

Thermal Spray Coatings

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THERMAL SPRAY is a generic term for a group of processes in which metallic, ceramic, cermet, and some polymeric materials in the form of powder, wire, or rod are fed to a torch or gun with which they are heated to near or somewhat above their melting point. The resulting molten or nearly molten droplets of material are accelerated in a gas stream and projected against the surface to be coated (i.e., the substrate). On impact, the droplets flow into thin lamellar particles adhering to the surface, overlapping and interlocking as they solidify. The total coating thickness is usually generated in multiple passes of the coating device.

The invention of the first thermal spray process is generally attributed to M.U. Schoop of Switzerland in 1911 and is now known as flame spraying. Other major thermal spray processes include wire spraying, detonation gun deposition (invented by R.M. Poorman, H.B. Sargent, and H. Lamprey and patented in 1955), plasma spray (invented by R.M. Gage, O.H. Nestor, and D.M. Yenni and patented in 1962), and high velocity oxyfuel (invented by G.H. Smith, J.F. Pelton, and R.C. Eschenbach and patented in 1958). A variant of plasma spraying uses a transferred arc to heat the surface being coated. It is considered by some to be a welding process akin to hard facing rather than a true thermal spray process, because the surface of the substrate becomes momentarily molten immediately beneath the torch.

A major advantage of the thermal spray processes is the extremely wide variety of materials that can be used to make a coating. Virtually any material that melts without decomposing can be used. A second major advantage is the ability of most of the thermal spray processes to apply a coating to a substrate without significantly heating it. Thus, materials with very high melting points can be applied to finally machined, fully heat-treated parts without changing the properties of the part and without thermal distortion of the part. A third advantage is the ability, in most cases, to strip and recoat worn or damaged coatings without changing the properties or dimensions of the part. A major 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

prohibiting the coating of small, deep cavities into which a torch or gun will not fit.

Figure 1 shows an example of the variety of shapes taken by the molten droplets as they impact, flow, and solidify on the surface. The mechanism of bonding of the particles to the surface is not well understood but is thought to be largely due to mechanical interlocking of the solidifying and shrinking particles, with asperities on the surface being coated unless supplemental fusion or diffusion heat treatment is used. Indeed, most thermal spray coatings require a roughened substrate surface for adequate bonding. Some interdiffusion or localized fusion of as-deposited coatings with the substrate has been observed in a few instances with unique combinations of coatings and substrates. There is evidence of chemical bonding in some coating/substrate systems, not unreasonable when the high-velocity impact of particles might be expected to rupture any films on either the powder particles or the substrate. In addition, van der Waals forces may play a role if the substrate is extremely clean and no significant oxidation occurs during deposition.

Thermal spray coatings are usually formed by multiple passes of a torch or gun over the surface.

Typical cross sections of several examples of thermal spray coatings are shown in Fig. 2, illustrating the lamellar nature of the coatings. A coating can be made of virtually any material that can be melted without decomposing. Moreover, the deposition process itself can substantially alter the composition as well as the structure of the material. As a result, the microstructure and properties of the coatings can be extremely varied. Specification of a coating, therefore, must often involve more than simply stating the composition of the starting powder or wire and the general type of process to be used.

The applications of thermal spray coatings are extremely varied, but the largest categories of use are to enhance the wear and/or corrosion resistance of a surface. Other applications include their use for dimensional restoration, as thermal barriers, as thermal conductors, as electrical conductors or resistors, for electromagnetic shielding, and to enhance or retard radiation. They are used in virtually every industry, including aerospace, agricultural implements, automotive, primary metals, mining, paper, oil and gas production, chemicals and plastics, and biomedical. Some specific examples are given in the section "Uses of Thermal Spray Coatings" in this article.

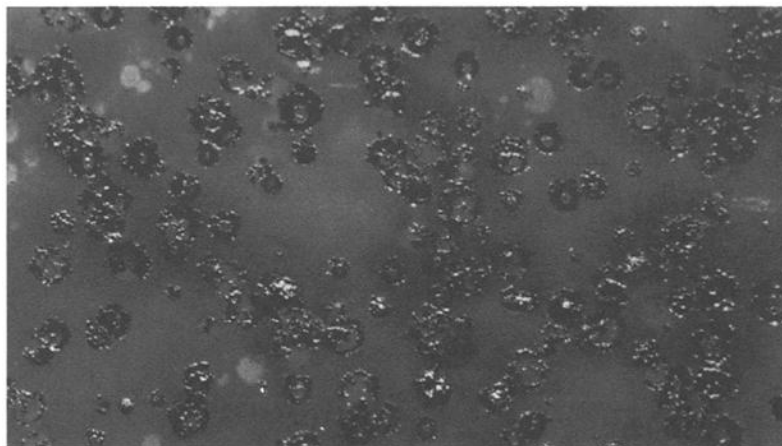


Fig. 1 Deformation of molten or semimolten particles resulting from spray impacting on a substrate

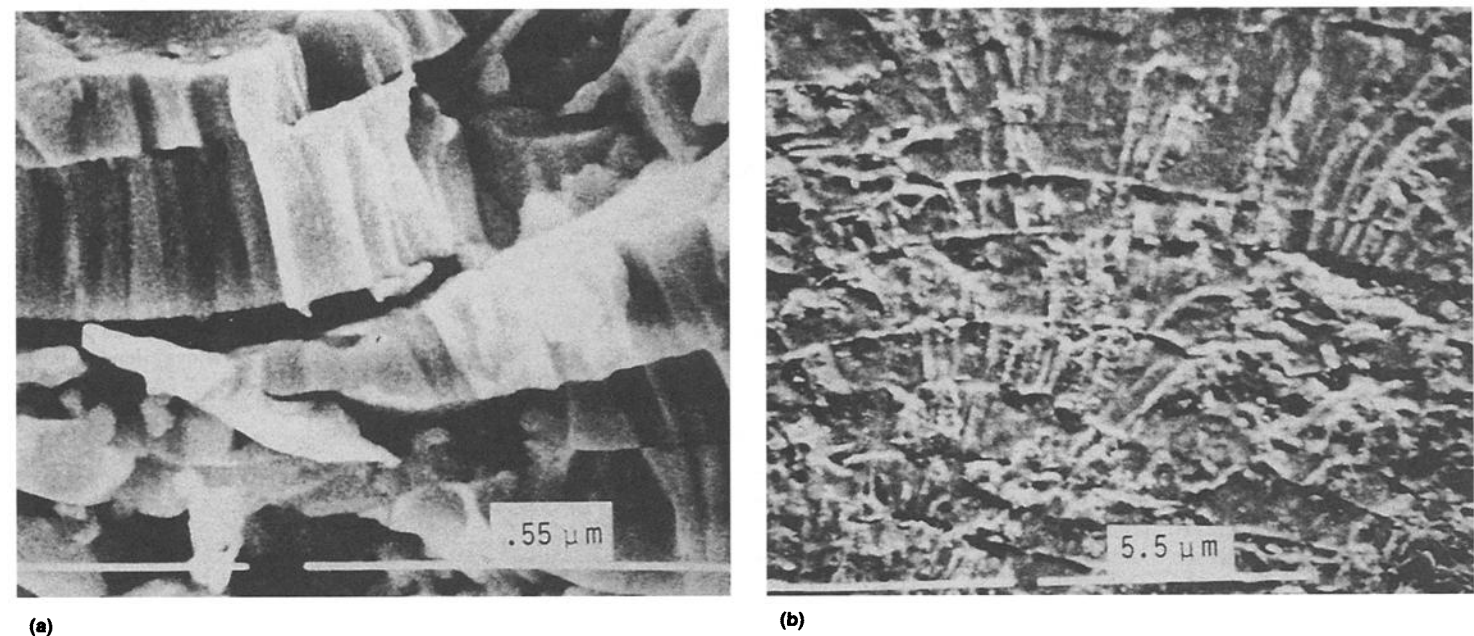


Fig. 2 Typical microstructure of a plasma-sprayed tungsten metal coating showing the splat structure and the fine crystalline structure within the splats. (a) Scanning electron micrograph of a fracture surface. (b) Light micrograph of the same coating. Courtesy of Praxair Surface Technologies, Inc.

