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THERMAL SPRAY COATING TECHNOLOGY – A REVIEW

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ABSTRACT

Thermal spray coating involves heating of coating materials (ceramic, carbide, and metal alloys) to a semi-molten or molten state and propels to substrate. The flame temperature is in the range of 3,000 to 16,000 ^{O}C but the surface temperature of the substrate rarely exceeds 500 ^{O}C depending on the thermal spray processes being used. The coating materials are feed into the spray gun in the form of powders, rods or wires. Thermal spray coating is use for the following purposes; (i) increase corrosion and wear resistance, (ii) protection against electromagnetic, or electrostatic, (iii) protection against radio frequency interference, (iv) metal buildup and, (iv) cosmetic. Thermal spray coating can be categorized into five most common processes; (i) Flame arc spraying, (ii) Electric Arc spraying, (iii) Plasma arc spraying, (iv) High-velocity Oxy/Fuel (HVOF) and (v) Detonation Gun. In this paper, thermal spraying processes will be explained, along with the advantages and disadvantages of one another.

INTRODUCTION

Thermal spraying is a process where the coating materials are melted and with kinetic energy, the particles are impacted onto the substrate surface to be coated. The coating material is propelled on the substrate using a stream of gas or compressed air depending on the thermal sparing process being used, creating a surface structure on a given substrate. The molten or semi-molten materials with kinetic energy impacted on the substrate surface, and rapidly solidified, and form splats. A splat is in the shape of pancake-like, single impacted particle. The diameter of the splat is less than tens of micrometer in case of plasma spraying [1].A coating is formed by the overlapping splat where it is solidified and interlocked each other.

The molten or semi-molten coating materials impacted on the substrate, will result in build up of coating through one or more these possible bonding mechanisms, i.e. (i) mechanical bonding as the particles splatter on the substrate. These particles interlock with the roughened substrate surfaces, (ii) Local diffusion of coating material with the substrate, and (iii) Bonding mechanism by means of Van der Waals forces [2]. The physical properties of thermal spraying coatings, such as porosity, coating density are depend on process parameters such as droplet size distribution, velocity, degree of solidification, substrate material and temperature [3].

The energy source use to heat and melt the coating particles can be combustion of fuel gas, electric arc and plasma arc. Thermal spraying process can be grouped in two categories. i.e. (i) low energy processes such as flame and arc spraying often referred as metallising, and (ii) high energy processes such as plasma spraying, the detonation gun and high velocity oxygen fuel [4]. Coatings can be applied manually, semi-automatic and robotic depending on the repeatability and accuracy of the final product to be achieved. . In order to control the formation of oxides on the coated surface, coatings can be done under vacuum environment. The thickness of coating may range from 25µm to 2.5 mm depending on the usage of that particle component or system [5].

THERMAL SPRAY PROCESSES

Thermal spray process is categorized according to the energy source used to heat or melt the coating materials and generally can be categorized three main groups, i.e. (i) combustion process, (ii) electric wire arc process, and (iii) plasma process. Figure 1 shows the main three category processes and its subcategories. Each thermal spray process has it own limitation, advantages and disadvantages, capability and capacity. The choice of using thermal spray process is depends on the mechanical properties, chemical properties and microstructure of the coated surfaces to be achieved. In the selection of the thermal process to be used, we need to study the thermal spray process characteristics as shown in Figure 2. By knowing what are the best parameters for that particular coating in term of flame temperature and particle velocity, then we can chose the best thermal spray process to be used. Particle size, morphology and type also play important role in getting the most beneficial coatings. Thus, the "Tv + p" plays significant role in getting the best coating characteristics where T is flame temperature, v is the particle velocity and p is particle characteristics.

