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Thermal Spraying

Practice, Theory, and Application



AMERICAN WELDING SOCIETY

Thermal Spraying

Practice, Theory, and Application

Thermal Spraying Practice, Theory, and Application

Prepared by
AWS Committee on Thermal Spraying

Under the Direction of
AWS Technical Activities Committee

Approved by
AWS Board of Directors

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Foreword

The Thermal Spraying manual published by the American Welding Society presents the considerations required to appraise any application of thermal spraying. This manual also surveys the basic methods that can be used and the equipment and consumables involved in thermal spraying.

Although thermal spraying has been used since the early part of the twentieth century, many of the first applications were concerned mainly with reclamation. Since 1960, there has been a dramatic expansion in the number and diversity of thermal spray applications. Technological advances and material developments have resulted in a multitude of new and potential applications. The present range and scope of the processes and uses can only be indicated in this manual.

The American Welding Society Committee on Thermal Spraying has prepared this first edition as a guide to the equipment and consumables available, and as a reference for selecting the process suitable for a particular application. The reader can acquire knowledge of the thermal spray processes and technology to investigate potential uses. Emphasis is placed on practical shop and field procedures, including factual, supportive data.

Comments and suggestions regarding this first edition are welcome. Please address them to the Secretary, AWS Committee on Thermal Spraying, American Welding Society, 550 N. W. LeJeune Road, P. O. Box 351040, Miami, Florida 33135.

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Chairman
C2c Subcommittee

Chapter 1

Fundamentals of the Process

1.1 General

1.2 Definition

1.3 Process Variations

- 1.3.1 Spraying Materials
- 1.3.2 Processes

1.4 Nature of Sprayed Coatings

- 1.4.1 Substrates
- 1.4.2 Bond Coats
- 1.4.3 Coating Structure

1.5 Applications

- 1.5.1 Manufacturing
- 1.5.2 Maintenance

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Chapter 1

Fundamentals of the Process

1.1 General

The thermal spraying processes are specialized, yet have a wide ranging utilization in both manufacturing and maintenance. The nature of the processes is truly synergistic. That is, there are many components and variables involved, which, when working together and properly applied, produce an effect far greater than indicated when they are considered individually. Yet each component and variable must be understood to permit the proper selection and operation of a particular process. With this background, the user is then in a position to tailor the process to a particular application.

1.2 Definition

Thermal spraying is a group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semimolten condition on a prepared substrate to form a spray deposit. (Also, see the terms *arc spraying*, *flame spraying*, and *plasma spraying* in the Glossary.) The surfacing material may be in the form of powder, rod, cord or wire. The thermal spraying gun generates the necessary heat by using combustible gases or an electric arc. As the materials are heated, they change to a plastic or molten state, and are accelerated by a compressed gas. The confined stream of particles are conveyed to the substrate. The particles strike the surface, flatten, and form thin platelets (splats) that conform and adhere to the irregularities of the prepared surface and to each other. As the sprayed particles impinge upon the substrate, they cool and build up, particle by particle, into a lamellar structure, thus a coating is formed.

1.3 Process Variations

The basic variations of the thermal spraying processes occur in the spray materials used, the method of heating, and the method of propelling the materials to the substrate.

1.3.1 Spraying Materials. The spray materials are

used in the form of wire, rod, cord (a continuous length of plastic tubing), or powder. Cord spraying is primarily used in Europe. Many metals, oxides, cermets, and intermetallic compounds, some organic plastics, and certain glasses can be deposited by one or more of the various processes.

1.3.2 Processes. Thermal spraying processes may be categorized into two basic groups according to the method of heat generation.

Group I Combustion

Flame
Detonation

Group II Electrical

Plasma (nontransferred arc)
Plasma (transferred arc)
Wire arc
Induction plasma

The first group uses combustible gases as the heat source. Processes using electrical power as the heat source such as plasma (transferred and nontransferred arc), electric arc, and induction plasma comprise the second group. Consumables used in this group are in powder or wire form.

1.4 Nature of Sprayed Coatings

Success in the use of thermally sprayed coatings relies on careful adherence to specific process procedures. A basic rule of thermal spraying is that any deviation from the standards for a particular application or inattention to detail will produce unreliable results. Succeeding chapters will discuss the process procedures in detail. The sprayed coating has three basic aspects, as follows:

1.4.1 Substrates. Substrates onto which the thermal sprayed coatings are applied include metals, oxides, ceramics, glass, most plastics, and wood. All spray materials cannot be applied to all substrates; some require special techniques.

Substrate preparation prior to spraying is required for every thermal spraying process, and is virtually the same for each process. Two important steps are as follows:

(1) Cleaning the surface to eliminate contamination that will inhibit the bonding of the coating to the substrate.

(2) Roughening the surface to provide minute asperities or irregularities to enhance coating adhesion and provide a greater effective surface area.

Proper substrate preparation prior to bond coat application is the most critical step influencing the bond strength and the adhesion of the coating to the substrate.

1.4.2 Bond Coats. The bond between the coating and the substrate may be mechanical or metallurgical. Adhesion is influenced by a number of factors: coating material, substrate condition, degree of surface roughness, cleanliness, the surface temperature before, during, and after spraying, and particle impact velocity.

1.4.3 Coating Structure. The deposited structure and chemistry of coatings sprayed in ambient air are different

from those of the same material in the wrought or presprayed form (Fig. 1.4.3A).

The differences in structure and chemistry are due to the incremental nature of the coating, the reaction with process gases, and the atmosphere surrounding the material while in the molten state. For example, when air or oxygen are used as process gases, oxides of the applied material are formed and become a part of the coating. Metal coatings tend to be porous and brittle, and to have a hardness different from that of the original 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 parameters, technique employed, and the material applied.

The spray deposit density ratio will vary with the particle velocity and the heat source temperature of the coating process (Table 1.4.3 and Fig. 1.4.3B).

