CHAPTER 28

THERMAL SPRAYING

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CHAPTER 28

THERMAL SPRAYING

INTRODUCTION

GENERAL HISTORY

ALTHOUGH THERMAL SPRAYING has been in use since the early part of the 20th Century, many of the early applications were concerned mainly with reclamation. Since 1960, there has been a dramatic expansion in the number and diversity of thermal spraying processes, methods, and materials.

Technological advances in equipment, process variations, and materials and forms (wire, rod, cord, or powder) now available have resulted in a multiplicity of new and potential applications. Only the present range and scope of the process variations and applications are reviewed in this chapter. The information will be useful as a guide to the equipment and consumables available, and as a reference for selecting the process variation suitable for each application. Attention is paid to setting variables once thermal spraying is selected as the production or repair process.

PROCESS DESCRIPTION

THERMAL SPRAYING (THSP) is a group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semimolten condition on a substrate to form a thermal spray deposit. The surfacing material may be in the form of wire, rod, cord, or powder. The spray material is heated to its plastic or molten state by an oxyfuel gas flame, electric arc, plasma, or by detonation of an explosive gas mixture. The hot material is propelled from the spray gun to the substrate in a gas stream. Most metals, cermets, oxides, and hard metallic compounds can be deposited by one or more of the process variations. The process is sometimes called "metallizing", "metal spraying", or "flame spraying". A schematic view of a wire flame spray system is shown in Figure 28.1.

The substrate is usually roughened before spraying, generally by grit blasting using aluminum oxide or chilled iron grit.

When the molten particles strike the substrate, they flatten and form thin platelets that conform to irregularities of the part geometry and to each other. The platelets rapidly cool and solidify. Successive layers are built up to the desired thickness by the impingement of particles upon the substrate, building up, particle by particle, into a lamellar structure, as shown in Figure 28.2.

The bond between the substrate and the coating material may be mechanical, metallurgical, chemical, or a combination of these. A post-spray heat treatment of the coating may be required to increase the bond strength, by
diffusion or by chemical reaction between the spray deposit and the substrate.

The density of the coating deposit will depend upon the material type, method of deposition, the spraying conditions, and post spray processing. The density is generally 85 to 90% percent of the filler metal density. The properties of the deposit depend upon such factors as porosity, the cohesion between deposited particles, adhesion to the substrate including interface integrity, and chemistry of the coating material.

**PROCESS SELECTION**

THE ANTICIPATED SERVICE conditions should be considered in choosing the thermal spray process, procedures, consumables, and quality requirements. This chapter covers basic knowledge about thermal spray processes and potential applications. Practical application procedures, to the extent that is possible, are also given. For more detailed information refer to the AWS publication *Thermal Spraying: Practice, Theory and Application*.

**ADVANTAGES AND APPLICATIONS**

**THERMAL SPRAYING** processes and procedures are specialized, yet find wide use in both manufacturing and maintenance applications. The nature of thermal spray processes is inherently synergistic. Many components and variables are involved, which, when working together and properly applied, produce an effect far greater than they would individually. Yet each component and variable must be separately and jointly understood, to permit the selection and operation of a suitable process. The background of this chapter will help the user tailor that process to particular applications.

The end use of sprayed coatings determines the properties needed in the final coating, the type of consumable employed, and the kind of equipment needed.

**Manufacturing**

**THERMAL SPRAYING** is used extensively in the manufacture of original equipment components. For example, the aerospace industry has developed hundreds of applications. In addition, marine, mining, food, automotive, petroleum, electrical power generation, thermal processing, chemical processing and electronic applications use thermally sprayed coatings to achieve results that no substrate by itself can provide.

**Maintenance**

EXISTING INDUSTRIAL FACILITIES save hundreds of millions of dollars annually through the use of thermal spraying for repair and maintenance. This includes not only in-plant but also on-site applications, to coat structures and equipment parts. Repair of components, where thermal spraying is applicable, is both economical and time saving. When corrosion or wear, or both, are encountered, thermal spraying should be considered. The use of sprayed coatings, often impregnated with sealers, has received worldwide acceptance by industry for such applications. In many cases, the thermal spray application ends up making the component better than new.

**LIMITATIONS**

APPLICATION ENGINEERS need to be aware of the nature of thermally sprayed coatings, as contrasted with fusion welding, and evaluate them accordingly. For example, thermally sprayed wear coatings usually should not be selected over welded overlays if high impact resistance or resistance to aggressive liquid corrosion is needed in the end-use of the component. For these applications, consideration should be given to fused coatings which have a true metallurgical bond. In addition, the engineer needs to consider the effect of part geometry on coating quality and buildup. In cases where fused coatings cannot be used, successful results have been obtained by applying sealers, selected for a specific environment, over a sprayed coating.

Thermal spraying embodies a group of processes, as does fusion welding, and selection should proceed in the normal fashion. For example, capital investment for plasma spraying equipment is 10 times more expensive than arc spraying. Careful consideration should be given to equipment and process costs.

The heterogeneous structure of sprayed deposits creates factors unique to thermal spraying:

(1) Microhardness is lower than that exhibited by the original spray consumable.
(2) Bond strength is mechanical, metallurgical, or a combination of these, and can be modified in a number of ways.

(3) Deposit densities are less than 100 percent.

(4) Shrinkage stresses may be a factor affecting coating bond strength in certain configurations and applications. Low shrinkage materials should be selected for difficult part geometries.

(5) Thermally sprayed deposits usually have some porosity, but sealers can be used to minimize coating penetration by corrosive media.

**SPRAY CONSUMABLES**

The spray materials are in the form of wire (both solid and cored), rod, cord (a continuous length of powder-filled plastic tubing), or powder. Cord spraying is primarily used in Europe. Many metals, oxides, ceramics, intermetallic compounds, some plastics, and certain types of glass can be deposited by one or more of the processes.

**PROCESS VARIATIONS**

Thermal spraying processes can be categorized under two basic groups, according to the methods of heat generation. Group I uses combustible gases as the heat source, while Group II uses electrical power. See Table 18.1. Additional heat is generated at impact during hypersonic flame spraying, as the spray material gives up its kinetic energy. This is discussed further in the section on Hypersonic Spraying.

**GROUP I: COMBUSTION**

**Subsonic Flame Spraying**

In subsonic flame spraying, the spray material is fed into and melted by an oxyfuel gas flame. Whether the material is in the form of wire, rod or powder, molten particles are propelled onto the substrate by the force of the flame.

A wide variety of materials in these forms can be sprayed with the flame. Materials that cannot be melted with an oxyfuel gas flame, and those that burn or become severely oxidized in the oxyfuel flame, cannot be flame sprayed.

Flame spray accessories in the form of air jets and air shrouds are available to change the flame characteristics. These accessories can be used to adjust the shape of the flame and the velocity of the sprayed materials.

Materials are deposited in multiple layers, each of which can be as thin as 0.0005 in. (130 μm) per pass. The total thickness of material deposited will depend upon several factors including the following:

<table>
<thead>
<tr>
<th>Table 28.1 Basic Groups of Thermal Spraying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I: Combustion</td>
</tr>
<tr>
<td>Group II: Electrical</td>
</tr>
<tr>
<td>1. Flame</td>
</tr>
<tr>
<td>a. Subsonic</td>
</tr>
<tr>
<td>b. Hypersonic</td>
</tr>
<tr>
<td>1. Arc</td>
</tr>
<tr>
<td>2. Plasma arc</td>
</tr>
<tr>
<td>3. Induction coupled plasma</td>
</tr>
</tbody>
</table>

**Hypersonic Flame Spraying**

Detonation and continuous flame guns are two types of hypersonic spray guns.

The detonation gun operates on principles significantly different from other flame spray methods. This method repeatedly heats and projects charges of powder onto a substrate by rapid successive detonations of an explosive mixture of oxygen and acetylene in the gun chamber.

The continuous flame hypersonic guns used in the United States use a propylene-oxygen flame. Overseas operators prefer ethylene, hydrogen, and propane as fuel gases. The powder is brought to the torch using a nitrogen carrier. The torch is designed to confine the powder in the center of the flame. The particles leave the gun at velocities generally in excess of mach 4. This speed is far greater than achieved in most other spray methods. The kinetic energy released by impingement upon the substrate contributes additional heat that promotes bonding, high density, and appreciable hardness values.

**GROUP II: ELECTRIC**

**Arc Spraying**

The spray materials used with arc spraying, commonly called "electric arc spraying", are metals and alloys in wire form, and powders contained in a metal sheath (cored wire). Two continuously fed wires are melted by an arc operating between them. The molten metal is atomized and propelled onto a substrate by a high-velocity gas jet, usually air. Recent work has been done using other gases.
This method is restricted to spraying consumables that can be produced in continuous wire form.

