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Introduction to Thermal Spray Processing

THERMAL SPRAY is a generic term for a group of coating processes used to apply metallic or nonmetallic coatings. These processes are grouped into three major categories: flame spray, electric arc spray, and plasma arc spray. These energy sources are used to heat the coating material (in powder, wire, or rod form) to a molten or semimolten state. The resultant heated particles are accelerated and propelled toward a prepared surface by either process gases or atomization jets. Upon impact, a bond forms with the surface, with subsequent particles causing thickness buildup and forming a lamellar structure (Fig. 1). The thin "splats" undergo very high cooling rates, typically in excess of 10^6 K/s for metals (Ref 1).

A major advantage of thermal spray processes is the extremely wide variety of materials that can be used to produce coatings (Ref 2). Virtually any material that melts without decomposing can be used. A second major advantage is the ability of most thermal spray processes to apply coatings to substrates without significant heat input. Thus, materials with very high melting points, such as tungsten, can be applied to finely machined, fully heat-treated parts without changing the properties of the part and without excessive thermal distortion of the part. A third advantage is the ability, in most cases, to strip off and recoat worn or damaged coatings without changing part properties or dimensions. A disadvantage is the line-of-sight nature of these deposition processes. They can only coat what the torch or gun can "see." Of course, there are also size limitations. It is impossible to coat small, deep cavities into which a torch or gun will not fit. The article "Introduction to Processing and Design" in this Handbook provides a more complete discussion of the advantages and disadvantages of thermal spray processes.

Characteristics of Thermal Spray Coatings (Ref 1)

Microstructural Characteristics. The term "thermal spray" describes a family of processes that use the thermal energy generated by chemical (combustion) or electrical (plasma or arc) methods to melt, or soften, and accelerate fine dispersions of particles or droplets to speeds in the range of 50 to >1000 m/s (165 to >3300 ft/s). The high particle temperatures and speeds achieved result in significant droplet deformation on impact at a surface, producing thin layers or lamellae, often called "splats," that conform and adhere to the substrate surface. Solidified droplets build up rapidly, particle by particle, as a continuous stream of droplets impact to form continuous rapidly solidified layers. Individual splats are generally thin (~1 to 20 μm), and each droplet cools at very high rates (>10^6 K/s for metals) to form uniform, very fine-grained, polycrystalline coatings or deposits. Figure 2 shows a schematic of a generic thermal spray powder consolidation process, illustrating the key features and a typical deposit microstructure.

Sprayed deposits usually contain some level of porosity, typically between 0 and ~10%, some unmelted or partially melted particles, fully melted and deformed "splats," metastable phases, and oxidation from entrained air. Thermal spray process jets or plumes

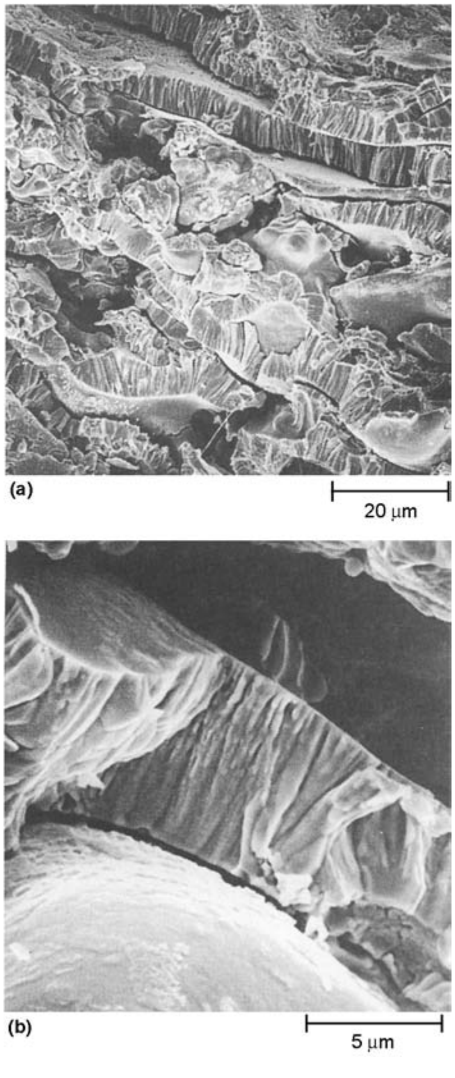

Fig. 1 Scanning electron micrographs of fracture cross sections of an air plasma-sprayed tungsten coating. (a) Lamellar microstructure. (b) Presence of a columnar grain structure within the splats. Source: S.J. Bull, AEA Technology

are characterized by large gradients of both temperature and velocity. Feedstock is usually in powdered form with a distribution of particle sizes. When these powdered materials are fed into the plume, portions of the powder distribution take preferred paths according to their inertia. As a result, some particles may be completely unmelted and can create porosity or become trapped as "unmelts" in the coating. Use of wire and rod feedstock materials produces particle size distributions because of nonuniform heating and unpredictable drag forces, which shear molten material from the parent wire or rod. The level of these coating defects varies depending on the particular thermal spray process used, the operating conditions selected, and the material being sprayed, as described later.