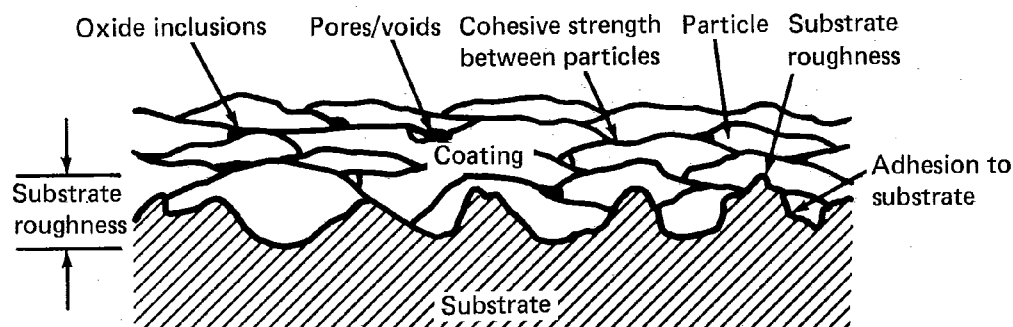


Fig. 1.4.3A — Typical coating cross section to illustrate lamellar structure of oxides and inclusions

Table 1.4.3
Heat source temperatures

Source	Temperature, °F	Temperature, °C
Propane, oxygen	4785	2640
Natural gas, oxygen	4955	2735
Hydrogen, oxygen	4875	2690
Acetylene, oxygen	5625	3100
Arcs & plasmas	4000-15,000	2200-8300

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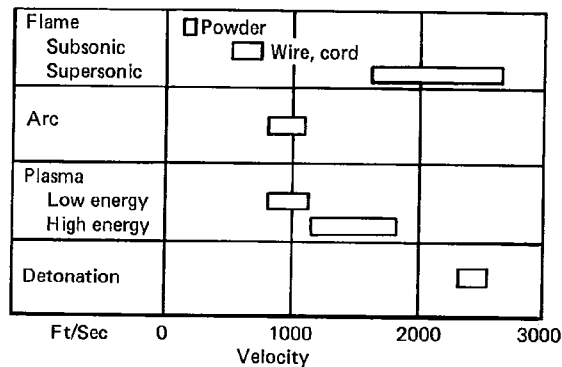


Fig.1.4.3B—Average particle impact velocities

1.5 Applications

The end use determines the properties needed in coating, the type of consumable, and the kind of equipment required.

1.5.1 Manufacturing. Thermal spraying is used extensively in the manufacture of original equipment components. The aerospace industry has provided hundreds of applications. In addition, marine, automotive, petroleum, electrical, power generation, and electronic industries use thermally sprayed coatings.

1.5.2 Maintenance. In maintenance, hundreds of millions of dollars are saved annually through the use of thermal spraying. This is not limited to in-plant applications, but also includes on-site applications to coat structures and equipment parts. Repair of components by thermal spraying, where applicable, is generally both economical and time saving.

Where corrosion or wear, or both, are problems, thermal spraying should be investigated. The use of sprayed coatings, often impregnated with sealers, has received worldwide acceptance by industry for such applications.

Chapter 2

Methods of Deposition

2.1 Basic Methods

2.2 Combustion

- 2.2.1 Wire and Rod
- 2.2.2 Powder
- 2.2.3 Oxygen Detonation Gun

2.3 Electrical Heating

- 2.3.1 Wire Arc Process
- 2.3.2 Plasma Nontransferred Arc
- 2.3.3 Plasma Transferred Arc

2.4 Controlled Atmosphere

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Chapter 2

Methods of Deposition

2.1 Basic Methods

The thermal spraying processes, and related equipment in commercial use, can be divided into two basic categories: combustion and electric heating.

2.2 Combustion

Thermal spraying utilizing the heat from a chemical reaction is known as *combustion gas* or *flame spraying*.

Any substance which does not sublime and which melts at temperatures less than 5000°F (2760°C) may be flame sprayed. The materials used are metals and alloys in the form of wire, cord, or powder, and ceramics as powder, cord, or rod.

2.2.1 Wire and Rod. The equipment for flame spraying wire and rod is similar, as shown in Fig. 2.2.1A. A typical wire thermal spraying gun cross section is shown in Fig. 2.2.1B.

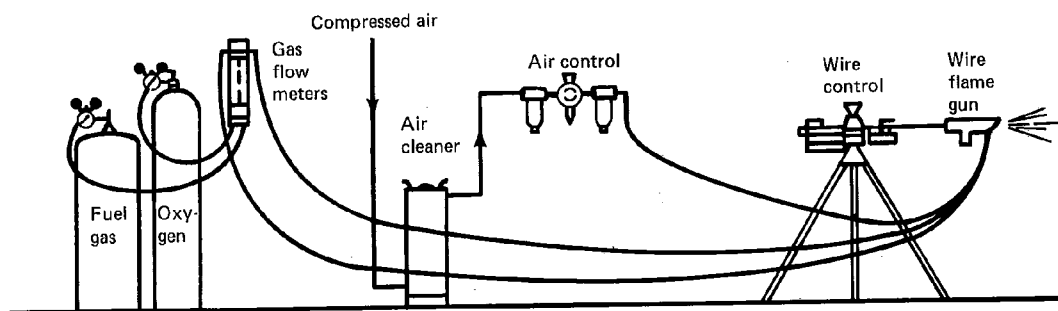


Fig. 2.2.1A — Typical wire flame spraying installation adaptable to rod and cord

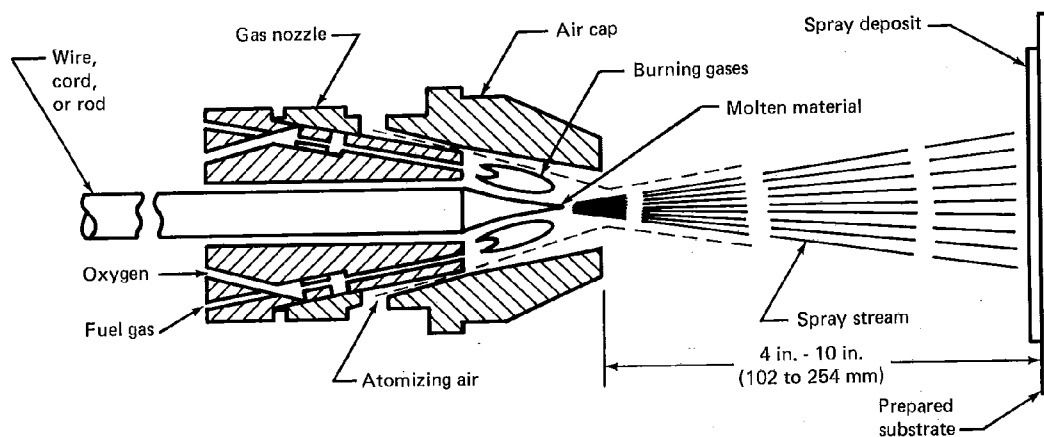


Fig. 2.2.1B — Cross section of typical wire rod or cord flame spray gun

The feedstock material is drawn by drive rolls into the rear of the gun. The rolls are powered by an electric motor, an air motor, or an air turbine. The feedstock proceeds through a nozzle where it is melted by a coaxial flame of burning gas.

One of the following fuel gases may be combined with oxygen for use in flame spraying: acetylene, methylacetylene-propadiene stabilized (MPS), propane, hydrogen, or natural gas. Acetylene is widely used, because higher flame temperatures are attainable (Table 1.4.3). However, in many cases, lower temperature flames can be used with economic advantages. A fuel gas flame is used for melting only, and not for propelling or conveying the coating material. To accomplish spraying, the flame is surrounded with a stream of compressed gas, usually air, used to atomize the molten material and to propel it onto the substrate. In special applications, an inert gas may be used.

