Thermal Spray Technology

Introduction
In the simplest terms possible, thermal spray coating involves heating a material in powder or wire form to a molten or semi-molten state. The material is propelled using a stream of gas or compressed air to deposit it, creating a surface structure on a given substrate. The coating material may consist of a single element, but is often an alloy or composite with unique physical properties that are only achievable through the thermal spray process.

Generally speaking, thermal sprayed coatings are a highly cost effective way to add superior performance qualities to a given substrate. The variations on this technical theme are virtually limitless. Coatings can be metallic, ceramic, plastic, or any combination desired to meet a broad range of physical criteria.

Thermal sprayed coatings can be the most cost-effective means of protecting substrate surfaces from wear or corrosion. Other primary uses of thermal sprayed coatings include dimensional restoration, maintaining precise clearances, and modifying thermal and electrical properties.
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.

Bonding Mechanisms at the coating/substrate interface and between the particles:

1. Mechanical keying, Interlocking / anchoring
2. Diffusion metallurgical bonding
3. Other adhesive like Chemical and physical bonding mechanisms - oxide films, Van de Waals forces, etc.
The coating materials can be applied using several different processes. Thermal coating methods utilize fuel combustion, plasma spray and electric arc delivery systems. Coatings can be applied under standard atmospheric conditions or in specialized, highly controlled atmospheric environments – even under water! Coatings can be applied manually or with the automated precision of software-driven robotics. Many industries use our coatings to extend product life, increase performance and reduce production and maintenance costs.

Thermal spray process are classified through:
- Feed stock material
- Thermal Energy source
- Kinetic Energy produced

### Thermal spray process positioning

![Graph showing thermal spray process positioning](image-url)
Flame Powder Spray has been serving industries for decades with economical, reliable surfaces. Relatively low initial investment cost makes this an ideal process for entry level thermal spray coating.

**Theory of Operation:**
The Powder Flame Spray process is similar to the Wire Flame Spray process except that it has the advantage of using powdered materials as the coating feedstock. This offers a much wider range of coating material options than the Wire Flame Spray process. In addition, the use of powder allows for a greater degree of freedom for spray gun manipulation. The spray material in powdered form is fed continually into a fuel gas oxygen flame where it is typically melted by the heat of combustion. A powder feed carrier gas transports the powder particles into the combustion flame, and the mixed gases transport the material towards the prepared workpiece surface. Typical choices for fuel gases are acetylene or hydrogen.
Flame Powder Spray

Process properties:
- Feed stock: powder
- Combustion of fuel and oxygen
- Fuel: propane, hydrogen, acetylene
- Flame temperature < 3,200 °C
- Flame velocity low
- Particle velocity ± 50 m/s

Typical coatings:
- Self-fluxing alloys (fusing)
- Iron based alloys
- Nickel based alloys
- Ceramics & Cermets
- Abradables

Features and Benefits:
- Good economy with long consumable life
- Versatile and reliable
- Easy to operate
- Relative low operational noise
- Large choice of coating materials
- High production spray rates
- Process can be automated
- Portability

Typical Applications:
- Rebuild and Salvage Operations
- Abrasion Resistance
- Sliding Wear Resistance
- Impact Resistance
- Resistance to Chemical Attack
- Atmospheric and Heat Corrosion Control
Flame Wire Spray

Wire Flame Spray is the earliest thermal spray processes to be developed, with its usefulness enduring even today. A low initial investment cost makes this an ideal process for entry level thermal spray coating. Easily transported for on-site applications makes wire flame spray a favorite for infrastructure corrosion applications, such as bridgework.

Theory of Operation:
The spray material in wire form is fed continually into a fuel gas-oxygen flame where it is melted by the heat of that combustion. Compressed air surrounds the flame and atomizes the molten tip of the wire. This accelerates the spray of molten particles towards the prepared workpiece surface. Typical choices for fuel gases are acetylene, propane, hydrogen or MAPP.
Flame Wire Spray

Process properties:
- Feed stock: wire or rod
- Combustion of fuel and oxygen
- Fuel: propane, hydrogen, acetylene
- Flame temperature < 3,200 °C
- Flame velocity low
- Particle velocity < 150 m/s

Typical coatings:
- Iron based alloys
- Nickel based alloys
- Molybdenum
- Copper & Copper alloys
- Aluminium, Zinc, Al/Zn alloys

Features and Benefits:
- Excellent economy
- Versatile and reliable
- Easy to operate
- Coat large structures with minimal facilities
- High production spray rates
- Process can be automated
- Portability

Typical Applications:
- Wear resistance
- Friction properties
- Corrosion protection
- Electromagnetic shielding
- Rebuild and Salvage Operations

Microscopic Cross Section of a flame wire sprayed FeCrNiMn coating
Arc Wire Spray

Simple. Fast. Economical. The simplicity of this process, which uses electricity and compressed air, and the speed at which it applies coatings without fuel gas are the hallmarks of electric wire arc spraying.