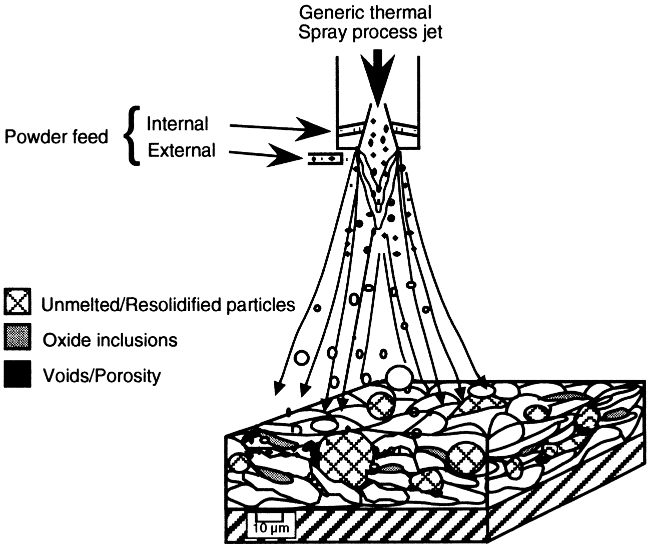

Fig. 2 Schematic of a typical thermal spray powder process. Source: Ref 1

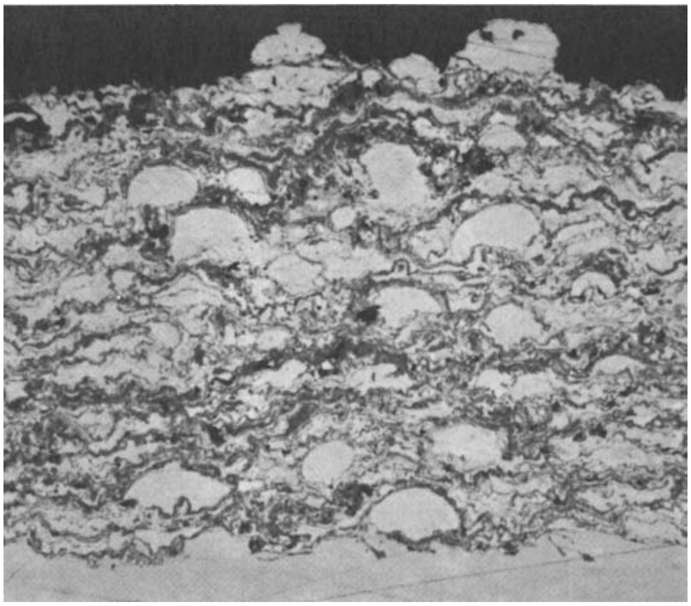

Fig. 3 Photomicrograph showing the microstructure of an HVOF-sprayed 80Ni-20Cr alloy. Source: Ref 1

Figure 3 is a photomicrograph of a thermal-sprayed 80Ni-20Cr alloy coating applied via the high-velocity oxyfuel (HVOF) process showing the characteristic lamellar splat structure. The microstructure shown in Fig. 3 includes partially melted particles and dark oxide inclusions that are characteristic of many metallic coatings sprayed in air. Such coatings exhibit characteristic lamellar microstructures, with the long axis of the impacted splats oriented parallel to the substrate surface, together with a distribution of similarly oriented oxides. Coating oxide content varies with the process—wire arc, plasma, or HVOF. The progressive increases in particle speed of these processes leads to differing levels of oxide and differing degrees of oxide breakup on impact at the surface. Oxides may increase coating hardness and wear resistance and may provide lubricity. Conversely, excessive and continuous oxide networks can lead to cohesive failure of a coating and contribute to excessive wear debris. Oxides can also reduce corrosion resistance. It is important to select materials, coating processes, and processing parameters that allow control of oxide content and structure to acceptable levels for a given application.

Thermal spray coatings may contain varying levels of porosity, depending on the spray process, particle speed and size distribution, and spray distance. Porosity may be beneficial in tribological applications through retention of lubricating oil films. Porosity also is beneficial in coatings on biomedical implants. Lamellar oxide layers can also lead to lower wear and friction due to the lubricity of some oxides. The porosity of thermal spray coatings is typically <5% by volume. The retention of some unmelted and/or resolidified particles can lead to lower deposit cohesive strengths, especially in the case of "as-sprayed" materials with no postdeposition heat treatment or fusion.

Other key features of thermal spray deposits are their generally very fine grain structures and columnar orientation (Fig. 1b). Thermal-sprayed metals, for example, have reported grain sizes of <1 µm prior to postdeposition heat treatment. Grain structure across an individual splat normally ranges from 10 to 50 µm, with typical grain diameters of 0.25 to 0.5 µm, owing to the high cooling rates achieved (~10^6 K/s).

The tensile strengths of as-sprayed deposits can range from 10 to 60% of those of cast or wrought materials, depending on the spray process used. Spray conditions leading to higher oxide levels and lower deposit densities result in the lowest strengths. Controlled-atmosphere spraying leads to ~60% strength, but requires postdeposition heat treatment to achieve near 100% values. Low as-sprayed strengths are related somewhat to limited intersplat diffusion and limited grain recrystallization during the rapid solidification characteristic of thermal spray processes. The primary factor limiting adhesion and cohesion is residual stress resulting from rapid solidification of the splats. Accumulated residual stress also limits thickness buildup.

Thermal Spray Processes and Techniques

Members of the thermal spray family of processes are typically grouped into three major categories: flame spray, electric arc spray, and plasma arc spray, with a number of subsets falling under each category. (Cold spray is a recent addition to the family of thermal spray processes. This process typically uses some modest preheating, but is largely a kinetic energy process. The unique characteristics of cold spray are discussed in the article "Cold Spray Process" in this Handbook.) A brief review of some of the more commercially important thermal spray processes is given below. Table 1 compares important process characteristics associated with these techniques. Selection of the appropriate thermal spray method is typically determined by:

- Desired coating material
- Coating performance requirements
- Economics
- Part size and portability

More detailed information on thermal spray processes can be found in the article "Introduction to Coatings, Equipment, and Theory" (see, in particular, Fig. 2 in the aforementioned article, which illustrates the three major coating categories and their subsets) and in the article "Thermal Spray Processes" in this Handbook.

Flame Spray Processes (Ref 3)

Flame spraying includes low-velocity powder flame, rod flame, and wire flame processes and high-velocity processes such as HVOF and the detonation gun (D-Gun) process (D-Gun is a registered trademark of Praxair Surface Technologies Inc.).

