1. Introduction

Thermal spray coatings are widely used in a variety of industrial applications. The thermal spray aluminum coating is most commonly used to protect the base metal from wear and corrosion [1]. The aluminum has low strength and ductility, so magnesium and manganese are added to it to increase its strength and ductility [2]. Molten powder or wire is heated either through oxy-fuel combustion or plasma—the flame of the spray device powers the heated mixture [3], and after even spray distribution onto a metal product, the mixture assumes its solid coating form. Aluminium alloy when thermal sprayed then there is change of phase of the aluminum due to temperature greater than 500˚C [4]. Thermal spray coatings can serve an array of functions; commonly used to treat planes, they can also protect products from wear, temperature extremes, chemicals, and even protect buildings from external environmental conditions like rain and humidity. The coating can also used in the machining operation, such as the hard carbide coating is applied on the steel tool so that the cost of the making of the tool carbide decrease, and the tool as whole acts as a carbide tool [5,6]. Numerous coatings and surface treatments have been developed and applied to mitigate wear and corrosion of engineering components and tools [7]. The choice of a particular treatment depends on many factors, viz., processing and fabrication temperature, temperature of the working environment, applied load, relative velocity, counter-face material to be in contact, lubrication and the environment itself. Coatings can be hard or soft, thin or thick, porous or dense, single or multilayer depending on the application. It is impossible and unrealistic to provide solutions to "all" the wear problems experienced in every industrial situation. In recent years there has been a tremendous output in the number of research coatings and surface treatments, particularly the so-called advanced variants produced by plasma assisted processes [7], and increasingly research platform in this field are from various disciplines - materials scientists, metallurgists, physicists, chemists, tribologists, mechanical engineers, electrical/electronic engineers and so on. The ultimate choice of a coating material critically depends on the application and the substrate. Although there are multiple methods and materials involved in thermal coating, they are distinguished by both heat source and the base material used for deposition. Combustion flame spraying, high velocity oxy-fuel spraying (HVOF), two-wire electric arc spraying, plasma spraying, and vacuum plasma spraying are several common coating application processes [8-10].

1.1 Classification of thermal spray coating process:

The thermal spray coating basis on the application of heat requires to melt the coating materials and their application can be classified into different categories. These different coating processes are used for different application or different material.

1.1.1. Combustion Flame Spraying coating process:

The flame is propelled by oxygen mixed with fuel, which also results in melting the mixture. These melted particles are carried away by the air at high velocity and get deposited over the surface to be coated (figure 1). The main parameter associated with the flame combustion are: oxygen pressure 170 kpa, acetylene pressure 100 kpa, oxygen flow 1.7 m^3/h; acetylene flow 0.93 m^3/h; spray distance 175-200 mm and Feed rate 9.1 kg/h. Combustion flame spraying results in a coating that isn't strongly bonded to the product because the spraying mechanism is driven by a relatively low flame velocity and temperature around 50 m/s velocity and below 3000 degrees C. Typically, combustion flame spraying uses powder or wire as the main coating mixture component. Flame spray serves to clad a substrate with a powder-based material. It is a widely applied technique not only because it is one of the most economical options but also because it can be applied to a wide range of materials. Amongst the spraying materials, nickel-based alloys are being widely used because they display good resistance to wear, oxidation and high temperature corrosion, as well as being low cost [11]. These coatings are commonly used in mechanical components such as rollers in cooling tables in hot strip mills, pump bushings and wearing plates [12].

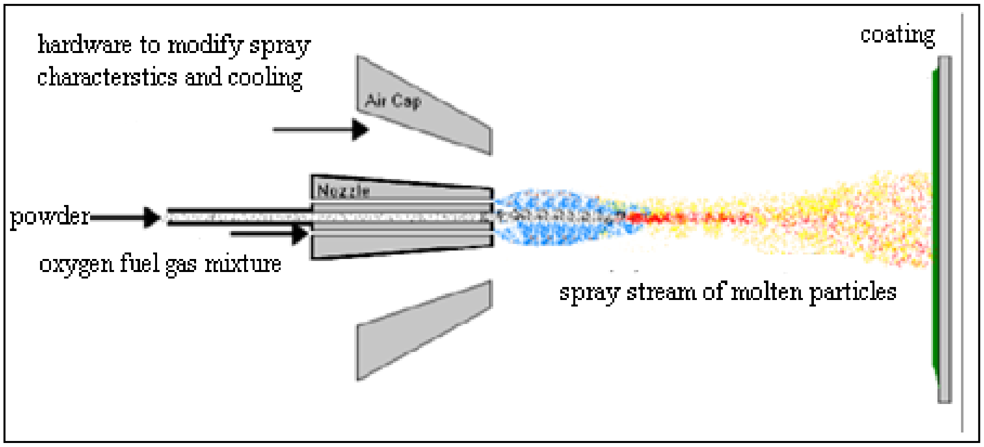

Figure 1. Combustion flame spray coating process

1.1.2. **High velocity oxy fuel coating process** (HVOF):

It is similar in theory to combustion flame spraying, but uses a different torch design that enables the flame to expand when the spray nozzle is activated. This causes a surge in acceleration, which in turn accelerates the mixture particles. When the mixture is released from the nozzle, the velocity of the mixture leads to a very thin and evenly applied coat (figure 2). The high velocity oxy-fuel (HVOF) process has been used to provide coatings with excellent mechanical properties. Such spraying processes use high kinetic energies and relatively low temperatures (~700 ◦C), causing the partially molten particles to interlock with each other, increasing the cohesive strength. Adhesion at the coating and substrate interface for a typical HVOF coating can be 10times higher than those from other flame spraying processes [13].

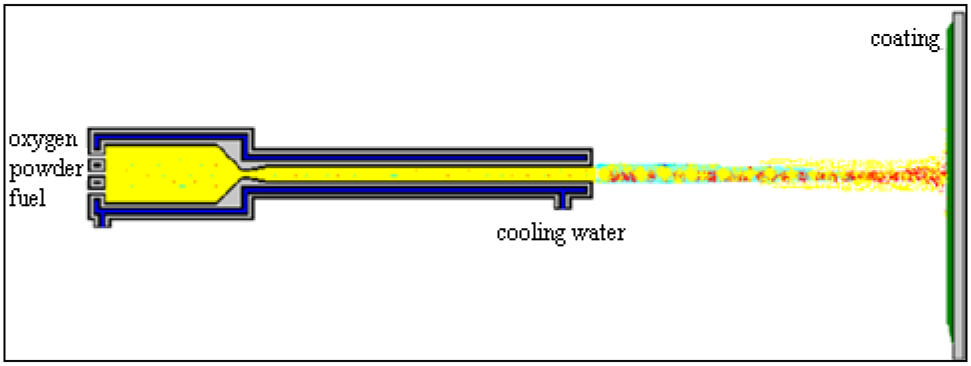

Figure 2. High velocity oxy fuel coating process (Reference 13)

The relatively low temperature minimises the amount of oxides and impurities within the coating matrix. A uniformly sprayed HVOF coating also usually contains less porosity (1–3%) than those from other conventional thermal spraying process (5–20%) [13]. High velocity oxy-fuel (HVOF) coatings have been used widely in various engineering components for combating wear and corrosion. Components that are coated by the HVOF method include propellers, pump impellers and casings, valve bodies/trim and pipe systems [14].