**Plasma Spraying**

**Plasma Spraying** is a thermal spraying process in which a nontransferred plasma arc gun is used to create an arc plasma that melts and propels the surfacing material to the substrate.

The term *nontransferred arc* means that the plasma arc is contained within the gun, and that the substrate is not part of the electric circuit. The arc is maintained between a tungsten cathode and a constricting nozzle which serves as the anode. An inert gas or a reducing gas, under pressure, enters the annular space between the anode and cathode, where it becomes ionized, producing temperatures up to 30,000°F (17,000°C). The hot plasma gas passes through the nozzle as a high velocity jet. The surfacing material, in powder form, is injected into the hot gas stream, where it becomes molten and is propelled onto the substrate.

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**NATURE OF SPRAYED COATINGS**

Success in the use of thermally sprayed coatings relies on careful adherence to specific process procedures. This is a basic rule of thermal spraying, and deviation from the standards for a particular application, or inattention to detail, especially preparation, will produce an unreliable result.

Sprayed coating systems have four basic components: substrate type, bond coats as necessary, coating structure, and finish.

**BOND COATS**

The bond between the coating and the substrate may be mechanical or metallurgical. Adhesion is influenced by a combination of: (1) coating material, (2) spray particle size, (3) substrate condition and geometry, (4) degree of surface roughness, (5) surface cleanliness, (6) surface temperature before, during, and after spraying, (7) particle impact velocity, (8) type of base material, and (9) spray angle.

**COATING STRUCTURE**

The structure and chemistry of coatings sprayed in ambient air are different from those of the same material in the wrought or presprayed form.

The differences in structure and chemistry are due to the incremental nature of the coating, and its reaction with the process gases and the atmosphere surrounding the coating material while in the molten state. For example, when air or oxygen is used as the process gas, oxides of the spray material are formed while the particles are in transit and become a part of the coating.

Metal coatings tend to be porous and brittle, and to differ in hardness from the original consumable material. The "as-sprayed" structures of coatings will be similar in their lamellar nature, but will exhibit varying characteristics, depending on the particular spraying process used.
process variables, techniques employed, and the nature of the spray material applied.

The coating density will vary with the particle velocity, the heat source temperature of the spray process, and the amount of air used. The density also varies with the type of powder, its mesh size, spray rate, standoff distance, and method of injection.

Microscopic examination is the only means of quality evaluation for porosity.

The average particle impact velocities for several thermal spray processes are shown in Figure 28.3.

The nature of the bond in the “as-sprayed” condition can be modified by post-spray thermal treatment. Modification is by diffusion, chemical reaction, or both, between the coating and the substrate.

<table>
<thead>
<tr>
<th>VELOCITY: m/sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
</tr>
<tr>
<td>FLAME SUBSONIC HYPERSONIC</td>
</tr>
<tr>
<td>POWDER</td>
</tr>
<tr>
<td>ARC</td>
</tr>
<tr>
<td>PLASMA LOW ENERGY</td>
</tr>
<tr>
<td>HIGH ENERGY</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VELOCITY: ft/sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>300</td>
</tr>
</tbody>
</table>

Figure 28.3—Average Particle Impact Velocities for Various Thermal Spray Processes

**THERMAL SPRAY EQUIPMENT**

**FLAME SPRAY EQUIPMENT**

A TYPICAL FLAME spraying arrangement consists of the following:

1. Spray gun
2. Spray material and the associated feeding equipment
3. Oxygen and fuel gas supplies, pressure regulators, and flowmeters
4. A compressed air source and control unit, when required
5. Workpiece holding device
6. Gun or workpiece handling device for semi-automatic or automatic processing, as required
7. Air cooling ring, air jets, or siphon

The gun design depends upon the type of material to be sprayed and its physical form (wire, rod, or powder). When automated, the gun or the workpiece, or both, are driven by mechanisms designed to produce the desired deposit configuration.

The four fuel gases most commonly used for flame spraying are: acetylene, propane, methylacetylene-propadiene (MPS), and propylene. Acetylene in combination with oxygen produces the highest flame temperature. The distinct characteristics of an oxyacetylene flame make it easy to adjust the stoichiometry to produce oxidizing, neutral, or reducing conditions. The significant changes in flame appearance are not so evident with the other three gases. Hydrogen, which is used occasionally, and propane, are suitable for flame spraying metals with low melting points such as aluminum, tin, zinc, and babbitt metal. Table 28.2 lists heat source temperatures for various fuel gases.

**Gas Controls**

OXYGEN AND FUEL gas flowmeters are used to provide good control of the gas ratio and flame intensity. Their use permits higher spraying rates than with valve control of gas flows. Since the molten particles are exposed to oxygen, an oxide film forms on them, even when a reducing gas mixture is used. The thickness of the oxide film does not vary greatly with changes in the fuel-gas-to-oxygen ratio.

**Table 28.2 Heat Source Temperatures**

<table>
<thead>
<tr>
<th>Source</th>
<th>Temperature, °F</th>
<th>Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene, oxygen</td>
<td>5825</td>
<td>3100</td>
</tr>
<tr>
<td>Arca and plasmas</td>
<td>4000-15000</td>
<td>2200-8300</td>
</tr>
<tr>
<td>Hydrogen, oxygen</td>
<td>4875</td>
<td>2600</td>
</tr>
<tr>
<td>MPS, oxygen</td>
<td>5200</td>
<td>2870</td>
</tr>
<tr>
<td>Natural gas, oxygen</td>
<td>4955</td>
<td>2735</td>
</tr>
<tr>
<td>Propane, oxygen</td>
<td>4785</td>
<td>2640</td>
</tr>
</tbody>
</table>

1. Properties of these and other fuel gases are discussed in Chapter 14, Oxyfuel Cutting, Welding Handbook, Vol. 2, 8th Ed.
Compressed Air Supply

The cleanliness and dryness of the compressed air, when used to atomize and propel the molten surfacing material, is important in producing a quality deposit. Oil or water in the compressed air will cause fluctuations in the flame, produce poor or irregular atomization of the spray material, reduce bond strength, and affect the quality of the deposit. Aftercoolers or a desiccant dryer and chemical filters should be installed between the air source and the spray unit. Accurate regulation of the air pressure is important for uniform atomization.

WIRE FLAME SPRAYING EQUIPMENT

With wire flame spraying, the metal wire to be deposited is normally supplied to the gun continuously from a coil or spool. In some cases, cut lengths of metal rods are used.

A cross section of a typical wire flame spray gun is shown in Figure 28.4. The gun consists essentially of two subassemblies: a drive unit which feeds the wire, and a gas head which controls and mixes the flows of fuel gas, oxygen, and compressed air. The principles of operation of all wire type gas guns are similar. Commercial equipment for wire flame spraying is shown in Figure 28.5.

The wire drive unit consists of a motor and drive rolls. They may be air or electrically powered, with adjustable speed controls. Speed controls may be mechanical, electromechanical, electronic, or pneumatic.

The wire is fed through a central orifice in the nozzle, where it is melted by a coaxial flame. The flame is surrounded by a coaxial stream of compressed gas, usually air, to shear the molten material into droplets and propel it onto the substrate. In special applications, inert gas may be used instead of air. Various sizes of nozzles and air caps are used to accommodate different wire sizes. The arrangement of the oxyfuel gas jets and compressed air orifices differs with the various manufacturers, as do the mechanisms for feeding the wire through the flame.

If the wire feed rate is excessive, the wire tip will extend beyond the hot zone of the flame and not melt or atomize properly. This produces very coarse deposits. If the feed is too slow, the metal will severely oxidize, and the wire may fuse to the nozzle. Such deposits have high oxide content.

Wire spraying units vary in size. Small hand-held units are manipulated in much the same manner as paint spray guns. They are often used to apply protective coatings of aluminum or zinc to large objects such as tanks, ship hulls, and bridges. Larger units are usually designed to be mechanically manipulated for spraying moving parts.

CERAMIC ROD FLAME SPRAYING EQUIPMENT

Ceramic rod flame spraying is similar to wire flame spraying. Straight lengths of ceramic rod are successively fed into the flame by driven plastic rollers in the gun.

The bond between a ceramic deposit and the substrate is mechanical in nature. The semi-molten particles deform and take the shape of the prepared surface. Proper surface preparation is therefore a prerequisite for a firmly bonded deposit.