Flame Powder. In the flame powder process, powdered feedstock is aspirated into the oxyfuel flame, melted, and carried by the flame and air jets to the workpiece. Particle speed is relatively low (<100 m/s), and bond strength of the deposits is generally lower than the higher velocity processes. Porosity can be high and cohesive strength is also generally lower. Spray rates are usually in the 0.5 to 9 kg/h (1 to 20 lb/h) range for all but the lower melting point materials, which spray at significantly higher rates. Substrate surface temperatures can run quite high because of flame impingement.

Wire Flame. In wire flame spraying, the primary function of the flame is to melt the feedstock material. A stream of air then atomizes the molten material and propels it toward the workpiece. Spray rates for materials such as stainless steel are in the range of 0.5 to 9 kg/h (1 to 20 lb/h). Again, lower melting point materials such as zinc and tin alloys spray at much higher rates. Substrate temperatures often range from 95 to 205 °C (200 to 400 °F) because of the excess energy input required for flame melting. In most thermal spray processes, less than 10% of the input energy is actually used to melt the feedstock material.

High-Velocity Oxyfuel. In HVOF, a fuel gas (such as hydrogen, propane, or propylene) and oxygen are used to create a combustion jet at temperatures of 2500 to 3100 °C (4500 to 5600 °F). The combustion takes place internally at very high chamber pressures, exiting through a small-diameter (typically 8 to 9 mm, or 0.31 to 0.35 in.) barrel to generate a supersonic gas jet with very high particle speeds. The process results in extremely dense, well-bonded coatings, making it attractive for many applications. Either powder or wire feedstock can be sprayed, at typical rates of 2.3 to 14 kg/h (5 to 30 lb/h).

Detonation Gun. In the detonation gun process, pre-encapsulated "shots" of feedstock powder are fed into a 1 m (3 ft) long barrel along with oxygen and a fuel gas, typically acetylene. A spark ignites the mixture and produces a controlled explosion that propagates down the length of the barrel. The high temperatures and pressures (1 MPa, or 150 psi) that are generated blast the particles out of the end of the barrel toward the substrate. Very high bond strengths and densities as well as low oxide contents can be achieved using this process.

Electric Arc Processes (Ref 3)

Electric Arc. In the electric arc spray process (also known as the wire arc process), two consumable wire electrodes connected to a high-current direct-current (dc) power source are fed into the gun and meet, establishing an arc between them that melts the tips of the wires. The molten metal is then atomized and propelled toward the substrate by a stream of air. The process is energy efficient because all of the input energy is used to melt the metal. Spray rates are driven primarily by operating current and vary as a function of both melting point and conductivity. Generally materials such as copper-base and iron-base alloys spray at 4.5 kg (10 lb)/100 A/h. Zinc sprays at 11 kg (25 lb)/100 A/h. Substrate temperatures can be very low, because no hot jet of gas is directed toward the substrate. Electric arc spraying also can be carried out using inert gases or in a controlled-atmosphere chamber (Ref 1).

Plasma Arc Processes (Ref 3)

Conventional Plasma. The conventional plasma spray process is commonly referred to as air or atmospheric plasma spray (APS). Plasma temperatures in the powder heating region range from about 6000 to 15,000 °C (11,000 to 27,000 °F), significantly above the melting point of any known material. To generate the plasma, an inert gas—typically argon or an argon-hydrogen mixture—is superheated by a dc arc. Powder feedstock is introduced via an inert carrier gas and is accelerated toward the workpiece by the plasma jet. Provisions for cooling or regulating the spray rate may be required to maintain substrate temperatures in the 95 to 205 °C (200 to 400 °F) range. Commercial plasma spray guns operate in the range of 20 to 200 kW. Accordingly, spray rates greatly depend on gun design, plasma gases, powder injection schemes, and materials properties, particularly particle characteristics such as size, distribution, melting point, morphology, and apparent density.

Vacuum Plasma. Vacuum plasma spraying (VPS), also commonly referred to as low-pressure plasma spraying (LPPS, a registered trademark of Sulzer Metco), uses modified plasma spray torches in a chamber at pressures in the range of 10 to 50 kPa (0.1 to 0.5 atm). At low pressures the plasma becomes larger in diameter and length, and, through the use of convergent/divergent nozzles, has a higher gas speed. The absence of oxygen and the abil-

Table 1 Comparison of thermal spray processes

Process	Gas flow		Flame or exit plasma temperature		Particle impact velocity		Relative adhesive strength(a)	Cohesive strength	Oxide content, %	Relative process cost(a)	Maximum spray rate		Power		Energy required to melt	
	m^3/h	ft^3/h	°C	°F	m/s	ft/s					kg/h	lb/h	kW	hp	kW/kg	kW/lb
Flame powder	11	400	2200	4000	30	100	3	Low	6	3	7	15	25–75	34–100	11–22	5–10
Flame wire	71	2500	2800	5000	180	600	4	Medium	4	3	9	20	50–100	70–135	11–22	5–10
High-velocity oxyfuel	28–57	1000–2000	3100	5600	610–1060	2000–3500	8	Very high	0.2	5	14	30	100–270	135–360	22–200	10–90
Detonation gun	11	400	3900	7000	910	3000	8	Very high	0.1	10	1	2	100–270	135–360	220	100
Wire arc	71	2500	5500	10,000	240	800	6	High	0.5–3	1	16	35	4–6	5–8	0.2–0.4	0.1–0.2
Conventional plasma	4.2	150	5500	10,000	240	800	6	High	0.5–1	5	5	10	30–80	40–110	13–22	6–10
High-energy plasma	17–28	600–1000	8300	15,000	240–1220	800–4000	8	Very high	0.1	4	23	50	100–250	135–335	9–13	4–6
Vacuum plasma	8.4	300	8300	15,000	240–610	800–2000	9	Very high	(b)	10	10	24	50–100	70–135	11–22	5–10

(a) 1 (low) to 10 (high). (b) ppm levels. Source: Ref 3 ity to operate with higher substrate temperatures produce denser, more adherent coatings with much lower oxide contents.