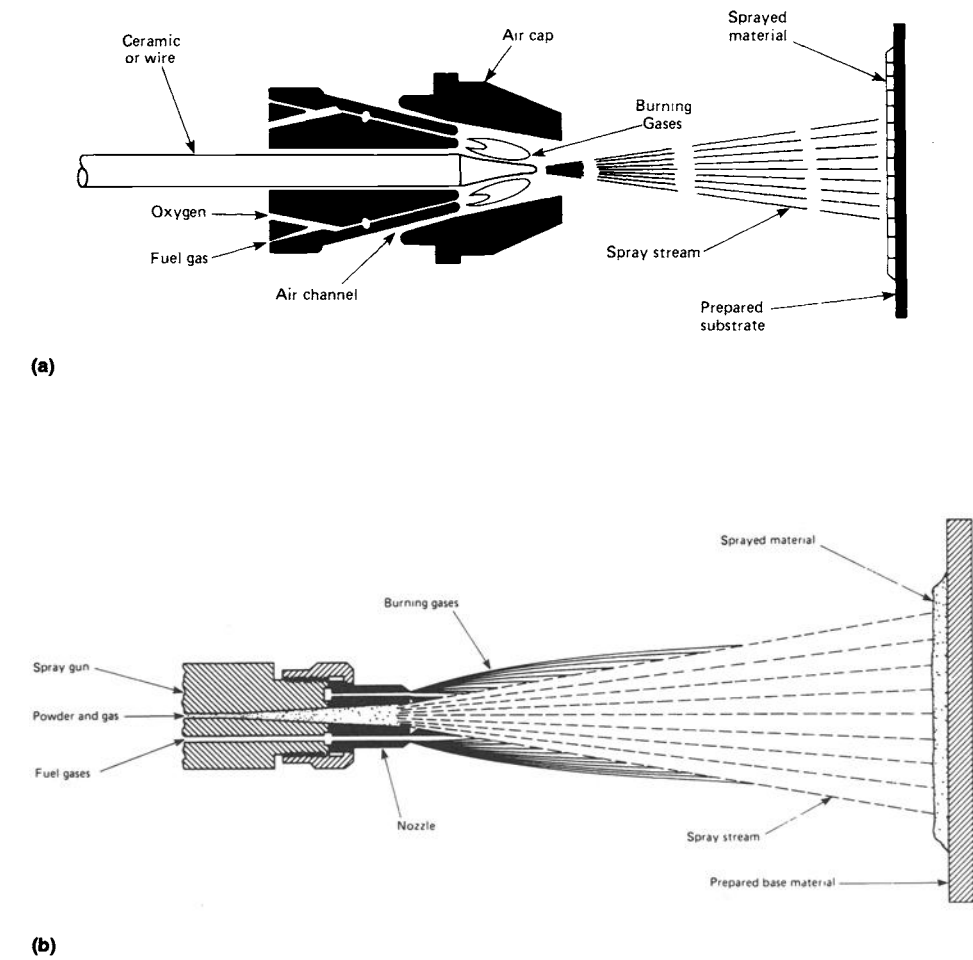


Fig. 3 Cross sections of typical flame spray guns. (a) Wire or rod. (b) Powder

Table 1 Maximum temperature of heat sources	
Heat source	Approximate temperature (stoichiometric combustion)
Propane-oxygen	2526 °C (4579 °F)
Natural gas-oxygen	2538 °C (4600 °F)
Hydrogen-oxygen	2660 °C (4820 °F)
Propylene-oxygen	2843 °C (5240 °F)
Methylacetylene/propadiene-oxygen	2927 °C (5301 °F)
Acetylene-oxygen	3087 °C (5589 °F)
Plasma arc	2200 to 28,000 °C (4000 to 50,000 °F)

Source: Adapted from Publication 1G191, National Association of Corrosion Engineers

Processes

Flame spray uses combustible gas as a heat source to melt the coating material (Fig. 3). Flame spray guns are available to spray materials in either rod, wire, or powder form. Most flame spray guns can be adapted to use several combinations of gases to balance operating cost and coating properties. Acetylene, propane, methyl-acetylene-propadiene (MAPP) gas, and hydrogen, along with oxygen, are commonly used flame spray gases. In general, changing the nozzle and/or air cap is all that is required to adapt the gun to different alloys, wire sizes, or gases. Figures 3(a) and (b) depict powder and wire flame spray guns. For all practical purposes, the rod and wire guns are similar.

Flame temperatures and characteristics depend on the oxygen-to-fuel gas ratio and pressure. The approximate temperatures for stoichiometric combustion at 1 atm for some oxyfuel combina-

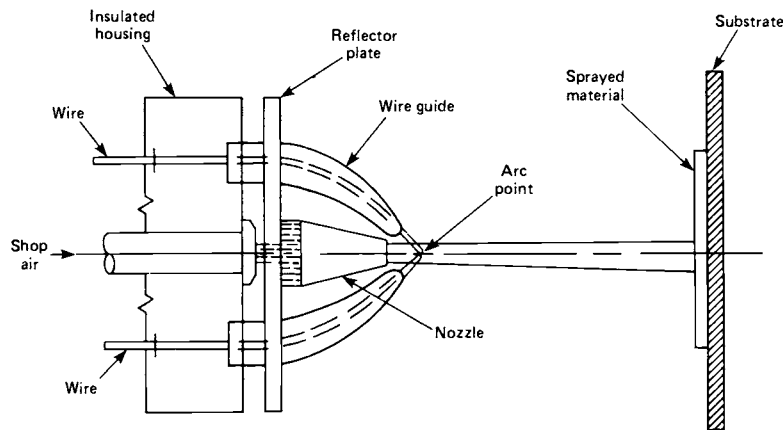


Fig. 4 Typical electric-arc spray device

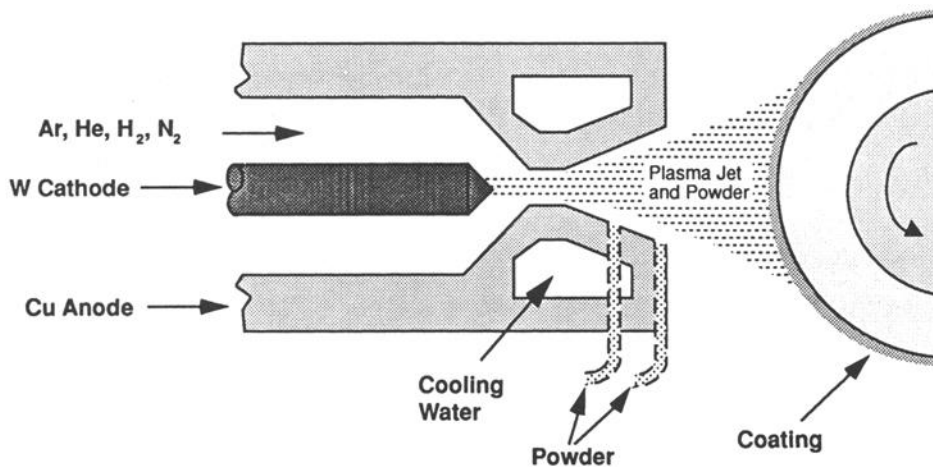


Fig. 5 Plasma spray process. Courtesy of Praxair Surface Technologies, Inc.

tions are shown in Table 1. The flame spray process is characterized by low capital investment, high deposition rates and efficiencies, and relative ease of operation and cost of equipment maintenance. In general, as-deposited (or cold spray) flame-sprayed coatings exhibit lower bond strengths, higher porosity, a narrower working temperature range, and higher heat transmittal to the substrate than most other thermal spray processes. The flame spray process is widely used for the reclamation of worn or out-of-tolerance parts, frequently using nickel-base alloys. Bronze alloys may be used for some bearings and seal areas. Blends of tungsten carbide and nickel-base alloys may be used for wear resistance. Zinc is commonly applied for corrosion resistance on bridges and other structures.

Flame spray and fuse is a modification of the cold spray method. The materials used for coating are self-fluxing (i.e., they contain elements that react with oxygen or oxides to form low-density oxides that float to the surface, thus improving density, bonding, etc.). They have relatively low melting points and require postspray heat treatment. In general, these are nickel- or cobalt-base alloys that use boron, phosphorus, or silicon, either singly or in

combination, as melting-point depressants and fluxing agents. In practice, parts are prepared and coated as in other thermal spray processes and then fused. There are two variants: Spray and fuse, and spray-fuse. In spray and fuse, the fusion is done after deposition using one of several techniques, such as flame or torch, induction, or vacuum, inert, or hydrogen furnaces. In spray-fuse, the deposition and fusion are done simultaneously.

The alloys used generally fuse between 1010 to 1175 °C (1850 to 2150 °F), depending on composition. Reducing atmosphere flames should be used to ensure a clean, well-bonded coating. In vacuum and hydrogen furnaces, the coating may have a tendency to wick or run onto adjacent areas. Several brushable stopoff materials are commercially available to confine the coating. It is recommended that test parts be coated and fused whenever the shape, coating alloy, or lot of material is changed, to establish the minimum and maximum fusing temperatures. Fusing temperature is known to vary slightly between lots of spray material. On vertical surfaces, coating material may sag or run off if the fusing temperature is exceeded by more than a few degrees. These coatings are fully dense and exhibit metallurgical

bonds. Excessive porosity and nonuniform bonding are usually indicative of insufficient heating.

Spray-and-fuse coatings are widely used in applications where excessive wear combined with high stresses on the coating/substrate (shear or impact) is a problem. These alloys generally exhibit good resistance to wear and have been successfully used in the oil industry for sucker rods and in agriculture for plowshares. In many applications, these coatings make possible the use of less expensive substrate materials. Coating hardnesses can be as high as 65 HRC. Some powder manufacturers offer these alloys blended with tungsten carbide or chromium carbide particles to increase resistance to wear from abrasion, fretting, and erosion. Grinding is usually necessary for machining a fused coating because of the high hardness. Use of spray-and-fuse coatings is limited to substrate materials that can tolerate the 1010 to 1175 °C (1850 to 2150 °F) fusing temperatures. Fusing temperatures may alter the heat-treated properties of some alloys. However, the coating will usually withstand additional heat treatment of the substrate. Slower cooling rates may be required to reduce cracking where greater thicknesses are needed or where there is a substantial difference in the thermal expansion coefficients between the coatings and the substrate.

The electric-arc (wire-arc) spray process uses metal in wire form. This process differs from the other thermal spray processes in that there is no external heat source such as gas flame or electrically induced plasma. Heating and melting occur when two electrically opposed charged wires, comprising the spray material, are fed together in such a manner that a controlled arc occurs at the intersection. The molten metal on the wire tips is atomized and propelled onto a prepared substrate by a stream of compressed air or other gas (Fig. 4).

Electric-arc spray offers advantages over flame spray processes. In general, it exhibits higher bond strengths, in excess of 69 MPa (10,000 psi) for some materials. Deposition rates of up to 55 kg/h (120 lb/h) have been achieved for some nickel-base alloys. Substrate heating is lower than in flame spray processes due primarily to the absence of a flame touching the substrate. The electric-arc process is in most instances less expensive to operate than the other processes. Electrical power requirements are low, and, with few exceptions, no expensive gas such as argon is necessary. The electric-arc process most commonly uses relatively ductile, electrically conductive wire about 1.5 mm (0.60 in.) in diameter. Electric-arc spray coatings of carbides, nitrides, and oxides are therefore not currently practical; however, the recent development of cored wires permits the deposition of some composite coatings containing carbides or oxides. By using dissimilar wires, it is possible to deposit pseudoalloys. A less expensive wear surface can be deposited using this technique. One wire, or 50% of the coating matrix, can be an inexpensive filler material.

