**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 finely 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.

**Table 1  Maximum temperature of heat sources**

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Approximate temperature (stoichiometric combustion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane-oxygen</td>
<td>2526 °C (4579 °F)</td>
</tr>
<tr>
<td>Natural gas-oxygen</td>
<td>2538 °C (4600 °F)</td>
</tr>
<tr>
<td>Hydrogen-oxygen</td>
<td>2660 °C (4820 °F)</td>
</tr>
<tr>
<td>Propylene-oxygen</td>
<td>2843 °C (5240 °F)</td>
</tr>
<tr>
<td>Methylacetylene/propadiene-oxygen</td>
<td>2927 °C (5301 °F)</td>
</tr>
<tr>
<td>Acetylene-oxygen</td>
<td>3087 °C (5589 °F)</td>
</tr>
<tr>
<td>Plasma arc</td>
<td>2200 to 28,000 °C (4000 to 50,000 °F)</td>
</tr>
</tbody>
</table>

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-
Figure 4: Typical electric-arc spray device

Figure 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 lower, 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 (0.06 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
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 characteristics. 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.
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 backfilled with inert gas to about 40 kPa (300 torr). Once the system has been sufficiently purged to achieve an acceptable atmospheric, 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 prepping 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 spraying 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 0.5 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 hard-facing 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-
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 ceramic 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

<table>
<thead>
<tr>
<th>Roughness</th>
<th>Grit size, mesh</th>
<th>Sieve openings, mm</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>−10/30</td>
<td>2.007/0.610</td>
<td>For coatings exceeding 0.25 mm (0.010 in.) and best adherence</td>
</tr>
<tr>
<td></td>
<td>−14/40</td>
<td>1.422/0.432</td>
<td>For fair adherence and smoother finishes of coatings less than 0.25 mm (0.010 in.) thick</td>
</tr>
<tr>
<td>Fine</td>
<td>−30/80</td>
<td>0.610/0.175</td>
<td>For smoothest finishes on coatings less than 0.25 mm (0.010 in.) thick to be used in the as-sprayed condition</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Coating metal</th>
<th>High-speed tool</th>
<th>Carbide tool(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed</td>
<td>Feed</td>
</tr>
<tr>
<td></td>
<td>m/s</td>
<td>sf/m</td>
</tr>
<tr>
<td>Steels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-carbon, medium-carbon, low-alloy</td>
<td>0.25-0.50</td>
<td>50-100</td>
</tr>
<tr>
<td>High-carbon, stainless</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Nonferrous metals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brass, bronze, nickel, copper, Monel</td>
<td>0.50-0.75</td>
<td>100-150</td>
</tr>
<tr>
<td>Lead, tin, zinc, aluminum, hatched</td>
<td>0.75-1.00</td>
<td>150-200</td>
</tr>
</tbody>
</table>

(a) Composition: 6% Co, 94% WC. (b) Aluminum only
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 with wrought materials. Figure 10 shows the configuration of typical carbide and steel tools. Burningish 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 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 50x 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 50x 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 non-dimensional finishing. These include various abrasive brushes, belt grinding, "super" finishing, peening, and vibratory techniques. The use of non-dimensional 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel selection</td>
<td></td>
</tr>
<tr>
<td>Abrasive</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>To cut ferrous substrates</td>
</tr>
<tr>
<td>SiC</td>
<td>To cut nonferrous and ceramic</td>
</tr>
<tr>
<td>Diamond</td>
<td>Fine, precise cuts on small samples</td>
</tr>
<tr>
<td>Bond</td>
<td></td>
</tr>
<tr>
<td>Rubber</td>
<td>General use, long life</td>
</tr>
<tr>
<td>Resin</td>
<td>Dry cutting</td>
</tr>
<tr>
<td>Combination</td>
<td>Wet cutting of hard materials</td>
</tr>
<tr>
<td>Grit size</td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>Rough cuts, fast</td>
</tr>
<tr>
<td>Fine</td>
<td>Precise cuts, slow</td>
</tr>
<tr>
<td>Fixturing</td>
<td></td>
</tr>
<tr>
<td>Direction of cut</td>
<td>Coating in compression</td>
</tr>
<tr>
<td>Clamps</td>
<td>Both sides of cut</td>
</tr>
<tr>
<td>Blocking</td>
<td>Wooden to protect coating</td>
</tr>
<tr>
<td>Coolant</td>
<td>Flood if possible</td>
</tr>
<tr>
<td>Cutting speed and pressure</td>
<td>Adjusted to prevent heating of part</td>
</tr>
</tbody>
</table>

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 (1/4 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 (1/4 in.) plate; automated grinding-polishing machine