1.1.3. Two wire Electric Arc Spraying coating process:

In arc spraying, an arc is formed between two wires. The molten ends of the wires are dispersed and accelerated by a gas stream (air or nitrogen gas). The temperature in the arc can reach 5000 ◦C. The particle velocity lies in the range of 100–300 m/s (figure 3). A combination of high arc temperature and particle velocities give arc sprayed coatings superior bond strengths and lower porosity levels when compared with flame sprayed coatings. However, use of compressed air for droplet atomisation and propulsion gives rise to high coating oxide content [15]. V.E. Buchanan et al.[16] used two wire arc spray coating for iron chromium based metal in their work coating was prepared with the following spraying parameters: atomising air pressure = 500 kpa, current = 165 A, voltage = 34V and spraying distance = 90 mm. Spraying proceeded until the coating was approximately 8 mm thick after which the disc was removed from the lathe and ground to a final thickness of 6 mm. Typical general applications are thermal barriers, wear resistance, corrosion resistance, high dielectric strength, hard dense coating, decorative arts, etc [15].

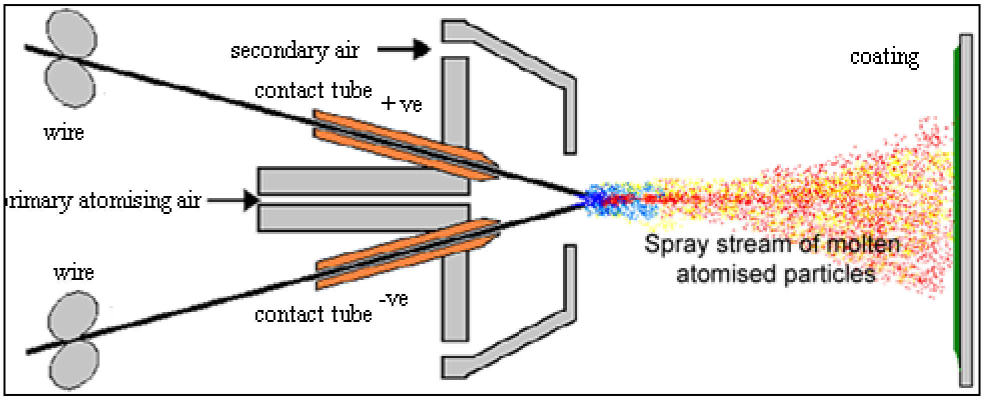

Figure 3. Two wire electric arc spray coating process (Reference 15)

1.1.4 Plasma Spraying coating process:

In plasma spraying, a plasma torch is the primary mode of heating and applying the coating. Once the material, usually powder, has been melted, it is subsequently applied to the product in much the same manner as combustion flame spraying. Coatings can range in thickness from a few micrometers to several millimeters. Plasma spray coating raw material isn’t limited to powder, and includes metals and ceramics-the spray gun can apply a combination mixture evenly (both ceramic and metal) and results in a rapid application process (figure 4). Plasma spray, one of the coating processes which is a widely used method among the thermal spray processes, is extensively used to improve the surface characteristics of materials [17]

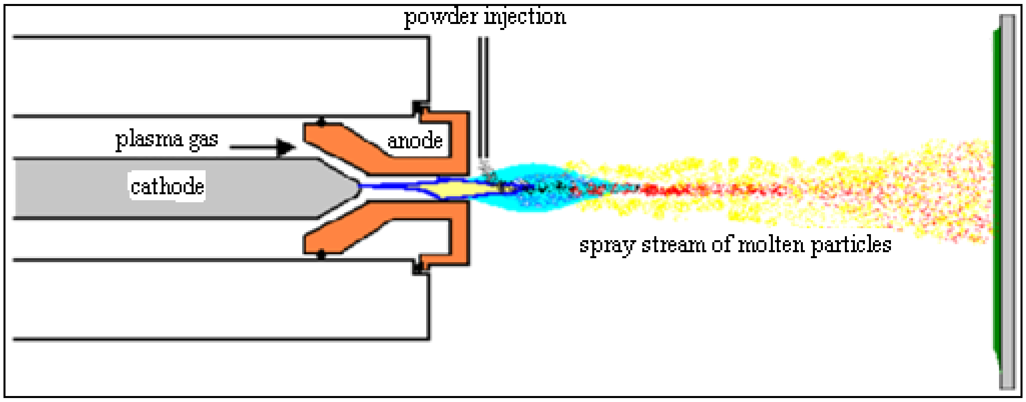

Figure 4. Plasma spraying coating process (Reference 17)

1.1.5 Vacuum Plasma Spraying coating process:

Vacuum Plasma Spray (VPS) technique is able to produce thick coatings in shorter times and at lower substrate temperature, in comparison with those obtained by traditional thermo chemical treatments [18]. The use of VPS technique to obtain iron boride coatings is particularly valuable, since it allows to continuously vary the composition of the single layers by means of different amounts of FeB, Fe_2B and alpha-Fe in the different spraying passes; in such a way that it is possible to design the characteristics of the coatings and, thus, the tribological properties of the coated steels [18]. Vacuum plasma spraying is often used to coat automobile components, such as bumpers, dashboard parts, and door mirror housings. Additionally, the process can help pretreat polyethylene moldings, enabling adhesion of water-based epoxy adhesives and other coatings.

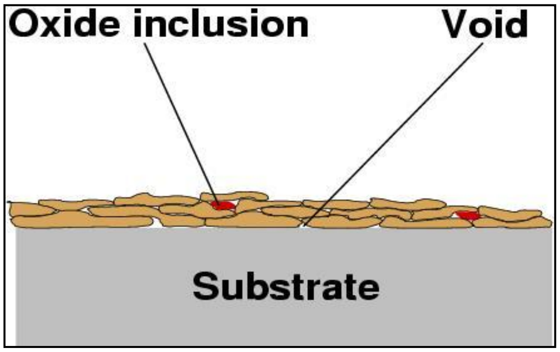

Figure 5. Vacuum plasma sprayed coating process

1.1.6 Cold sprays coating process:

The cold-gas dynamic-spray process, often referred to as ‘‘cold spray’’, is a high-rate coating and free-form fabrication process in which fine, solid powder particles (generally 1–50 lm in diameter) are accelerated to velocities in a range between 500 and 1000 m/s by entrainment in a supersonic jet of compressed (propellant) gas.