Electric-arc coatings are widely used in high-volume, low-cost applications such as application of zinc corrosion-resistant coatings. In a

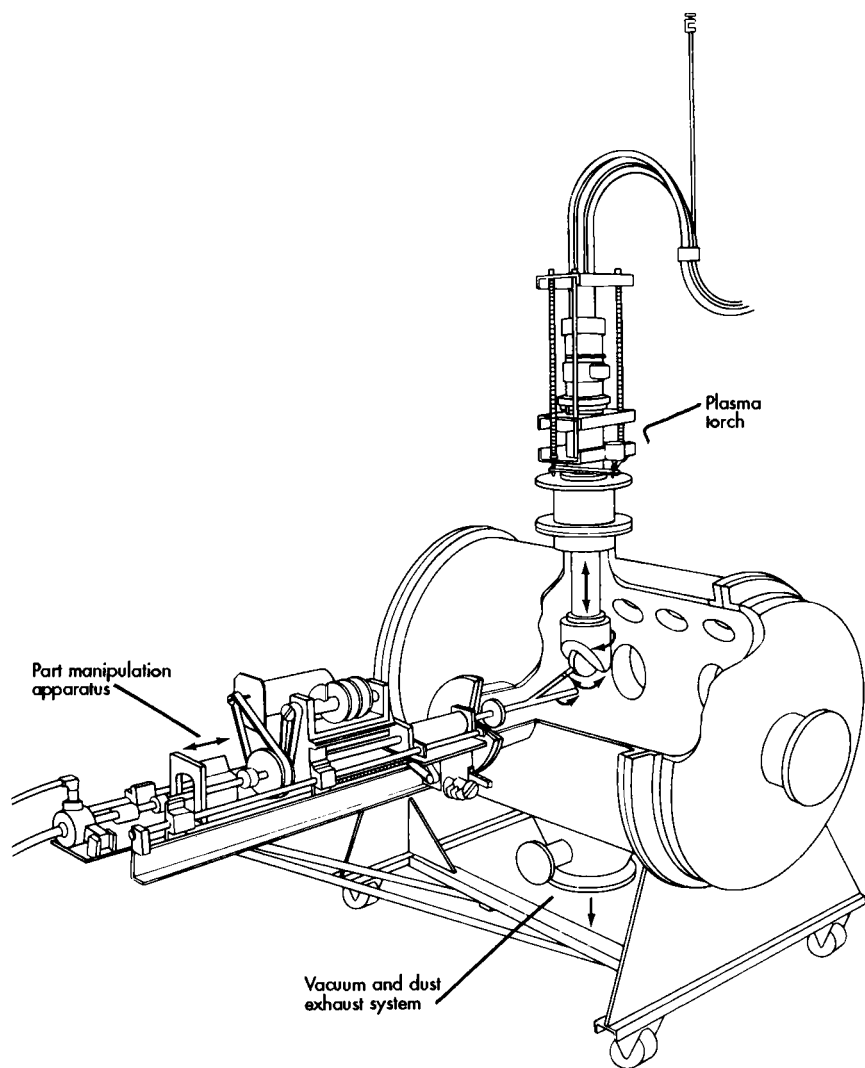


Fig. 6 Typical inert-atmosphere and/or low-pressure plasma chamber. Courtesy of Metco, Inc.

more unusual application, metal-face molds can be made using a fine spray attachment available from some manufacturers. Molds made in this way can duplicate extremely fine detail, such as the relief lettering on a printed page.

Plasma Spray. A plasma spray torch is shown schematically in Fig. 5. A gas, usually argon, but occasionally including nitrogen, hydrogen, or helium, is allowed to flow between a tungsten cathode and a water-cooled copper anode. An electric arc is initiated between the two electrodes using a high-frequency discharge and then sustained using dc power. The arc ionizes the gas, creating a high-pressure gas plasma. The resulting increase in gas temperature, which may exceed 30,000 °C, in turn increases the volume of the gas and, hence, its pressure and velocity as it exits the nozzle. (Gas velocities, which may be supersonic, should not be confused with particle velocities.) Power levels in plasma spray torches are usually in the range of 30 to 80 kW, but they can be as high as 120 kW. Argon is usually chosen as the base gas because it is chemically inert and because of its ionization charac-

teristics. The enthalpy of the gas can be increased by adding the diatomic gases, hydrogen or nitrogen.

Powder is usually introduced into the gas stream either just outside the torch or in the diverging exit region of the nozzle (anode). It is both heated and accelerated by the high-temperature, high-velocity plasma gas stream. Torch design and operating parameters are critical in determining the temperature and velocity achieved by the powder particles. The operating parameters include not only the gas flows, power levels, powder feed rate, and carrier gas flow, but also the distance from the torch to the substrate (standoff) and the angle of deposition. Standoff is of substantial importance because adequate distance must be provided for heating and accelerating the powder, but too great a distance will allow the powder to cool and lose velocity, because the gas stream is rapidly expanding, cooling, and slowing. The size and morphology of powder particles strongly influence their rate of heating and acceleration and, hence, the efficiency of deposition and quality of the coating. Frequently,

a somewhat higher price paid for a powder with a tighter size distribution is more than compensated for by improved deposition efficiency.

The powder velocities usually achieved in plasma spray deposition range from about 300 to 550 m/s. Temperatures are usually at or slightly above the melting point. Generally, higher particle velocities and temperatures above the melting point, but without excessive superheating, yield coatings with the highest densities and bond strengths. The density of plasma spray coatings is usually much higher than that of flame spray coatings and is typically in the range of 80 to 95% of theoretical. Coating thickness usually ranges from about 0.05 to 0.50 mm (0.002 to 0.020 in.) but may be much thicker for some applications (e.g., dimensional restoration or thermal barriers). Bond strengths vary from less than 34 MPa (5000 psi) to greater than 69 MPa (10,000 psi).

In addition to powder temperature and velocity, a third very important factor is the extent of reaction of the powder particles with process gases or surrounding environmental gases (e.g., air) during the deposition process. With normal plasma spraying in air, the extent of oxidation of the powder particles is a function of the specific torch design, operating parameters, and standoff. Extensive oxidation of metallic and carbide powders can result in drastic reduction in coating density, cohesive strength, and bond strength with concomitant changes in performance. Such oxidation can be virtually eliminated by either effective gas shrouding of the effluent or spraying in a reduced-pressure, inert gas chamber.

Thermal spray done in an inert atmosphere and/or low-pressure chamber has become a widely accepted practice, particularly in the aircraft engine industry. Inert-atmosphere, low-pressure plasma spray systems have proven to be an effective means for applying complex, hot corrosion-resistant coatings of the Ni-Co-Cr-Al-Y type to high-temperature aircraft engine components without oxidation of the highly reactive constituents. Simple inert-atmosphere chamber spraying can also be used to confine hazardous materials. Hazardous materials are grouped into two categories: toxic and pyrophoric. Toxic materials include beryllium and its alloys. Pyrophoric materials include magnesium, titanium, lithium, sodium, and zirconium, which tend to burn readily when in a finely divided form or when purified by the plasma process.

A simple inert-atmosphere chamber spray system may include a jacketed, water-cooled chamber, an air lock, a plasma system, workpiece handling equipment, glove ports, a vacuum pumping system, and an inert gas backfill manifold. Usually, the chamber is pumped down to a pressure of 0.001 to 0.01 Pa (10^{-4} to 10^{-5} torr), then backfilled with high-purity dry argon. In any good inert-gas chamber, oxygen levels can be easily maintained below 30 ppm. Some metal powders tend to "clean up" when sprayed in an inert-gas chamber by the reduction of surface oxides. By the same mechanism, some oxide powders tend to be partially reduced when sprayed in an inert-gas chamber.

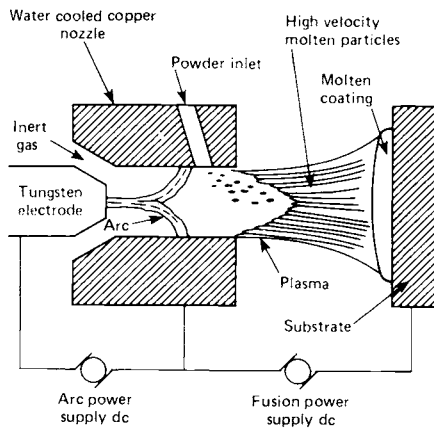


Fig. 7 Transferred plasma-arc spraying

Inert-atmosphere spraying in a low-pressure chamber offers several unique advantages over conventional plasma spraying in an inert atmosphere at atmospheric pressure. Because of the lower pressure, the plasma gas stream temperature and velocity profiles are extended to greater distances, so the coating properties are less sensitive to standoff. In addition, the substrate can be preheated without oxidation. This allows better control of residual stress and better bond strengths. Deposition efficiency can be increased because of increased particle dwell time in the longer heating zone of the plasma and higher substrate temperature. The closed system also minimizes environmental problems such as dust and noise.

Figure 6 shows a typical inert-atmosphere and/or low-pressure plasma chamber. Normal operating procedures require that the spray chamber be pumped down to quite low pressures, as noted above, or be repeatedly cycled after pumping to approximately 55 Pa (0.4 torr) and then be back-filled with inert gas to about 40 kPa (300 torr). Once the system has been sufficiently purged to achieve an acceptable inert atmosphere, the plasma spray operation is activated and the chamber pressure is adjusted to the desired level for spraying. The entire spray operation is accomplished in a soft vacuum of approximately 6700 Pa (50 torr). The optimum spray condition exists when the plasma temperature at the substrate approximates the melting point of the powder particles; however, the optimum spraying conditions will vary with the chemistry and particle size of each spray material. These variables are similar to those of conventional plasma spraying. Because of the complexity of low-pressure spraying, the entire process is best controlled by computer to ensure complete reproducibility and uniformity throughout the coating. Productivity can be increased by using load/lock prepumping and venting chambers and robotics.

The complex low-pressure plasma spraying process is not required for all applications. Plasma spray using an inert-gas shroud around the plasma gas effluent can be just as effective in preventing oxidation during deposition as spray-

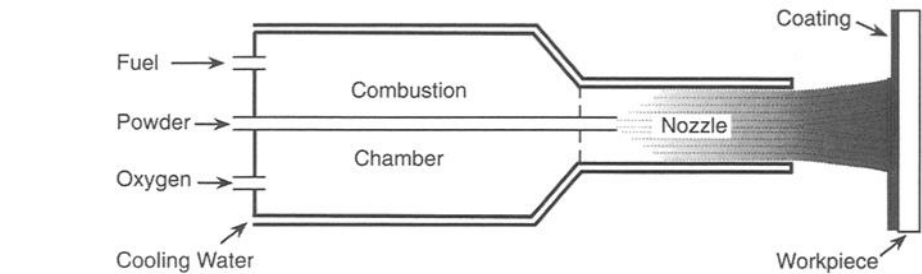


Fig. 8 High-velocity oxyfuel process. Courtesy of Praxair Surface Technologies, Inc.