The equipment for ceramic rod spraying is similar to wire spraying equipment (Figure 28.1). This equipment requires greater care in adjusting the spraying variables than does wire spraying equipment because of the higher melting points and lower thermal conductivities of ceramics as compared to metals.

Some ceramics applied by this technique are:

1. Alumina-titania
2. Alumina
3. Zirconia

Figure 28.4—Cross Section of Typical Wire, Rod, or Cord Flame Spray Gun
conditions, with due consideration of the following factors:

1. Thermal, electrical, and chemical characteristics
2. Melting point
3. Adherence or bond strength
4. Density
5. Cost

Some of the important characteristics of ceramic spray deposits are:

1. Good adherence to a variety of substrate materials
2. Economically applied in controlled thicknesses
3. Good physical and chemical properties
4. Low thermal and electrical conductivities
5. High wear resistance
6. Good finishing characteristics.

**POWDER FLAME SPRAYING**

In powder flame spraying, the material to be sprayed is supplied to the gun in powder form from a hopper. The hopper may be remote from the gun or mounted onto it. The powder may be aspirated or carried into the flame by an air feed system, by the oxygen stream, or by gravity. The powder is melted by the flame and propelled onto the substrate by either a compressed air jet or the combustion gases. A hypervelocity powder flame spray torch is shown in operation in Figure 28.6.

In all thermal spraying processes, the powder particle velocity feed rate affects the structure and the deposit efficiency of the coating. If the raw material is not properly heated, deposit efficiency will rapidly decrease, and the coating will contain trapped, unmelted particles. If the particle velocity is too low, some powder will be volatilized, resulting in coating deterioration and higher operating costs.

Powder flame spraying equipment is simpler and less costly than plasma spray equipment. However, the spray rate with flame spraying is lower. The equipment is designed for easy portability.

A special case is a powder flame spray gun which is similar to an oxyacetylene welding torch. Powder to be sprayed is metered into the gas stream before it leaves the tip. Compressed air is not used. The torch can be used for preheating or fusing spray deposits, when powder is not being injected into the gas stream.

Metals, ceramics, and ceramic-metal mixtures can be flame sprayed by the powder method. The metals are usually hard alloys designed for specific wear or corrosion resistant applications. Very hard metallic compounds, such as carbides and borides, can be blended with metal powders to form a composite, wear-resistant coating. The degree of melting of the particles of spray powder depends upon both the melting point of the material and the time.

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**Figure 28.5—Oxyfuel Gas Wire Spray Equipment Capable of Spraying Wires Ranging from Low Melting Alloys (Babbit) to Higher Melting Point Steels. Aluminum Wire Shown on Top Spool and Carbon Steel Wire on the Bottom Reel.**

(4) Rare earth oxides
(5) Zirconium silicate
(6) Magnesium zirconate
(7) Barium titanate
(8) Chromium oxide
(9) Magnesia-alumina
(10) Mullite
(11) Calcium titanate

Each ceramic surfacing material has specific characteristics, economics, advantages, and limitations. The material is selected to provide specific properties for the service.
that the particles are exposed to the heat of the flame (called the dwell time). Powders with low melting points will become completely molten, and those with high melting points, such as ceramics, may melt only on the particle surface.

Due to the lower particle velocities and lower temperatures obtained, the coatings produced by powder flame spraying generally have lower adhesion strength, higher porosity content, and lower overall corrosion strength than coatings produced by other spray processes.

The powder feedstock may be pure metal, an alloy, a composite, a carbide, a ceramic, or any combination of these. The process is used to apply "self fluxing" metallic alloy coatings. These materials contain boron and silicon, which serve as fluxing agents, and oxidation is minimized. Fusion or metallurgical bonding to a metal substrate is accomplished by heating the deposit to its melting temperature range. The fusing temperature is usually in excess of 1900°F (1040°C), and is accomplished with any heating source such as a flame, induction coil, or a furnace.

A small amount of gas is diverted to carry the powder from the hopper into the oxyfuel gas stream, where the powder is melted and carried by the flame onto the substrate.

Variations in the powder flame spraying process include compressed gas to feed powder to the flame, additional air jets to accelerate the molten particles, a remote powder feeder with an inert gas to convey powder through a pressurized tube into the gun, and devices for high speed powder acceleration at atmospheric pressure. Such refinements tend to improve flow rate, and sometimes to increase particle velocity, which enhances bond strength and coating density.

**DETONATION SPRAYING**

Detonation spraying is accomplished with a specially designed gun shown in Figure 28.7. The detonation gun is different from other combustion spraying devices. It uses the energy of explosions of oxygen-acetylene mixtures, rather than a steady flame, to blast powdered particles onto the surface of the substrate. The resulting deposit is extremely hard, dense, and tightly bonded.

The detonation gun, schematically shown in Figure 28.8, consists of a long barrel into which a mixture of oxygen, fuel gas, and powdered coating material, suspended in nitrogen, is introduced. The oxygen-acetylene mixture is ignited by an electric spark several times per second, creating a series of controlled detonation waves (flame fronts) which accelerate and heat the powder particles as they move down the barrel. Exit particle velocities of approximately 2,500 ft/sec. (760m/sec.) are produced. After each ejection of powder, nitrogen purges the unit prior to successive detonations. Multiple detonations per second build up the coating to the specified thickness.
Temperatures above 6000°F (3315°C) are achieved within the detonation gun, while the substrate temperature is maintained below 300°F (150°C) by a carbon dioxide cooling system.

Coating thicknesses range between 0.002 and 0.02 in. (50 and 500 μm). The process produces a sound level in excess of 150 decibels, and is housed in a sound isolating room. The actual coating operation is completely automatic and remotely controlled. The high particle impingement velocity results in a strong bond with the substrate. Excellent finishes are achievable. The porosity content of the coating is low.

Figure 28.7—Detonation Flame Spraying Equipment

Flame sprayed deposits produced by the hypersonic gun are similar to those produced by detonation spraying. Because of the high impingement velocities, the sprayed particles are very tightly bonded to the substrate.

ARC SPRAYING

The arc spray process uses an arc between two wires (feedstock). They are kept insulated from each other and automatically advance to meet at a point within an atomizing gas stream. A potential difference of 18 to 40 volts applied across the wires initiates an arc as they converge, melting the tips of both wires. An atomizing gas, usually compressed air, is directed across the arc zone, shearing off molten droplets which form the atomized spray.

The velocity of the gas through the atomizing nozzle can be regulated over a range of 800 to 1100 ft/min. (4.0 to 5.5 m/s) to control deposit characteristics desired. Molten metal particles are ejected from the arc at the rate of several thousand particles per second.

In comparison with wire flame spraying, the quantity of metal oxides is better controlled and spray rates are higher in wire arc spraying. Thus wire arc spraying is often more economical.
The wire control unit consists of two reel (or coil) holders, which are insulated from each other, and connected to the spray gun with flexible insulated wire guide tubes. Wire sizes range from 1/16 to 1/8 in. (1.6 to 3.2 mm).

Arc Equipment

A wire arc spray gun is shown schematically in Figure 28.9. A welding type power supply is required to maintain the arc between the two wires.

The arc temperatures exceed the melting point of the spray material. During the melting cycle, the metal is superheated to the point where some volatilization may occur, especially with aluminum and zinc. The high particle temperatures produce metallurgical interactions or diffusion zones, or both, after impact with the substrate. These localized reactions form minute weld spots with good cohesive and adhesive strengths. Thus the coatings develop excellent bond strengths.

The wire arc spray process can deposit as little as one lb/hr. Higher deposition rates than those possible with other spray processes are also available with arc spraying. Factors controlling the rate of application are the current rating of the power source and the permissible wire feed rate to carry the available power.

Direct current constant potential power sources are normally used for wire arc spraying; one wire is positive (anode) and the other is negative (cathode). The tip of the cathode wire is heated to a higher temperature than the tip of the anode wire and melts at a faster rate. Consequently, the particles atomized from the cathode are much smaller than those from the anode wire when the two wires are of the same diameter.

The power source, providing a voltage of 18 to 40 volts, permits operation over a wide range of metals and alloys. The arc gap and spray particle size increase with a rise in voltage. The voltage should be kept at the lowest possible level, consistent with good arc stability, to provide the smoothest coatings and maximum coating density.