<table>
<thead>
<tr>
<th>Process step</th>
<th>Disk or cloth</th>
<th>Abrasive</th>
<th>Grit or grain size</th>
<th>Abrasive dosing</th>
<th>Speed, rpm</th>
<th>Load per specimen, N</th>
<th>Lubricant/dosing</th>
<th>Time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding</td>
<td>Paper</td>
<td>SiC</td>
<td>220</td>
<td>...</td>
<td>150</td>
<td>25</td>
<td>Water</td>
<td>Until plane</td>
</tr>
<tr>
<td>Fine grinding</td>
<td>Paper</td>
<td>SiC</td>
<td>320</td>
<td>...</td>
<td>150</td>
<td>25</td>
<td>Water</td>
<td>30-45</td>
</tr>
<tr>
<td>Step 1</td>
<td>Paper</td>
<td>SiC</td>
<td>500</td>
<td>...</td>
<td>150</td>
<td>25</td>
<td>Water</td>
<td>30-45</td>
</tr>
<tr>
<td>Step 2</td>
<td>Paper</td>
<td>SiC</td>
<td>1200</td>
<td>...</td>
<td>150</td>
<td>25</td>
<td>Water</td>
<td>30-45</td>
</tr>
<tr>
<td>Final polishing</td>
<td>Soft, chemical-resistant cloth</td>
<td>Alumina polishing suspension</td>
<td>0.04 µm</td>
<td>10</td>
<td>150</td>
<td>10</td>
<td>Low-viscosity alcohol-base lubricant/5</td>
<td>5-10 min</td>
</tr>
</tbody>
</table>

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 (1/4 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 (1/4 in.) plate

<table>
<thead>
<tr>
<th>Process step</th>
<th>Disk or cloth</th>
<th>Abrasive</th>
<th>Grit or grain size</th>
<th>Abrasive dosing</th>
<th>Speed, rpm</th>
<th>Load per specimen, N</th>
<th>Lubricant/dosing</th>
<th>Time, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding</td>
<td>Paper</td>
<td>SiC</td>
<td>220</td>
<td>...</td>
<td>150</td>
<td>25</td>
<td>Water</td>
<td>Until plane</td>
</tr>
<tr>
<td>Fine grinding</td>
<td>Very hard polishing cloth</td>
<td>SiC</td>
<td>9 µm</td>
<td>4</td>
<td>150</td>
<td>25</td>
<td>Alcohol-base lubricant</td>
<td>5</td>
</tr>
<tr>
<td>Polishing</td>
<td>Diamond polishing</td>
<td>Spray diamond</td>
<td>3 µm</td>
<td>4</td>
<td>150</td>
<td>25</td>
<td>Low-viscosity alcohol-base lubricant</td>
<td>5-10</td>
</tr>
<tr>
<td>Final polishing</td>
<td>Soft, chemical-resistant cloth</td>
<td>Alumina polishing suspension</td>
<td>0.04 µm</td>
<td>10</td>
<td>150</td>
<td>10</td>
<td>...</td>
<td>1/2-1</td>
</tr>
</tbody>
</table>

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 (1/4 in.); no etchant used after polishing

<table>
<thead>
<tr>
<th>Process step</th>
<th>Grinding/polishing surface</th>
<th>Abrasive</th>
<th>Grit or grain size</th>
<th>Abrasive dosing</th>
<th>Force per sample, lb</th>
<th>Speed, rpm</th>
<th>Relative rotation</th>
<th>Dispensing sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar grinding</td>
<td>Very hard grinding platen</td>
<td>Diamond suspension</td>
<td>45</td>
<td>2 or until plane</td>
<td>5</td>
<td>240</td>
<td>Against</td>
<td>1 s spray on; 30 s spray off</td>
</tr>
<tr>
<td>Fine grinding</td>
<td>Medium-hard grinding platen</td>
<td>Diamond suspension</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>120</td>
<td>Same</td>
<td>1 s spray on; 30 s spray off</td>
</tr>
<tr>
<td>Step 1</td>
<td>Hard cloth</td>
<td>Diamond suspension</td>
<td>3</td>
<td>1.5</td>
<td>5</td>
<td>120</td>
<td>Same</td>
<td>1 s spray on; 30 s spray off</td>
</tr>
<tr>
<td>Step 2</td>
<td>High-purity alumina-base</td>
<td>...</td>
<td>1.5</td>
<td>10</td>
<td>120</td>
<td>Against</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

Source: Buethler Ltd.
terial and oxide inclusions. These may be detec-
ted quantitatively by comparison with
photographic standards or by standard metal-
lographic techniques including point counting,
line segment measurement, or optical elec-
tronic analysis techniques. Most of these
analyses use light microscopes; however, scan-
ning electron microscopes can be used if nec-
essary.