The solid particles are directed toward a substrate, where upon impact; they undergo plastic deformation and bond to the surface, rapidly building up a layer of the depositing material [19]. Compressed gas of an inlet pressure on the order of 30 bar (500 psi) enters the device and flows through a converging/diverging De Laval-type nozzle to attain a supersonic velocity (figure 6). The solid powder particles are metered into the gas flow upstream of the converging section of the nozzle and are accelerated by the rapidly expanding gas. To achieve higher gas flow velocities in the nozzle, the compressed gas is often preheated. However, while preheat temperatures as high as 900 K are sometimes used, due to the fact that the contact time of spray particles with the hot gas is quite short and that the gas nozzle, the temperature of the particles remains substantially below the initial gas preheat temperature and, hence, below the melting temperature of the powder material.

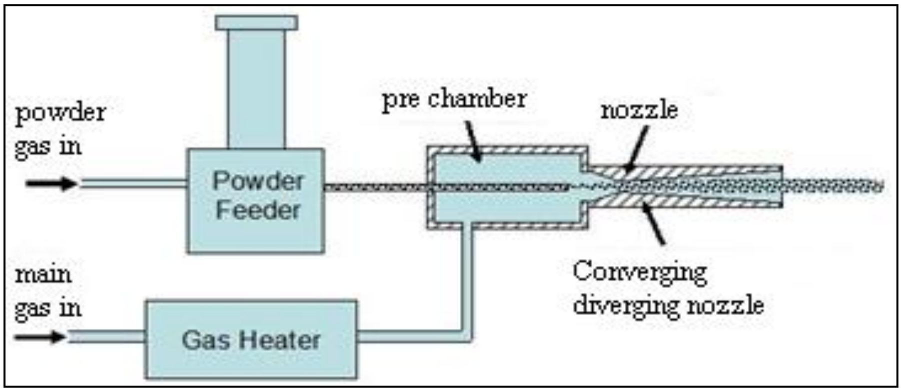

Figure 6. Cold spray coating process.

1.2. Properties of thermal sprayed coating:

1.2.1. Stresses and strength in thermal spray coatings:

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 (figure 7). 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.

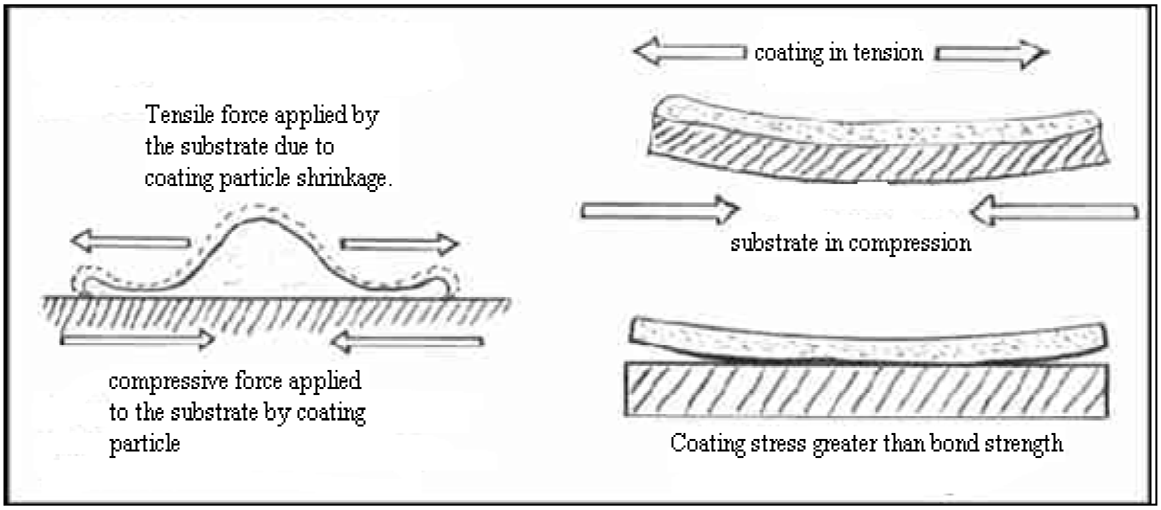

Figure 7. Stresses on coating

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.

Spraying 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) 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 [20].

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 [20].

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 affects 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.

1.2.2. Porosity:

In most thermally sprayed coatings (except VPS, post heat treated coatings or fused coatings) 1 to 25% porosity is normal but can be further manipulated by changes in process and materials [20].Porosity can be detrimental in coatings with respect to:

- Corrosion - (sealing of coatings advised).
- Machined finish.
- Strength, micro hardness 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.

1.2.3. 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 [20].

1.2.4. 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). 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 without finishing like that of electroplated deposits [20]. For the aluminum coating the texture and final grain size in recrystallized products are determined by amount of cold work, annealing conditions that are rate of heating, annealing temperature and time, compositions and the size and distribution of intermetallic compounds which tends to restrict grain growth. Texture developed by cold-working cause directionality in certain mechanical properties. Texture hardening causes moderate increase in both yield and tensile strength in the direction of working and it has been estimated that with an ideal fibre texture, the strength in the fibre direction may be 20% higher than that for sheet with randomly oriented aggregates of grains [57].

1.3. Application of the thermal spray coating:

Coatings are different types depends on application these may be given below

1. Wear resistance coating.
2. Medical coatings.
3. Corrosion protection coatings.
4. Coatings for carbon fiber composites.
5. Dielectric coating.
6. Electrically conductive coatings.
7. EMI/RFI coatings.
8. Food processing equipment coatings.
9. Thermal barrier coatings.

1.3.1. Wear resistance thermal sprayed coatings:

Some of the more common materials thermal spray technologies use to provide wear resistant coatings include ceramics such as carbides and metal oxides. Carbide coatings are produced in the form of cermets (ceramic and metal) they provide hardness and wear resistance coatings similar to solid sintered carbide components like carbide metal cutting tools [10]. Metal oxides such as chromium oxide are also very hard and are very resistant to chemical attack so they can be an ideal solution when wear and corrosion are both present. Several metals and even some plastics are also used to provide wear resistant coatings. One of the main purposes for which this coating is chosen, is the production of very hard surfaces, resistant to pressure, impacts and wear; many types of tools can be made as gauges, mechanical components, rolls of many kinds [1], plates and weapons (barrel of guns).