Systems Operations

Wire arc spray systems can be operated from a control console or from the gun. The control console will have the switches and regulators necessary for controlling and monitoring the operating circuits that power the gun and control the spray procedure, namely the following:

1. A solid-state direct current power source, usually of the constant voltage type
2. A dual wire feeding system
3. A compressed gas supply with regulators and flowmeters built into the control assembly
4. Arc spray gun and pertinent console switching
PLASMA ARC SPRAYING

The term "plasma arc" is used to describe a family of metal working processes used in spraying, fusion welding and surfacing, and cutting. They all use a constricted arc to provide high density thermal energy. Arc constriction is accomplished by forcing the electric arc through an orifice. During heating, the accompanying gas is partially ionized, producing a plasma. In plasma spraying, a nontransferred arc is established between an electrode and a constricting nozzle. The substrate is not part of the electrical circuit.

Turbine and rocket engine components are exposed to extreme service conditions. Existing engineering materials are not adequate without a protective thermally sprayed coating. In many cases, the spray coating consists of ceramic oxides and carbides which require temperatures higher than those possible with flame and arc processes. The plasma spray process evolved to meet these needs. The plasma spray process also stimulated the evolution of a new family of materials and application techniques for a greatly expanded range of industrial applications. Plasma spraying supplements the older processes of flame and wire arc spraying.

The process uses powdered materials in a plasma (hot ionized or dissociated gas) as the heat source. Plasma generators provide controllable temperatures of from 4000 to 15 000°F (2200 to 8300°C). These temperatures will melt most substances.

In the plasma spray process, a gas or gas mixture is passed through an electric arc between a coaxially aligned tungsten alloy cathode and an orifice within a copper anode. The process is illustrated in Figure 28.10. The gas passing through the orifice is ionized. The temperature of the ionized plasma is much higher than that obtained with a combustion flame.

Figure 28.10—Sectional View of Plasma Arc Spraying Torch
**EQUIPMENT**

A plasma spray unit will consist of a plasma gun, power source, powder, powder feed system, and associated fixtureing and traversing devices. This is shown schematically in Figure 28.11.

**Torch Design**

Several types of plasma spray guns are available. An 80 kW plasma spray gun is shown in Figure 28.12. In each instance, the arc is generated between an electrode and a water-cooled chamber (nozzle) into which a plasma gas is injected. The gas expands in the heat of the arc, is accelerated, and exits through a nozzle in a cone-shaped configuration.

As shown in Figure 28.10, the rear electrode may be fixed or adjustable, but it must be aligned coaxial with the nozzle or front electrode. Flowmeters are used to control the flow of gas through the gun. Several nozzle configurations can be used to accommodate various plasma gases and to spray different types of powders.

Quality deposits require introducing powder at the proper point in the arc plasma and at the correct feed rate. Since the particles are in the plasma for very short times, slight variations in the location of the feed point may significantly change the amount of heat transmitted to the powder.

Current gun designs have power capacities of from 40 to 100 kW. Direct current of 100 to 1100 A is used at 40 to 100 V. High power is necessary when spraying with high particle velocities. Particle velocity is an important variable with respect to bond strength and deposit density and integrity.

**Power Supply**

Power supplies for plasma spraying should have the following characteristics:

1. Constant current dc output
2. Variable open-circuit and load voltages
3. Variable current control
4. Low ripple
5. Good regulation
6. Arc starting capability

Rectifier type, solid-state units generally meet the above requirements. Units are easily operated in parallel for high-power operations. In general, they resemble arc welding power sources.

**Powder Feed Devices**

Powder feed mechanisms are of three types: aspirator, mechanical, and localized fluid bed. Mechanical feed is the most popular type. It uses the metering action of a screw or wheel to deliver powder at a constant rate to a mixing chamber. The powder is introduced into the carrier gas stream in the mixing chamber.

Units are available to cover a wide range of spray rates. The range of a particular design is determined by the specific gravity of the surfacing material. Modifications are usually available to meet specific spray rate requirements.

**System Control**

A complete system, including the spray unit, can be operated from a control console. The console provides adjustment of the plasma gas flow rates, plasma current, starting
and stopping functions, and, in some cases, operation of the powder feed unit. These functions are common to all plasma spray systems.

GASES

Gases serve three purposes in plasma spray systems: as primary plasma gas; as secondary gas mixed in small volumes with the plasma gas; and as the powder carrying gas, usually the same as the primary gas.

Monatomic and diatomic gases can be used for plasma spraying. Argon and helium are the two most frequently used monatomic gases. With monatomic gases, it is possible to attain powder heating rates sufficiently high for most applications. Plasmas generated with polyatomic gases have greater heat content. They not only release ionization energy but also the energy of molecular recombination. The choice of gas affects the quality of the plasma. The gases should be welding grade with low moisture and oxygen contents.

The four gases commonly used for plasma spraying and their important characteristics are as follows:

1. Nitrogen is widely used because it is inexpensive, diatomic, and permits high spraying rates and deposit efficiencies. Nozzle life will be shorter than with monatomic gases, but this factor may be offset by the lower cost of this gas.

2. Argon provides a high velocity plasma. It is used to spray materials that would be adversely affected if hydrogen or nitrogen were used. Carbides and high temperature alloys are most commonly sprayed with argon, especially in aircraft applications.

3. Hydrogen may be used as a secondary gas in amounts from 5 to 25 percent, with nitrogen or argon. Hydrogen additions raise the arc voltage, and thus the power and heat content of the arc. Hydrogen may have a detrimental affect on certain metals which tend to absorb hydrogen when in a molten condition.

4. Helium is usually used as a secondary gas mixed with argon, especially when titanium is the substrate. It will also tend to raise the arc voltage.

PLASMA SURFACING

It is necessary to use plasma spraying equipment for powders with melting points above 5000°F (2800°C). Because this method is capable of depositing refractory metals and ceramics, it can also deposit powdered materials that are normally applied by flame spraying, but it does so at a higher rate.

A partial list of surfacing materials applied by this method is shown in Table 28.3. Many commercial compositions are proprietary and designed for specific applications.

Plasma sprayed ceramic coatings exhibit higher densities and hardness than flame sprayed deposits. High density
### Table 28.3
Materials Commonly Applied by Plasma Spraying

<table>
<thead>
<tr>
<th>Metals</th>
<th>Carbides*</th>
<th>Oxides</th>
<th>Carmets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>Chromium carbide</td>
<td>Alumina</td>
<td>Alumina-nickel</td>
</tr>
<tr>
<td>Chromium</td>
<td>Titanium carbide</td>
<td>Chromium oxide</td>
<td>Alumina-nickel</td>
</tr>
<tr>
<td>Copper</td>
<td>Tungsten carbide</td>
<td>Magnesia</td>
<td>Alumina-aluminide</td>
</tr>
<tr>
<td>Molybdenum</td>
<td></td>
<td>Zirconia</td>
<td>Zirconia-nickel</td>
</tr>
<tr>
<td>Nickel</td>
<td></td>
<td>Zirconia</td>
<td>Zirconia-nickel</td>
</tr>
<tr>
<td>Nickel-chromium alloys</td>
<td></td>
<td></td>
<td>Alumina-aluminide</td>
</tr>
<tr>
<td>Tantalum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Normally combined with a metal powder that serves as a binder.

Plasma sprayed deposits can be thinner in some cases, but may be more susceptible to cracking. Deposition procedures can be designed to overcome differences in coefficients of thermal expansion of the ceramic coating and the metal substrate. This can be achieved by spraying mixtures of the ceramics and a suitable metal in various proportions to produce graded (layered) deposits.

### CONTROLLED ATMOSPHERE PLASMA SPRAYING

Plasma arc spraying lends itself to controlled atmosphere applications. Temperature regulation of both the substrate and atmosphere are more precise in controlled atmospheres. This results in lower oxidation of the sprayed materials and less porosity in the sprayed deposit. It also produces closer control of the composition and morphology of the sprayed coating. This results in greater structural homogeneity, absence of oxide, increased hardness, and a thicker deposit capability. These benefits are produced at a higher deposition rate.

When spraying in an inert gas atmosphere chamber, improvements are achieved only with considerable capital equipment cost. The need for improved coating properties must be weighed against the additional expense of the equipment.

### INDUCTION COUPLED PLASMA TORCH

The induction coupled plasma torch generates a plasma by producing a conductive load (arc) within the inductive field by an ignition system. The inductive field then couples to the conductive gas as it would to an iron bar. See Figure 28.13.

Plasma stability, power conversion efficiency, and maximum heat content are all related to the gas flow pattern, and this pattern varies with different gases. Since there are no electrodes, continuous operation on reactive as well as inert gases is possible without torch deterioration. These gases include air, argon, nitrogen, and oxygen.