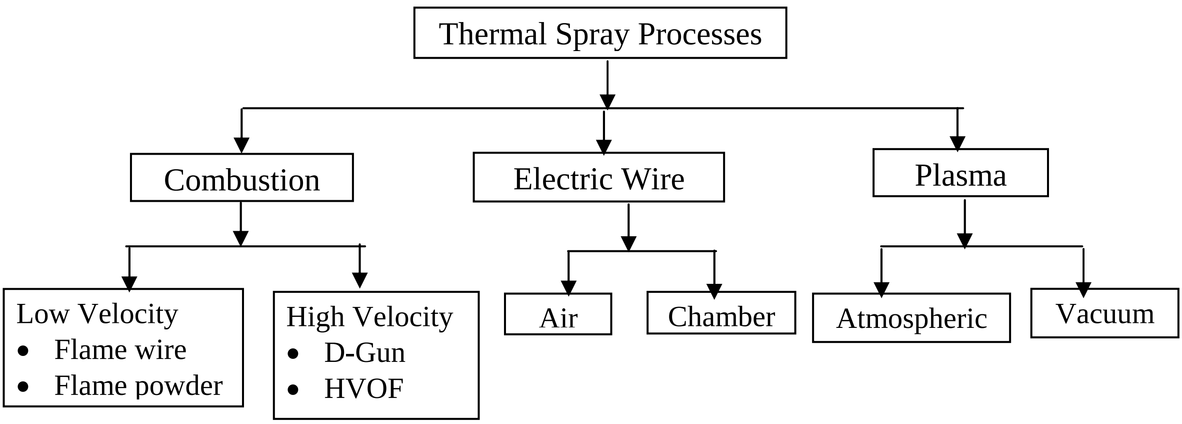

Figure 1. Thermal spray process

Thermal spray process generally comprises of the following items; (i) gas supply, (ii) power supply, (iii) control panel, (iv) powder/wire feeder, (v) spray torch, and (vi) substrate (Figure 3). Flame spraying uses oxyacetylene flame to melt the targets (Figure 4a). This process was the first thermal spraying process developed by modifying oxy-acetylene torches. The targets may be in the form of powders, rods or wires. The powders are fed through central passage by carrier gases such as argon and nitrogen, or gravity fed from canister mounted directly on gun. The powders are then transport into the combustion flame, and the mixed gases transport the material towards the prepared substrate surface. This process has high oxide inclusions in metals. Generally, metals or metal alloys are use as the coating materials in the flame spraying where flame temperature in the range of 2,800 ^{O}C to 3,200 ^{O}C.