Kinetic Energy Processes

Kinetics has been an important factor in thermal spray processing from the beginning. With the introduction of detonation gun, HVOF, and high-energy plasma spraying, the kinetic-energy component of thermal spraying became even more important. The latest advance in kinetic spraying is known as "cold spray."

Cold spray is a material deposition process in which coatings are applied by accelerating powdered feedstocks of ductile metals to speeds of 300 to 1200 m/s (985 to 3940 ft/s) using gas-dynamic techniques with nitrogen or helium as the process gas. The process is commonly referred to as "cold gas-dynamic spraying" because of the relatively low temperatures (0 to 800 °C, or 32 to 1470 °F) of the expanded gas and particle stream that emanates from the nozzle. Powder feed rates of up to 14 kg/h (30 lb/h) are possible. More details are provided in the article "Cold Spray Process" in this Handbook.

Materials for Thermal Spray (Ref 1)

Three basic types of deposits can be thermal sprayed:

- Single-phase materials, such as metals, alloys, intermetallics, ceramics, and polymers
- Composite materials, such as cermets (WC/Co, Cr_3C_2/NiCr, NiCrAlY/Al_2O_3, etc.), reinforced metals, and reinforced polymers
- Layered or graded materials, referred to as functionally gradient materials (FGMs)

Examples of these, along with their particular advantages and applications, are described below.

Single-Phase Materials

Metals. Most pure metals and metal alloys have been thermal sprayed, including tungsten, molybdenum, rhenium, niobium, superalloys, zinc, aluminum, bronze, mild and stainless steels, NiCr alloys, cobalt-base Stellites, cobalt/nickel-base Tribaloys, and NiCrBSi "self-fluxing" alloys. Sprayed alloys have advantages due to their similarity to many base metals requiring repair, their high strength, and their corrosion, wear, and/or oxidation resistance. Applications include automotive/diesel engine cylinder coatings; piston rings or valve stems; turbine engine blades, vanes, and combustors; protection of bridges and other corrosion-prone infrastructure; petrochemical pumps and valves; and mining and agricultural equipment.

Ceramics. Most forms of ceramics can be thermal sprayed, including metallic oxides such as Al_2O_3, stabilized ZrO_2, TiO_2, Cr_2O_3, and MgO; carbides such as Cr_3C_2, TiC, Mo_2C, and SiC (generally in a more ductile supporting metal matrix such as cobalt or NiCr); nitrides such as TiN and Si_3N_4; and spinels or perovskites such as mullite and 1-2-3-type superconducting oxides. Sprayed deposits of these materials are used to provide wear resistance (Al_2O_3, Cr_2O_3, TiO_2, Cr_3C_2, TiC, Mo_2C, and TiN), thermal protection (Al_2O_3, ZrO_2, and MgO), electrical insulation (Al_2O_3, TiO_2, and MgO), and corrosion resistance. Ceramics are particularly suited to thermal spraying, with plasma spraying being the most suitable process due to its high jet temperatures.

Intermetallics such as TiAl, Ti_3Al, Ni_3Al, NiAl, and $MoSi_2$ have all been thermal sprayed. Most intermetallics are very reactive at high temperatures and very sensitive to oxidation; hence, inert atmospheres must be used during plasma spraying. Research has also been conducted on thermal spray forming/consolidation of bulk intermetallic deposits (Ref 1).

Polymers also can be thermal sprayed successfully, provided they are available in particulate form. Thermal spraying of polymers has been practiced commercially since the 1980s, and a growing number of thermoplastic and thermosetting polymers and copolymers have now been sprayed, including urethanes, ethylene vinyl alcohols (EVAs), nylon 11, polytetrafluoroethylene (PTFE), ethylene tetrafluoroethylene (ETFE), polyetheretherketone (PEEK), polymethylmethacrylate (PMMA), polyimide, polycarbonate, and copolymers such as polyimide/polyamide, Surlyn (DuPont), and polyvinylidene fluoride (PVDF). Conventional flame spray and HVOF are the most widely used thermal spray methods for applying polymers.

Composite and Cermet Materials

Particulate-, fiber-, and whisker-reinforced composites have all been produced and used in various applications. Particulate-reinforced wear-resistant cermet coatings such as WC/Co, Cr_3C_2/NiCr, and TiC/NiCr are the most common applications and constitute one of the largest single thermal spray application areas; cermet coatings are discussed extensively throughout this Handbook. Thermal spray composite materials can have reinforcing-phase contents ranging from 10 to 90% by volume, where the ductile metal matrix acts as a binder, supporting the brittle reinforcing phase.

Functionally Gradient Materials

Developed in the early 1970s, FGMs are a growing application area with significant promise for the future production of (a) improved materials and devices for use in applications subject to large thermal gradients, (b) lower-cost clad materials for combinations of corrosion and strength or wear resistance, and (c) improved electronic material structures for batteries, fuel cells, and thermoelectric energy conversion devices. The most immediate application for FGMs is thermal barrier coatings (TBCs), where large thermal stresses are minimized. Component lifetimes are improved by tailoring the coefficients of thermal expansion, thermal conductivity, and oxidation resistance. These FGMs are finding use in turbine components, rocket nozzles, chemical reactor tubes, incinerator burner nozzles, and other critical furnace components. Figure 4 illustrates an example of a thermal-sprayed FGM proposed for the protection of copper using a layered FGM ceramic structure. Successful fabrication of this structure would have application for improved burner nozzles, molds, and furnace walls.