1.3.2. Medical thermal sprayed coatings:

Thermal spray technologies offer several coatings for the medical industry. These coatings are used in variety of applications. In each application our understanding of materials engineering is used to provide the exact coating properties required for the application. Thermal spray medical device coatings can be found in electrosurgical instruments, X-ray and MRI machines, and dental and orthopedic implants, prosthetics, etc. A promising technique of thermal spraying has been successfully developed to improve the mechanical properties of surfaces. The two main drawbacks of this technique for tribological applications are generally considered to be the small surface hardness and low wear resistance. These drawbacks significantly restrict applicability of thermal spraying. For these reasons there has been an increasing interest in developing hardening processes that improve the mechanical surface properties of thermal sprayed coatings. Nitriding is one very common process of surface thermal chemical treating, which improves the wear resistance of steels. Technology of low energy, high-current-density ion implantation developed recently is an efficient instrument for surface engineering. Investigations have shown that ion implantation at low energies (1–5 keV), but with high-current densities (1–3mA/cm^2) can produce several microns thick modified layers with a high nitrogen content, when the processing is performed at moderate temperature. Low energy high-current-density ion implantation is especially effective in processing of alloys with high concentration of chemically active elements and structure defects. It makes this technique prospective for surface engineering of thermal sprayed high-alloyed steel coatings. The article attempts to briefly summarize the recent progress in our understanding of low energy high-current-density nitrogen ion beam processing on tribological properties of the thermal sprayed coatings [21].

1.3.3 Corrosion protection thermal sprayed coatings:

There are several corrosion resistant coatings that can be engineered to provide a corrosion resistant barrier for many substrate materials in many corrosive environments. Nickel-chromium and cobalt-chromium alloys produce very good corrosion resistant coatings. These materials can be deposited with very low porosity levels (less than 1%) to prevent corrosive attack through porous connections. Oxide ceramics are also very corrosion resistant materials and can be applied to most metal substrates to provide corrosion resistant coatings. The corrosion behavior of aluminum and its alloys mainly depends on the process parameters, chemical composition of the materials and the electrolytes used. Alumina ceramic nanocomposite coatings are potentially very effective in developing wear resistant surface that also exhibit excellent corrosion resistance. A number of deposition techniques such as arc-discharge plasma, gas-flame spray, and vacuum deposition methods, high temperature glass annealing and laser surface modification have been employed to produce ceramic nanocomposite coatings on metals. These techniques require a high substrate temperature to provide adequate coating adhesion at high contact loads. Earlier research showed that the nanocomposite coatings offered attractive combination of wear resistance, corrosion resistance, mechanical strength, interfacial adhesion and thermal property. This is especially true for aluminum and its alloys in aerospace, automotive, textile engineering etc [22]. Plasma Electrolytic Oxidation (PEO) sometimes also referred as micro arc oxidation (MAO), plasma anodizing and spark anodizing is a promising surface treatment for aluminium and magnesium alloys for hexavalent chromium replacement in corrosion protection or to improve the tribological properties of the alloys. PEO technology has been successfully used for producing ceramic coatings on aluminum, magnesium and titanium alloys. The corrosion behaviour of aluminum and its alloys mainly depends on the process parameters, chemical composition of the materials and the electrolytes used [22].

1.3.4 Thermal sprayed coatings for carbon fiber composites:

The increased need for composite structures and components to reduce weight, inertia and other engineering factors has created the need to improve the surface properties of these composites to prevent wear, corrosion, EMI/RFI leakage, oxidation, etc. Thermal spray coatings can be applied as thermal barriers (TBC), for wear resistance, corrosion resistance, oxidation barriers, and much more. When engineering a coating for composite parts, thermal spray technologies use its strong expertise in materials engineering and its strength of understanding the processes of thermal spray to produce solutions. Solutions include the unique transition layers and surface preparation techniques required to enhance adhesion, mitigate stress, and enhance coating performance. The combination of this knowledge provides application specific solutions to our customers' coating needs. There are few limitations to thermal coating materials that can be applied to composite parts. Yttria-stabilized zirconia (YSZ), chromium oxide, aluminum oxide, tungsten carbide, aluminum, tin, zinc, nickel chromium, and many more have been applied to production composite materials [23].

1.3.5. Dielectric thermal sprayed coatings:

Dielectric coatings are used for high and low voltage applications over the range of DC to RF. With the ability of thermal spray to apply an almost limitless number of materials, a well-engineered dielectric coating can be produced to solve even some of the most complex electrical problems. Dielectric strengths for ceramic coatings range from 350 to over 1000 volts per mil, as a function of thermal spray process and parameters. When engineering a dielectric coating thermal spray technologies uses its strong expertise in materials engineering and its strength of understanding of the processes of thermal spray and electrical phenomena. The combination of this knowledge provides application specific solutions to our customers' electrical problems.

The most commonly used thermal spray dielectric materials are oxide ceramics and polymers. Ceramics are more durable, wear and corrosion resistant, and have higher dielectric strengths than polymers. Common materials include oxides of aluminum, titanium, and yttrium [24]. Other materials, alloys, and compounds are used as well. Practical uses for dielectric coatings includes semiconductor heat sinks, electro-surgical instruments, corona treated rolls for printing, corona suppression in high voltage systems (including PVD processing), application of high-temperature strain gages, fabrication of thermal spray resistance heaters, as substrates for sprayed electrical conductors, free-standing electrical insulators such as laser wave guides, etc.

1.3.6. Electrically conductive thermal sprayed coatings:

A wide variety of materials can be engineered into thermal spray coatings to provide different degrees of electrical conductivity. Materials such as copper, aluminum, and molybdenum are the most commonly used. Materials such as iron-chrome-aluminum and molybdenum-disilicide are used for higher temperature applications. Some oxide ceramics are used as conductors and semi-conductors for specialized applications [23]. When engineering an electrically conductive coating thermal spray technologies uses its strong expertise in materials engineering and its strength of understanding the processes of thermal spray. Operating temperatures, environmental medium, and life cycle requirements are just a few of the considerations for developing an effective solution for electrical conductivity. The combination of this knowledge provides application specific solutions to our customers' electrical design issues.

Coatings material: Electrical conductivity exists at some level in most materials and can be affected by temperature and environment. Metals, metal alloys, and some ceramics are useful conductors. Generally, electrically conductive coatings require low resistivity making aluminum, copper, and their alloys the best solutions. Where high temperatures are involved, materials that produce a protective, self-healing scale are more suitable. These materials include iron-chrome-aluminum, moly-disilicide, and others. Gradated coatings are often employed for high-temperature applications.

Substrate material: Electrically conductive thermal spray coatings can be applied to everything from polymers and composites to ceramics. Considerations for application include power levels and coating/substrate interactions under power and at temperature.

Example: Conductive thermal spray coatings can and have been used to create heating elements, slip rings, static dissipative elements, ground straps, flexible circuits, in situ thermocouples, commutator segments, contact points for silicon carbide heating elements, and much more.