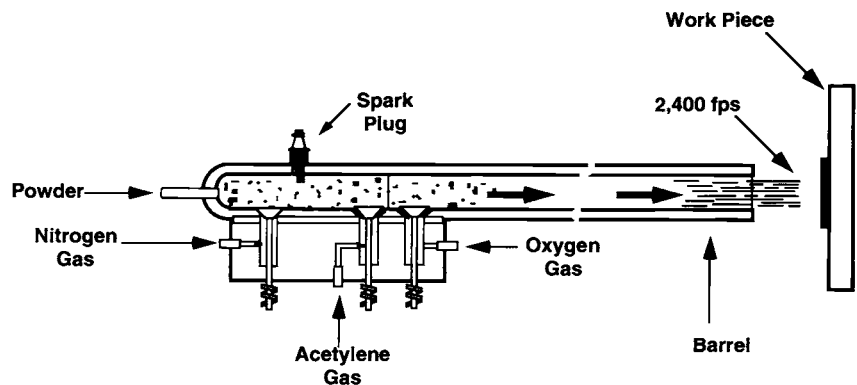


Fig. 9 Detonation gun process. Courtesy of Praxair Surface Technologies, Inc.

ing in an inert-gas, low-pressure chamber. It has been used extensively to spray Ni-Co-Cr-Al-Y alloys on turbine blades, vanes, and outer air seals, and thermal barriers as an undercoat. Compared to chamber spraying, it has much lower capital costs but greater sensitivity to standoff. It is difficult to preheat the substrate to high temperatures without oxidizing the substrate, a technique used with low-pressure chamber spray to control the residual stress in some high-temperature, oxidation-resistant coatings. However, residual stress in these coatings can nonetheless be controlled when using inert-gas shrouding through control of deposition rates, auxiliary cooling, and so forth.

Plasma spray can be used to produce coatings of virtually any metallic, cermet, or ceramic material. The coatings are used for most of the types of applications described in a subsequent section.

The transferred plasma-arc process adds to plasma spray the capability of substrate surface heating and melting. Figure 7 is a schematic representation of the process. A secondary arc current is established through the plasma and substrate that controls surface melting and depth of penetration. Several advantages result from this direct heating: metallurgical bonding, high-density coatings, high deposition rates, and high thicknesses per pass. Coating thicknesses of 0.50 to 6.35 mm (0.020 to 0.250 in.) and widths up to 32 mm (1.25 in.) can be made in a single pass at powder feed rates of 9 kg/h (20 lb/h). In addition, less electrical power is required than with nontransferred arc processes. For example, for an 88% tungsten carbide, 12% Co

material, plasma spray deposition 0.30 mm (0.012 in.) thick and 9.50 mm (0.375 in.) in width might require 24 passes at 40 to 60 kW to achieve maximum coating properties. This same material can be applied, using the transferred plasma-arc process, in one pass at approximately 2.5 kW.

The method of heating and heat transfer in the transferred plasma-arc process eliminates many of the problems related to using powders with wide particle size distributions or large particle sizes. Larger-particle-size powders, for example in the 50-mesh range, tend to be less expensive than closely classified 325-mesh powders.

Some limitations of the process should be considered for any potential application. Because substrate heating is a part of the process, some alteration of its microstructure is inevitable. Applications are also limited to substrates that are electrically conductive and can withstand some melting. The transferred plasma-arc process is used in hardfacing applications such as valve seats, plowshares, oil field components, and mining machinery.

High-Velocity Oxyfuel. A schematic of a high-velocity oxyfuel (HVOF) device is shown in Fig. 8. Fuel, usually propane, propylene, MAPP, or hydrogen, is mixed with oxygen and burned in a chamber. In other cases, liquid kerosene may be used as a fuel and air as the oxidizer. The products of the combustion are allowed to expand through a nozzle where the gas velocities may become supersonic. Powder is introduced, usually axially, in the nozzle and is heated and accelerated. The powder is usually fully or partially melted and achieves veloci-

Table 2 Comparison of typical thermal spray processes

Process	Materials	Feed material	Surface preparation	Substrate temperature		Particle velocity	
				°C	°F	m/s	ft/s
Powder flame spray	Metallic, ceramic, and fusible coatings	Powder	Grit blasting or rough threading	105-160	225-325	65-130	200-400
Wire flame spray	Metallic coatings	Wire	Grit blasting or rough threading	95-135	200-275	230-295	700-900
Ceramic rod spray	Ceramic and cermet coatings	Rod	Grit blasting	95-135	200-275	260-360	800-1100
Two-wire electric-arc	Metallic coatings	Wire	Grit blasting or rough threading	50-120	125-250	240	800
Nontransferred arc plasma	Metallic, ceramic, plastics, and compounds	Powder	Grit blasting or rough threading	95-120	200-250	240-560	800-1850
High-velocity oxyfuel	Metallic, cermet, some ceramic	Powder	Grit blasting	95-150	225-300	100-550	325-1800
Detonation gun	Metallic, cermet, and ceramic	Powder	Grit blasting or as-machined	95-150	225-300	730-790	2400-2600
Super D-Gun	Metallic, cermet, and ceramic	Powder	Grit blasting or as-machined	95-150	225-300	850-1000	2800-3300
Transferred arc plasma	Metallic fusible coatings	Powder	Light grit blasting or chemical cleaning	Fuses base metal	Fuses base metal	490	1600

ties of up to about 550 m/s. Because the powder is exposed to the products of combustion, they may be melted in either an oxidizing or reducing environment, and significant oxidation of metallics and carbides is possible.

With appropriate equipment, operating parameters, and choice of powder, coatings with high density and with bond strengths frequently exceeding 69 MPa (10,000 psi) can be achieved. Coating thicknesses are usually in the range of 0.05 to 0.50 mm (0.002 to 0.020 in.), but substantially thicker coatings can occasionally be used when necessary with some materials.

HVOF processes can produce coatings of virtually any metallic or cermet material and, for some HVOF processes, most ceramics. Those few HVOF systems that use acetylene as a fuel are necessary to apply the highest-melting-point ceramics such as zirconia or some carbides. HVOF coatings have primarily been used for wear resistance to date, but their field of applications is expanding.

Detonation Gun. In the detonation gun process, shown schematically in Fig. 9, a mixture of oxygen and acetylene, along with a pulse of powder, is introduced into a barrel and detonated using a spark. The high-temperature, high-pressure detonation wave moving down the barrel heats the powder particles to their melting points or above and accelerates them to a velocity of about 750 m/s. By changing the fuel gas and some other parameters, the Super D-Gun process achieves velocities of about 1000 m/s. This is a cyclic process, and after each detonation the barrel is purged with nitrogen and the process is repeated at up to about 10 times per second. Instead of a continuous swath of coating as in the other thermal spray processes, a circle of coating about 25 mm (1 in.) in diameter and a few micrometers thick is deposited with each detonation. A uniform coating thickness on the part is achieved by precisely overlapping the circles of coating in many layers. Typical coating thicknesses are in the range of 0.05 to 0.50 mm (0.002 to 0.02 in.), but thinner and much thicker coatings can be used.

The detonation gun coatings have some of the highest bond strengths (usually exceeding the epoxy strength of the test, that is, 69 MPa) and lowest porosities (usually less than 2% when measured metallographically) of the thermal spray coatings. They have been the benchmark

against which the other coatings have been measured for years. Careful control of the gases used generally results in little oxidation of metallics or carbides. The extremely high velocities and consequent kinetic energy of the particles in the Super D-Gun process allow most of the coatings to be deposited with residual compressive stress, rather than tensile stress as is typical of most of the other thermal spray coatings. This is particularly important relative to coating thickness limitations and the effect of the coating on the fatigue properties of the substrate.

Virtually all metallic, ceramic, and cermet materials can be deposited using detonation gun deposition. Detonation gun coatings are used extensively for wear and corrosion resistance as well as for many other types of applications. They are frequently specified for the most demanding applications, but often can be also the most economical choice because of their long life.

Process Comparison. A comparison of some of the characteristics of the major thermal spray processes is given in Table 2.

Ancillary Equipment. All thermal spray processes depend on the accurate control of gas flows, electric power, and powder, wire, or rod feedrates. A variety of equipment is available to do this, but it is essential for the best quality control of the coatings produced that all of this equipment be accurately calibrated, not only when it is initially installed, but also on a periodic basis thereafter. In addition, all of the plumbing for gases and water cooling, both internal to the torch or gun and external, must be checked to ensure that it is leak-tight.

Computer control of the more advanced thermal spray processes is being developed. On-line monitoring with closed-loop feedback control of electrical power, gas flows, cooling water flow and temperature, and powder feed rates are all possible. Although a variety of real-time coating thickness measurement techniques have been evaluated, most have been unsuccessful. The best technique currently seems to be that of accurate, reproducible deposition rate.

While some thermal spray devices are handheld, the only way to ensure uniform deposits is to automate the coating process to accurately control the rate of traverse of the gun or torch relative to the part being coated. This not only provides a uniform deposition of coating mass per unit area per unit of time, but also provides an

accurate overlap between passes and uniform thermal input to the part. (Obviously this control is only meaningful if it is coupled with a uniform spray rate, which in turn requires uniform material flow and power to the torch or gun.) One of the simplest and most commonly used methods of automation for cylindrical parts is to rotate the part in a lathe-type machine and traverse the torch on what would correspond to the tool post. Small parts can be mounted on a circular plate and rotated on the lathe as an annular plate. Large, flat parts can be coated using a traversing two-axis machine. More complex shapes can be coated using robotics.

Surface Preparation

To ensure adequate bonding of thermal spray coatings, it is critical that a substrate be properly prepared. Surfaces must be clean, and usually substrates must be roughened after cleaning by grit blasting or some other means. Of course, the surface must remain uncontaminated by lubricants from handling equipment or body oils from hands and arms after it is prepared. It is recommended that the prepared surface be coated as soon as possible after preparation to prevent the possibility of contamination or surface oxidation.