Other FGMs are being developed for:

- Thermal protection of lightweight polymeric insulating materials in aircraft components
- Production of graded metallic/oxide/intermetallic advanced batteries and solid oxide fuel cells
- Production of oxide/metal/air-type electrode/electrolyte systems
- Forming of composite gun barrels
- Biomedical implant devices for enhanced bone-tissue attachment
- Ceramic outer air seals in aircraft gas turbines and other "clearance-control" coatings in rotating machinery
- Thick, multilayer TBCs for heavy-duty diesel engine pistons
- High-performance dielectric coatings for electronic devices
- Wear-resistant coatings for diesel engine piston rings
- Oxidation-resistant coatings for high-temperature conditions

Future growth of FGM applications will ensure that thermal spray processes, particularly HVOF and plasma spray processes, will increase and develop, provided that material properties can be controlled and processing costs optimized.

Markets and Applications

As shown in Fig. 5, the thermal spray industry underwent unprecedented growth during the period between 1960 and the late 1990s. Major contributors to this growth include the commercial introduction of plasma, electric arc, and HVOF, improved process control equipment, and the introduction of new materials and original equipment manufacturer (OEM) applications. Figure 5 also shows the influence that aircraft engine applications have had on the growth of the industry. Thermal spray coatings have been used for advanced gas turbine components such as compressor blades, compressor stator vanes, bearing housings, and labyrinth seals since the early 1960s. Common coating materials include cobalt-base (Co-Mo-Cr-Si) Laves-phase alloys such as Tribaloy T-400 and T-800, WC/Co materials, Cr_3C_2/20-30NiCr cermets, and MCrAlY coatings. Figure 6 shows current and potential gas turbine component applications for thermal spray coatings.

The global thermal spray market consists of:

Market segment	Market value (in U.S. dollars)
OEM/end users	1,400,000,000
Large coating service companies	800,000,000
Small coating service companies	600,000,000
Powder/equipment sales	700,000,000
Estimated total market	**3,500,000,000**

Source: Ref 5

According to Business Communications Company, Inc. (Norwalk, CT), the average annual growth rate of the thermal spray market in North America was +6.1% from 1997 through 2002.

As shown in Tables 2 and 3, a wide variety of industrial sectors rely on thermal spray processes and coatings. As summarized in

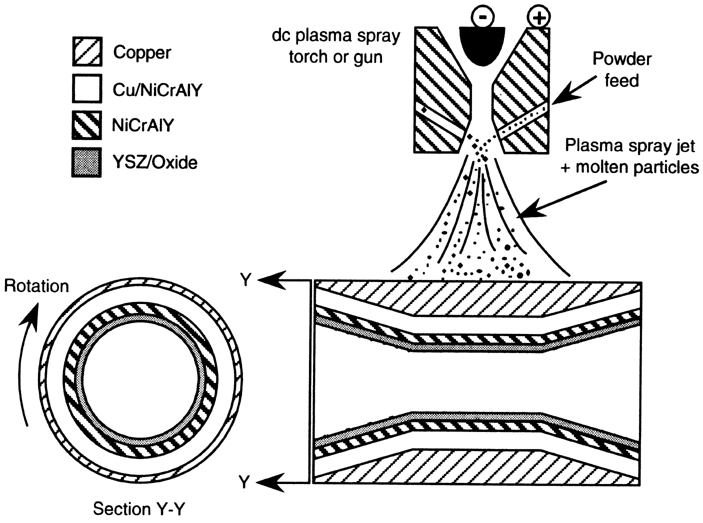

Fig. 4 Schematic of a thermal-sprayed FGM for a burner nozzle application in a pyrometallurgical operation. Source: Ref 1

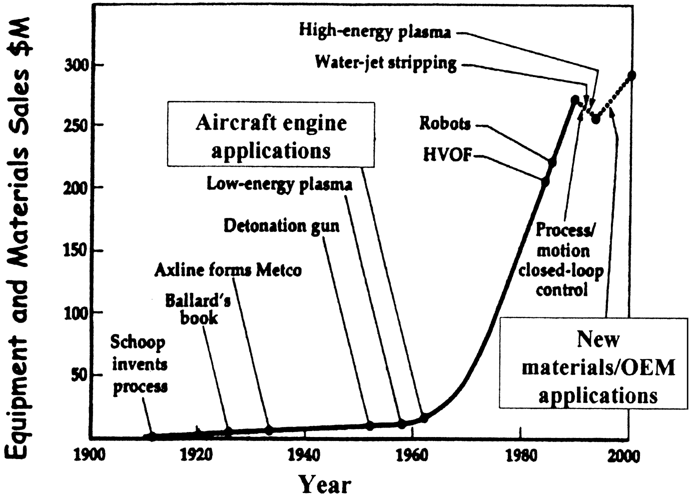

Fig. 5 Timeline of significant developments during the growth of the thermal spray industry. Source: C.C. Berndt, State University of New York at Stony Brook

Table 4, these industries use thermal spray coatings because they offer improved:

- Wear resistance
- Heat resistance (thermal barrier coatings)
- Clearance and dimensional control
- Corrosion and oxidation resistance
- Electrical properties (resistance and conductivity)

Additional information on thermal spray application areas can be found in the articles "Material Categories for Thermal Spray Coatings" and "Selected Applications" in this Handbook.

Future Areas of Growth. As discussed earlier, FGMs offer the thermal spray industry a number of opportunities for growth. Other important areas that will determine future growth include (Ref 1 and 4):

- Continued advances in process control equipment (robotics, motion control, gas pressure technology, real-time sensors, etc.)
- Improved methods for nondestructive testing and evaluation of coatings
- Improved understanding and optimization of the cold spray process
- Thermal spray forming of near-net-shape parts
- Spray forming of high critical temperature (T_c) superconducting oxide ceramics
- Computer-aided design (CAD)/rapid prototyping techniques such as stereolithography
- Diamond synthesis and deposition
- Thin-film deposition via LPPS
- Improved feedstock production techniques and quality control
- New materials (e.g., composites, nanophase materials, perovskites, and zirconates)

Appendix: Historical Development of Thermal Spray Processing and Equipment

Ronald W. Smith, Materials Resources, Inc.