**Theory of Operation:**
Arc Wire Spray uses two metallic wires as the coating feedstock. The two wires are electrically charged with opposing polarity and are fed into the arc gun at matched, controlled speeds. When the wires are brought together at the nozzle of the (spray gun), the opposing charges on the wires create enough heat to continuously melt the tips of the wires. Compressed air is used to atomize the now molten material and accelerate it onto the workpiece surface to form the coating. In arc wire spray, the weight of coating that can be deposited per unit of time is a function of the electrical power (amperage) of the system and the density and melting point of the wire.
Arc Wire Spray

Process Properties:
- Feed stock: wire
- El. Conductive wire (also cored wire)
- Heat is produced by electrical gas discharge (arc)
- Temperature < 4,000 °C
- Accelerating gas: air or nitrogen
- Particle velocity < 200 m/s

Typical coatings:
- Iron based alloys
- Nickel based alloys
- Copper & Copper alloys
- Aluminium, Zinc, Al/Zn alloys
- Babbitt alloys

Features and Benefits:
- Minimal facilities required
- Many substrate materials can be coated
- No combustible gas supply is required
- Versatile, reliable and easy to operate
- Large structures can be coated
- Excellent coating bond strength and density
- High production spray rates
- Produces easily to machine coatings
- Process can be automated
- Portability

Typical Applications:
- Atmospheric and heat corrosion control
- Rebuild and Salvage Operations
- Bond Coats
- Electrically Conductive and solderable Coatings
- Anti-skid and Traction Coatings
- Wear resistance
Air (atmospheric) Plasma Spray

Versatile. Only one word is necessary to describe what plasma spray does best... apply the widest variety of coating materials, by far, of any thermal spray process for an unlimited number of applications. Plasma spray performs where other processes cannot and is the best choice for facilities where many different surfaces must be applied. A superb choice for high-quality ceramic coatings. Plasma spray produces high-performance coatings that deliver workhorse durability and reliability.

Theory of Operation:
Plasma Spray is perhaps the most flexible of all of the thermal spray processes as it can develop sufficient energy to melt any material. Since it uses powder as the coating feedstock, the number of coating materials that can be used in the plasma spray process is almost unlimited. The plasma gun incorporates a cathode (electrode) and an anode (nozzle) separated by a small gap forming a chamber between the two. DC power is applied to the cathode and arcs across to the anode. At the same time, gases are passed through the chamber. 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°C to 16,600°C (12,000ºF to 30,000ºF), which exceeds surface temperatures of the sun. By injecting the coating material into the gas plume, it is melted and propelled towards the target component.

Typical plasma gases are Hydrogen, Nitrogen, Argon and Helium. Various mixtures of these gases (usually 2 of the 4) are used in combination with the applied current to the electrode to control the amount of energy produced by a plasma system. Since the flow of each of the gases and the applied current can be accurately regulated, repeatable and predictable coating results can be obtained. In addition, the point and angle that the material is injected into the plume as well as the distance of the gun to the target component can also be controlled. This provides a high degree of flexibility to develop appropriate spray parameters for materials with melting temperatures across a very large range.

The distance of the plasma gun from the target components, gun and component speeds relative to each other and part cooling (usually with the help of air jets focused on the target component) keep the part at a comfortable temperature that is usually in the range of 38°C to 260°C (100°F to 500°F).
Air (atmospheric) Plasma Spray

Process features:
- Feed stock: powder
- Process gasses: Ar, H2, N2, He
- APS, VPS, LPPS, HE-plasma, ...
- Plasma Temp. < 15,000 ºC
- Particle velocity: up to 500 m/s
- Plasma gas is neutral

Typical coatings:
- Ceramics
- Carbides & Cermets
- Iron, Nickel & Cobalt based alloys
- Abradables

Features and Benefits:
- High degree of flexibility
- Very versatile
- Largest choice of coating materials
- High production spray rates
- Process can be highly automated

Typical Applications:
- Rebuild and Salvage Operations
- Abrasion or Erosion Resistance
- Sliding Wear Resistance
- Resistance to Fretting, Galling or Adhesive Wear
- Resistance to Cavitation Effects
- Impact Resistance
- Resistance to Chemical Attack
- Control of Oxidation and Sulfdation
- Atmospheric and Heat Corrosion Control
- Galvanic Corrosion Control
- Thermal or Electrical Insulation
- Clearance Control

Microscopic Cross Section of a plasma sprayed
MCrAlY bond coat
ZrO2-Y2O3 top coat
High Velocity Oxy-Fuel (HVOF) Spray

Tenacious. Durable. Tough. HVOF produces premium quality hard, dense coatings exhibiting high adhesion to the substrate and excellent wear resistance for extended component longevity and profitability.

**Theory of Operation:**
The HVOF process efficiently uses high kinetic energy and controlled thermal output to produce dense, very low porosity coatings that exhibit very high bond strengths (some exceeding 12,000 PSI or 83 MPa), low oxides and extremely fine as-sprayed finishes. The coatings have low residual internal stresses and can be sprayed to thicknesses not normally associated with dense, thermal sprayed coatings. The process uses an oxygen-fuel mixture. Depending on user requirements, propylene, propane, hydrogen, natural gas or liquid fuel may be used as the fuel. The coating material, in powdered form, is fed axially through the gun using nitrogen as a carrier gas. The fuel is mixed with oxygen and ignited. A supersonic flame is formed by the combustion in a chamber in combination with a nozzle configuration. The ignited gases form a circular flame configuration which surrounds and uniformly heats the powdered spray material as it exits the gun and is propelled to the workpiece surface.