1.3.7. EMI/RFI thermal sprayed coatings:

With lightweight requirements, higher frequency CPU's, higher power devices, and increased use of personal electronics such as cell phones and PDA's there is an increasing need to shield sensitive electronics from spurious and stray electromagnetic radiation. Thermal spray techniques are suitable for such applications. Electromagnetic interference (EMI) and radio frequency interference (RFI) can be mitigated with the use of thermal spray coatings. Attenuation levels of 80 dB are practical. When engineering an EMI/RFI shielding coating thermal spray technologies uses its strong expertise in materials engineering, its strength of understanding of the processes of thermal spray, and its understanding of EMI/RFI shielding issues. The combination of this knowledge provides application specific solutions to our customers' electrical noise problems.

Coatings material: Some of the more common materials thermal spray technologies uses to provide EMI/RFI shielding include a variety of pure metals and metal alloys such as aluminum, copper, tin, and zinc [8]. Substrate material: Thermal spray EMI/RFI coatings can be deposited onto virtually all substrate materials. Typically, these coatings are applied to materials that are transparent to noise and include carbon-based materials such as carbon composites, polymers, paper, wood, etc. The low thermal transfer of thermal spray processes permits the coating of these heat sensitive materials. Permanent structures, including concrete, are coated using thermal spray to produce a Faraday cage.

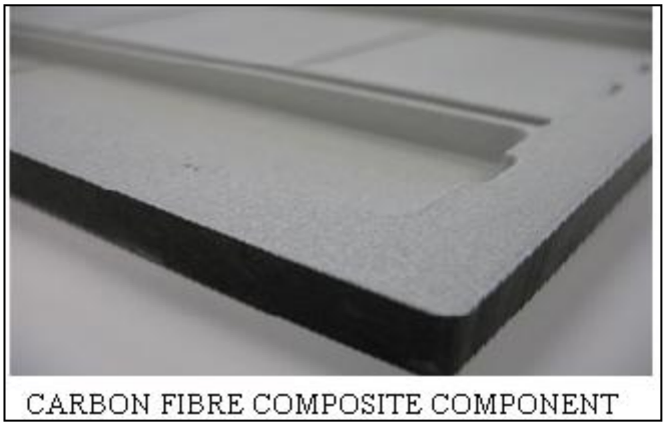

Figure 8. Carbon fiber composite component with thermal coating

Example: Lightweight electronic enclosures are coated to provide EMI/RFI shielding that prevents stray radiation from either entering or exiting the enclosure to protect the onboard electronics as well as peripheral electronics. Noise sources include switches, oscillator circuits, transformers, CPU's, etc. Plastic cases for consumer products like computers, cell phones, calculators, radios, and more can be coated economically. Thermal spray can be also used to suppress commutator noise from motor brushes by coating the enclosure near the motor. Industrial applications include process control enclosures, high-energy enclosures such as x-ray equipment, motor controls, etc.

1.3.8. Food processing equipment thermal sprayed coatings:

Thermal Spray Technologies offers a variety of coatings for industrial food processing equipment. The coatings are typically used to provide excellent wear and corrosion resistance against the food product being processed. These coatings are also used to provide wear and corrosion resistance on similar equipment used to process pharmaceuticals and personnel hygiene products. In the sugarcane industry, hard facing is carried out on grey cast iron mill roller shells to reduce wear, to permit higher extraction loads and to aid the movement of the crushed cane through the rollers [25]. Manufacturers have developed specialized welding electrodes for the sugarcane mill roller shells that optimize the deposition efficiency and the resulting wear resistance when typical welding environments, such as hard facing the wet surface of a rotating roller are encountered. Ternary Fe–Cr–C based alloys containing more than 20% alloying additions are the most popular group of hard facings in the sugar cane industry due to their relatively low cost and ease of application. These alloys generally have a composition in which primary carbides are formed during the weld deposition process, and the good wear resistance is attributable to a microstructure in which hard carbides are dispersed in a softer eutectic matrix [25].

Figure 9. Thermal spray coated food processing equipments

1.3.9. Thermal barrier thermal sprayed coatings:

One of the most common uses of Thermal barrier coatings TBC's is in the combustion sections of aircraft turbine engines. With the demand for fuel economy and increased power, combustion temperatures are approaching the design limits of the metal alloys from which turbine components are made. The use of thermal barrier coatings in this and other application enables the use of the alloys at higher temperatures, by reducing the temperature to which the parts are exposed. With the ability of thermal spray to apply an almost limitless number of materials, well-engineered thermal barrier coatings can be produced to solve even some of the most complex thermal barrier problems.

Figure 10. Thermal spray coated jet engine components

When engineering a thermal barrier coatings system, thermal spray technologies uses its strong expertise in materials engineering and its strength of understanding of the processes of thermal spray. The combination of this knowledge provides application specific solutions to our customers' thermal management problems.

Practical uses for thermal barrier coatings include turbine blades, burner cans, and aft liners for turbine engines to increase fuel efficiency and power. Thermal barrier coatings have been used in racing engines since the 70's. Automotive and heavy equipment pistons and missile components are also coated with thermal barrier coatings. Thermal barrier coatings are also use in braking systems to keep heat away from hydraulic components.

1.4. Material which can be thermal spray:

Just like the diversity of the technologies of thermal spray, the types of materials that can be used to produce coatings, and the materials onto which coatings can be deposited, are very wide in variety. At thermal spray technologies we like to use the philosophy that the imagination is the only limitation to what can be produced using thermal spray.

Almost all metals can be thermal sprayed to produce coatings. Many plastics can also be thermal sprayed, especially plastics that have a good melting range. With some of the thermal spray processes capable of generating temperatures as high as 30,000 °F, (> 16,500 °C) very high melting point materials can be thermal sprayed such as oxide ceramics [27-28]. In general, if a material melts there is a very good chance the material can be used to create a thermal spray coating. Even materials that sublime in many cases can be used in thermal spray coatings. One common method to produce a coating with a material that sublimes is to combine it with a material that does melt. The material that melts will act like a cement when the two materials deposit together to create a composite coating.

1.5. Wear of thermal spray coating:

It is the erosion of coating by the action of another surface [28]. It is related to surface interactions and more specifically the removal of material from a coating as a result of mechanical action. The need for mechanical action, in the form of contact due to relative motion, is an important distinction between mechanical wear of coating and other processes with similar outcomes [8].The definition of coating wear does not include loss of dimension from plastic deformation, although coating wear has occurred despite no material removal, because it may lack the action of another surface. This definition also fails to include impact wear of the coating, where there is no sliding motion, cavitations, where the counter body is a fluid, and corrosion, where the damage is due to chemical rather than mechanical action [1,22].

Coating wear can also be defined as a process in which interaction of the surfaces or bounding faces of a solid with its working environment results in dimensional loss of the solid, with or without loss of material. Aspects of the working environment which affect coating wear include loads (such as unidirectional sliding, reciprocating, rolling, and impact loads), speed, temperature, type of counter body (solid, liquid, or gas), and type of contact (single phase or multiphase, in which the phases involved can be liquid plus solid particles plus gas bubbles) [9].