THE EARLIEST RECORDS OF THERMAL SPRAY originate in the patents of M.U. Schoop (Zurich, Switzerland), dating from 1882 to 1889. These patents describe a process that fed lead and tin wires into a modified oxyacetylene welding torch. Later torches were modified to accept powdered materials. The powders were caught up in the hot expanding jet flow where the particles were heated while being accelerated toward the surface to impact, spread (if molten), and solidify. The results were coatings that were incrementally formed from impacting droplets.

Electric arc spray was also patented by Schoop around 1908, which enabled more metals to be sprayed. Steel, stainless steel, and zinc by wire-arc metallizing advanced through improvements in equipment and process control as well as through promotion of

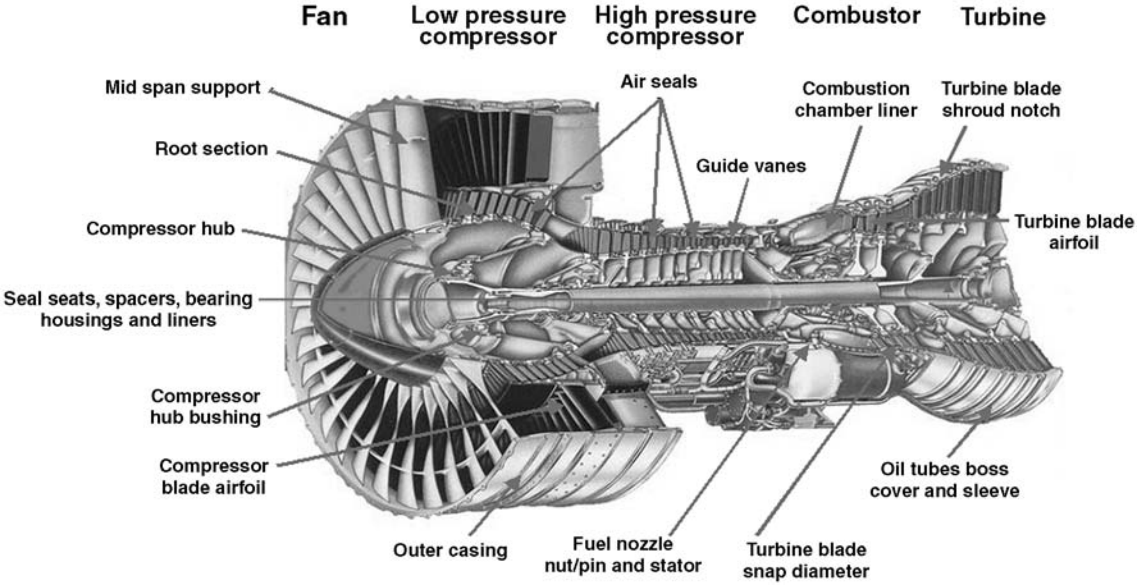

Fig. 6 Current and potential thermal spray coating applications for aircraft turbine engine parts. Source: Ref 4

process applications for applying zinc as a protective coating, primarily to prevent corrosion on structures. The "metallizing" industry thus began.

Developments after World War II

Thermal Spray Process Developments. Significant expansion of the technology did not occur, however, until after World War II, when powder spraying and plasma spray were developed and introduced. Many improvements in these processes have been made since then, but the basic operating principles remain unchanged. Powders are now fed more directly into the flames of combustion devices, which have been modified to generate higher-velocity jets. In addition, feedstock materials have improved significantly, to the point where they are now tailored for the process. Figure 7 summarizes the thermal spray process, applications, and materials growth, highlighting important milestones in its development history.

Application interest grew in these two thermal spray processes, with the first plasma spray coating process introduced by Reinecke in 1939. As welding technology developed, the plasma spray process also grew. Just prior to Reinecke, a confined arc gas heater was developed to assist in cutting and joining. Reinecke was the first to demonstrate that powders injected into a plasma arc gas heater could create molten particles, which could be accelerated toward a surface to form a coating. One advantage of the plasma spray process was significantly higher process temperatures compared to the combustion spray jet. Another advantage was the independence of the material feed from the heat source, compared to the electric current-carrying wires of the wire arc spray process. Plasma processes—with their inert plasma-forming gases, greater heating potential (due to the high process temperatures), and higher particle speeds—were largely responsible for the increased coating quality and subsequent growth of high-technology thermal spray applications through the 1980s.

Thermal spray equipment technology saw much of its progress in the late 1950s, with flame or combustion spray, electric arc, and

Table 2 Thermal spray processes used in various industrial sectors

Industry sector	Oxyfuel	Spray/fuse	HVOF	D-Gun	Air plasma	Vacuum plasma	Shroud plasma
Aero gas turbine	X		X	X	X	X	X
Agriculture	X	X			X		
Architectural	X	X			X		
Automotive engines	X		X		X		
Business equipment			X	X	X		
Cement and structural clays	X	X	X				
Chemical processing	X	X	X	X	X		
Copper and brass mills	X						
Defense and aerospace	X		X	X	X	X	
Diesel engines	X		X		X		
Electrical and electronic			X	X	X	X	
Electric utilities			X		X		
Food processing	X	X	X	X	X		
Forging	X		X				
Glass manufacture		X		X	X		
Hydro-steam turbines	X		X	X	X	X	X
Iron and steel casting			X		X		
Iron and steel manufacture	X	X			X		
Marine manufacture and repair	X						
Medical			X	X	X	X	X
Mining, construction, and dredging	X	X	X		X		
Nuclear			X	X	X		
Oil and gas exploration	X	X	X	X	X		
Printing equipment			X	X	X		
Pulp and paper	X		X		X		
Railroad	X		X		X		
Rock products	X	X	X		X		
Rubber and plastics manufacture	X	X	X		X		
Screening							
Ship and boat manufacture and repair	X						
Land-based gas turbine	X		X	X	X	X	
Steel rolling mills	X	X	X		X		
Textile	X		X	X	X		
Transportation, non-engine	X			X	X		

Source: Frank Hermanek

plasma spray all making parallel but separate advances. The detonation gun (D-Gun) process and further improved arc gas heater technology for powder spray applications were introduced. At its inception, the D-Gun proved capable of producing the highest bond strength and the most adherent, dense, and reliable wear-resistant coatings that thermal spray technology could offer. From 1960 to today, no equivalent process has emerged for producing D-Gun-type coatings. However, HVOF coatings are now challenging this position. Prior to the inception of the D-Gun process, aircraft engine manufacturers did not specify thermal spray coating methods, due to relatively low coating adherence and high coating porosity levels. Plasma spray, with its higher level of materials flexibility, had experienced similar high application growth for many noncarbide and carbide coatings and oxides for thermal protection. This was partially due to the acceptance of the process by aircraft engine manufacturers.