As a result of the high kinetic energy transferred to the particles by the HVOF process, the coating material generally does not need to be fully melted. Instead, the powder particles are in a molten state and flatten plastically as they impact the workpiece surface. The result are coatings with more predictable chemistries that are very homogeneous with a fine granular structure.

All of this adds up to coatings that can survive harsher service conditions, particularly in wear and many corrosion applications, greatly increasing service life. The smooth as-sprayed surface finishes, uniform chemistry and low porosity of the coating can be machined to very high surface finishes.
High Velocity Oxy-Fuel (HVOF) Spray

Process properties:
- Feed stock: powder
- Combustion of fuel and oxygen
- Fuel: propylene, hydrogen, kerosene, etc.
- Temperature < 3.200 ºC
- Flame velocity < 2.100 m/s
- Particle velocity < 600 m/s

Typical coatings:
- Nickel & Cobalt based alloys,
- Stellite, Triballoy, Inconel,
- Iron based alloys, AISI 316L, etc.
- Carbides & Cermets
- MCrAlY

Features and Benefits:
- Excellent, tenaciously bonded coatings
- Low oxide metallic coatings
- Dense with low porosity
- Very high coating thicknesses achievable
- Optimized micro hardness
- Predictable coating chemistries
- Smooth as-sprayed surface finish
- Excellent machined surface finish
- Process can be automated

Typical Applications:
- Rebuild and Salvage Operations
- Abrasion or Erosion Resistance
- Sliding Wear Resistance
- Resistance to Fretting, Galling or Adhesive Wear
- Resistance to Cavitation Effects
- Resistance to Chemical Attack
- Control of Oxidation and Sulfidation
- Atmospheric and Heat Corrosion Control
Cold spray can be considered as a new "HVOF" technology were the kinetic energy is increased while the thermal energy is lowered. With Cold Spray is possible to spray virtually oxide free coatings. The coating material particles are being accelerated in a heated gas stream (600°C/1112°F), up to a particle velocity of >1000 m/s. The extreme high particle velocity in combination with the low particle temperature results in very dense and oxide free coatings.

Applications are found in the automotive industry, corrosion protection and electronics industry.

**Theory of Operation:**
The cold spray process efficiently uses high kinetic gas jet with limited thermal output to produce dense, very low porosity coatings that exhibit very high bonding and lowest oxides levels. Cold gas spraying is a coating deposition method using a supersonic gas jet to accelerate a ductile spherical powder to a velocities up to 500–1000 m/s. During impact with the substrate, particles undergo plastic deformation and adhere to the surface.

The high kinetic energy gas jet is generated by the expansion and overheating (up to 1100°C) of nitrogen or helium gas at a pressure up to 50 bar. Coating material is radial or axial injected into spray torches at the gas expansion section, rapidly accelerating the particles before impact the surface, converting the kinetic energy in to plastic deformation energy during bonding. Unlike thermal spraying techniques, e.g., plasma spraying, arc spraying, flame spraying, or high velocity oxygen fuel (HVOF), the powders are not melted during the spraying process.

The most prevailing bonding theory in cold spraying is attributed to "adiabatic shear instability" which occurs at the particle substrate interface at or beyond a certain velocity called critical velocity. When a spherical particle travelling at critical velocity impacts a substrate, a strong pressure field propagates spherically into the particle and substrate from the point of contact. As a result of this pressure field, a shear load is generated which accelerates the material laterally and causes localized shear straining. The shear loading under critical conditions leads to adiabatic shear instability where thermal softening is locally dominant over work strain and strain rate hardening, which leads to a discontinuous jump in strain and temperature and breakdown of flow stresses. This adiabatic shear instability phenomena results in viscous flow of material at an outward flowing direction with temperatures close to melting temperature of the material. This material jetting is also a known phenomenon in explosive welding of materials (source Wikipedia).
Specification

Process properties:
- Feed stock: powder
- Process gasses: He, N2
- Gas jet Temp. 550 - 1100 °C
- Particle velocity: 500 - 1500 m/s
- Deposition rate: 3 to 15 kg/h

Typical coatings:
- Ductile materials: Zn, Al, Ni, Ti, Cu, Ag, etc.
- Ductile metal alloys: NiCr, CuAl, MCrAlY’s, etc.
- High-end materials: Nobium or Tantalum

Typical Applications:
- Rebuild and Salvage Operations
- Resistance to Chemical Attack
- Pre-placement of solders
- Electrical conductivity
- Thermal conductivity

Features and Benefits:
- Only ductile materials co
- Excellent coating bond strength and density
- Excellent machined surface finish
- Very Low oxide metallic coatings
- No combustible gasses or flame
- High thermal and electrical conductivity
- High deposition rates and efficiencies

Microscopic Cross Section of a Cold sprayed Tantalum coating