Control of the plasma effluent is obtained by varying the plasma gas and its flow rate, power input to the induction coil, and the design of the exit nozzle. Gas velocity can be varied from a few feet per second to over 10,000 ft/s (3000 m/s) by changing the exit nozzle size.

This heat source has been used to spray intermetallic powders such as titanium aluminide with excellent results. Lack of an electrode, which might deteriorate during operation, eliminates that potential source of contamination and results in a purer deposit.

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**Figure 28.13—Schematic View of Induction Coupled Plasma Torch**

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**ARC FORMING GAS**

**WATER-COOLED NOZZLE**

**INDUCED PLASMA ARC**

**NOTE GAS SWIRL**

**WATER-COOLED INDUCTION COIL**
FUSED SPRAY DEPOSITS

GENERAL DESCRIPTION

A FUSED SPRAY deposit is a self-fluxing alloy deposited by thermal spraying, which is subsequently heated to coalescence within itself and with the substrate. The materials wet the substrate without the addition of a fluxing agent, provided the substrate is properly cleaned and prepared to receive it. The materials are powdered nickel or cobalt alloys, and they may be applied by powder flame spraying or by plasma spraying.

The application of a fused deposit involves four operations:

1. Surface preparation
2. Spraying the self-fluxing alloy
3. Fusing the coating to the substrate
4. Finishing the coating to meet surface and dimensional requirements

Fused coatings are dense and nearly porosity free. The alloy compositions can result in hardness levels greater than 50 Rc. Coating thickness is limited to those ranges which can be heated to melting temperature without spalling. Self fluxing coatings are limited to applications where the effects of fusing temperatures and any distortion can be tolerated. Thick coatings of dissimilar metals can be applied in multiple passes. For optimum results, the surface to be coated should be cleaned of all oxide residues after each fusing stage or layer.

A finishing operation is not always required if the as-fused surface is suitable for the application. Centrifuge screw flutes, buffing fixtures, and process piping are examples of components that may be used in the as-fused condition. Pump packing sleeves, pump plungers, piston rods, and process rolls are examples of surfaced machine parts that require a subsequent finishing operation on fused deposits.

A properly sprayed and fused deposit will be nearly homogeneous, metallurgically bonded to the substrate, and have no open or visible porosity. It will have higher hardness than an equivalent mechanically bonded deposit, and will withstand pressures and environments better than nonfused deposits.

SELF-FLUXING ALLOYS

MOST SELF-FLUXING ALLOYS fall into two general groups: Nickel-chromium-boron-silicon alloys and Cobalt-chromium-boron-silicon alloys.

In some cases tungsten carbide or chromium carbide particles are blended with an alloy from one of the above groups.

The boron and silicon additions are crucial elements that act as fluxing agents and as melting point depressants. They permit fusing at temperatures compatible with steels, certain chromium-iron alloys, and some nickel base alloys.

The hardness of fused coatings will range from 20 to 60 Rc, depending upon alloy composition. Hardness is virtually unaffected by the thermal spraying procedures since there is almost no dilution with the base metal.

Selection of an alloy composition for a particular application should be based on certain considerations, including the following:

1. Fusion temperature of the alloy and thermal effects on the base metal
2. Relative difference in the coefficients of thermal expansion of the base metal and alloy deposit
3. Service requirements of the part
4. Finish requirements of the fused deposit and available finishing equipment

EQUIPMENT

IN ADDITION TO cleaning, blasting, thermal spraying, and work-handling equipment, some device or method is needed to fuse the sprayed deposit. Fusing may be done with an oxyfuel gas torch, in a furnace, or by induction heating.

Fusing Torches

A FUSING TORCH can have a single or multiple jet tip, depending upon the mass of the workpiece. The fusing gas is usually oxy-acetylene, and a neutral or reducing flame is used. Other fuel gases may be used except for cobalt-base alloys, where an oxyacetylene reducing flame is recommended. A combination spraying and fusing torch is available for applying these types of deposits. The coating is alternately deposited and fused. This type of equipment is particularly suited for repair work, but not for large workpieces nor for production work.

Fusing Furnaces

SPRAY DEPOSITS can be fused by placing the coated workpiece in an atmosphere furnace operating at the fusing temperature. Argon, dry hydrogen, or vacuum atmospheres may be used. Furnace fusing is advantageous for high production applications, intricate part geometries, or parts with significant variations in section thickness.

BASE METALS

FUSED THERMAL SPRAYED deposits can be applied to a wide variety of metals. However, varying degrees of skill, technique, and procedures are required. Some base metals are easier to surface than are others. Those which can be
readily sprayed with one or more self-fluxing alloys and then fused are as follows:

1. Carbon and low alloy steel with less than 0.25 percent carbon
2. AISI 300 series stainless steels, except Types 303 and 321
3. Certain grades of cast iron
4. Nickel and nickel alloys that are free of titanium and aluminum

Metals that require special procedures to avoid undesirable metallurgical changes are carbon and low alloy steels with more than 0.25 percent carbon, and AISI 400 series stainless steels, except Types 414 and 431. Types 414, 431, and the precipitation hardening stainless steels are not recommended as base metals for self-fluxing alloys.

Cracking of some types of fused sprayed deposits on hardenable steels can be avoided by isothermal annealing of the parts from the fusing temperature. The isothermal anneal prevents the formation of martensite in the substrate material. Fused deposits with a hardenable steel composition and hardenesses above 25 Rc will likely crack when the steel transforms to martensite. Surface cracking results from the rapid expansion that takes place during the transformation. However, there are applications in which cracks in the fused deposit are not detrimental to service requirements.

**FUSING**

Fusing a sprayed deposit is accomplished by heating the workpiece to a temperature range dependent on the particular self-fluxing alloy. The fusing temperatures of nickel-chromium-boron-silicon alloys range from 1875 to 2150°F (1025 to 1175°C). The cobalt-chromium-boron-silicon alloys fuse in the range of 2150 to 2250°F (1175 to 1230°C). The actual fusing temperature depends upon the composition of the alloy.

The most common method of fusing is with one or more oxyfuel gas heating torches, using a reducing flame. A typical torch fusing operation is shown in Figure 28.14. First, the torch is directed on the workpiece, which is heated to a dull red color, about 1400 to 1600°F (760 to 870°C). Then the torch is moved across the spray deposit to gradually increase the surface temperature until the de-
posits shows a glossy or greasy appearance. This indicates that the deposit has fused. Overheating should be avoided to prevent flow of the molten alloy. The temperature of the workpiece and deposit must be maintained as uniform as possible.

The fusing operation may also be done with other methods of heating, including furnace and induction heating. With these processes, heating is done in a neutral or reducing atmosphere, to avoid oxidation of both the deposit and the base metal.

POST-TREATMENTS

SEALING

Sealing of sprayed deposits is performed to lengthen the service life or prevent corrosion of the substrate, or both. Sprayed deposits of aluminum or zinc may be sealed with vinyl coatings, either clear or aluminum pigmented. The sealer may be applied to fill only subsurface pores in the deposit, or both subsurface pores and surface irregularities. The latter technique will provide a smooth coating to resist industrial atmospheres. The vinyl coatings may be applied with a brush or spray gun.

Sealing is also used on coated machine parts. Where the spray deposit will be exposed to acids, it is recommended that the surface be sealed with either a high melting point wax sealer or a phenolic plastic solution. Spray deposits on high-pressure hydraulic rams, pump shafts, and similar parts should be sealed with air-drying phenolics, to prevent the seepage of liquid through the coating around the packing. Pressure cylinders of all types are reclaimed by thermal spraying. Prior to finish grinding, the cylinder bore is sealed with a phenolic. This prevents grinding wheel particles from embedding in the pores of the sprayed metal and causing premature wear.

Epoxies, silicones, and other similar materials are used as sealants for certain corrosive conditions. Vacuum impregnations with plastic solutions is also possible.

DIFFUSING

A thin layer of aluminum may be diffused into a steel or silicon bronze substrate at 1400°F (760°C). The diffused layer can provide corrosion protection against hot gases up to 1600°F (870°C). After depositing the aluminum, the part can be coated with an aluminum pigmented bitumastic sealer or other suitable material, to prevent oxidation of the aluminum during the diffusion heat treatment. There are similar aircraft applications with diffusion temperatures dependent upon the base material to which the aluminum is applied.

SURFACE FINISHING

Techniques for surface finishing of thermal spray deposits differ somewhat from those commonly used for metals. Most sprayed deposits are primarily mechanically bonded to the substrates, except for fused coatings. Excessive pressure or heat generated in the coating during the finishing operation can cause damage such as cracking, crazing, or separation from the substrate.

