upsetting with a knurling tool.

Tons of Refrigeration

A rate of heat exchange equal to 12,000 BTU/h.

Torch

A device used for fusing sprayed coatings; it mixes and controls the flow of gases.

Torch Fusing

The use of a torch to heat and melt a fusable spraying deposit to produce coalescense.

Transferred arc

In a plasma torch the plasma jet is emitted from the torch and the current flows from the internal cathode to the internal anode represented by the nozzle of the torch. When the jet is carried to another anode with it being electrically favourable to do so the current will then transfer to the second anode, usually the workpiece and the arc is said to be transferred.

Travel Angle

The angle that the gun makes with a reference line perpendicular to the axis of the deposit in the plane of its axis.

This angle can be used to define the position of thermal spraying torches and thermal spraying guns.

Traverse Speed

The linear velocity at which the thermal spraying gun traverses across the workpiece during the spraying operation.

Tribology

The science and technology concerned with interacting surfaces in relative motion.

U

Undercoat

A deposited coat of material which acts as a substrate for a subsequent thermal spraying deposit. See Bond Coat.

Undercutting

A step in the sequence of surface preparation involving the removal of substrate material.

Ultrasonic

An NDE technique which relies on an ultrasonic beam passing through a coating and substrate and providing a signal from the back wall which is then detected. The height of this backwall echo depends on the discontinuity in impedance from the sprayed coating to the substrate. Bonding flaws can be easily seen by the weakening of the back wall echo.

V

Vacuum or Low Pressure Plasma Spraying

Plasma spraying carried out in a chamber which has been evacuated to a low partial pressure of oxygen. It is then usually partially backfilled with argon to avoid the possibility of forming a glow discharge.

Van der Waals Force

A secondary force arising from the fluctuating dipole nature of an atom with all occupied electron shells filled.

W

Water Wash

The forcing of exhaust air and fumes from a spraying booth through water so that the vented air is free of thermal sprayed particles or fumes.

Wire spraying

A thermal spray process whereby the supply for the coating material is fed into the gun in the form of a continuous wire.

Wear

Loss of material from a surface by means of some mechanical action.

Welding

-in tribology, the bonding between surfaces in direct contact, at any temperature.

Welding Process

The joining of materials by the application of heat or friction. Usually involves the localized fusion of both contacting surfaces.

Wire Feed Speed

The rate of speed at which the wire is consumed.

Wire Flame Spraying

A thermal spraying process variation in which the surfacing material is in wire form.

See Flame Spraying (FLSP).

Wire Metallizing

See preferred term Wire Flame Spraying.

Wire Straightener

A device used for controlling the cast of coiled wire to enable it to be easily fed into the gun.

Workpiece

The object or surface to be coated.

See preferred term substrate.

Workpiece Cooler

See Auxiliary Cooler.

Z

Zinc (Zn)

Thermal spray coatings of zinc or zinc alloys (eg. Zn/Al, Zn/Sn) provide galvanic corrosion protection.

Zinc Plating

The electro-deposition of zinc or zinc alloys (eg. Zn/Ni, Zn/Sn) to provide galvanic corrosion protection.

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