Driven by aerospace industry needs, many companies modified plasma arc heaters to improve coatings and advance application development. Hence, plasma spray emerged in the early 1970s as the most widely used high-tech thermal spray coating technology. Many equipment and materials developments were aimed at this growing market. Plasma spray guns, initially with 72 to 145 MJ (20 to 40 kW) input powers, now exceed 900 MJ (250 kW). Continuous system operation was enabled by improvements in water cooling and electrodes and by the use of higher arc voltages. Gas flows have concurrently increased, with plasma guns evolving from subsonic to supersonic gas-exit speeds. Subsequent increases in particle speeds have increased coating densities and bond strengths to the point where today thermal spray (especially plasma spray) is widely used in critical aircraft and even in biomedical coating applications. Although spray device developments have slowed, many thermal spray advances now focus on improved process control, targeting computer-controlled consoles, robotics, real-time sensors, and automated handling systems.

Combustion spray technology, with the exception of D-Gun, has also seen advances due to the development of HVOF spray systems. The HVOF spray has improved the combustion spray jet by increasing particle temperatures and speeds through confinement of combusting gases and particles. The resulting higher particle temperatures and speeds have significantly increased coating densities and bond strengths compared to conventional flame spray. The HVOF processes are seriously challenging the D-Gun and plasma coating market. It has been reported that higher particle speeds reduce particle overheating, thus preventing the oxida-

Table 3 Thermal spray coatings used in various industrial sectors

Industry sector	Carbides	Self-fluxing	Iron and steel	Nickel alloys	Superalloys	MCrAlY	Cobalt alloys	Nonferrous
Aero gas turbine	X		X	X	X	X	X	X
Agriculture		X	X	X				X
Architectural	X							X
Automotive engines	X			X	X	X	X	
Business equipment								X
Cement and structural clays		X	X					X
Chemical processing			X	X	X		X	
Copper and brass mills							X	
Defense and aerospace	X	X	X	X	X	X	X	X
Diesel engines	X		X	X	X	X	X	
Electrical and electronic								X
Electric utilities		X	X	X			X	X
Food processing		X	X					
Forging		X	X	X	X		X	
Glass manufacture	X	X	X					
Hydro-steam turbine	X	X	X	X	X		X	X
Iron and steel casting		X	X					X
Iron and steel manufacture		X	X	X	X		X	X
Medical								X
Mining, construction, and dredging		X	X					X
Nuclear								
Oil and gas exploration		X	X	X			X	X
Printing equipment								X
Pulp and paper		X	X	X				X
Railroad		X	X	X				X
Rock products		X	X					X
Rubber and plastics manufacture		X	X	X			X	
Screening			X					
Ship and boat manufacture/repair			X	X				X
Land-based gas turbine	X		X	X	X	X	X	X
Steel rolling mills		X	X	X	X		X	X
Textile			X					
Transportation, non-engine			X	X				X

Source: Frank Hermanek

tion and decarburization of carbides sometimes seen in plasma-sprayed coatings.

Advances in feedstock materials (consumables) led to growth in thermal spray technology applications. Metals, ceramics, and now composite feedstock materials are all being developed for specific thermal spray processes. The manufacture of wire by extrusion and drawing was limited to materials that could be drawn to 0.8 mm (0.032 in.) diameter; the introduction of cored wires enabled electric wire-arc spray to produce wear-resistant cermet (composites of ceramics and metals) coatings. Powders, the original sprayed materials, were first produced by crushing and sieving to size. Powder and particulate spray method developments provided a much broader range of materials that could be made into coatings. To support the need for particulate materials, powder-atomization techniques have advanced, yielding a wide range of high-quality materials for powder spray processes.

Other powder production methods are now available for making thermal spray feedstock, such as those for ceramic and ceramic-alloy powders. For example, chemical methods can form particulates from solutions by sol-gel processing and/or by fusing and crushing. Agglomeration by spray drying, sintering, and even plasma spray densification are recent advances used to make metal, ceramic, and composite cermet powders, as shown in Fig. 8. Powder production technology now produces powder sizes and

Table 4 Thermal spray coating properties of importance for various industrial applications

	Wear							Clearance control				Electrical	
Industry sector	Abrasive	Adhesive	Fretting	Erosion	Cavitation	Impact	Thermal barrier	Abradable	Abrasive	Restoration	Corrosion/ oxidation	Resistance	Conductivity
Aero gas turbines	X	X	X	X			X	X	X	X	X		
Agriculture	X			X		X				X			
Architectural	X					X							
Automotive engines	X	X		X		X	X	X	X	X	X	X	
Business equipment	X	X	X										
Cement and structural clays	X					X				X	X		
Chemical processing	X			X						X	X		
Copper and brass mills	X									X	X		
Defense and aerospace	X	X	X	X	X	X	X			X			
Diesel engines	X	X		X		X	X			X	X		
Electrical and electronic													
Electric utilities	X	X		X	X	X				X	X		
Food processing	X									X			
Forging	X	X				X				X	X		
Glass manufacture	X	X								X	X		
Hydro-steam turbines	X	X	X	X	X					X	X		
Iron and steel casting	X			X		X				X	X		
Iron and steel manufacture	X			X		X				X	X		
Medical	X		X								X		
Mining, construction, and dredging	X			X	X	X				X	X		
Nuclear											X		
Oil and gas exploration	X	X		X		X				X	X		
Printing equipment	X	X								X			
Pulp and paper	X				X	X				X	X		
Railroad	X	X				X				X	X		X
Rock products	X					X				X	X		
Rubber and plastics manufacture	X			X		X				X	X		
Screening	X					X				X	X		
Ship and boat manufacture/repair	X			X						X	X		
Land-based gas turbines	X	X	X	X			X	X	X	X	X		
Steel rolling mills	X	X				X				X	X		
Textile	X									X			
Transportation, non-engine	X	X					X			X	X	X	