Since the composition of an as-sprayed deposit is an aggregation of individual particles, improper finishing techniques can dislodge particles singly or in clusters. This may cause a severely pitted surface. The deposited particles should be cleanly cut and not pulled from the surface. Even so, a totally finished surface will probably not be shiny but may have a matte finish due to porosity of the deposit.

The selection of a finishing method depends on the type of deposit material, its hardness, and the coating thickness. Consideration should be given to the properties of the substrate material as well as dimensional and surface roughness requirements. Spray deposits of soft metals are usually finished by machining, especially those applied to machine components. A good finish is obtained using high cutting speeds and carbide tools for such applications. More often, however, sprayed deposits are finished by grinding, particularly the hardfacing and ceramic coatings.

Various other finishing methods are occasionally used. These include buffing, tumbling, burnishing, belt polishing, lapping, and honing.

Machining

Tungsten carbide tools are commonly used for machining sprayed metal deposits and fused coatings. Proper tool angles play a critical role in the success of machining these coatings. The surface speeds and the depth of cut are of equal importance. Improper tool angle and tool pressure can result in excessive surface roughness and the destruction of the bond between the coating and the substrate.

A cutting tool with a slightly rounded tip and a rake angle of three degrees should be used. On outside circumferences, the tip of the tool should be set three degrees below center; in bores, this should be three degrees above center. This will help to limit the stress on the deposit. Peripheral speed should not exceed 75 ft/min. (400 mm/sec.). The feed should be slow with light cuts for best surface finish.

Special cutting tools, such as oxide-coated carbide, cubic boron-nitride, ceramics, cermet, and diamonds may be used to machine very hard metal, ceramic, and cermet.
deposits. In many cases, machining with these tools is replacing grinding of intricate shapes and large pieces. Machining of flat deposits requires extreme care at the corners and edges to avoid damage. Depth-of-cut and feed rate should be low.

Grinding

Metal Deposits. Wet grinding is the preferred method. Large, wide wheels are used, and the required amount of stock can be removed with one operation. Wet grinding permits closer tolerances than does dry grinding. Grinding wheel manufacturers can recommend wheel types and grinding procedures for various metal deposits, using a particular type of grinding machine.

If it is necessary to grind metal deposits dry, as is done with portable grinders mounted on a lathe, the major amount of materials should be removed first by machining. Then the deposit is ground to the required finish and dimensions.

Wheels used for dry grinding operations may be either aluminum oxide or silicon carbide, depending upon the metal to be ground. The factors to be considered in selecting a wheel for a spray deposit are similar to those for grinding the same metal in wrought or cast form. The grinding technique should be designed to minimize heat buildup in the deposit. The structure of the wheel should be as open as possible and the grain size as coarse as possible, consistent with the finish requirements. The wheel should be narrow, the infeed light, and the traverse as fast as possible without spiraling.

When grinding equipment is not available, metal deposits can be machined to within 0.002 to 0.006 in. (50 to 150 μm) of final size. Then they can be finished to size with a belt polishing unit. Close tolerances and fine finishes are possible with belt polishing, by proper selection of abrasive type and grit size.

Grinding Fused Deposits. Because most fused deposits are designed for hard-facing purposes, grinding is usually the most economical method for finishing them.

Although most fused deposits can be machined with the proper type of cutting tool, close tolerance work is difficult because of rapid tool wear and the large amount of heat generated. Dry grinding may be suitable for some operations, but, in this case also, heat and fast wheel wear make close tolerance difficult. Wet grinding can produce close tolerance parts, fine finishes, and economical stock removal rates. Nickel-base alloys are best ground with silicon carbide grinding wheels, and cobalt-base alloys with aluminum oxide grinding wheels.

Grinding wheel manufacturers should be consulted for recommendations of the appropriate type for the job. Good practice usually suggests a coarse wheel, consistent with finish requirements; an open structure or soft bond; as large a wheel as possible; and good wheel dressing techniques. Surface finish of fused coatings can often be improved after grinding by polishing with fine grit belts.

Grinding Ceramic Deposits. The as-sprayed surface finish of flame sprayed ceramics is, in general, more coarse than 150 μm. Many applications require a better finish, and this can be accomplished by grinding. Although the individual particles of a ceramic deposit have extreme hardness, the deposit can be finished by conventional grinding techniques on standard equipment. However, it is necessary to use the proper grinding wheel, in some cases a diamond wheel, and to follow correct procedures. General recommendations for grinding ceramic deposits are available from grinding wheel manufacturers.

Flood cooling should be employed during grinding. Water containing a rust inhibitor is best. Water-soluble coolants are likely to stain light-colored ceramic deposits.

Other Finishing

Other methods of surface finishing are sometimes used for as-sprayed and fused deposits. These include:

1. Manual buffing or polishing
2. Abrasive tumbling
3. Honing
4. Lapping

As-sprayed or machined deposits may be buffed or polished manually with abrasive stones, cloth, or paper. Abrasive tumbling of small parts will polish the surface by removing the “high spots.” An abrasive medium, cleaners, and usually a liquid are vibrated or rotated in a drum in which the parts are finished.

Honing is done with abrasive stones mounted in a loading device. The part normally moves in one direction or rotates while the stones are oscillated under pressure, transverse to the work motion. Lapping is done with a fine, loose abrasive mixed with a vehicle, such as water or oil. The mixture is spread on lapping shoes or plates that are then rubbed against the spray deposit. The lap rides against the deposit, and their relative movements are continually changed.
QUALITY CONTROL

A PROPERLY DESIGNED quality control program can ensure consistent quality in thermal sprayed deposits. Proper quality control consists of more than just the examination of the workpiece after the spraying is complete. Each step in the operation should be monitored by an inspector. This includes not only the spraying and fusing steps, but also the preparation of the substrate and the various stages of handling and storage of the workpiece between operations. In addition, the quality of the spray materials must be controlled. Since bond strength and spray deposit soundness are difficult to determine by nondestructive techniques, the procedures for accomplishing each step of the thermal spraying operation should be documented. The procedures should be qualified by appropriate destructive tests of sample parts.

In general, sprayed deposits are inspected visually for quality and soundness. With fused deposits, lack of bonding may be detected by localized torch heating of the suspected area. Lack of bonding will be indicated by a hot spot or spalling of the deposit material. Ultrasonic techniques may also be used to detect lack of bonding. Penetrant or magnetic particle inspection can detect surface porosity and cracks. Magnetic particle inspection can be used only on ferromagnetic spray deposits.

PROPERTIES

THE QUALITY AND the properties of thermal sprayed deposits are largely determined by the size, temperature, and velocity of the spray droplets as they impinge on the substrate, and the degree of oxidation of both the droplets and the substrate during spraying. These factors will vary with the method of spraying and the procedures employed.

Metals and alloys deposited by the thermal spray process do not retain their original chemical composition unless special techniques are used. Their properties may change significantly depending upon the spray method used. With plasma and other arc methods, appreciable amounts of low melting point constituents may be lost by vaporization. Oxidation of the droplets may also be significant when air is used as the propellant.

The physical and mechanical properties of a spray deposit normally differ greatly from those of the original material. The deposit structure is lamellar and nonhomogeneous. Its cohesion is generally the result of mechanical interlocking, some point to point fusion, and sometimes oxide to oxide bonding. The tensile strengths of these structures are low compared to those of the same materials in wrought or cast form. Sometimes the compressive strength is quite high but the ductility is low. Deposits from wire or rod are less dense than the original material.

In any case, spray deposits should be considered as a separate and distinct form of fabricated material.

Oxide spray deposits tend to retain their physical properties with only modest losses. In many cases, the deposit will have a crystalline structure. Alpha alumina may deposit with a metastable gamma structure. The chemical compositions of reactive type ceramics, such as carbides, silicides, and borides, normally change when the materials are sprayed in air with the flame or plasma methods.

MICROSTRUCTURE

THE MICROSTRUCTURE of a transverse section through a flame sprayed metal deposit will show a heterogeneous mixture of layered metal particles (white), metal oxide inclusions (gray), and pores (black). A photomicrograph of a transverse section through a flame sprayed deposit of 0.80 percent carbon steel is shown in Figure 28.15. The light layered particles are bonded to one another by chemical and mechanical interactions. A photomicrograph of a transverse section through a copper deposit and its substrate at the bond line is shown in Figure 28.16. The roughness of the prepared substrate surface is apparent.