Different gun feed parts are used to drive wire (a continuous metal feedstock), rod (a 24 inch long brittle ceramic), and cord (a flexible continuous length of plastic tubing containing powder).

2.2.2 Powder. Powder flame spray guns are lighter and more compact than other types of thermal spraying equipment. Due to the lower particle velocities and temperatures obtained, the coatings produced generally have lower adhesive strength, lower overall cohesive strength, and higher porosity than coatings produced by other spray processes.

The powder feedstock may be a pure metal, an alloy,

a composite, a carbide, a ceramic, a cermet, or any combination of these. The process is generally 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 coating to its melting temperature. The fusing temperature is usually in excess of 1900°F (1040°C), and is accomplished with any heat source including a flame, an induction coil, or a furnace.

Feedstock is stored in a hopper which may be integral with or connected to the gun. A small amount of gas is diverted to carry the powder into the oxygen-fuel gas stream, where the powder is melted and carried by the flame onto the substrate. The general arrangement of an installation for powder flame spraying is shown in Fig. 2.2.2A, and a typical gun cross section is shown in Fig. 2.2.2B.

Variations in the powder flame spraying process include (1) compressed gas to feed powder into the flame, (2) additional air jets to accelerate the molten particles, (3) a remote powder feeder with an inert gas to convey powder through a pressurized tube into the gun, and (4) devices for high speed acceleration at atmospheric pressure. Such refinements tend to improve powder flow rate, and sometimes to increase particle velocity, which enhances bond strength and spray deposit density.

Fused coatings are dense and nearly porosity free. The alloy compositions can result in Rockwell hardness levels greater than 50C. Coating thickness is limited to those ranges which can be heated to the melting temperature

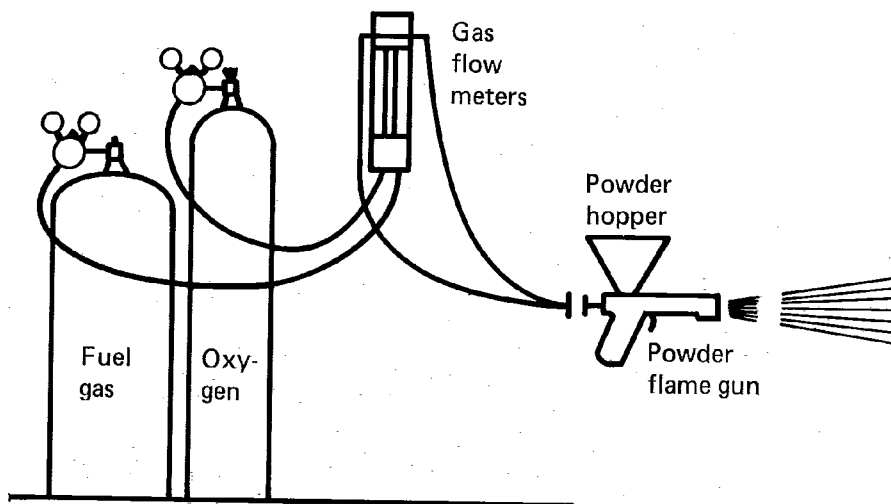


Fig. 2.2.2A — Typical installation of a powder flame spray process

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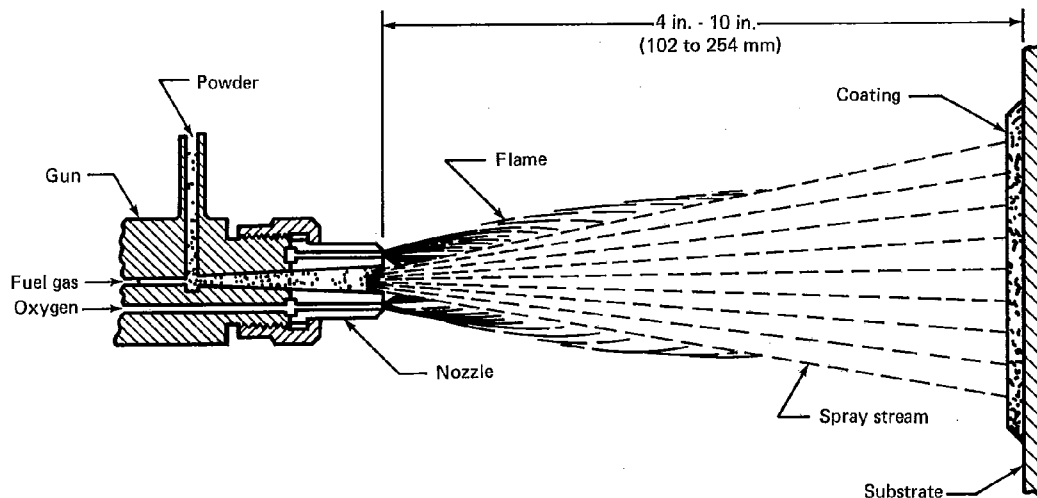


Fig. 2.2.2B — Cross section of a powder flame spray gun

without spalling. Self-fluxing coatings are limited to applications where the effects of the fusing temperatures and any distortion can be tolerated. Thick coatings of dissimilar metals can be applied in multiple passes. The surface to be recoated should be cleaned of all oxide residues after each fusing stage.

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 decrease rapidly, and the coating will contain trapped, unmelted particles. If the particle velocity is too low, some powder may be volatilized and result in coating deterioration and elevated operating costs. The typical powder feeding mechanism incorporates a container and a metering device which regulates the feed rate of the material into the carrier gas stream.

2.2.3 Oxygen Detonation Gun. The detonation gun differs from other combustion spraying devices. It utilizes the energy of explosions of oxygen-acetylene mixtures, rather than a steadily burning flame, to thrust powdered materials onto the surface of the substrate. The resulting deposit is extremely hard, dense, and tightly bonded.

The detonation gun, shown in Fig. 2.2.3, consists of a long barrel into which a mixture of oxygen, fuel gas, and powdered coating material is introduced. When the gas mixture is ignited, a controlled detonation wave, or flame front, accelerates and heats the powder particles as they move down the barrel. Exit particle velocities of approximately 2,500 ft/s (760 m/s) are produced. After each injection of powder has been discharged, a pulse of nitrogen gas purges the barrel and chamber. Multiple detonations during each second build up the coating to

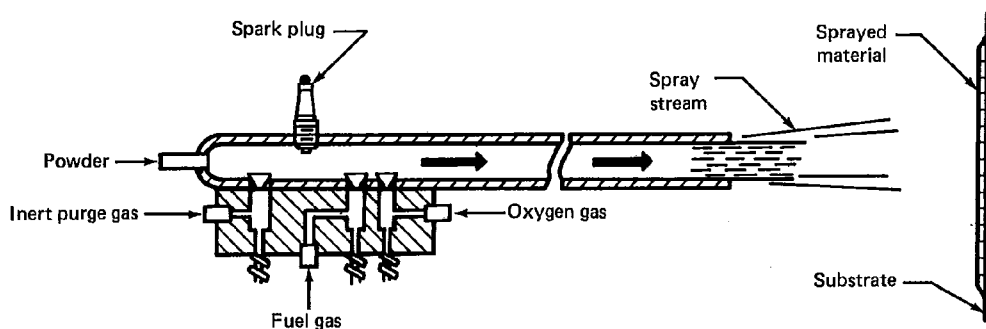


Fig. 2.2.3 — Schematic arrangement of an oxygen-fuel gas detonation gun

the specified thickness while the workpiece substrate is rotated or passed in front of the gun.