Source: Frank Hermanek

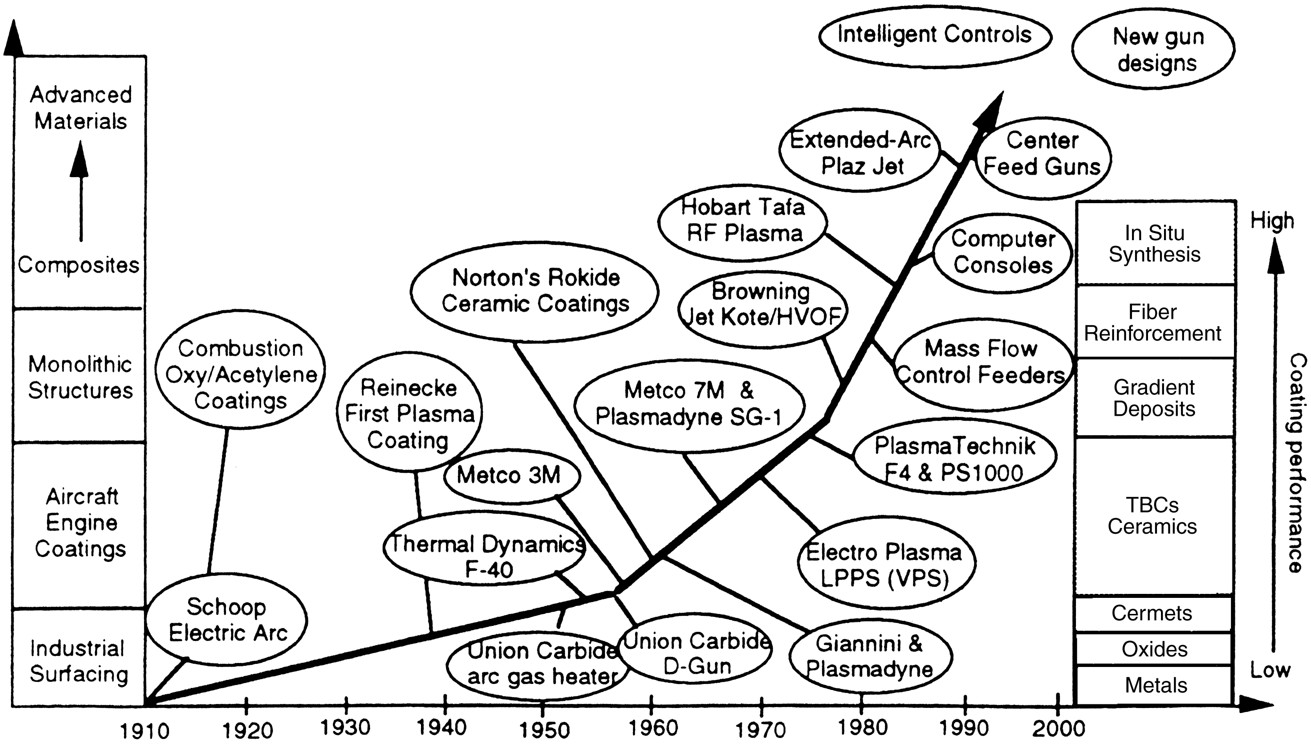

Fig. 7 Timeline of thermal spray developments, equipment, processes, and materials

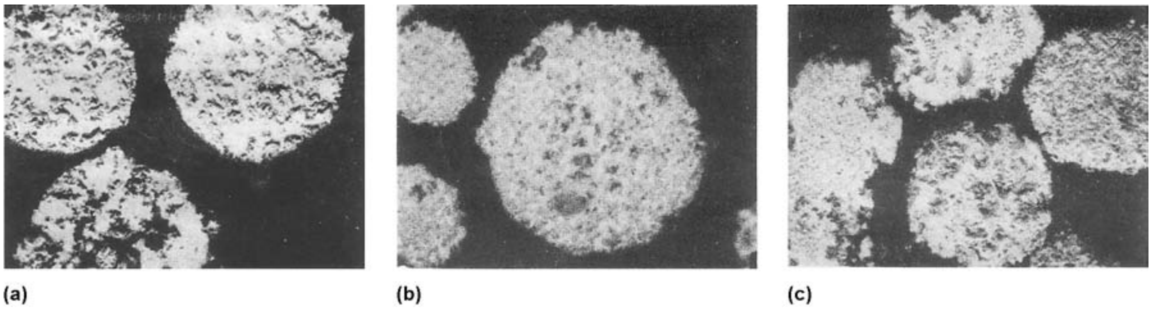
(a) (b) (c)

Fig. 8 Recent advances in thermal spray applications. Optical micrographs of powder cross sections. (a) Fe/TiC. (b) Tool steel/TiC agglomerated, metal/TiC plasma densified. (c) NiCr/TiC. Courtesy of Alloy Technology International

distributions tailored to fit particular thermal spray devices. The variation and supply of materials that can now be thermal sprayed is unlimited, with even cermet electric arc spray coatings available via cored wires. More detailed information on advances in feedstock materials can be found in the Section "Materials Production for Thermal Spray Processes" in this Handbook.

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