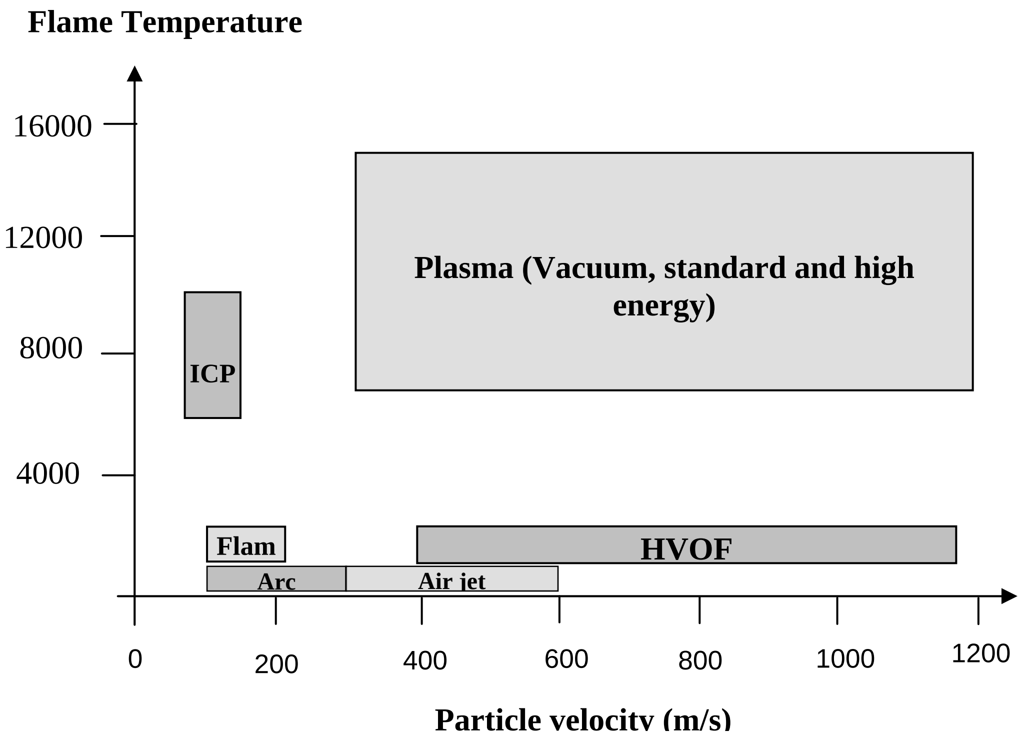

Figure 2. Thermal spray process characteristics

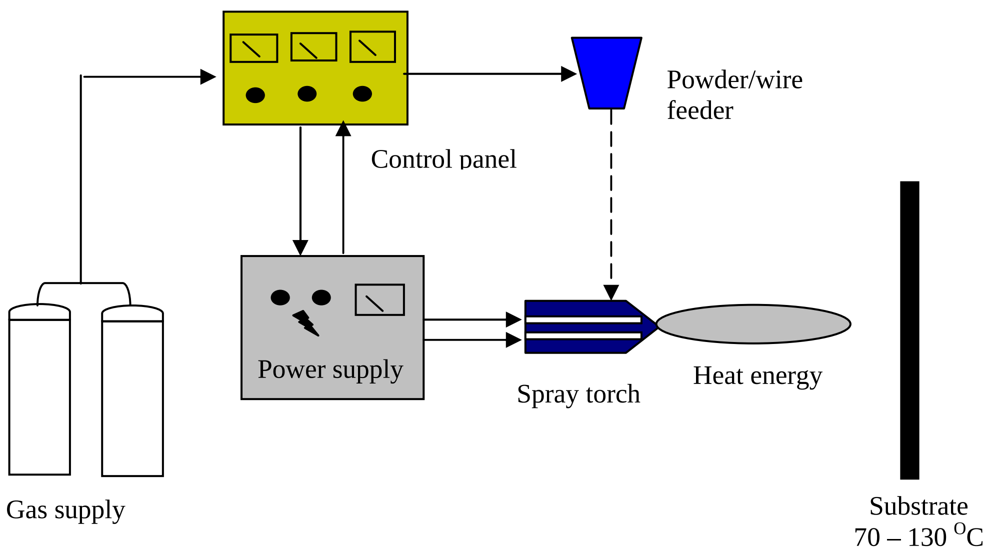

Figure 3. Thermal spray coating layout

Gas detonation is capable of producing the highest pressure, velocity, and density in the gas flow, which is not achievable by all other spraying techniques As a result, the detonation coatings are characterized by extremely high density, microhardness, and low porosity, and are suitable for applications requiring very high standards, such as aircraft engine components [6]. Detonation gun (D-gun) use combustion and jet expansion of the fuel (oxygen and acetylene) to melt and propel the coating materials onto the substrate surface (Figure 4b). Detonation is initiated by spark ignition of gas in a gun This process is a low cost of operation as compared to the typical HVOF and plasma spray systems. In this system, the gases are fed into the combustion chamber at slightly exceeding atmospheric pressure. This process is used to deposit coatings of approximately 250 µm or less for increasing the wear resistance of parts that subjected to extreme service conditions.