Cleaning and Degreasing. Rust or other corrosion products; oils, grease, or other lubricants; paint; or other surface contaminants must be removed before coating deposition is begun. They can be removed by scraping, wire brushing, machining, grit blasting, or chemical action. Care should be taken not to embed scale and the like in the surface when trying to remove it, particularly when using grit blasting. Solvent degreasing has been the most common method for removal of lubricants and body oils, most conveniently with vapor degreasers. Large parts, and parts with attached hardware that may be damaged by vapor degreasing, should be degreased manually using the least hazardous material available. All solvents should be used only in well-ventilated areas, by properly protected personnel who are trained in their use and who follow local regulations for the use, care, and handling of solvents. More recently there has been a trend toward the use of aqueous detergents and alkaline cleaners, sometimes with ultrasonic agitation, to avoid the hazards and environmental concerns of organic sol-

Table 3 Recommended grit sizes for preparation of surfaces to be thermal spray coated

Roughness	Grit size, mesh	Sieve openings		Applications
		mm	in.	
Coarse	-10/+30	2.007/0.610	0.079/0.024	For coatings exceeding 0.25 mm (0.010 in.) and best adherence
Medium	-14/+40	1.422/0.432	0.056/0.017	For fair adherence and smoother finishes of coatings less than 0.25 mm (0.010 in.) thick
Fine	-30/+80	0.610/0.175	0.024/0.007	For smoothest finishes on coatings less than 0.25 mm (0.010 in.) thick to be used in the as-sprayed condition

vents. Additional information is available in the Section "Surface Cleaning" in this Volume.

Surface Roughening. Three methods of surface roughening for thermal spray are widely used: rough threading, grit blasting, and a combination of rough threading followed by grit blasting. Rough threading is generally used for cylindrical surfaces and with thick flame sprayed coatings. The part to be prepared is mounted in a lathe and a single thread cut is taken. Tools for this purpose have a 60° to 70° point with a slight negative back rake. Screw feeds are approximately 0.80 to 1.25 mm (0.032 to 0.050 in.) or 0.78 to 1.26 threads/mm (20 to 32 threads/in.). The depth of the cut should vary with the screw feed and the required coating thickness. This technique is obviously limited to substrate sections thick enough to support the machining without significantly reducing its strength. It is most frequently used with flame sprayed coatings and is not recommended for thin coatings. Higher bond strengths are obtained when threading is followed by grit blasting. When the use of cutting fluid is necessary for threading, the part must be degreased before grit blasting or coating.

Grit blasting equipment used for thermal spray should not be used for other purposes, because dirt, paint, and lubricants contaminating the grit can be redeposited on the grit blasted surfaces. The grit should be continuously reclassified to remove fines. The air supply to the grit blast equipment must be clean and dry (including oil and particle filtration).

Aluminum oxide and chilled iron are the most widely used abrasive grits for thermal spray surface preparation. However, sand, crushed steel, and silicon carbide are also used in some situations. Sand is commonly used on large exterior structures such as bridges, towers, and piping where recovery of the grit is impractical. Crushed steel grit, obtained commercially in hardnesses to 65 HRC, is used in preparing some steels. Silicon

carbide is used for some special applications (e.g., for very hard substrates or to minimize contamination), but it is relatively expensive, breaks down quickly, and tends to embed in softer substrates.

Consideration should be given to the substrate material in the selection of grit type. Traces of residual grit may adversely affect some coatings. Chemical compatibility in the finished coating system must be considered. Alumina, sand, and especially silicon carbide may embed in softer metals such as aluminum, copper, and their alloys. For these metals, lower air pressures are recommended to minimize embedding. Chilled iron or crushed steel should be used in preparing surfaces to be flame sprayed and fused. Alumina, silica, or silicon carbide may inhibit bonding of some of these coatings.

Practical grit size ranges are -10/+30 mesh, -14/+40 mesh, and -30/+80 mesh. Surface roughness is primarily the result of grit particle size, so the selection of the grit size is determined, in part, by the roughness required for adequate bonding and may be limited by coating thickness. Table 3 gives general recommendations for grit size selection. Surface roughness can also be varied slightly by air pressure. This factor should be considered on an individual basis for each combination of grit size, type, and substrate material. Grit blasting air pressure varies from 210 to 620 kPa (30 to 90 psi), with standoff or working distances of 50 to 150 mm (2 to 6 in.). Grit blast nozzle openings are generally 6 to 10 mm (0.25 to 0.375 in.) in diameter. The grit blasting angle to the substrate should be about 90°. Excessive grit blasting should be avoided to minimize grit inclusion in the surface.

The substrate should be cleaned following grit blasting to remove residual dust. Clean, dry air may be used. Again, it is very important that the surface remain uncontaminated by lubricants

from handling equipment or body oils from hands and arms. It is recommended that the prepared surface be coated as soon as possible after preparation to prevent surface oxidation or contamination.

Finishing Treatment

Sealing. Thermal spray coatings usually have a structure with inherent porosity that ranges from less than 2 to more than 15 vol%, depending on the process by which the coating is deposited and the material sprayed. At least some of this porosity is interconnected. In many applications, coatings are exposed to corrosive fluids (liquids or gases) or hydraulic fluids that can infiltrate the pores, resulting in fluid leakage or corrosion throughout the coating or of the base material. These conditions can contribute to the premature failure of the coating. Many such applications, therefore, require the coating to be sealed before finishing. Sealing a coating may also help to reduce particle pullout from the surface during finishing for coatings with low cohesive strength.

To ensure as complete a sealing of the coating as possible, it is necessary to apply the sealant material as soon after coating as possible and prior to surface finishing. Sealant materials such as waxes, epoxies, phenolics, and inorganics are readily available and easily applied. The wax sealants are useful in preventing infiltration of liquids at low service temperatures. Resin-based sealants may be effective at temperatures up to about 260 °C (500 °F). Some silicone-based sealants have been reported to provide effective protection in salt spray tests conducted in accordance with military standards up to 480 °C (900 °F). Epoxy and phenolic sealants are usually more effective on coatings with higher porosity within their limits of stability (up to about 300 °C, or 570 °F).

One of the most effective methods of sealing coating porosity is vacuum impregnation. This method will usually fill all interconnected pores open to the exterior surface. To vacuum impregnate, the part is immersed in the sealant and placed in a vacuum chamber, and a soft vacuum is drawn. When the vacuum is released, air pressure forces the sealant into the pores. Most applications do not require this procedure, however. Low-viscosity anaerobic sealers may also be par-

Table 4 Typical ranges of speeds and feeds used in machining thermal sprayed metal coatings

Coating metal	High-speed steel tool				Carbide tool(a)			
	Speed		Feed		Speed		Feed	
	m/s	sfm	mm/rev	in./rev	m/s	sfm	mm/rev	in./rev
Steels								
Low-carbon, medium-carbon, low-alloy	0.25-0.50	50-100	0.075-0.125	0.003-0.005	0.25-0.50	50-100	0.075-0.125	0.003-0.005
High-carbon, stainless	0.15-0.200	30-40	0.075-0.100	0.003-0.004
Nonferrous metals								
Brass, bronze, nickel, copper, Monel	0.50-0.75	100-150	0.075-0.125	0.003-0.005	1.25-1.80	250-350	0.050-0.150	0.002-0.006
Lead, tin, zinc, aluminum, babbitt	0.75-1.00	150-200	0.075-0.175	0.003-0.007	1.25-1.80(b)	250-350(b)	0.050-0.100	0.002-0.004(b)

(a) Composition: 6% Co, 94% WC. (b) Aluminum only

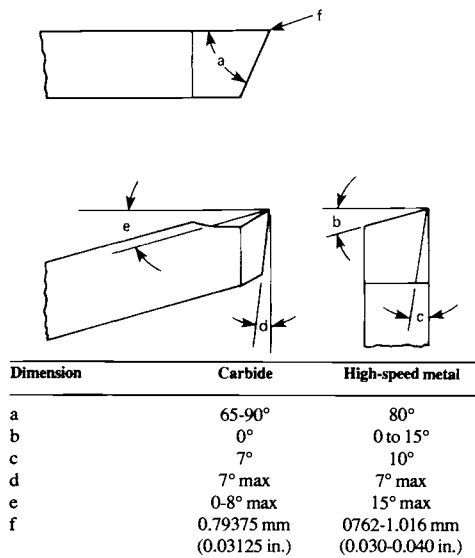


Fig. 10 Recommended shapes for carbide and high-speed steel cutting tools used in machining sprayed metal coatings

ticularly penetrating. The depth of penetration of some sealants may exceed 1.8 mm (0.070 in.). Regardless of the method or type of sealant used, pores or interconnected channels that are not connected to the exterior surface cannot be sealed and machining or wear in service may open these with consequent loss of corrosion protection.

Coating Finishing. Although thermal spray coatings are used with their surfaces in the as-deposited condition for some applications, these surfaces are too rough for most service conditions. Therefore they are usually finished by methods such as grinding, lapping, polishing, machining, abrasive brushing, or vibratory finishing. Although the techniques are common to those used for finishing solid metallics and ceramics, great care must be taken not to damage the coatings, causing excessive surface porosity due to pullout of coating particles or cracking due to thermal stresses. The ultimate surface finish that can be achieved with a thermal spray coating is a function not only of its composition, but also of the deposition parameters used to produce it, because they are largely responsible for the amount and size of the true porosity in the coating and the cohesive strength or particle-to-particle bonding within the coating. The best finish that can be achieved may vary, therefore, from a matte surface with a roughness of about 1 μm (40 $\mu\text{in.}$) R_a and pits exceeding 0.05 mm (0.002 in.) in diameter for a flame-sprayed coating to a virtually pit-free mirror finish with a roughness of less than 0.025 μm (1 $\mu\text{in.}$) R_a for some very-high-velocity coatings.

If a coating is to be sealed, the sealing should be done before any finishing operation. It is extremely difficult to remove finishing fluids and debris from an unsealed surface, and these will interfere with the sealing. Sealing may also help to prevent the embedment of finishing debris in a surface, which would cause abrasive wear in service.

Some of the softer metallic coatings can be machined with single-point high-speed tool steels. Better surface finishes can be achieved with carbide or coated carbide tools. Table 4 includes typical parameters for machining some classes of metallic coatings. Usually, lower infeeds are used than with wrought materials. Figure 10 shows the configuration of typical carbide and steel tools. Burnishing is occasionally used with soft materials such as tin, zinc, and babbitt to produce a smooth, dense bearing surface.