Temperatures above 6000°F (3315°C) are attained within the detonation gun while the substrate temperature is maintained below 300°F (150°C) by a carbon dioxide cooling system.

Coating thickness ranges between 0.002 and 0.020 in. (0.05 and 0.50 mm). The process produces a sound level in excess of 150 decibels, and is therefore 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 because porosity in the coating is low.

2.3 Electrical Heating

2.3.1 Wire Arc Process. In the wire arc process, two consumable wire electrodes, that are at first insulated from each other, automatically advance to meet at a point in an atomizing gas stream. A potential difference of 18 to 40 volts applied across the wires, initiates an arc that melts the tips of the wire electrodes. An atomizing gas, usually compressed air, is directed across the arc zone, shearing off molten droplets which form the atomized spray.

The arc spray system is comprised of components as illustrated in Fig. 2.3.1A.

Arc SprayGun. The spray gun is illustrated in Fig. 2.3.1B. The wire electrodes (1) are fed through the wire guides (2) and into the contact tips (3). The atomizing nozzle (4) conducts the compressed air (5) and directs it across the arc zone. Insulated power cables connect the gun to the dc power source. Arc guns also include mechanisms for feeding the wire at a controlled rate. Contact tips are sized for a particular wire diameter. **ON** and **OFF** switches are provided on the gun to control the wire feed, compressed air supply, and electric power supply.

The arc temperatures considerably exceed the melting point of the spray material. During the melting cycle, the spray metal is super heated 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 strengths.

The arc process normally has higher spray rates than other spray processes. Factors controlling the application rate are the current rating of the power source and the permissible wire feed rate to utilize the available power.

Power Source. A dc power source providing a voltage between 18 to 40 volts permits operation with various melts and alloys. Constant potential power sources are usually used. The arc gap and spray particle size increase with a rise in voltage. The voltage should be kept at the lowest level, consistent with arc stability, to provide smooth and dense coatings.

Wire Control Unit. The wire control unit is comprised of two reel or coil holders, which are insulated from each other. Wires of larger diameters are usually in coil form, while smaller diameter wires are preferably layer level wound on reels or in barrels. The unit is connected to the gun by flexible insulated cables.

Control Console. The control console incorporates the switches and regulators necessary for controlling and monitoring the operating circuits that power the gun.

2.3.2 Plasma Nontransferred Arc. The development of turbine and rocket engines presented conditions with increased severity for existing engineering materials. In many cases, the approaches used to cope with these conditions were based on oxides and carbides, which required thermal spraying equipment capable of producing temperatures higher than the capability of the then existing

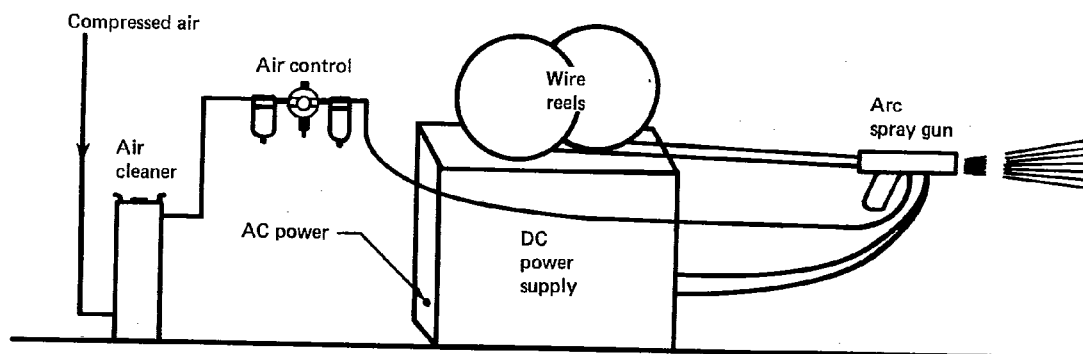


Fig. 2.3.1A — Arc spray components combined into a single unit

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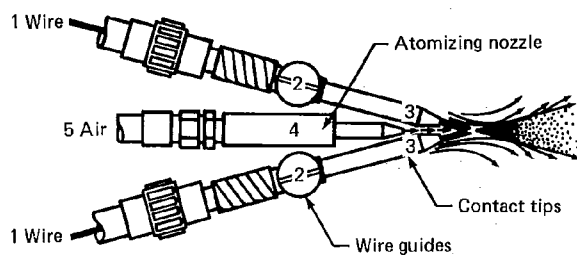


Fig. 2.3.1B — Cross section schematic of an arc spray gun

processes. The plasma spray process evolved to meet these needs. It also brought into existence a new family of coating materials and application techniques for a wide variety of industrial conditions.

This process uses powdered materials and a plasma (hot ionized gas) as the heat source. Plasma generators provide controllable temperatures well in excess of the melting range of most substances.

In the plasma process, a gas or gas mixture is passed through an electric arc between a coaxially aligned tungsten cathode and an orifice in a copper anode (Fig. 2.3.2A).

The gas passing through the orifice is heated to temperatures much higher than those obtained with a combustion flame (Table 1.4.3).

During heating, the gas is partially ionized, producing a plasma. As the plasma exits the gun, disassociated molecules of a diatomic gas recombine and liberate heat. The powder is introduced into the plasma, melted, and propelled onto the workpiece by a high velocity stream. The heat content, temperature, and velocity of the plasma jet are controlled by the nozzle type, the arc current, the mixture ratio of gases, and the gas flow rate.

The arc operates on direct current from a rectifier type power supply. The electric power to the arc is governed by a central control unit that also regulates the flow of plasma gas and cooling water, and sequences these elements to allow the process to be carried on reliably and precisely (Fig. 2.3.2B). Either nitrogen or argon is used as the primary plasma forming gas. A secondary gas, either hydrogen or helium, may be added to increase the heat content and velocity of the plasma.

2.3.3 Plasma Transferred Arc. The plasma transferred arc (PTA) process is a combination of welding and thermal spraying processes. Powder or wire is introduced into the plasma arc stream issuing from the nozzle. The emitted spray forms a molten puddle on the substrate, which cools and solidifies as a parent metal dilution (weldment). The process uses a power source, controls, and

feedstock somewhat similar to the plasma nontransferred arc process previously described.