HVOF process efficiently uses high kinetic energy and controlled thermal energy. This process is similar to the detonation gun, except that HVOF uses the continuous combustion of oxygen fuel. HVOF uses oxygen, hydrogen, and a fuel gas (methane, propylene, kerosene) to melt the target powder. The thoroughly mixed gases are ignited externally of the gun. Pressurised internal combustion and supersonic jet expansion to atmosphere resulting in high jet speed greater than 1,200 m/s^{-2}. In this process, the coating materials are in a molten state and flatten plastically as they propel onto the substrate surface. This process produces premium quality hard, dense coatings exhibiting high bond strength, low porosity and excellent wear and corrosion resistance [7].

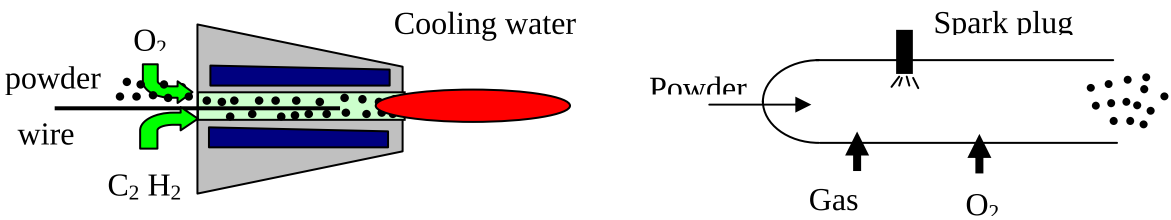

Figure 4. Thermal spray process principle (a) flame spray, (b) detonation gun

Wire-Arc (Arc-Spray) uses direct current arc between two conducting wires to melt consumable wires. The two wires are electrically charged with opposing polarity and are fed into the arc gun. The wires are motorized fed into the spray torch. The opposing charges on the wires create enough heat to continuously melt the tips of the wires. The melted droplets are then propelling to the substrate surface by atomisng gases such as air, argon and nitrogen. This process has higher deposition rates than HVOF and plasma spray.

Plasma spray is used to coat metallic and ceramic materials onto the substrate for corrosion resistance, wear resistance, and thermal barrier application. Plasma is the 4th state of matter and generated by passing plasma gases through spray torch. Typical plasma gases are Argon, Hydrogen, Nitrogen, and Helium. Various mixtures of these are used in combination with the applied current to the electrode to control the amount of energy produced by a plasma system. Direct current arc is applied between central thoriated tungsten cathode electron and water cooled concentric Cu anode (Figure 5). The powerful arc is sufficient to strip the gases of their electrons and the state of matter known as plasma is formed. As the unstable plasma recombines back to the gaseous state thermal energy is released. Because of the inherent instability of plasma, the ions in the plasma plume rapidly recombine to the gaseous state and cool. At the point of recombination, temperatures can be 6,600 ºC to 16,600 ºC [7]. By injecting the coating material into the gas plume, it is melted and propelled towards the target component. The power to operate this system usually between 30 to 200 kW with amperage operates between at 250 – 2,000 A.

Plasma spray performs where other processes cannot and is the best choice and usually produced coating of denser, contain less porosity, and have better adhesion that flame spraying process. Plasma spraying produces high temperature even up to 16,00 ^{O}C. However the surface temperature of the substrate rarely exceeds 150 ^{O}C. Coating characteristics of plasma spray process depend on many variables such gun type, power, gas used and its flow rate, stand off distance, speed of torch, powder injector diameter, substrate cooling, and powder characteristics.

