CTS APPLIED INNOVATION

THERMAL SPRAY:

Functionality, Process & Benefits

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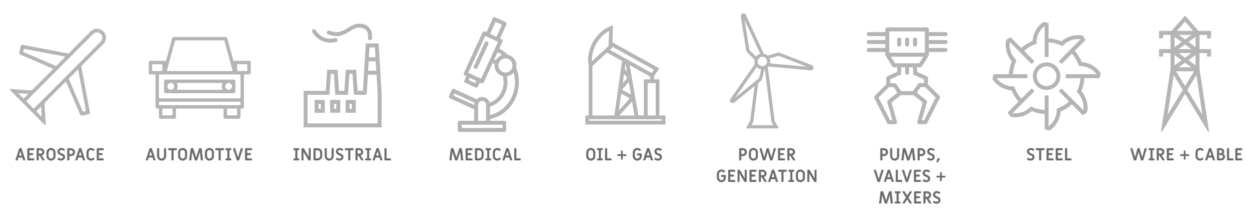
Thermal spray is a unique coating method used in both preventative measures to enhance resistance to wear and corrosion, as well as in various forms of repair and restoration. This versatile process has existed for over a century, but has become highly specialized in the last several decades due to technological advancement and its need in the marketplace of aviation. As this process serves a wide variety of manufacturing and performance industry parts, it is directly correlated to the growth and success of these industries as well. While the Thermal spray process includes complicated compounds and scientific reactions, this paper will explore the fundamental process of its application, the specifics of a coating structure, a detailed inclusion of tools utilized in the process, as well as the benefits associated with thermal spray and its supplementary processes.

On a basic level, thermal spray is a coating applied to a myriad of surfaces that require protection or restoration based on their use. Often, as the parts involved in coating are functioning elements of machinery, these parts receive a high amount of use and wear. Thermal spray allows industries and its individual contributors the opportunity to optimize their parts by safeguarding their surfaces, thus contributing to productivity and budgetary concerns long-term.



Surfaces of Use & Adaptable Materials

As many surface materials can be coated, this process is widely advantageous. In determining if a product fits the specifications for coating, the material as well as its capacity for adhesion and its durability under heat should all be considered. Metallics, ceramics, polymers, glass and even paper can all be coated, provided they retain a clean surface that can be properly prepared. As the process of thermal spray includes high heat and stress on the material, the surface should be able to withstand its intensity as well. Finally, this surface should allow a line-of-sight access to the spray to receive its application most accurately.

Any adaptable material with useful physical and chemical properties has the propensity to be applied through the process of thermal spray. This includes metals, ceramics and polymers, which melt as the sprayable particulates in a hot gas jet, adhering through its impact to the surface.

Thermal Spray Powders

Thermal spray creates a unique coating structure that involves a basic formation made more nuanced by the complexities of its materials and application. The spray starts initially in powder form then turns to a liquid and solidifies as a coating through its impact on the surface. Particles have a closely controlled size distribution and morphology. Both characteristics also significantly affect the efficiency of the spray's deposit. Particles are fine, measuring 10-200 um (0.00039-0.00787 in.) with various 'cuts' and /or 'bell' size distributions generally within that micron range. They can be cast and crushed into angular particulates, agglomerated, sintered, atomized by water or gas into solid or hollow spheres and chemical sol-gel precipitants.