Cermet and ceramic coatings require grinding, and many metallic coatings can be more effectively ground than single-point machined. Some coatings can be ground with oxide or silicon carbide wheels, but cubic boron nitride or diamond wheels may be necessary for some of the hardest coatings, and they are frequently more cost-effective and produce better finishes for many other coatings. Specific grinding wheel selection is important and varies with the coating composition and type. It is probably best to consult with wheel manufacturers for specific coatings. Some guidelines for diamond grinding:

1. Check diamond wheel specifications. (a) Use only 100 concentration. (b) Use only resinoid bond.
2. Make sure your equipment is in good mechanical condition. (a) Machine spindle must run true. (b) Backup plate must be square to the spindle. (c) Gibs and ways must be tight and true.
3. Balance and true the diamond wheel on its own mount—0.005 mm (0.0002 in.) maximum runout.
4. Check peripheral wheel speed—25 to 33 m/s (5000 to 6500 sfm).
5. Use a flood coolant—water plus 1 to 2% water-soluble oil of neutral pH. (a) Direct coolant toward point of contact of the wheel and the workpiece. (b) Filter the coolant.
6. Before grinding each part, clean wheel with minimum use of a silicon carbide stick.
7. Maintain proper infeeds and crossfeeds. (a) Do not exceed 0.01 mm (0.0005 in.) infeed per pass. (b) Do not exceed 2.03 mm (0.080 in.) crossfeed per pass on revolution.
8. Never spark out—stop grinding after last pass.
9. Maintain a free-cutting wheel by frequent cleaning with a silicon carbide stick.
10. Clean parts after grinding. (a) Rinse in clean water, then dry. (b) Apply a neutral-pH rust inhibitor to prevent atmospheric corrosion.
11. Visually compare the part at 50 \times with a control sample of known quality.

Regardless of the type of grinding wheel used, the wheel should be dressed frequently enough, and operating parameters should be chosen, to ensure clean cutting of the coating. Sparkout passes (passes with low contact pressure run until virtually no contact is being made) should never be used. The smeared material created by such a procedure can be easily dislodged in service and cause abrasive wear and other problems.

If grinding does not produce a sufficiently smooth surface, it may be necessary to lap the

coating after grinding. Again, it is advisable to consult the manufacturers of lapping materials for specific recommendations. Some guidelines:

1. Use a hard lap.
2. Use a serrated lap.
3. Use recommended diamond abrasives—Bureau of Standards No. 1, 3, 6, or 9.
4. Embed the diamond firmly into the lap.
5. Use a thin lubricant such as mineral spirits.
6. Maintain lapping pressures of 0.14 to 0.17 MPa (20 to 25 psi) when possible.
7. Maintain low lapping speeds of 0.5 to 1.5 m/s (100 to 300 sfm).
8. Recharge the lap only when lapping time increases 50% or more.
9. Clean parts after grinding and between changes to different-grade diamond laps—use ultrasonic cleaning if possible.
10. Visually compare the part at 50 \times with a control sample of known quality.

In addition to the traditional finishing techniques discussed above, a variety of other methods have been developed, particularly for nondimensional finishing. These include various abrasive brushes, belt grinding, “super” finishing, peening, and vibratory techniques. The use of nondimensional finishing is usually possible only when the dimensional specifications for the part are very loose, or when the part can be precisely and accurately preground and the deposition thickness and other characteristics such as waviness can be tightly controlled.

Coating Repair. The repair of thermal spray coatings by coating over service-worn or in-process damaged coatings is not generally recommended, even if the predeposited coating is reference ground, cleaned, and grit blasted. Adequate bond strength between the coating layers is seldom achieved, and there are no reliable nondestructive test techniques currently available to verify an adequately bonded interface. Therefore, the preferred procedure is to strip the existing coating and apply a completely new coating. Note that when applying a multilayered coating, it is best to apply each new layer over the as-deposited surface of the previous layer, not to grind and grit blast between layers.

Quality Assurance

There are few, if any, nondestructive evaluations that can be performed on a final coating, so the assurance of the quality of thermal spray coatings is more dependent on process control than on inspection of the final coating. This implies, of course, that the equipment used must be accurately and precisely produced and assembled, that all gages, flow meters, and the like must be calibrated, that the powders or other feedstocks must be tightly controlled, and that standard procedures and operating parameters must be developed and followed for each coating. To ensure that the process is in control, it is common practice to coat a small sample using a standard set of parameters (standoff, traverse rate, angle of deposition, etc.) for metallographic examination

Table 5 Guidelines for abrasive cutting of thermal spray coatings

Parameter	Notes
Wheel selection	
Abrasive	
Al ₂ O ₃	To cut ferrous substrates
SiC	To cut nonferrous and ceramic
Diamond	Fine, precise cuts on small samples
Bond	
Rubber	General use, long life
Resin	Dry cutting
Combination	Wet cutting of hard materials
Grit size	
Coarse	Rough cuts, fast
Fine	Precise cuts, slow
Fixturing	
Direction of cut	Coating in compression
Clamps	Both sides of cut
Blocking	Wooden to protect coating
Coolant	Flood if possible
Cutting speed and pressure	Adjusted to prevent heating of part

of the coating before coating a part. The cross section of the coating sample is compared with standards to ensure that its microstructure, and usually its microhardness, are within acceptable ranges.

It should be kept in mind that the microstructure, hardness, and other properties of the coating on a small metallographic sample may not be the same as those of the coating on a part because of differences in standoff, angle of impingement, masking effects, cooling, and so on. Thus the evaluation of the coating on the metallographic sample only ensures that the process is in control. However, this, in turn, should ensure that the coating on the part will perform as it has in the past on the same part in the same environment, if the other deposition parameters, such as setup, traverse speed, and cooling, are unchanged.

Other features of a coating that must be controlled include finished surface characteristics and part dimensions. Standard techniques are adequate for these purposes. There is growing recognition that the average roughness of a surface may not be an adequate characterization of its fitness for service, and that other parameters, such as bearing area, peak-to-valley, skewness, and kurtosis, may need to be specified. Areas of coating coverage, including areas of optional overspray, must be specified and controlled in addition to dimensions such as diameters or thicknesses.

Metallography is usually done on cross sections of small samples coated under standard setup conditions of standoff, angle of deposition, traverse rate, and so on. These samples, if appropriately sized, may be mounted for examination directly, or, if too large, sectioned using abrasive cutoff saws. Some recommendations for cutting are found in Table 5. Standard mounting and polishing techniques may be used, but special precautions should be taken to ensure minimal damage to the coatings and as accurate and reproducible a representation of the structure as possible. It is fairly easy to induce cracking and pullout of the coating using overly aggressive cutting, grinding, and polishing tech-

Table 6 Typical metallographic preparation procedure for metallic and cermet thermal spray coatings using silicon carbide grinding paper

Number of specimens, 1-6; specimen size, 32 mm (1¼ in.); cutting equipment, universal cutoff saw with an Al₂O₃ thin wheel; mounting equipment, vacuum impregnation unit; mounting resin, fast-curing epoxy cold mount; holder, 32 mm (1¼ in.) plate; automated grinding-polishing machine

Process step	Disk or cloth	Abrasive	Grit or grain size	Abrasive dosing	Speed, rpm	Load per specimen, N	Lubricant/dosing	Time, s
Grinding								
Planar grinding	Paper	SiC	220	...	150	25	Water	Until plane
Fine grinding								
Step 1	Paper	SiC	320	...	150	25	Water	30-45
Step 2	Paper	SiC	500	...	150	25	Water	30-45
Step 3	Paper	SiC	1200	...	150	25	Water	30-45
Polishing								
Diamond polishing	Hard polishing cloth	Spray diamond	3 µm	4	150	25	Low-viscosity alcohol-base lubricant/5	5-10 min
Final polishing	Soft, chemical-resistant cloth	Alumina polishing suspension	0.04 µm	10	150	10	...	30-60

Source: Struers

Table 7 Typical metallographic preparation procedure for metallic and cermet thermal spray coatings using an advanced diamond grinding format

Number of specimens, 1-6; specimen size, 32 mm (1¼ in.); cutting equipment, universal cutoff saw with an Al₂O₃ thin wheel; mounting equipment, vacuum impregnation unit; mounting resin, fast-curing epoxy cold mount; holder, 32 mm (1¼ in.) plate

Process step	Disk or cloth	Abrasive	Grit or grain size	Abrasive dosing	Speed, rpm	Load per specimen, N	Lubricant/dosing	Time, min
Grinding								
Planar grinding	Paper	SiC	220	...	150	25	Water	Until plane
Fine grinding	Very hard polishing cloth	Spray diamond	9 µm	4	150	25	Alcohol-base lubricant/6	5
Polishing								
Diamond polishing	Hard polishing cloth	Spray diamond	3 µm	4	150	25	Low-viscosity alcohol-base lubricant/5	5-10
Final polishing	Soft, chemical-resistant cloth	Alumina polishing suspension	0.04 µm	10	150	10	...	½-1

Source: Struers

Table 8 Typical metallographic preparation procedure for tungsten carbide-cobalt thermal spray coatings

Specimens sectioned using a precision cutting saw with a diamond wafering blade and mounted using a pressure-cooled mounting press and edge-retention molding compound; specimen size 32 mm (1¼ in.); no etchant used after polishing

Process step	Grinding/polishing surface	Abrasive	Abrasive grain size, µm	Time, min	Force per sample, lb	Speed, rpm	Relative rotation	Dispensing sequence
Planar grinding	Very hard grinding platen	Diamond suspension	45	2 or until plane	5	240	Against	1 s spray on; 30 s spray off
Fine grinding								
Step 1	Medium-hard grinding platen	Diamond suspension	9	5	5	120	Same	1 s spray on; 30 s spray off
Step 2	Hard cloth	Diamond suspension	3	1.5	5	120	Same	1 s spray on; 30 s spray off
Final polishing	Hard cloth	High-purity alumina-base mild attack polishing suspension	...	1.5	10	120	Against	...