1.6. Types of wear of the coating:

The study of the processes of wear of coating is part of the discipline of Tribology. The complex nature of coating wear has delayed its investigations and resulted in isolated studies towards specific wear mechanisms or processes. Some commonly referred to wear mechanisms of coating (or processes) include [59]:

1. Adhesive wear ,
2. Abrasive wear
3. Surface fatigue
4. Fretting wear
5. Erosive wear

A number of different wear phenomena of coating are also commonly encountered and represented in literature. Impact wear, cavitations wear, diffusive wear and corrosive wear are all such examples. These wear mechanisms; however, do not necessarily act independently in many applications. Wear mechanisms of the coatings are not mutually exclusive. "Industrial Wear" is the term used to describe the incidence of multiple wear mechanisms occurring in unison. Wear mechanisms and/or sub-mechanisms frequently overlap and occur in a synergistic manner, producing a greater rate of wear than the sum of the individual wear mechanisms.

1.6.1. Adhesive wear of coating:

Adhesive wear is defined as the transfer of material from one surface to another during relative motion by a process of solid-phase welding or as a result of localized bonding between contacting surfaces. Particles that are removed from one surface are either permanently or temporarily attached to the other surface [29]. Adhesive wear of coating occurs when two body slides over each other, or are pressed into one another, which promote material transfer between the two surfaces. When either one of two surfaces of tribo-elements in sliding or rolling contact has thin soft surface layer that can partly transfer to the counter surface by adhesion, relative displacement takes place at the interface between the surfaces of coating and transfer layer with smaller shear strength of the soft material than that of the underlying element material. Low friction is obtained as a result, and wear of the tribo elements is much reduced. Soft metal coating is introduced for this purpose, and Au, Ag, Pb and In are representative ones [30]. However, material transfer in coating is always present when two surfaces are aligned against each other for a certain amount of time and the cause for material transfer or wear-categorization have been a source for discussion and argumentation amongst researchers for quite some time and there are frequent misinterpretations or misunderstandings due to overlaps and symbiotic relations between "wear" and physical-chemical mechanisms as previously mentioned. Having described the restriction on the subject wear, we can focus on what causes material transfer in wear of coating.

Adhesive wear of the coating can be described as plastic deformation of very small fragments within the surface layer when two surfaces slides against each other. The asperities (i.e., microscopic high points) found on the mating surfaces will penetrate the opposing surface and develop a plastic zone around the penetrating asperity [31].

Dependent on the surface roughness and depth of penetration will the asperity cause damage on the oxide surface layer or even the underlying bulk material of the coating surface. In initial asperity/asperity contact, fragments of coating are pulled off and adhere to the other, due to the strong adhesive forces between atoms. It is thereby clear that physical-chemical adhesive interaction between the surfaces plays a role in the initial build-up process but the energy absorbed in plastic deformation and relative movement is the main cause for material transfer and wear of the coating.

Adhesive wear is the most common form of wear of coating and is commonly encountered in conjunction with lubricant failures. In engineering science, some aspects of adhesive wear is commonly referred to as welding wear due to the exhibited surface characteristics and the Tribology process is usually referred to as galling and is a common fault factor in sheet metal forming (SMF) and other industrial applications.

The tendency of contacting coating to adhere arises from the attractive forces that exist between the surface atoms of the two materials. The type and mechanism of attraction varies between different materials. Most solids will adhere on contact to some extent, however, oxidation films and contaminants naturally occurring; generally suppress adhesion. Surfaces also generally have low energy states due to reacted and absorbed species. The mechanism of adhesive wear of coating occurs due to contact possibly producing surface plastic flow, scraping off soft surface films or breaking up and removing oxide layers. This brings clean regions into contact and introduces the possibility of strong adhesion. The removal of material from coating surface, or wear, takes the form of small particles. These small particles are usually transferred to the other surface but may come off in loose form.

1.6.2. Abrasive wear of coating:

The abrasive wear of a material is defined as the progressive loss of material due to abrasive action of hard particles present between the counter surfaces. The abrasive wear depends on various factors like abrasive size, rake angle of abrasives, applied load and shape, size, volume fraction of the dispersed phases. In addition to these factors the abrasive wear rate of a material also depends on the surface hardness and materials properties like fracture toughness [32]. Abrasive wear of coating occurs when a hard rough surface slides across a softer surface. ASTM (American Society for Testing and Materials) defines it as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface. Abrasive wear of coating is commonly classified according to the type of contact and the contact environment. The type of contact determines the mode of abrasive wear of coating. The two modes of abrasive wear of coating are known as two-body and three-body abrasive wear. Two-body wear occurs when the grits, or hard particles, are rigidly mounted or adhere to a surface, when they remove the material from the surface of coating [33]. The common analogy is that of material being removed with sand paper. Three-body wear occurs when the particles are not constrained, and are free to roll and slide down a surface of coating. The contact environment determines whether the wear is classified as open or closed. An open contact environment occurs when the surfaces are sufficiently displaced to be independent of one another.

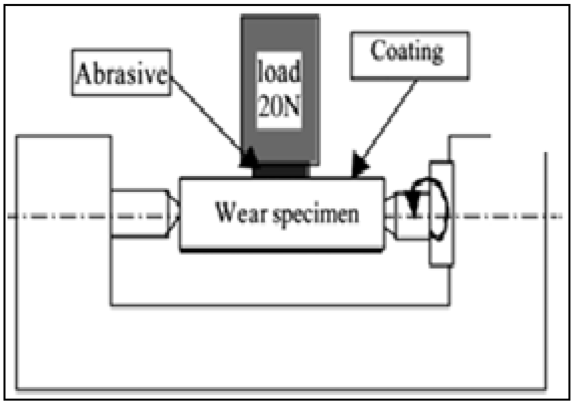

Figure 11. Abrasive wear of thermal spray coating (Reference 33)

There are a number of factors which influence abrasive wear of coating and hence the manner of material removal. Several different mechanisms have been proposed to describe the manner in which the material is removed. Three commonly identified mechanisms of abrasive wear of coatings are:

1. Plowing
2. Cutting
3. Fragmentation

Plowing occurs when coating material is displaced to the side, away from the wear particles, resulting in the formation of grooves that do not involve direct material removal from the coating surface. The displaced material forms ridges adjacent to grooves, which may be removed by subsequent passage of abrasive particles. Cutting occurs when coating material is separated from the surface in the form of primary debris, or microchips, with little or no material displaced to the sides of the grooves. This mechanism closely resembles conventional machining. Fragmentation occurs when material is separated from a surface by a cutting process and the indenting abrasive causes localized fracture of the coating material. These cracks then freely propagate locally around the wear groove, resulting in additional material removal by spalling.