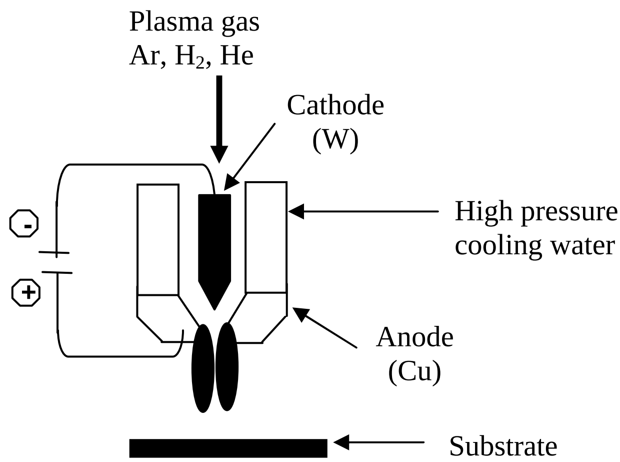

Figure 5. Plasma spray – process principle

Coating characteristics such as oxide content, porosity, bond strength, corrosion and wear resistance depend on the thermal spray process used and spray parameter conditions. Spray parameters include gas flow rate, coating materials morphology, standing distance, material flow rate, and surface preparation. Table 1 shows the comparison of different thermal spray processes and coating characteristics.

SURFACE PREPARATION

Prior to thermal spray coating process, the substrate surface should be cleaned and roughened adequately. After degreasing, the surface is subjected to grid blasting for further cleaning and usually for metal spraying. At the same time, blasting increases the surface area and creates a surface profile for the splat to be interlocked with the substrate surface. The grid blasted is performed by projected sharp abrasive grit such as Al_2O_3, onto the surface, either mechanically or by compressed air. The substrate surface roughness has a significant influence on the spreading velocity, flattening ratio, flattening time, splat size, and shape [8]. The smoother the surface, the larger the splat surface, the bigger the splat diameter, the thinner the splat thickness, the higher the flattening ration, and the longer the flattening time.

Surface roughing on the substrate surface is usually prepared for thicker coating. By doing this, the surface area increases and the shear strength between the coating and the substrate surface also become higher. In another method to increase the bond strength between the substrate surfaces the coating materials is to apply bond coating on the grid blasted substrate surface. Choice of bonding materials depends on the substrate materials to be coated and thermal spraying process going to be used. For example, molybdenum is applied by flame spraying as a bond for steels and aluminium materials and should not be used more than 400^{O}C [9].

Table1. Comparison of different thermal spray processes [6]

Type of System	Flame or Plasma Exit Temperature (^{0}C)	Heat Transfer or Substrate (^{0}C)	Particle Impact Velocity (m/s)	Oxide Content (%)	Porosity (%)	Adhesion (Bond Strength)
Detonation Gun	3000	20-150 MAX	800-1000	0.1	0.1 – I.0	Extremely High
HVOF	2500-3100	500- 700	500-800	0.2	1.0 - 10	Very High
Plasma Spraying	5500-8300	700-1000	200-600	0.1-1	1.0 - 10	Very High
Wire Arc	4000-6000	500-800	240	0.5-3	10-20	High
Flame Spraying	2500-3000	500-700	30-180	4-6	10	Low

FEED STOCKS

The coating materials can be ceramics, metal alloys, metallic, carbides or any combination and can be fed into the torch in the form of powders, rods or wires. Powder particles need to be characterized to ensure the coating produced will be in high quality in term of hardness, high bond strength, less porosity and oxide content. Some of the powder quality control are; (i) sieving for checking particle size, (ii) Microstructural examination using scanning electron microscope for getting information on particle morphology (angular, rounded), (iii) flowability test using hall flow meter, (iv) x-ray diffraction for phase analysis, and (v) chemical analysis or energy dispersive analysis x-ray for chemical composition.

Feedstock in the wire or rod form is fed axially in the middle of the spray torch into a flame. It was fed from the rear using motorized mechanism. Whereas feedstock in the powder forms, the coating material is metered by powder hopper into a flame where it heated to a molten state and propels onto the substrate. In the plasma spray process, the feedstocks in powder form can be injected internally [10] or externally [11].

Powder particle size plays important role in determine the coating characteristics. Smaller particles travel in the upper portion of the flume with a lower velocity and reach higher temperatures. As a result, lower density coatings are formed by splats of slower, hotter particles that posses a larger fraction of intrasplat and intersplat porosity [12].