Source: Buehler Ltd.

niques. It is also very important to minimize edge rounding of the coating, because the coating being examined is usually only about 0.25 mm (0.010 in.) thick. The major manufacturers of metallographic consumables and equipment have taken an interest in the metallography of thermal spray coatings in recent years and can provide useful recommendations for mounting and polishing. A substantial amount of training and skill is necessary to be able to grind and polish thermal spray coatings properly and reproducibly by hand. It is therefore recommended that automated polishing equipment be used following procedures established for each coating. A few guidelines are listed in Tables 6 to 8.

The microstructural features frequently examined include compositional phases, porosity, and oxide inclusions. These may be determined quantitatively by comparison with photographic standards or by standard metallographic techniques including point counting, line segment measurement, or optical electronic analysis techniques. Most of these analyses use light microscopes; however, scanning electron microscopes can be used if necessary.

Porosity is one of the more frequently specified parameters, but it is probably one of the most difficult to accurately determine metallographically. A distinction should always be made between absolute porosity and metallographically apparent porosity. Some porosity may be too small to be visible using light microscopy, or the amount of porosity on the surface may be more or less than the absolute bulk porosity because of pullout of coating or because polishing debris fills some real porosity. Thus, metallographic porosity standards or specifications can only have meaning if very reproducible grinding and polishing procedures are used.

The same considerations apply to other metallographic characterizations, although they may be somewhat less sensitive to preparation. The identification of the various phases present in a coating can be enhanced using standard etching techniques or optical enhancement, such as differential interference or polarized lighting. The use of advanced scanning electron microscopy techniques may minimize the need for these techniques.

Hardness Testing. Both surface and cross-sectional hardness measurements can be used for the quality control of coatings. If surface hardness measurements (e.g., Rockwell hardness measurements) are used, the thickness of the coating and the hardness of the substrate must be high enough to ensure that an accurate measurement is achieved. Microhardness measurements on cross sections are used more often than surface hardness measurements for the quality control of thermal spray coatings.

The guidelines of the ASTM recommended practices should be followed, regardless of the type of test used. The coating must be thick

enough to support the indentation for the load chosen, and particular attention should be paid to the positioning of the indentations. Statistically valid procedures should be followed. These include calibration of the hardness tester, confirmation of the operator's skill using frequent measurement of standard test blocks, the proper placement of indentations, and an adequate number of indentations. All of these should be monitored using control charts and other statistical quality control tools. A greater number of measurements may be needed than with wrought materials because of the greater inhomogeneities in the microstructures of most thermal spray coatings.

Bond Strength Testing. A variety of tests have been developed to measure both the tensile and shear strength of thermal spray coatings. The most commonly used test is defined by ASTM C 633, "Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings," which measures the strength in tension perpendicular to the surface. In this test, a 25.4 mm (1 in.) diameter cylinder is coated on one end and then bonded to a mating cylinder, usually with epoxy. The couple is then pulled apart using a tensile testing machine. ASTM C 633 calls for a coating thickness of 0.45 mm (0.018 in.) to prevent penetration of the coating by the bonding agent. This may be necessary for some flame-sprayed coatings, but it is much thicker than necessary for the denser plasma, HVOF, or detonation gun coatings. A thickness of 0.25 mm (0.010 in.) is frequently used for the denser coatings, because it is closer to the thicknesses used in service and provides a more realistic measure of strength in light of the residual stresses that may be present in the coatings. The ASTM procedure should be referred to for dimensional and alignment requirements as well as specific preparation, coating, bonding, and testing procedures.

For the ASTM C 633 test to have practical meaning in a given application, the coated cylinder must be of the same or a very similar material and of the same hardness as the part, must be prepared in the same manner (e.g., grit blasted with the same grit at the same pressure and angle), and must be coated with the same deposition parameters (i.e., coated at the same angle, standoff, and traverse rate) as the part. This test is limited by the strength of the epoxy or other bonding agent used, currently a maximum of approximately 69 MPa (10 ksi). Most detonation gun coatings, many HVOF coatings, and a few plasma coatings exceed this, so the test is simply a proof test and not a measure of the actual bond or cohesive strength of the coating.

While a few lap shear and bend tests have been used to qualify coatings for specific applications, none is universally recognized. All of the known tests of this type have significant theoretical limitations, making interpretations of the results difficult. Because few applications place a coating in tension perpendicular to the surface, the value of the ASTM C 633 test is limited as well.

Health, Safety, and Environmental Concerns

There are some health, safety, and environmental concerns associated with thermal spray coating processes, as with most industrial processes. In general they are similar to those associated with welding processes. Obviously, all plant or laboratory, local, state, and federal government directives should be followed. None of the thermal spray processes should be attempted without proper training of all of the personnel involved and careful consideration of any hazards associated with the particular materials being used to prepare for or produce the coating. Proper care and maintenance of the equipment, including all gas and electric lines, will greatly reduce any hazards. In addition, design and procedure reviews for safety by qualified engineers are advisable. These should include the ancillary processes of surface preparation, part handling, and finishing as well as the coating process itself.

Dust and Fumes. All thermal spray processes produce dust and fumes, so operators must be protected and the dust and fumes collected. When possible, the coating process should be conducted in a cubicle equipped with ventilation and dust collection equipment and with the operators outside. Each thermal spray process has its own airflow requirement to provide adequate ventilation, and the equipment manufacturer should be able to provide guidelines. Nonetheless, dust monitors should be periodically used to ensure that the ventilation system is working properly. If the operators must be in the cubicle or the coating must be done in the open, the operators should wear respirators. It is no longer considered adequate to rely only on air flow away from the operator to provide adequate protection. The type of respirator used depends on the material being deposited. The effluent from the dust collection system should be periodically monitored to ensure compliance with all regulations.

Noise generated by thermal spray processes ranges from about 80 dB for some of the flame spray processes to over 120 dB for some of the HVOF processes, over 140 dB for some plasma spray processes, and to over 150 dB for the detonation gun processes. Individual ear protection is adequate for the former, but the latter must be oper-

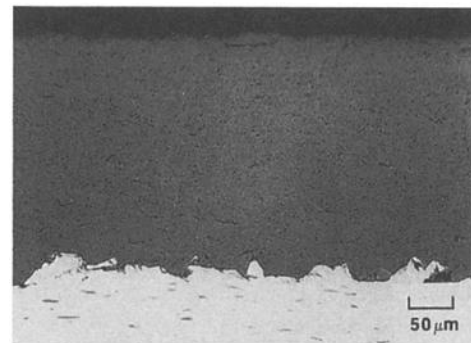


Fig. 11 Microstructure of plasma-sprayed chromium oxide. As-polished

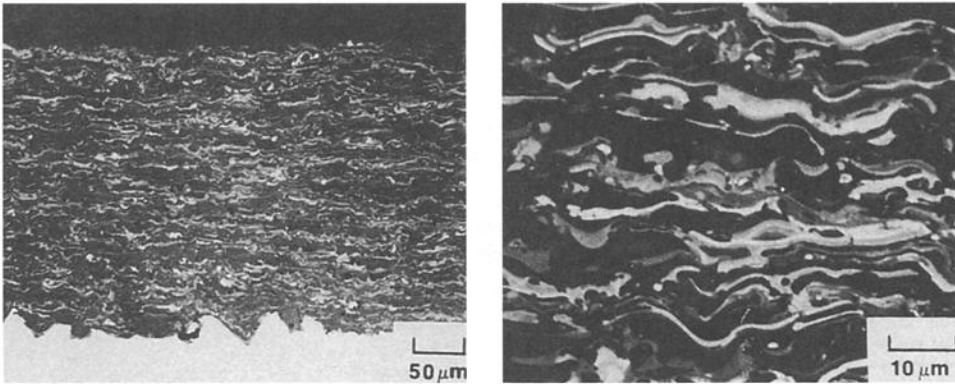


Fig. 12 Microstructure of detonation gun deposited alumina and titania. As-polished

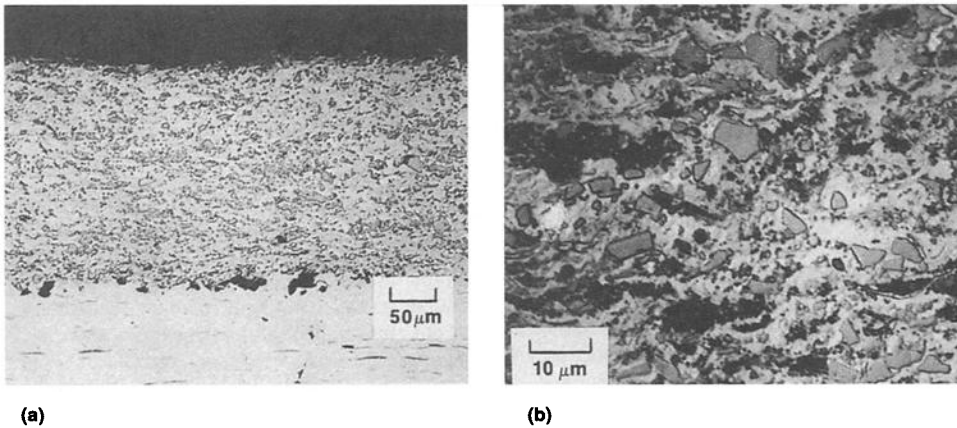


Fig. 13 Microstructure of a detonation gun deposited tungsten carbide/cobalt cermet coating. (a) As-polished. (b) Etched

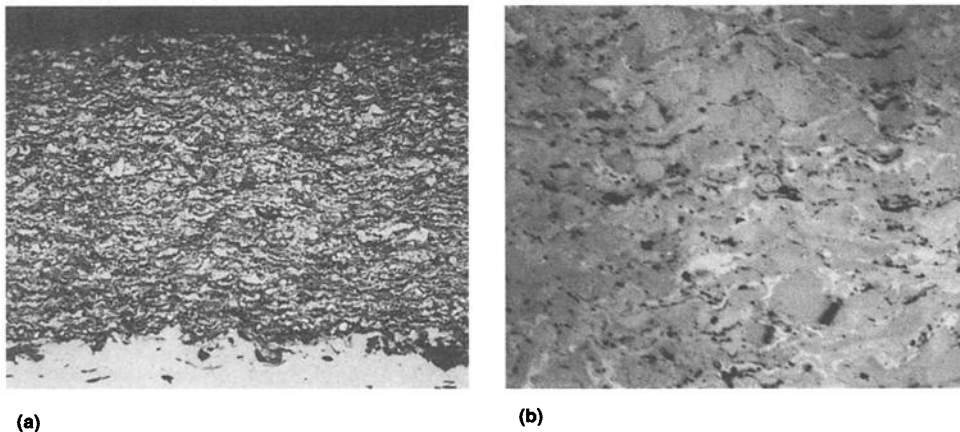


Fig. 14 Microstructure of a mechanically mixed chromium carbide/nickel chromium cermet coating. (a) As-polished. (b) Etched

ated in sound-reducing cubicles. Sound levels at the operator's position should be measured and compliance with all regulations ensured. In addition, all personnel in the vicinity of the spray operation should have their hearing checked periodically.