1.6.3. Surface fatigue wear of the coating:

Surface fatigue wear of the coating is a process by which the surface of coating is weakened by cyclic loading, which is one type of general material fatigue. Fatigue wear in coating is produced when the wear particles are detached by cyclic crack growth of micro cracks on the surface of the coating. These micro cracks are either superficial cracks or subsurface cracks. It is extremely important to improve the resistance of the material against fracture in aerospace applications.

In the case where this alloy is, for example, used for turbine engine blades, the fretting fatigue, which is caused by the combination of cyclic fatigue stress and frictional wear, occurs at turbine engine blade roots. As a result, many small cracks will easily initiate on the material surface. Also, it has been reported that the fretting fatigue life decreases remarkably as compared with plain fatigue life [34]. The use of high strength steels instead of tool steels brought out a new aims for material scientists – increase endurance of the tool materials in cyclic loading (cold forging, stamping and blanking). To solve the fatigue damage problems of high-speed steels (HSS) the powder metallurgy (PM) routes are used. As a result of the finer and more uniform microstructure that PM-HSSs exhibit, as compared to their conventionally produced counterparts, they also present enhanced cross-sectional hardness uniformity (wear resistance), fracture toughness and fatigue strength [35].

1.6.4. Fretting wear of coating:

Fretting wear of the coating is the repeated cyclical rubbing between coating and another surface, which is known as fretting, over a period of time which will remove material from one or both surfaces in contact. It occurs typically in bearings, although most bearings have their surfaces hardened to resist the problem. Another problem occurs when cracks in either surface are created, known as fretting fatigue [35]. It is the more serious of the two phenomena because it can lead to catastrophic failure of the bearing. It is extremely important to improve the resistance of the material against fracture in aerospace applications. In the case where this alloy is, for example, used for turbine engine blades, the fretting fatigue, which is caused by the combination of cyclic fatigue stress and frictional wear, occurs at turbine engine blade roots [36]. As a result, many small cracks will easily initiate on the material surface. An associated problem occurs when the small particles removed by wear are oxidized in air. The oxides are usually harder than the underlying metal, so wear accelerates as the harder particles abrade the metal surfaces further. Fretting corrosion acts in the same way, especially when water is present. Torsional fretting wear tests of the coating were conducted on a flat-on-ball contact on a torsional fretting rig with a controlled environmental chamber.

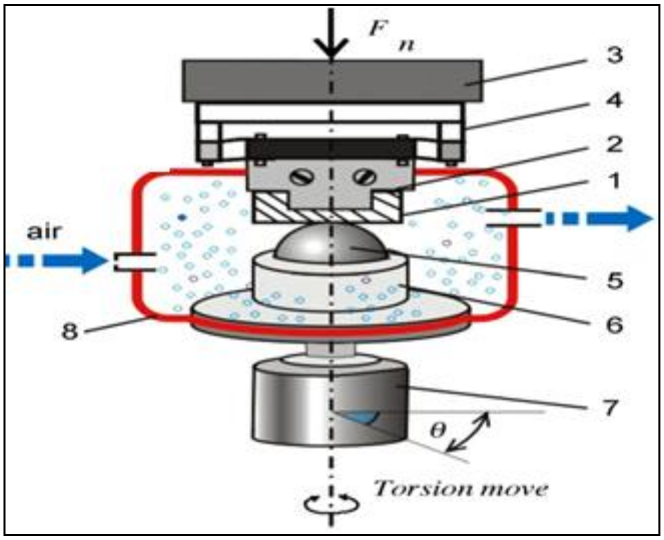

Figure 12. Fretting wear of thermal spray coating (Reference 8)

A plate specimen (1) was fixed on the upper holder (2) to link a six-axis torque/force sensor (3) (three loads of *x*, *y* and *z* direction; three torques of *x*, *y* and *z* direction) through a spring suspension (4). A ball specimen (5) was mounted on the lower holder (6), which fixed on the low-speed reciprocating rotary motor system (7). The flat specimen rotated following the motion of the motor at a constant rotary velocity (in the range of 0.01–5∘/s). In order to ensure pure torsional fretting, the centerline the ball specimen was superposed strictly to the rotary axis of the motor system at all times [8]. Angular displacement of the contact pair was measured by a sensor in the motor system and unprotected bearings on large structures like bridges can suffer serious degradation in behaviour, especially when salt is used during winter to deice the highways carried by the bridges. The problem of fretting corrosion was involved in the Silver Bridge tragedy and the Mianus River Bridge accident.

1.6.5. Erosive wear of coating:

Erosive wear of the thermal spray coating is caused by the impact of particles of solid or liquid against the surface of coating [13]. The impacting particles gradually remove material from the coating surface through repeated deformations and cutting actions. It is a widely encountered mechanism in industry. A common example is the erosive wear associated with the movement of slurries through piping and pumping equipment (fig 13).

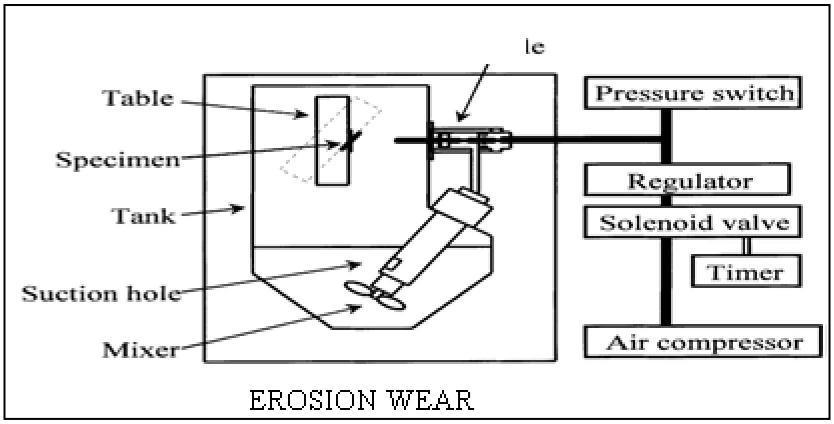

Figure 13. Erosion wear of thermal spray coating (Reference 13)

The rate of erosive wear is dependent upon a number of factors. The material characteristics of the particles, such as their shape, hardness, and impact velocity and impingement angle are primary factors along with the properties of the surface of the coating [13,28]. The impingement angle is one of the most important factors and is widely recognized in literature. For ductile coating materials the maximum wear rate is found when the impingement angle is approximately 30°, whilst for non ductile coating materials the maximum wear rate occurs when the impingement angle is normal to the surface.