In the PTA process, the electrical arc from the non-consumable electrode passes through the torch nozzle and is carried by the plasma to the conductive workpiece. The feedstock powder, or wire, which is usually a nickel-, cobalt-, or iron-based alloy similar to that used in flame spraying, is introduced into the arc as it exits the nozzle. Here, it is melted and puddled onto the surface, and a deposit is constructed. The deposit is usually applied to greater thicknesses than a thermal spraying coating, and it is metallurgically bonded to the base material. PTA deposition lends itself particularly to repetitive applications on conductive materials and is usually mechanized. The absence of slag removes a source of impurities, and the completed deposit is smoother and more uniform, because melting and puddling take place in an inert gas shroud. As compared to a thermal spraying deposit, a PTA deposit is generally more localized, denser, and metallurgically bonded to the base. However, the selection of coating materials and suitable substrates is more limited.

2.4 Controlled Atmosphere

Controlled atmosphere spraying offers the possibility of improving coating quality and bond strength. Immediate benefits are

- (1) Temperature regulation of both substrate and atmosphere.
- (2) Minimal chemical changes in the sprayed material, leading to closer control of the composition and morphology of the sprayed coating. This is demonstrated in greater structural homogeneity, absence of oxides, and improvements in hardness, thickness capability, and deposit efficiency.

When using inert atmosphere chamber spraying, improvements are achieved only with considerable capital cost. The need for the improved coating properties must be weighed against the additional expense of the equipment. A typical installation for controlled atmosphere thermal spraying is illustrated in Fig. 2.4.

A less expensive approach to achieve some of the improvements of chamber spraying is to provide an inert gas shroud around the molten particle stream to minimize oxidation while the material is in the molten state.

Other devices utilize higher velocity acceleration at atmospheric pressure to increase particle velocity and thus improve coating adhesion and density.

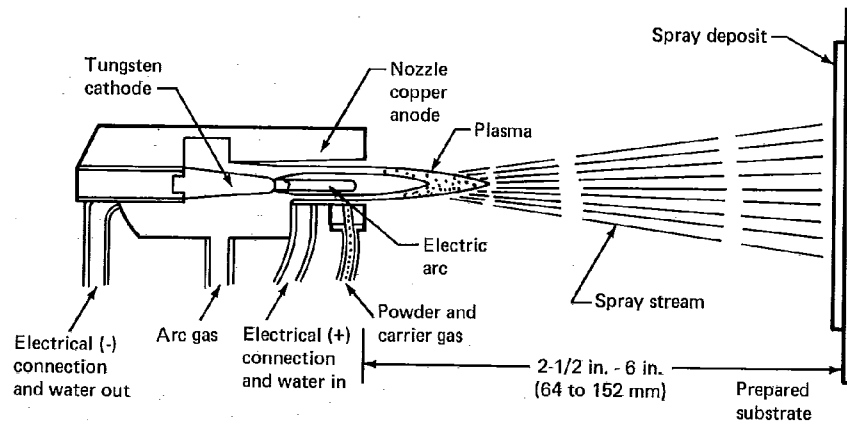


Fig. 2.3.2A — Sectional view of plasma torch

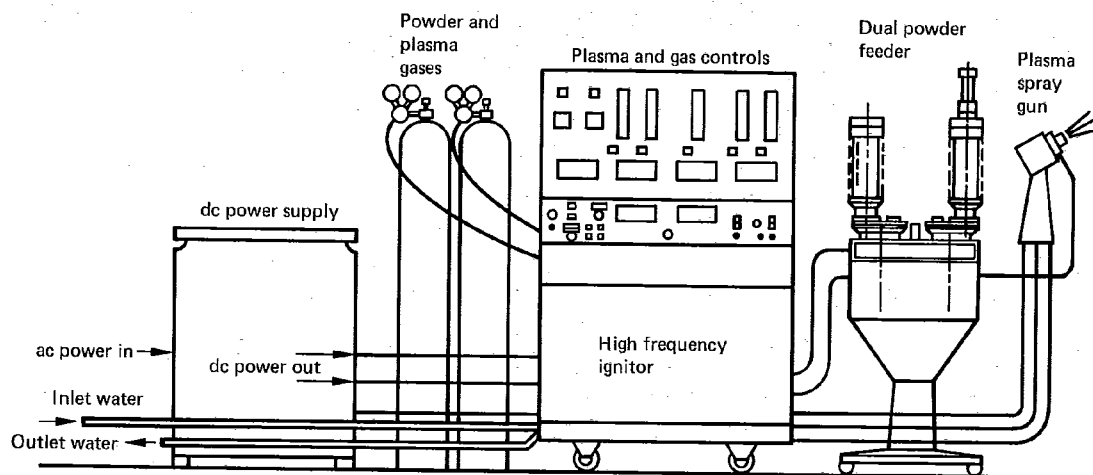
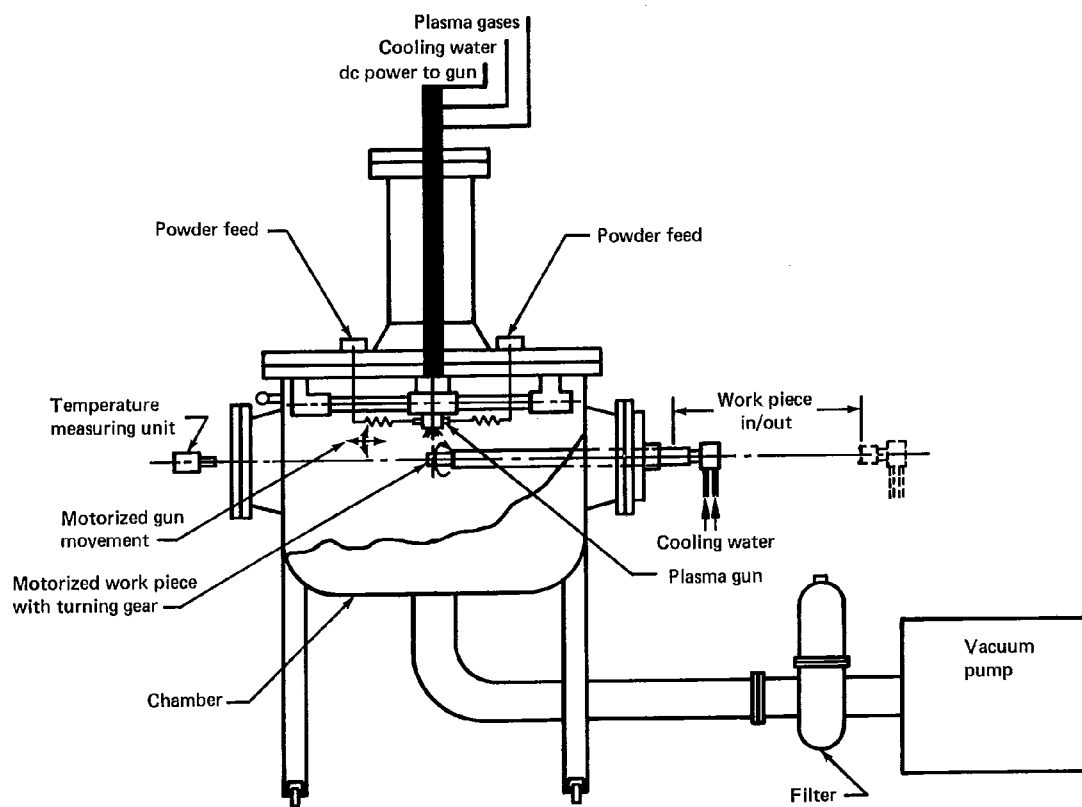