APPLICATIONS

Thermal spray process can be applied to many sectors of industries such as transportation, oil & gas exploration, chemical processing, paper & pulp, defense & aerospace, medical & dental and electric/electronic. Coating materials to be spray onto the substrate also depend on the purpose of coating and it compatibility with the substrate materials. The coating materials can be ceramics, metal alloys, metallic, carbides, polymers or any combination and fed into the torch in the form of powders, rods or wires. Coatings are use to extend product life, increase performance and reduce production and maintenance costs. Other primary uses of thermal spray coatings include corrosion and wear resistance, dimensional restoration, modifying thermal and electrical properties, and medical application, decorative, and optical.

Abradable coating is use to reduce the gap between the rotating blade tips and the compressor housing of aircraft compressor. A gap that becomes too large may result in poor efficiency, thus high fuel consumption. In this case, AlSi-polyester and AlSi-polyimide were used as coating material in plasma spraying process [7]. MCrAlY alloys were used to provide a corrosion and oxidation resistance barrier in this area, and they are usually applied as thermal spray coating [13]. This coating was performed using Vacuum plasma spraying [14] and HVOF process [15]. Zicornia coatings were used as thermal barrier coating in hot sections of aero-engine and this offer a high thermal resistance. This coating can reduced the maximum metal temperature up to about 170^{O}C [16].

In automotive industry, combustion chamber is coated with Zirconia oxide for thermal insulation, and resistance to hot gas oxidation. Atmospheric plasma spraying technique is use in this type of coating. The crankshaft bearing surfaces will wear-off with time. Dimensional restoration of bearing surfaces crankshaft can produce considerable savings over the replacement coat. On large scale this process can save as much as 90 % saving [17]. The crankshaft can be coated with molybdenum or nickel base using atmospheric or vacuum plasma spray process.

In medical applications, thermal spray coatings are used to spray bio-active materials onto the implant. Knee and hip-joint implant required bio-compatible where the bone growth should be produce a strong interface between the bone and the implant. Porous Ti and hydroxylapatite exhibit bio-active properties. In this type of coating, vapour plasma spraying, and atmospheric plasma spraying can be used to spray titanium or hydroxylapatite onto the implant respectively.

Printing rolls are coated with Cr2O3 to improve wear and corrosion resistance using APS technique. Pump housing for the chemical industry is exposed to corrosion, erosion, and abrasion. To reduce this effect, the pump housings are coated with Cr2O3 or TiO2 using APS process. Gas turbine blade needs to be protected against hot gas corrosion and erosion. In achieving this requirement the turbine blades are coated with CrAlY using VPS process [7].

HEALTH AND SAFETY

Hazards to health and safety in the thermal process to be taken care off are dust and fumes, noise, and light radiation. In general, some of the coating materials are not bond to substrate surface and these powder particles are in size of micrometer. All fine powder particles (size of less than 5 µm) are potentially pyprophorric and therefore some safety precautions need to be considered before performing this coating process. Filtered exhaust hoods are normally used to collect dust and to vent fumes to the atmosphere. Besides, the operators are advised to wear respirators to prevent from inhaling fine dust and fumes. Thermal spray devices emitted light in the range of infrared to ultraviolet. To protect the eye and skin damage, the operator must be equipped with proper apparels such as goggle and fire retardant clothes. The spray torch used high compressed air and should not be directed toward people.

Thermal spray processes produced high noise level depends with the type of process and operating parameters. Table 3 shows typical noise level measured at a distance from the thermal spray devices to the operator's ear. A few safety measures can be used to reduce noise level such as wearing ear plug, acoustic panel, and chamber.

Table 3. Typical noise levels during thermal spray process

Process	Conditions	Noise [dB (A)]
Arc-spray	24V 200A	111
Flame spray (powder)	Acetylene	90
Flame spray (wire)	Propane	118
Plasma spray	Argon/ hydrogen	128

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