Figure 28.15—Transverse Section Through a Flame Sprayed AISI 1080 Steel Deposit (x500 Reduced on Reproduction)
The microstructure of the polished and etched surface of the 0.80 percent carbon steel deposit is shown in Figure 28.17. It has an emulsified appearance because the flattened steel particles (light) are separated by the oxide (gray).

As-sprayed, self-fluxing alloy deposits are similar in appearance to any typical metal deposit, except that there is significantly less oxide. These materials are oxidation resistant in nature. After fusing, the deposit will have a cast structure with some porosity and inclusions. The microstructure of a fused nickel-chromium self-fluxing alloy deposit is shown in Figure 28.18. The roughness of the prepared substrate is also evident.

**HARDNESS**

The heterogeneous structures of spray deposits generally have a lower macrohardness than the original rod or wire supplied to the gun. However, the hardness of individual deposit particles (microhardness) may be much higher than that of the overall deposit. The hardness test should be selected to give the overall deposit hardness or the particle hardness. The thickness of the deposit must also be considered in selecting the type of test. If the deposit is too thin, the indenter may penetrate through it and into the substrate. This would obviously give a false reading.

The Brinell and Rockwell hardness tests can be used to determine the hardness of fairly thick metallic deposits. Superficial Rockwell and Vickers hardness tests are suitable for thin metallic deposits. Requirements for various hardness tests are covered in the appropriate ASTM Standards. Table 28.4 relates the minimum spray deposit thickness to the various Rockwell hardness tests.

Hardness tests with diamond indenters are not entirely satisfactory for determining the true hardness of heterogeneous spray deposits, but they can be used for spot checks and shop guides. Microhardness tests can be used to determine the hardness of individual particles. Since the deposited particles are relatively thin, hardness impressions
should be taken on a transverse section. The Knoop indentation hardness test is best suited for this.

**BOND STRENGTH**

The strength of the bond between a spray deposit and the substrate depends upon many factors, including the following:

1. Substrate material and its geometry
2. Preparation of the substrate surface
3. Spray angle to substrate
4. Preheat
5. Bond layer material and its application method and procedures
6. Deposit material and its application method and procedures
7. Thickness of deposit
8. Post spraying thermal treatment

A standard test for determining the bond or cohesive strength of thermal spray deposits is described in ASTM C633, Standard Test Method for Adhesion or Cohesive Strength of Flame Sprayed Coatings.

In this test, each specimen is an assembly of a coated substrate block and a loading block. The flat end of the substrate block is prepared, and the deposit is applied. Then, the deposit is machined or ground flat and uniform in thickness using procedures appropriate for the deposited material. The loading block is then adhesive bonded to the flat deposit surface to produce a tension specimen. The specimen is loaded in tension at a constant rate using a self-aligning device. The maximum load is recorded. From this, the bond strength or the cohesive strength of the deposit can be calculated, depending upon the fracture location. The bond strengths of several self-bonding spray materials are presented in Table 28.3.

This test method is limited to deposit thicknesses greater than 0.015 in. (0.4 mm), because adhesive bonding agents tend to infiltrate porous deposits. If the bonding agent penetrates to the substrate, it will affect the test results.

**Table 28.4**

<table>
<thead>
<tr>
<th>Rockwell Scale</th>
<th>Minimum Thickness (in.)</th>
<th>Minimum Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15N</td>
<td>0.015</td>
<td>0.38</td>
</tr>
<tr>
<td>30N</td>
<td>0.025</td>
<td>0.64</td>
</tr>
<tr>
<td>45N</td>
<td>0.035</td>
<td>0.89</td>
</tr>
<tr>
<td>A</td>
<td>0.040</td>
<td>1.0</td>
</tr>
<tr>
<td>B</td>
<td>0.060</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>0.070</td>
<td>1.8</td>
</tr>
<tr>
<td>D</td>
<td>0.080</td>
<td>1.3</td>
</tr>
</tbody>
</table>

**Table 28.5**

<table>
<thead>
<tr>
<th>Bonding strength, psi (kPa)</th>
<th>Plasma Sprayed</th>
<th>Powder Sprayed</th>
<th>Flame Sprayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Columbium</td>
<td>2400 (16600)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molybdenum</td>
<td>3200 (22100)</td>
<td>3000 (20800)</td>
<td>3300 (22800)</td>
</tr>
<tr>
<td>Nickel-alumide</td>
<td>3000 (20700)</td>
<td>2750 (19000)</td>
<td>3150 (21700)</td>
</tr>
<tr>
<td>Tantalum</td>
<td>2750 (19000)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Applied to a smooth, unprepared metal surface.

**DENSITY**

Thermal sprayed deposits have densities less than 100 percent of the filler metals because they are porous and contain some oxide. The densities of the flame sprayed deposits and the original wire for several metals are given in Table 28.6.

Porosity in spray deposits consists of isolated and sometimes interconnected pores. It is difficult to determine the amount accurately. However, it can be estimated by several methods. The simplest one is to superimpose a grid over the microstructure (photomicrograph) of a prepared surface and then count the number of grid squares occupied by pores. Other methods include water or toluene immersion, and paraffin absorption. Because of lack of total interconnection of the pores, however, no method is perfect.

The porous nature of spray deposits can be used to advantage, especially for bearing surfaces. The porosity permits oil retention and provides an escape for foreign material from actively loaded areas. Where corrosion is a factor, porosity is a disadvantage. It limits the use of deposits to those that are anodic to the base material, unless special overcoatings of paint or sealers are used.

**SHRINKAGE**

Spray deposits contract upon cooling. The amount of shrinkage varies widely with different materials and spray-

**Table 28.6**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Density, lb/in.³ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flame Sprayed Deposit</td>
</tr>
<tr>
<td>Type 1100 Alumina</td>
<td>0.087 (2406)</td>
</tr>
<tr>
<td>Copper</td>
<td>0.271 (7601)</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.326 (9024)</td>
</tr>
<tr>
<td>AISI 1025 steel</td>
<td>0.244 (6754)</td>
</tr>
<tr>
<td>Type 304 stainless steel</td>
<td>0.249 (6892)</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.229 (6339)</td>
</tr>
</tbody>
</table>
ing methods, but it will not be the same as that of the original material in cast or wrought form. Contraction sets up tensile stresses in the deposit as well as shear stresses across the bond between the deposit and substrate. These stresses tend to crack or spall the deposit. Surface preparation, selection of material, and coating thickness are important factors in preventing these problems. Metals having low coefficients of thermal expansion should be used where possible, especially for thick deposits and buildup of internal surfaces.

APPLICATIONS

CORROSION AND OXIDATION PROTECTION

Thermal spray deposits can provide protection against many types of corrosive attack on iron and steel. Zinc, aluminum, stainless steel, bronze, hard alloys, and ceramics are used as surfacing materials. Service conditions determine both the material type and its application procedures. Undercoatings for organic materials, such as paints and plastic finishes, can be applied by this process. A thick layer of zinc or aluminum can protect steel against oxidation and provide a strong bond for an organic coating.

Nickel, nickel-copper alloys, stainless steels, and bronzes are some metals that are cathodic to steel. They should be used as a deposit on steel only if they are made impermeable to corrosive agents by sealing. The sealer is likely to entrap air bubbles in pores of the spray deposits. The component should not be heated because expansion of the air bubbles may rupture the sealer.

Hard alloy deposits are often used on machine components such as pump plungers, pump rods, hydraulic rams, packing sections of steam turbine shafts, and valves. When sealed, these materials provide both corrosion and wear resistance.

Several different materials may be used to give oxidation protection, the choice depending on the operating temperature. For applications up to 1600°F (870°C), the part can be aluminumized by depositing a thin layer of aluminum. The aluminum is then diffusion into the surface by a suitable heat treatment. For temperatures above 1600°F (870°C), a nickel-chromium alloy deposit may be used. This is followed by a coating of aluminum. Often, this combination deposit is then covered with an aluminum pigmented bituminous sealer. The part is then diffusion heat-treated in a furnace, or it is placed directly in service if the operating temperature is above 1600°F (870°C). Such deposits are sometimes used for cyanide pots, furnace kiln parts, annealing boxes, and furnace conveyors.

Zirconia and alumina ceramics are sometimes used for thermal barrier layers. When the workpiece will be exposed to thermal cycling, a bond layer of nickel aluminide or nickel-chromium alloy may help to minimize thermal stresses in the ceramic deposits.

WEAR RESISTANCE

In the mechanical field, thermal spray hardfacing materials can be used to combat many types of wear. The ability of metal spray deposits to absorb and maintain a film of lubricant is a distinct advantage in many applications. Spray deposits often give longer life than the original surfaces, except where severe conditions of shock loading or abrasion are encountered. A low cost base metal can be protected on just the areas of wear with a high quality, wear resistant deposit.