Fig. 2.3.2B — Complete installation plasma spray system

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**Fig. 2.4 — Controlled atmosphere thermal spray system**

Chapter 3

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Chapter 3

Surface Preparation

3.1 General

Surface preparation is the most critical step in a thermal spraying operation. Coating adhesion quality is directly related to the cleanliness and the roughness of the substrate surface. Adherence to accepted procedures in preparing a substrate surface is necessary to ensure successful application of the thermal spray coating. The coating material and the substrate type are the major factors in determining what surface preparation is necessary to achieve consistent bonding.

On highly stressed mechanical parts, inspection prior to coating, is necessary to detect flaws in the base metal. This is done by nondestructive inspection methods. Structural flaws in the part will produce similar flaws in the coating. Cracks in the substrate cannot be repaired by thermal spraying. Sprayed deposits do not add strength to the substrate.

3.2 Cleaning and Handling

The first step in the preparation of a substrate for thermal spraying is to remove all surface contaminants such as scale, oil, grease, and paint. The heat of spraying will not remove contaminants, and contamination will inhibit bonding. After all contaminants have been removed, the cleanliness should be maintained until the spray cycle has been completed. Parts should be protected from airborne debris and fingerprints, and should be handled with clean fixtures and materials.

3.2.1 Vapor Degreasing. Hot vapor degreasing is a common, economical, and efficient method for removing organic contaminants. Parts should be soaked 15 to 30 minutes to remove oil from interstices and surface pores. Porous materials, such as sand castings or graphitic cast irons, should be soaked for longer periods. If objects are too large for vapor degreasing, steam cleaning, submerging in hot detergent solutions, or manually cleaning with an oil free solvent may be required. Residue should be mechanically removed.

The common degreaser solvents perchlorethylene,

trichlorethylene, and 1,1,1 trichlorethane, are normally selected for safety considerations and the temperature range needed for cleaning. Most hydrocarbon solvents are hazardous, and manufacturer's instructions should be followed regarding usage, location, and disposition.

Recycling of solvents should be investigated with the supplier. Chlorinated solvents leave a slight residue which can be removed by immersion washing or wiping with isopropyl alcohol or methylethyl ketone (MEK).

The use of chlorinated solvents on titanium and titanium alloy parts is prohibited, since chlorine can induce cracking in these materials. Alternative cleaning methods such as an alkaline wash, steam blasting, pickling, washing with flammable solvents, or all of these, may be necessary.

3.2.2 Vapor Blasting. Vapor blasting, wet abrasive blasting, and liquid honing use a dilute slurry of abrasive media projected by an air jet onto the surface. Cleaning is performed in an enclosure, similar to a grit blasting cabinet, using such abrasive media as aluminum oxide, novaculite, or garnet flour. Most abrasives fall within the 200 to 1200 mesh size range, and are mixed with water in the ratio of five pounds per gallon (0.6 kg/L). Other slurry additives include rust inhibitors and antisolidifying compounds. Parts should be thoroughly rinsed after cleaning.

Vapor blasting may be used for any of the following purposes:

- (1) Remove light burrs
- (2) Remove corrosion products
- (3) Remove previous plating or coating material
- (4) Roughen surfaces for plasma or arc coatings

3.2.3 Acid Pickling. Pickling or dilute acid etching is a more drastic cleaning procedure than vapor blasting. Pickling should be performed when the part is in the final machining stage, thereby minimizing the danger of acid entrapment or subsequent intergranular attack. The pickling procedure requires the total immersion of the part in an acid solution. The time cycle depends upon the tenacity of the surface condition, the stock removal desired, or

both. After pickling, a hot water rinse, an alkaline solution immersion, and a thorough hot water or steam blast cleaning are used.

Acid contaminated surfaces may be neutralized by scrubbing with a sodium bicarbonate solution or immersing in a hot alkaline bath. Similarly, alkali contaminated surfaces may be neutralized by scrubbing with dilute 1% hydrochloric acid or with a 10% acetic acid solution. The surface should then be rinsed with clean cold water, and air or force air dried.

3.2.4 Oven Baking. Various machine elements manufactured from porous materials, such as sand castings, may absorb considerable quantities of oil, which may bleed out during a subsequent spraying operation. Welded assemblies that have received fluorescent penetrant inspection are particularly subject to this condition. Oven baking at 600°F (315°C) for four hours dries the oil and prevents bleed out.

3.2.5 Ultrasonic. Ultrasonic cleaning can be used when contaminants are lodged in confined areas. The equipment consists of a holding tank for the cleaning solution and a source producing ultrasonic vibrations within it. The cleaning solution is selected based on the problem encountered. Due to the heat generated, flammable or highly volatile solvents are not recommended for long term operations.

3.2.6 Abrasive. Dry abrasive blasting is an effective method for removing baked-on deposits, scale, or oxides. Abrasive blasting is accomplished by directing a compressed air stream containing abrasive particles through a nozzle and against the surface of the substrate. The blasting operation should be conducted by equipment other than the unit assigned for preparing substrates for spraying. This prevents contamination of the blasting materials. Careful consideration is required in selecting the type and size of abrasive.

Sheet metal panels, stampings, and weldments are more difficult to prepare than machined parts. Original sheet stock is usually identified by continuous printing of the manufacturer's name, material type, and heat number, using inks, dyes, or paint. The surface often contains rolled in mill scale or final heat treatment scale which should be removed. Subsequent manufacturing processes frequently add to or produce a surface oxide condition that should also be eliminated. There are numerous methods used for localized cleaning; however, vapor blasting or pickling is the most effective method for general cleaning purposes and very light stock removal.

3.2.7 Brushing. Wire brushing is used when only localized cleaning is needed. Small rotary wire brushes,

driven by a power tool, clean by a scuffing action.

3.3 Roughening

After cleaning, several methods are used to produce a surface to which a sprayed coating will adhere. The principal methods are (1) abrasive grit blasting, (2) macroroughening, and (3) applying a bond coating. Combinations of these methods are often employed. These include grit blasting with a subsequent bond coating, or machine roughening followed by grit blasting.