Function, Process & Application

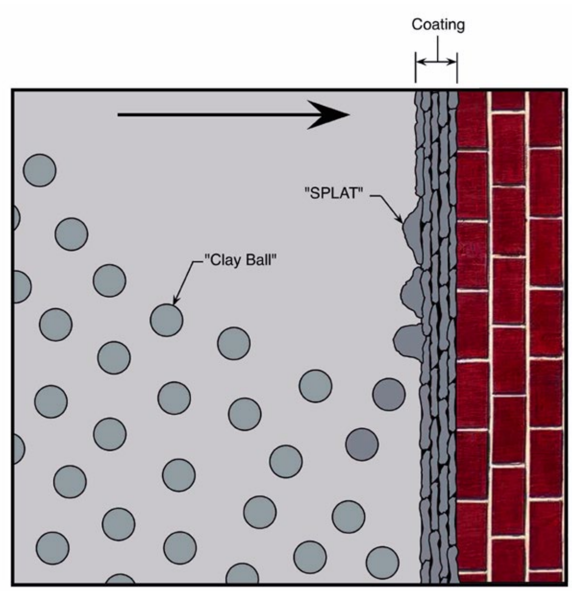
FUNCTION

Thermal spray is unlike any other coating method, set apart by its utility and versatility. Its functional force is thermal energy, used to melt the feed materials and develop kinetic energy within the gas jet. Heat is obtained from usual sources of fuel combustion and electric arc resistance. The array of spray devices used are essentially miniatures rockets, forming dynamic gas jet either chemically, as seen in the fuel-oxygen flame, or by physical transfer from an electric arc to a flow of inert gas. Material particulares are then injected by calibrated powder feeders, or wire push-pull devices, to be heated and expelled as a continuous stream within the gas plume, coating the target surface.
In this process, guns and targets are robot controlled. The cubicles utilized for this process are isolated for sound suppression and extensively ventilated and filtered, ensuring compliance with environmental guidelines.

PROCESS

The transformation from powder to final coating can be hard to visualize, but when considered in as a similar technique to spray painting, it can be clearly imagined. This particle stream, however, is more complicated. Its substance is softened, melted and then projected by the hot gas jet to its impending surface. The particles involved are microscopic and the velocity at which they travel is supersonic, thus this application process—though simple in the effective attributes of its result—is highly complex.

However, to visualize the transformation from a macroscopic viewpoint, one can imagine modeling clay balls the size of golf balls thrust at a brick wall (see illustration). This illustration demonstrates the micro phenomena the billions of microscopic particles undergo in the Thermal spray process. While coatings can be produced with varying levels of porosity, hardness, propensity for erosion, and even with functional cracking, they are all results of the same six stages in the thermal spray process.



6 STAGES OF THE THERMAL SPRAY PROCESS

1ST: The surface is prepped for spraying, including degreasing and activation through controlled grit blasting. In our illustrative example, the texture of the brick wall represents this roughening.

2ND: Through its velocity, the powder particle flattens when at impact. First forming an initial adherent ‘bond layer’ on the surface, subsequent particles impact and adhere to that layer, forming the thickness of the coating. As there is no chemical reaction, no practical metallurgical diffusion happens on the surface material. Instead, it retains its wall building properties. This was key in adapting Thermal spray coatings, ensuring that alloy structural components are not subject to alteration by fusion or other thermal effects. This attribute remains essential to Thermal spray processes used in jet engines, for example.

3RD: The bond that forms is mechanical, characterized by a physical grip of the surface its forming to, with an inter-lapping of the deforming particles. Through the Van der Waals atomic attraction, a profound mechanism defines this critical phenomenon: SPLAT. The accumulation and release of SPLAT constitutes the unique Thermal spray structural feature.

4TH: In this phase, the usefulness of the particle velocities, size variations and composure of resultant structures can be seen in its extraordinary and varying effects. For example, the faster the clay balls are thrown, the more they will flatten, interlap and densify. The density and texture of the clay impacts its malleability, as softer clay will be more malleable in this process. Upon impact, smaller particles fill gaps, creating fewer holes and limiting porosity. This results in a more dense, solid coating, that varies in his hardness based on the powder material used. However, if the intent is to create more porous, abradable structures, such as those used in jet engine blade tip clearance control, lobbing the clay balls at a slower velocity can purposefully achieve this. Similarly, adjunct thermal conditioning can form deliberate cracking with vertical orientation. Such coatings can accommodate substrate high thermal expansion cycling, such as those pot and furnace rolls, and jet engine combustors, undergo.

5TH: This process grows more complex with the addition of supplementary materials. In our macro example, sand may be mixed into the clay, and stones can also be thrown alongside the clay balls, thus yielding a composite of hard matter in the coating resistant to wear. Furthermore, different clays may be blended, or formed in two or more individual layers of different compositions as well. In the field of thermal spray, there is an unlimited amount of materials that can be created and sprayed onto a surface.

6TH: Thermal spray coatings function at a relative thinness, so as not to significantly alter selected component performance. For example, the thinness of a credit card, or even much less, is adequate for the intense stress and friction shear occurring in many aircraft engines or other complex machinery. As these coatings do not “wear out,” they require no reserve of extra coating thickness to function properly.

Application: Spray Devices

There is an existing array of spray devices, referred to as guns or torches. However, even in their varying forms, they all operate on the same basic principles. Each unique thermal spray gun uses differing levels of thermal capacity, related to their design characteristics, stoichiometry and enthalpy, as well as economic spray application. There are two functional spray gun types, headed by heat source:

COMBUSTION FUEL	ELECTRIC ARC
FLAME	WIRE ARC
HVOF, HVAF	PLASMA

All guns generate sufficient enthalpy for efficient deposition rates, but are categorized further by their major temperature differentiation. For example, the electric arc is a much hotter source, with a megawatt I^2R thermal energy and consequent high enthalpic BTU heat content. The arc temperature exceeds 10,000ºF, enabling them to melt any sprayable material, while combustion systems are limited to Oxygen-Acetylene flame stoichiometry of ~5800ºF. These details illustrate the enthalpy generated by these devices, as well as the nominal temperature of their heat sources.