An arc spray gun being used to deposit a nickel aluminide bonding material on the I.D. of a four inch steel cylinder is shown in Figure 28.19. Compressed air shears off molten droplets at a right angle to the axis of the spray gun.

Some metal deposits, such as nickel-copper alloys, nickel, and stainless steel, are virtually impervious to penetration by corrosives when they are applied in sufficient thickness and are exposed only to moderate pressure. These surfaces can be vacuum impregnated with various phenolic or vinyl solutions or with fluorocarbon resins for high-pressure operation. For applications where extreme wear or corrosion resistance, or both, are encountered, fused spray coatings may be used.

ELECTRICAL CHARACTERISTICS

The electrical resistance of a metal spray deposit may be 50 to 100 percent higher than that of the same metal in cast or wrought form. This should be taken into consideration in the design of spray deposits for electrical conductors. Such applications include spraying of copper on electrical contacts, carbon brushes, and glass in automotive fuses, as well as silver or copper contacts.

In the field of electrical insulation, various ceramic deposits can be used for insulators. Magnetic shielding of electrical components may be provided with deposits of zinc or tin zinc applied to electronic cases and chassis. Condenser plates can be made by spraying aluminum on both sides of a cloth tape.

FOUNDRY

Changes in contour of expensive patterns and match plates can be readily accomplished by the application of thermal spray deposits followed by appropriate finishing. Patterns and molds can be repaired with wear resistant deposits. Blow holes in castings that appear during machining can be filled to salvage the parts.
BRAZING AND SOLDERING

Thermal spraying is frequently used for the preplacement of soldering or brazing filler metals. The usual practice is to apply the filler metal using standard thermal spraying techniques.

AIRCRAFT AND MISSILES

Thermal spraying is used for air seals and wear resistant surfaces to prevent fretting and galling at elevated temperatures. Deposits of alumina and zirconia are used for thermal insulation.

A robot set up for plasma arc spraying of a bond coat on a part from the hot section of a gas turbine engine is shown in Figure 28.20. The bond coat is part of a thermal barrier coating system.
SAFETY

The potential hazards to the health and safety of personnel involved in thermal spraying operations and to persons in the immediate vicinity can be grouped as follows:

1. Electrical shock
2. Fire
3. Gases
4. Dust and fumes
5. Arc radiation
6. Noise

These hazards are not unique to thermal spraying methods. For example, flame spraying has hazards similar to those associated with the oxyfuel gas welding and cutting processes. Likewise, arc spraying and plasma spraying are similar in many respects to gas metal arc and plasma arc welding, respectively. However, thermal spraying does generate dust and fumes to a greater degree than the welding processes do.
GAS SYSTEMS

Local, state, and federal regulations relative to the storage of gas cylinders should be investigated and complied with. Safe storage, handling, and use of gas cylinders are described in ANSI Z49.1, Safety in Welding and Cutting, and CGA P-1, Safe Handling of Compressed Gases. Improper storage, handling, and use of these cylinders constitute safety hazards in thermal spraying operations. Oil or grease must not be used on oxygen equipment; only special oxidation resistant lubricants may be used.

Acetylene pressures in excess of 1.5 psi (103 kPa) are dangerous and should not be used. When acetylene pressure of 1.5 psi is too low for the application, another fuel gas should be used. Alloys containing more than 67 percent copper or silver must not be used in acetylene systems, because dangerous explosive compounds may be formed.

FLAME SPRAY GUNS

Flame spray guns must be maintained in accordance with the manufacturer's recommendations. Each operator should be familiar with the operation of the flame spray gun and should read the instruction manual thoroughly before using it.

A friction lighter, a pilot light, or arc ignition should be used to ignite the fuel gas. Matches are not safe. A flame spray gun and its hoses should not be hung on gas regulators or cylinder valves because of the danger of fire or explosion.

PLASMA AND ARC SPRAYING EQUIPMENT

Plasma and arc spraying use equipment where high voltages and amperages present a hazard. Operators should be thoroughly instructed and trained in the operation of the unit. They should be familiar with the operating and safety recommendations, and at the same time observe proper safety precautions for electrical equipment.

The plasma spraying equipment itself should be kept in a condition safe to operate. Exposed electrodes of plasma guns should be grounded or adequately insulated. Periodic inspections should be made of cables, insulation, hoses, and gas lines. Faulty equipment must be repaired or replaced immediately. The entire system, including the power supply, must be shut down before repairing any part of the power supply, console, or gun.

Arc spray guns should be cleaned frequently according to the manufacturer's operation manual to prevent the accumulation of metal dust. If the arc spray gun is suspended on a cable, the suspension hook must be insulated or grounded. Contact between any ungrounded portion of the plasma or arc spray gun and the spray chamber must be avoided.

FIRE PREVENTION

Finely divided airborne solids, especially metallic dusts, must be treated as explosives. To minimize danger from dust explosions, adequate ventilation should be provided to spray booths. A wet collector of the water-wash type is recommended to collect the spray dust. Bag or filter type collectors are not recommended. Good housekeeping in the work area should be maintained to avoid accumulation of metal dusts, particularly on rafters, tops of booths, and in floor cracks.

Paper, wood, oily rags, and other combustibles in the spraying area can cause a fire and should be removed before the equipment is operated.

PROTECTION OF PERSONNEL

The general requirements for the protection of thermal spray operators are the same as for welders, set forth in ANSI Z49.1, Safety in Welding and Cutting; ANSI Z87.1, Practices for Occupational and Educational Eye and Face Protection; ANSI Z88.2, Practices for Respiratory Protection; and ANSI Z89.1, Safety Requirements for Industrial Head Protection.

Eye Protection

Helmet, hand held shields, face shields, and goggles should be used to protect the eyes, face, and neck during all thermal spraying operations. These are described in ANSI Z87.1 and Z89.1. Safety goggles should be worn at all times. Helmets, hand held shields, and goggles must be equipped with suitable filter plates to protect the eyes from excessive ultraviolet, infrared, and intense visible radiation. A guide for the selection of the proper filter shade number is shown in Table 28.7.

Respiratory Protection

Most thermal spraying operations require that respiratory devices be used by the operator. The nature, type, and magnitude of the fume and gas exposure determine which

| Table 28.7 Recommended Eye Filter Plates for Thermal Spraying Operations |
|-----------------------------|------------------|
| Operation                   | Filter Shade Numbers |
| Wire flame spraying         | 5                |
| (except molybdenum)         |                  |
| Wire flame spraying         | 5 to 6           |
| of molybdenum               |                  |
| Flame spraying              | 5 to 6           |
| of metal powder             |                  |
| Flame spraying              | 5 to 8           |
| of esothermites or ceramics|                  |
| Plasma and arc spraying     | 9 to 12          |
| Fusing operations           | 5 to 6           |
respiratory protective device should be used. The selection of these devices should be in accordance with ANSI Z88.2, Practices for Respiratory Protection. This standard contains descriptions, limitations, operational procedures, and maintenance requirements for standard respiratory devices. All devices selected should be of a type approved by U.S. Bureau of Mines, National Institute for Occupational Safety and Health, or other approving authority for the purpose intended.

Ear Protection

EAR PROTECTORS OR properly fitted soft rubber ear plugs must be worn to protect the operator from the high intensity noise from the thermal spray gun. Such protection should reduce the noise level to below 80 decibels. Cotton wads are not recommended for ear protection, as they are ineffective against high-intensity noise. Federal, State, and local codes should be followed for noise protection requirements.

Protective Clothing

APPROPRIATE PROTECTIVE CLOTHING requirements for a thermal spraying operation will vary with the size, nature, and location of the work to be performed. When working in confined spaces, flame resistant clothing as well as leather or rubber gauntlets should be worn. Clothing should be fastened tightly around the wrists and ankles to keep dusts from contacting the skin.

For work in the open, ordinary clothing such as overalls and jumpers may be used. However, open shirt collars and loose pocket flaps are potential hazards. High-top shoes are recommended and cuffless trousers should cover the shoe tops.

The intense ultraviolet radiation of plasma arc spraying can cause skin burns through normal clothing. When using this process, the clothing should provide protection against such radiation. For exposure to more intense radiation, leather welder caps are necessary. Protection against radiation with arc spraying is essentially the same as that used for electric arc welding.

SUPPLEMENTARY READING LIST

Papers of the Eighth International Thermal Spray Conference, Miami Beach, FL: September 27 to October 1, 1976; American Welding Society, 1976.