Proper roughening is as important as cleaning. During thermal spraying, the plasticized or molten particles form platelets upon impact with the substrate. The platelets, as they cool and harden, must adhere to a surface that is conducive to mechanical adherence.

3.3.1 Purpose. Surface roughening is used to strengthen both the coating and the bond by

- (1) providing compressive surface stresses
- (2) interlocking laminations (or layers)
- (3) increasing the bond area
- (4) decontaminating the surface

3.3.2 Degree. The degree of roughness required to produce a sound and serviceable coating is dependent upon the material being applied, the process, and the subsequent service conditions of the finished part.

3.3.3 Measurement. Surface roughness values are expressed in micro (μ) inch and meter units. The American National Standard¹ for surface roughness measurement specifies an arithmetical average (AA) deviation from the mean surface. Mean surface designates a perfectly flat surface with no asperities, also referred to as the center line. AA values are obtained by an instrument (profilometer) using a very fine stylus that moves over the surface of the part. It takes measurements of the heights (h) of the peaks and valleys (distances from the center line) and averages them.

The arithmetical average is calculated by adding all of the distances or heights (h), without regard to sign, and dividing by the total number of measurements (n)

$$\text{AA Average} = \frac{h_1 + h_2 + h_3 + h_4 + \dots + h_n}{n}$$

1. Refer to ANSI B46.1-1978, *Surface Texture*, New York: The American Society of Mechanical Engineers.

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The root mean square (RMS) is derived as follows:

$$\text{RMS Average} = \sqrt{\frac{(h_1)^2 + (h_2)^2 + (h_3)^2 + \dots + (h_n)^2}{n}}$$

RMS values are approximately 11% higher than AA values. This is because the large numbers are exaggerated when the heights (h) are squared.

The current trend is to adopt the American National Standard, in which surface roughness is specified in arithmetical average (AA) deviation values.

3.4 Abrasive Grit Blasting

Abrasive grit blasting is the most commonly used roughening technique. The surface to be coated is disturbed by the impingement of abrasive particles.

3.4.1 Factors Influencing Grit Selection. Care must be exercised in grit selection. Factors that must be considered include the following:

- (1) part material and hardness
- (2) part construction and thickness in the area being grit blasted
- (3) part size
- (4) type of coating and roughness requirement for good adhesion
- (5) service requirements
- (6) production rate requirement

- (7) grit particle size
- (8) blast pressure
- (9) blast nozzle size
- (10) life cycle

3.4.2 Type and Size of Abrasives. The effects of grit blasting depend on the type and size of abrasive. Sharp, hard, angular particles provide the best results. Spherical or rounded particles should not be used. All abrasives must be clean, dry, and free of oil, feldspar, or other contaminants.

Abrasive Grit Types. Several types of commercial abrasive grit are tabulated in Tables 3.4.2A and 3.4.2B. The most commonly used types are

- (1) aluminum oxide
- (2) chilled iron
- (3) angular steel
- (4) silicon carbide
- (5) garnet

Proper selection of the blasting medium depends on the substrate hardness.

Refractory oxides with sharp cutting edges may embed in soft substrates, such as aluminum. Chilled iron grit, which dulls rather than fractures on impact, is better for cleaning most substrates with hardnesses of less than 40-45 Rockwell C. Chilled iron grit generally creates greater stresses in the substrate than aluminum oxide. For this reason, it should not be used on thin substrates which may be warped by blasting.

Table 3.4.2A
Characteristics of abrasives commonly used for grit blasting prior to thermal spraying

Abrasive	Natural or mft'd	Major chemical component	Shape	Bulk density 100 g/cc	Breakdown* % of sample	Rc hardness
Chilled steel grit	Mft'd	Iron	Angular	765	0	100
Chilled iron grit	Mft'd	Iron	Angular	740	8	97
Virgin alum. oxide	Mft'd	Aluminum	Cubic	380	24	76
Reclaimed alum. oxide	Mft'd	Aluminum	Cubic	376	34	66
Garnet	Nat.	Iron silica	Cubic	409	46	54
Mineral slag	Mft'd	Silica alum. iron	Cubic	279	61	39
Flintbrasive	Nat.	Silica	Very angular	261	67	33
Silica sand	Nat.	Silica	Cubic	261	77	23
Silica sand	Nat.	Silica	Angular	263	90	10
Silicon carbide	Mft'd	Silicon carbide	Blocky	381	57	43
Standard sand	Nat.	Silica	Angular	262	84	16

* Amount of sample reduced to unacceptable size in standard blast test.

Table 3.4.2B
Recommended abrasives as used in abrasive blast cleaning applications

Recommended service ^{1,2}	Aluminum	Silica abrasives	Slag sand	Slag shot	Flint abrasives	Natural mineral abrasives	Synthetic abrasives	Special abrasives	Vegetable abrasives	Glass abrasives	Chilled iron grit	Chilled iron shot	Annealed abrasives	Steel grit
General blast cleaning where abrasives can be recycled and reused economically	C	C	C	C	C	C	P		C		P	C	C	
General blast cleaning where abrasives cannot be economically reclaimed		P	C	C	C									
Pre-thermal spray blasting	P	C	C		P	C	C				P		C	C
Blasting where metal tolerances cannot be changed								C	P					
Blasting in rooms and cabinets	P	C	C	C	C	C	P	C	C	C	P	C	C	
Blasting where the elimination of food contamination or nonmagnetic abrasives are required									P					
Blasting to obtain a high luster on aluminum, brass, etc.								C	C	P				
Liquid hone, hydro hone, wet hone blasting		C				C	P	P	P	P				
Centrifugal wheel blasting	C												C	P

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1. C=commonly used abrasives; P=preferred for thermal spraying applications.

2. Federal and State safety regulations governing the use of silica and mineral type abrasives for abrasive blasting are revised occasionally. The user of a recommended abrasive should be certain of compliance with the latest regulations.

Aluminum oxide may be used on hard substrates such as martensitic steel. When used on soft substrates, subsequent air blasting may help to remove any embedded particles.

Silicon carbide has a much greater tendency to embed, and breaks down more rapidly than aluminum oxide.

Abrasive Grit Sizes. Since the roughness of the finish depends on the size of the grit, abrasives are furnished in different grades. Smaller sized particles will allow for the preparation of more area per hour. Larger abrasive particles result in more rapid removal of material from the substrate, and produce rougher finishes. Table 3.4.2C shows the particle size distribution for a given grit mesh size, and Table 3.4.2D shows sieve standards. It is recommended that the particle size should be 16 to 60 grit for metal substrates, and 60 to 100 grit for most plastics.

For thin coatings, particularly when used on thin substrates, fine grit (25 to 120) should be used. Coarser

grits (18 to 25) that produce rougher finishes are used for thick coatings [greater than 0.010 in. (0.25 mm)], and best coating adherence.