1.7. Types of wear test of thermal spray coating:

Wear behavior of the can be measured on the different test and is mainly depends on the application of the coating and thickness of the coating. The test is carried out at different wear conditions and the parameter are taken into consideration on which the wear is mainly depends. These tests are such mainly divided into these categories:

1.7.1. Scratch test of thermal spray coating:

The scratch tester is used to test the scratch resistance of flat solid surfaces such as coatings, metals, ceramics, composites, polymers, and other material surfaces. The test is performed by sliding a stylus over the surface of the test specimen. The normal load, sliding speed, direction, stylus geometry, and stylus material can be varied. The resultant tangential force at the contact interface can be monitored using tribodata, the supplied windows-based data acquisition Software. The onset of scratch or adhesion failure of coatings can be inferred from this data. A CMOS camera is built-in to capture the scratch scar image. Y. Xie et al. [7] was investigated scratching an alumina coating, using conical diamond indenters with different tip radii under either progressively increasing or constant loading. The interaction between the coating and the indenter was studied by performing single scratching on a polished virgin surface, repeated scratching over the same track and closely-spaced, multiple parallel interacting scratching.

1.7.2. Slurry Abrasion Test of thermal spray coating:

The Slurry Abrasion Tester is used to test the abrasive resistance of solid materials to slurry compositions. Slurry erosion problems are especially important during rainy seasons in hydroelectric power plants due to the increase in the number of solid particles impacting the surfaces, especially in systems where the installation of an exhaustive filtration process is not possible [37]. Various materials such as metals, minerals, polymers, composites, ceramics, coatings, and heat-treated materials can be tested with this instrument. The test is performed by rotating a rectangular test sample within a cup filled with abrasive slurry (figure 14). The mass of the test sample is recorded before and after conducting a test and the difference between the two values is the resultant mass loss due to slurry abrasion [13].

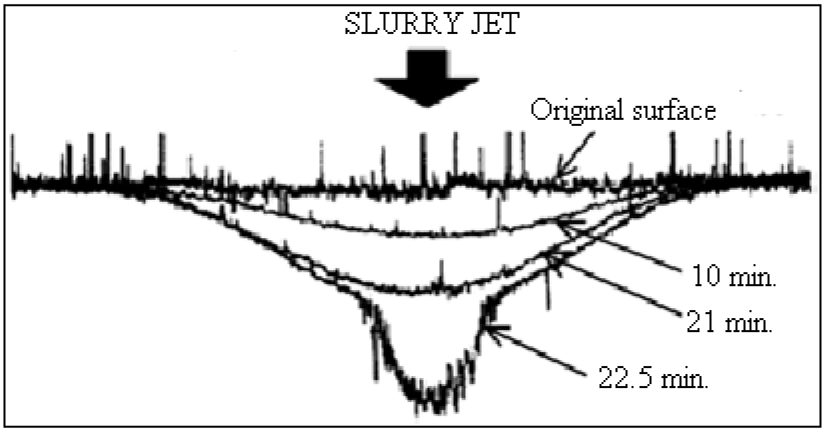

Figure 14. Slurry abrasion wears of thermal spray coating

To develop a comparison table for ranking different materials with respect to each other, it is necessary to convert this mass loss to volume loss to account for the differences in material densities. The test speed, temperature, duration, as well as test sample size and slurry composition, can be varied. The instrument is configured to run up to six test samples simultaneously at the same speed. The test temperature is maintained by immersing the slurry vessels in a water bath.

1.7.3. Friction Test of thermal spray coating:

The Friction Tester is used to test the frictional characteristics of materials in dry or lubricated reciprocating motion contact. A wide variety of materials including fluid lubricants, greases, cutting fluids, metals, composites, ceramics, polymers, and coatings can be tested. The test is performed by loading the test specimen against a ball, pin, or cylinder undergoing reciprocating linear motion. The frictional force developed at the contact interface is measured by a force transducer. The output signal can be captured by a storage oscilloscope or tribodata, Koehler's data acquisition software, for evaluation. The reciprocating motion of the ball results in a unique velocity profile which allows for monitoring of static and dynamic friction force over a wide range of linear sliding speeds. The test load, stroke, frequency, and temperature can be adjusted to simulate different testing conditions. Wear testing may also be performed on the test specimen by evaluating the resulting wear scar with a profilometer. Yucong Wang et al. [38] were performed with a modified Cameron Plint reciprocating machine to determine the scuffing and wear behavior of piston coatings against 390 Al engine cylinder bore. The tested piston coatings included nickel–tungsten (Ni–W).plating, electro less Ni plating, Ni–P coatings with ceramic particles such as boron nitride (BN), Sic, as well as titanium nitride physical vapor deposition (PVD) coating, diamond-like carbon (DLC) coating, and hard anodizing.

1.7.4. Air Jet Erosion Test of thermal spray coating:

The Air Jet Erosion Tester is used to test the erosion resistance of solid materials to a stream of gas containing abrasive particulate. The test is performed by propelling a stream of abrasive particulate gas through a small nozzle of known orifice diameter toward the test sample. Material loss, in this case, is achieved via the impingement of small abrasive particles upon the surface of the test sample. Materials such as metals, ceramics, minerals, polymers, composites, abrasives, and coatings can be tested with this instrument [13]. The test specimen, temperature, angle of incidence of the jet stream, abrasive particulate speed and flux density, can be varied to best simulate actual conditions. Special adapters are available to test various geometries and components for user-specified testing applications.

1.7.5. Pin on Disc Test of thermal spray coating:

The Pin-On-Disc Tester is used to test the friction and wear characteristics of dry or lubricated sliding contact of a wide variety of materials including metals, polymers, composites, ceramics, lubricants, cutting fluids, abrasive slurries, coatings, and heat-treated samples. The test is performed by rotating a counter-face test disc against a stationary test specimen pin (figure 15). The advantage of a wear test, when compared to indentation or scratch testing, is that it can give a measure of the lifetime of a particular coating-substrate system. In many applications of coatings, the resistance to wear can be more important than the load required to permanently damaging the material [39]. A spherical ended pin has the advantage that contact conditions can be relatively well controlled. No matter the degree of misalignment between pin axis and disk axis the initial apparent area of contact should be the same, for a given load. However, the apparent area of contact will then change during the test up to the maximum given by the pin-diameter [40]. The pin on disc test can be used for a variety of coatings it may be thick or thin and can be made of any material such as metals, ceramics, cermets and composites [9,13,48,49].

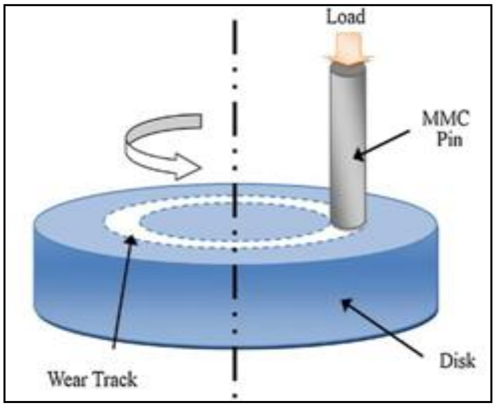

Figure 15. Pin on disc wear test of thermal spray coating (Reference 40)