Those two heat source categories are each further divided by two subgroups, thus we will review four in total. The first listed has lower jet stream velocity, but is, in general, more economical to operate. These features that influence jet velocity differences are inherent to each category. Within these four gun types are the individual manufacturers' features of powder ingestion, chambering, nozzle shapes, arcing, heat-kinetic energy transfer, deposit efficiency, enthalpy, stoichiometry and overall utility.

THE 4 BASIC THERMAL SPRAY GUN SYSTEMS:

[1] **FLAME SPRAY:** Combustion flame spray guns originated from modified oxy-acetylene torches. They burn the highest temperature acetylene fuel gas (5800ºF). Combustion chambering and nozzle convergent-divergent designs add velocity to source gas pressure per PV=nRT and combustion driven hot gas expansion. They handle materials in powder, wire or rod forms. Various fuel gases may be used such as propylene (5200F), Hydrogen (3990F), Methane (3810F) and others. All these fuels produce gas jet temperatures capable to melt most common metals and alloys, as well as alumina and titania ceramics. The Flame Spray devices produce coatings suitable for many applications.

[2] **TWIN-WIRE ARC:** TWA guns simply pull-push two energized wires off reels, parallel through the device, guiding the tips together in front of a nozzle to form a 'short circuit' arc. The wires continuously melt, while a compressed gas jet blows through an accelerating nozzle to atomize the metal droplets and propel particulates to a target surface. These devices are most effective and economical for common metal wires. Their SPLAT velocity is adequate for many commercial spray applications.

[3] PLASMA ARC: Plasma guns are most widely used because of their high temperature, megawatt thermal energy developed by I^2R electrical principle and velocity transferred to the gas jet. They are perhaps the most scientific of the gun systems. Basically inert gas—Argon, Nitrogen and others—is pressured into the gun body, chambered to exit through a DC electrified annular nozzle. An axial anode is positioned at the concentric cathode nozzle entrance, forming a closely dimensioned annular gap, through which the primary gas flows into nozzle. A high amperage DC arc is struck across the gap, conducted by ionization of primary gas flow. The arc is sustained by voltage against primary gas resistance, which is variable using incremental H2 and He gas mixing. Gas flow is heated to 10,000ºF or more, and accelerated. That which is ionized in the arc path is much hotter, having transformed into the plasma state. Primary gas transfers latent arc heat, ionization and diatomic binding thermal energy. Such a hot gas plume is easily able to melt any metal, metallic alloy or ceramic, including tungsten metal, suitable for whatever engineering function is needed. Powder is injected external or internally to the nozzle exit, into the exited super-hot gas plume. Enthalpy enables high powder feed rates, gas expansion velocity and material versatility. Thus the plasma system is often the work-horse of spray devices, producing a wide variety of coating compositions and structural characteristics.

[4] HVOF: High Velocity Oxy Fuel guns, for the clay-ball thrown velocity visualization, are the big league pitchers of spray devices. These literal rocket engines produce B-1 bomber gas jets of supersonic velocity, exhibiting the characteristic shock diamonds. As combustion systems, they burn the various fuel gases, also liquid kerosene, with oxygen or air. Their significant advantage is high particle velocity by which they achieve the highest levels of coating adhesion and essentially pore-free density.

Also available in the industry is the HVAF thermal spray gun, which is similar to the process of HVOF. However, the HVAF guns utilize air-fuel instead of oxy-fuel propellants. This produces a slightly lower flame temperature, but also reduces the amount of oxygen within the plume. These shift in plume properties, although slight, can produce very unique characteristics within the deposited coating.

Each gun system incorporates a variety of gas and electric control consoles. Chilled water cooling systems are vital for hot guns, as clean compressed air is required for surface temperature control. Material feed devices are critical to achieving consistent coating formation. Various mechanical and robotic manipulators uniformly traverse the gun spiral or X-Y across spray areas, rotating or indexing the part into various positions and distances. Thermocouple and optical pyrometry are used, in addition to newer electronic survey systems for heat and velocity.