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

The same considerations apply to other
metallographic characteristics, although
they may be somewhat less sensitive
to preparation. The identification of the vari-
ous phases present in a coating can be en-
hanced using standard etching techniques or
optical enhancement, such as differential in-
terference 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 hard-
ness measurements (e.g., Rockwell hardness
measurements) are used, the thickness of the
cylinder must be 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, stand-
off, 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 appli-
cations, none is universally recognized. All of
the known tests of this type have significant
theoretical limitations, making interpretations
of the results difficult. Because few applica-
tions 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 environ-
mental concerns associated with thermal spray
coating processes, as with most industrial proc-
esses. In general they are similar to those associ-
ated with welding processes. Obviously, all plant
or laboratory, local, state, and federal government
directives should be followed. None of the ther-
amal spray processes should be attempted without
proper training of all of the personnel involved
and careful consideration of any hazards associ-
ated 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 re-
views for safety by qualified engineers are advis-
able. These should include the ancillary proc-
esses 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 con-
ducted in a cubicle equipped with ventilation
dust collection equipment and with the operators
outside. Each thermal spray process has its own
airflow requirement to provide adequate ventila-
tion, 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 ade-
quate 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 en-
sure 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 ade-
quate for the former, but the latter must be oper-
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-

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 substrate, hot gases, or light. Ultraviolet radiation will burn exposed skin and penetrate loosely woven fabrics, causing burns similar to a severe sunburn in minutes.
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-CrAl-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 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 cermets 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 paring films for hot isostatic presses. Thermal spray materials can also be used to produce freestanding components such as rocket nozzles, crucibles, and molds.

ACKNOWLEDGMENT

The author recognizes the contributions of James H. Clare and Daryl E. Crawmer, authors of the article “Thermal Spray Coatings” in Metals Handbook, 9th ed., Vol 5. In particular, the sec-

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tungsten-carbide-cobalt</th>
<th>W-1Co-4C Detonation gun</th>
<th>W-1Co-4C Plasma</th>
<th>W-1Co-4C Detonation gun</th>
<th>WC-Co Plasma spray</th>
<th>WC-Co Super D-Gun</th>
<th>WC-Co High-velocity oxyfuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal composition, wt%</td>
<td>72</td>
<td>75</td>
<td>23</td>
<td>21</td>
<td>23</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Thermal spray process</td>
<td>W-7Co-4C Detonation gun</td>
<td>W-9Co-5C High-velocity combating</td>
<td>W-11Co-4C Detonation gun</td>
<td>W-14Co-4C Detonation gun</td>
<td>Al2O3 Detonation gun</td>
<td>Al2O3 Plasma</td>
<td></td>
</tr>
<tr>
<td>Rupture modulus, 103 psi(a)</td>
<td>30</td>
<td>120</td>
<td>22</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elastic modulus, 103 psi(a)</td>
<td>11</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bond strength, 103 psi(c)</td>
<td>&gt;10,000(b)</td>
<td>&gt;10,000(b)</td>
<td>&gt;6500</td>
<td>&gt;10,000(b)</td>
<td>&gt;10,000(b)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


### Table 10: Abrasive wear data for selected thermal spray coatings

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Wear rate, mm²/10,000 rev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbolloy 883</td>
<td>Sintered</td>
<td>1.2</td>
</tr>
<tr>
<td>WC-Co</td>
<td>Detonation gun</td>
<td>0.8</td>
</tr>
<tr>
<td>WC-Co</td>
<td>Plasma spray</td>
<td>16.0</td>
</tr>
<tr>
<td>WC-Co</td>
<td>Super D-Gun</td>
<td>0.7</td>
</tr>
<tr>
<td>WC-Co</td>
<td>High-velocity oxyfuel</td>
<td>0.9</td>
</tr>
</tbody>
</table>

### Table 11: Erosive wear data for selected thermal spray coatings

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Wear rate, μm/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbolloy 883</td>
<td>Sintered</td>
<td>0.04</td>
</tr>
<tr>
<td>WC-Co</td>
<td>Detonation gun</td>
<td>1.3</td>
</tr>
<tr>
<td>WC-Co</td>
<td>Plasma spray</td>
<td>4.6</td>
</tr>
<tr>
<td>AISI 1018 steel</td>
<td>Wrought</td>
<td>21</td>
</tr>
</tbody>
</table>

Silica-based erosion test; particle size, 15 μm; particle velocity, 139 m/s; particle flow, 5.5 g/min, ASTM Recommended Practice G 75.
tions on flame spray, flame spray and fuse, and electric wire-arc spray, as well as several of the figures, were substantially adapted from the earlier edition.

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- *Surface and Coatings Technology*, Elsevier Science S.A.