Light Radiation. The spectrum of light emitted by the thermal spray devices ranges from the far

infrared to extreme ultraviolet. Adequate eye and skin protection must be used. Shade 5 lenses may be sufficient for some flame spray processes, but shade 12 is required for plasma spray and electric (wire) arc. Fire-retardant, closely woven fabrics should be worn to protect the skin from burns. Burns can be caused by heated particles bouncing from the sub-

strate, hot gases, or light. Ultraviolet radiation will burn exposed skin and penetrate loosely woven fabrics, causing burns similar to a severe sunburn in minutes.

Coating Structures and Properties

Coating Microstructures. Thermal spray coatings consist of many layers of thin, overlapping, essentially lamellar particles, frequently called splats. Cross sections of several typical coatings are shown in Fig. 2 and 11 to 14. Generally, the higher-particle-velocity coating processes produce the densest and better bonded coatings, both cohesively (splat-to-splat) and adhesively (coating-to-substrate). Metallographically estimated porosities for detonation gun coatings and some HVOF coatings are less than 2%, whereas most plasma sprayed coating porosities are in the range of 5 to 15%. The porosities of flame sprayed coatings may exceed 15%.

The extent of oxidation that occurs during the deposition process is a function of the material being deposited, the method of deposition, and the specific deposition process. Oxidation may occur because of the oxidizing potential of the fuel-gas mixture in flame spraying, HVOF, or detonation gun deposition or because of air inspired into the gas stream in plasma spraying or any of the other methods. Recall that the latter cause can be ameliorated by using inert-gas shrouds or low-pressure chambers with plasma spraying. Using carbon-rich gas mixtures with oxyfuel processes can cause carburization rather than oxidation with some metallic coatings. Metallic coatings are probably most susceptible to oxidation, but carbide coatings may suffer a substantial loss of carbon that is not particularly obvious in metallographic examination. Oxidation during deposition can lead to higher porosity and generally weaker coatings, and it is usually considered to be undesirable.

Most of the thermal spray processes lead to very rapid quenching of the particles on impact. Quench rates have been estimated to be 10^4 to 10^6 °C/s for ceramics and 10^6 to 10^8 °C/s for metallics. As a result, the materials deposited may be in thermodynamically metastable states, and the grains within the splats may be submicron-size or even amorphous. The metastable phases present may not have the expected characteristics, particularly corrosion characteristics, of the material, and this factor should be kept in mind in the selection of coating compositions.

The mechanical properties of thermal spray coatings are not well documented with the exception of their hardness and bond strength. These are discussed in the section "Quality Control" in this article. The sensitivity of the properties of the coatings to specific deposition parameters makes universal cataloging of properties by simple chemical composition and general process (e.g., WC-12Co by plasma spray) virtually meaningless. The situation is even more complex because the properties of coatings on test specimens may differ somewhat from those on parts because of differences in ge-

Table 9 Mechanical properties of representative plasma, detonation, and high-velocity combustion coatings

Parameter	Type of coating					
	Tungston-carbide-cobalt			Alumina		
Nominal composition, wt%	W-7Co-4C	W-9Co-5C	W-11Co-4C	W-14Co-4C	Al ₂ O ₃	Al ₂ O ₃
Thermal spray process	Detonation gun	High-velocity combustion	Plasma	Detonation gun	Detonation gun	Plasma
Rupture modulus, 10 ³ psi(a)	72	...	30	120	22	17
Elastic modulus, 10 ⁶ psi(a)	23	...	11	25	14	7.9
Hardness, kg/mm ² , HV ₃₀₀	1300	1125	850	1075	>1000	>700
Bond strength, 10 ³ psi(c)	>10,000(b)	>10,000(b)	>6500	>10,000	>10,000(b)	>6500

(a) Compression of freestanding rings of coatings. (b) Epoxy failure. (c) ASTM C 633-89, "Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings," ASTM, 1989. Source: Publication 1G191, National Association of Corrosion Engineers

ometry and thermal conditions. Nonetheless, coatings made by competent suppliers using adequate quality control will be quite reproducible, and therefore the measurement of various mechanical properties of these standardized coatings may be very useful in the selection of coatings for specific applications. Properties that may be of value include the modulus of rupture, modulus of elasticity, and strain-to-fracture in addition to hardness. Examples of some of these are given in Table 9.

Any measurement or use of mechanical properties must take into account the anisotropic nature of the coating microstructure and hence its properties (i.e., the coating properties are different parallel to the surface than perpendicular to the surface because of the lamellar nature of the microstructure). Most mechanical properties are measured parallel to the surface, in part because it is easier to produce test specimens in this plane because the coatings are typically thin. Unfortunately, the major load in service is usually perpendicular to the surface. This does not, however, make measurements in the plane of the coating useless. It is frequently important to know, for example, how much strain can be imposed on a coating due to extension or deflection of the part without cracking the coating. Cracks in a coating may not only affect its performance, but also initiate cracks and fatigue failures in the part.

Uses of Thermal Spray Coatings

Wear Resistance. One of the most important uses of thermal spray coatings is for wear resistance. They are used to resist virtually all forms of wear, including abrasive, erosive, and adhesive, in virtually every type of industry. The materials used range from soft metals to hard metal alloys to carbide-based cermets to oxides. Generally, the wear resistance of the coatings increases with their density and cohesive strength, so the higher-velocity coatings such as HVOF and particularly detonation gun coatings provide the greatest wear resistance for a given composition.

A variety of laboratory tests have been developed to rank thermal spray coatings and compare them with other materials. Examples of abrasive and erosive wear data are shown in Tables 10 and 11. It should be kept in mind that laboratory tests can seldom duplicate service conditions. Therefore these tests should only be used to help select

candidate coatings for evaluation in service. Only rarely, with good baseline data, can any precise prediction of wear life in service be made from laboratory data.

Friction Control. Thermal spray coatings are used in some applications to provide specific frictional characteristics to a surface, covering the full spectrum from low friction to high. Obviously, the surface topography is critical in these applications, and unique finishing techniques have been developed to provide the desired coefficient of friction without causing excessive wear or damage of the mating surface. The textile industry provides, as an example, applications covering the complete range of friction characteristics and surface topography to handle very abrasive synthetic fiber. Oxide coatings such as alumina are usually used with surfaces that vary from very smooth to nodular to quite rough, depending on the coefficient of friction required.

Corrosion Resistance. Flame sprayed aluminum and zinc coatings are frequently used for corrosion resistance on bridges, ships, and other structures. In this application, reliance is placed primarily on their anodic protection of the substrate. Other thermal spray coatings are used for their corrosion resistance, often coupled with their wear resistance, but the inherent porosity of the coatings must be taken into account and the coatings sealed, either by using an epoxy or other infiltrant or by sintering, as in the case of the M-Cr-Al-Y coatings. These aspects are discussed in the section "Processes" in this article.

Dimensional Restoration. Thermal spray coatings are often used to restore the dimensions of a worn part. On occasion, a coating with low residual stress and/or low cost is used to build up the worn area and then a thin, more wear-resistant coating is applied over it. In any use of thermal spray coatings for buildup, it should be kept in mind that the properties of the coating are probably far different than those of the substrate, and that the coating will not add any structural strength to the part. In fact, if care is not taken, the coating may degrade the fatigue strength of the part.

Thermal Applications. Plasma spray coatings, and to a more limited extent other thermal spray coatings, are used as thermal barriers. In particular, partially stabilized zirconia coatings are used on gas-turbine combustors, shrouds, and vanes and on internal combustion cylinders and valves to improve efficiency and reduce metal temperatures or

Table 10 Abrasive wear data for selected thermal spray coatings

Material	Type	Wear rate, mm ³ /1000 rev
Carballoy 883	Sintered	1.2
WC-Co	Detonation gun	0.8
WC-Co	Plasma spray	16.0
WC-Co	Super D-Gun	0.7
WC-Co	High-velocity oxyfuel	0.9

ASTM G 65 dry sand/rubber wheel test, 50/70 mesh Ottawa silica, 200 rpm, 30 lb load, 3000-revolution test duration

Table 11 Erosive wear data for selected thermal spray coatings

Material	Type	Wear rate, μm/g
Carballoy 883	Sintered	0.04
WC-Co	Detonation gun	1.3
WC-Co	Plasma spray	4.6
AISI 1018 steel	Wrought	21

Silica-based erosion test; particle size, 15 μm; particle velocity, 139 m/s; particle flow, 5.5 g/min, ASTM Recommended Practice G 75

cooling requirements. In other applications they may be used to dissipate heat as either surface conductors or thermal emitters. Because of their unique lamellar microstructure and porosity, the thermal conductivity of thermal spray coatings is usually anisotropic and significantly less than that of their wrought or sintered counterparts.

Electrical Applications. As with thermal properties, the electrical conductivity of thermal spray materials is anisotropic and is reduced compared to their wrought or sintered counterparts due to their lamellar microstructure and porosity. Metallic or conductive cermet coatings are, however, used as electrical conductors where wear resistance must be combined with electrical conductivity. Conversely, thermal spray oxide coatings are used as electrical insulators. In this application, it is usually important to seal the coating to prevent moisture, even from the air, from penetrating the coating and reducing its insulating capability. Thermal spray coatings have also been used to produce high-temperature thermocouples and strain gages. Electromagnetic or radio-frequency shielding can also be provided by flame or electric-arc sprayed layers of zinc, tin, or other metals.

Other Applications. A variety of other applications have been developed for thermal spray coatings, including coatings used as nuclear moderators, catalytic surfaces, and parting films for hot isostatic presses. Thermal spray materials can also be used to produce freestanding components such as rocket nozzles, crucibles, and molds.

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