The net effect—to impart and control the wide variety of coating properties—is dependent on the spray device parameters including:

- Combinations of gas and electric flows
- Pressures and voltage
- Distances
- Traverse rates
- Feed rates
- Temperature ranges
- Particle compositions and characteristics

Recent Advancements in Thermal Spray Materials

In recent years, a significant amount of research and development has been focused on enhancing the materials that are injected into the plumes of the thermal spray torches. Notable coating benefits have been achieved, for example, by reducing the particle size of the injected powders to below 1 micron. Traditional powder delivery equipment is not effective at handling these submicron powders; therefore new liquid suspensions have been added as “carriers” to the fine powders, thus creating a slurry material. The process of using a plasma gun to spray these slurries is referred to as Solution Plasma Spray (SPS).

In the case of Solution Precursor Plasma Spraying (SPPS), powders have been completely removed from the thermal spray process. This is a new approach to plasma coatings wherein a liquid chemical precursor, containing the desired cations, is atomized into the plasma plume. The injected solution evaporates and the resulting salts are pyrolyzed, followed by melting and deposition as micron-sized SPLATs. The SPPS process results in smaller SPLAT sizes of <2 microns compared to 30-100 microns with traditional APS processes using powder, which makes many unique microstructures possible ranging from highly porous to highly dense. For example, the SPPS process can enable the deposition of thin (<50 microns), dense (<5% porosity) coatings, which is very difficult to do with powder-based processes.

Benefits of Application

The use of thermal spray coatings enhances the ability to withstand heat and wear, making its use both important to many industries, and limitless in its benefit. Essentially all surfaces that require protection or rehabilitation are candidates for this process. Thermal spray is widely used with aircraft gas turbine engines and bodies and automotive engines and transmissions, making it highly important to both industries as well. Its functionality is also present in the steel industry, in everything from continuous strip galvanizing, aluminizing and galvalume molten metal bath processes, as well as dipping and electrolysis, continuous caster molds and furnace and bridle rolls. But thermal spray also impacts other more niche industries and subtle, or often behind-the-scenes processes as well, serving as a key component in nuclear power plants, wind turbines, drilling, surgical devices, paper mills and even ocean shipping containers.

As it relates to both its application on surfaces and adapted materials, thermal spray is growing exceedingly popular. While it has been adopted in many industries already, the process is continually proven to be valuable in new industries as well, providing new uses and boosting the scope of its benefit. As it becomes even more widely used, the demand in the thermal spray industry will increase as well, impacting the prolific nature of its presence overall. Continually growing in use, market share and value, the scope of its benefits remains limitless.

Adjunct Processes for Coatings & Benefits of their Application

While the typical process of thermal spray already provides many benefits, safeguarding its protected surface against wear and corrosion, adjunct processes and post-treatments can further enhance thermal spray coatings. The 'SPLAT' structure of mechanical bonding and physical characteristics of such coatings are adequate for widespread applications, however, the addition of sealers, dry-film lubricants and thermal treatments can further their advantages. Such methods may incorporate heat treatment, sealers, lubricants, and fusing.

Heat treatment, at suitable conditions of temperature and environment, relieves the residual impact and shock-cool stress of the SPLATting process. It also promotes diffusion among the SPLAT particles into a denser structure and/or to develop a metallurgical diffusion bond to the substrate.

Sealers act as final top coats, covering and infiltrating the natural, or potentially deliberate, levels of inter-SPLAT porosity, adding further corrosion resistance. As with coatings themselves, there are many varieties of sealers including silicates, epoxies, and polymers that can be used. The usual application is through painting, but immersion vacuum impregnation techniques may be used as well. Sealers are often heat cured for robust performance too. For many uses, the synergistic combination of a Thermal spray coating topped with a sealer is ideal option. The Thermal coating is well-bonded and textured to anchor the sealer, for an extraordinarily long life.

Lubricants of a dry-film type, such a MoS_2, which reduce friction, may be applied to enhance wear function as well. The combinations are synergistic like sealers, in that the lube is anchored and contained by a well-bonded and textured Thermal sprayed coating. The low friction property of the lube enhances the dual-coating life by reducing sliding shear stress of the robust base coating.

A Spray & Fuse thermal spray coating is an extension of a flame-type Thermal spray process used to apply coatings including levels of boron composited with functional metallic ingredients. As boron is a melt temperature suppressant, this promotes densification and bonding of the coating through a relatively simple lowered-temperature post-heat treatment, with oxy-acetylene torch, induction, or furnace fusing, usually immediately following application.

Closing

While the subject of Thermal spray Coatings is simple in principle, its process involves a complex combination of techno-scientific factors and nuances, all impacting the specifics of its application, as well as its final result. As covered in this paper, there are a variety of materials and tools used in the process, all creating precise interactions to achieve a coating that endures time and wear.

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