3.4.3 Blasted Surface Roughness. The National Association of Corrosion Engineers (NACE) Technical Committee T-60 has conducted research and development to set standards for surface preparation. The following information and additional data may be obtained from the *Surface Preparation Handbook*.

There are four grades of blast cleaning presented on two Visual Standards (order #TM-01-70) which have been prepared to conform to the four surface conditions defined by NACE. These are recommended for use in describing or specifying degrees of surface preparation on steel by abrasive blasting. The most preferred grade for thermal spraying is NACE No. 1 (Table 3.4.3).

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Table 3.4.2C
Particle size distribution vs. grit sizes

Grit sizes

Sieve No.	6	8	10	12	14	16	20	22	24	30	36	40	46	54	60	70	80	90	100	120	150	180	220	240
4	0																							
5	15									PARTICLE SIZE DISTRIBUTION STANDARD MESH RANGES														
6	45	0																						
7	25	15	0																					
8	12	45	15	0																				
10	3	30	45	15	0																			
12		7	30	45	15	0																		
14		3	7	30	45	15	0	0																
16			3	7	30	45	15		0															
18				3	7	30	45	20		0														
20					3	7	30	45	25		0													
25						3	7	25	45	25		0												
30							3	7	25	45	25		0											
35								3	2	25	45	25		0										
40									3	2	25	45	30		0									
45										3	2	25	40	30		0								
50											3	2	25	40	30		0							
60												3	2	25	40	15		0						
70													3	2	25	45	25		0					
80														3	2	25	40	15		0				
100															3	12	25	40	15		0			
120																3	7	30	45	15		0		
140																	3	12	20	30	15		0	
170																		3	10	30	20	15		0
200																			7	15	20	20	15	5
230																			3	7	35	20	20	
270																				3	7	25	20	8
325																					3	17	20	30
-325																						3	25	57

Note: Procedures for determining the particle size distribution are described in the following standards:

ASTM C371-77, Standard Method for Wire-Cloth Sieve Analysis of Nonplastic Ceramic Powders.

ASTM B214-76, Standard Test Method for Sieve Analysis of Granular Metal Powders

Table 3.4.2D

Nominal Dimensions, Permissible Variations for Wire Cloth of Standard Test Sieves (U.S.A. Standard Series)

Sieve Designation		Nominal Sieve Open- ing, in. ^c	Permissible Varia- tion of Average Opening from the Standard Sieve Designation	Maximum Open- ing Size for Not More than 5% of Openings	Maximum Indi- vidual Opening	Nominal Wire diame- ter, mm ^a
Standard ^b	Alternative					
(1)	(2)	(3)	(4)	(5)	(6)	(7)
125 mm	5 in.	5	±3.7 mm	130.0 mm	130.9 mm	8.0
106 mm	4.24 in.	4.24	±3.2 mm	110.2 mm	111.1 mm	6.40
100 mm ^d	4 in. ^d	4	±3.0 mm	104.0 mm	104.8 mm	6.30
90 mm	3½ in.	3.5	±2.7 mm	93.6 mm	94.4 mm	6.08
75 mm	3 in.	3	±2.2 mm	78.1 mm	78.7 mm	5.80
63 mm	2½ in.	2.5	±1.9 mm	65.6 mm	66.2 mm	5.50
53 mm	2.12 in.	2.12	±1.6 mm	55.2 mm	55.7 mm	5.15
50 mm ^d	2 in. ^d	2	±1.5 mm	52.1 mm	52.6 mm	5.05
45 mm	1¾ in.	1.75	±1.4 mm	46.9 mm	47.4 mm	4.85
37.5 mm	1½ in.	1.5	±1.1 mm	39.1 mm	39.5 mm	4.59
31.5 mm	1¼ in.	1.25	±1.0 mm	32.9 mm	33.2 mm	4.23
26.5 mm	1.06 in.	1.06	±0.8 mm	27.7 mm	28.0 mm	3.90
25.0 mm ^d	1 in. ^d	1	±0.8 mm	26.1 mm	26.4 mm	3.80
22.4 mm	⅞ in.	0.875	±0.7 mm	23.4 mm	23.7 mm	3.50
19.0 mm	¾ in.	0.750	±0.6 mm	19.9 mm	20.1 mm	3.30
16.0 mm	⅝ in.	0.625	±0.5 mm	16.7 mm	17.0 mm	3.00
13.2 mm	0.530 in.	0.530	±0.41 mm	13.83 mm	14.05 mm	2.75
12.5 mm ^d	½ in. ^d	0.500	±0.39 mm	13.10 mm	13.31 mm	2.67
11.2 mm	⅞ in.	0.438	±0.35 mm	11.75 mm	11.94 mm	2.45
9.5 mm	⅜ in.	0.375	±0.30 mm	9.97 mm	10.16 mm	2.27
8.0 mm	⅝ in.	0.312	±0.25 mm	8.41 mm	8.58 mm	2.07
6.7 mm	0.265 in.	0.265	±0.21 mm	7.05 mm	7.20 mm	1.87
6.3 mm ^d	¼ in. ^a	0.250	±0.20 mm	6.64 mm	6.78 mm	1.82
5.6 mm	No. 3½	0.223	±0.18 mm	5.90 mm	6.04 mm	1.68
4.75 mm	No. 4	0.187	±0.15 mm	5.02 mm	5.14 mm	1.54
4.00 mm	No. 5	0.157	±0.13 mm	4.23 mm	4.35 mm	1.37
3.35 mm	No. 6	0.132	±0.11 mm	3.55 mm	3.66 mm	1.23
2.80 mm	No. 7	0.111	±0.095 mm	2.975 mm	3.070 mm	1.10
2.36 mm	No. 8	0.0937	±0.080 mm	2.515 mm	2.600 mm	1.00
2.00 mm	No. 10	0.0787	±0.070 mm	2.135 mm	2.215 mm	0.900
1.70 mm	No. 12 ^e	0.0661	±0.060 mm	1.820 mm	1.890 mm	0.810
1.40 mm	No. 14	0.0555	±0.050 mm	1.505 mm	1.565 mm	0.725
1.18 mm	No. 16	0.0469	±0.045 mm	1.270 mm	1.330 mm	0.650
1.00 mm	No. 18	0.0394	±0.040 mm	1.080 mm	1.135 mm	0.580
850 μm ^f	No. 20	0.0331	±35 μm	925 μm	970 μm	0.510
710 μm	No. 25	0.0278	±30 μm	775 μm	815 μm	0.450
600 μm	No. 30	0.0234	±25 μm	660 μm	695 μm	0.390
500 μm	No. 35	0.0197	±20 μm	550 μm	585 μm	0.340
425 μm	No. 40	0.0165	±19 μm	471 μm	502 μm	0.290
355 μm	No. 45	0.0139	±16 μm	396 μm	425 μm	0.247
300 μm	No. 50	0.0117	±14 μm	337 μm	363 μm	0.215
250 μm	No. 60	0.0098	±12 μm	283 μm	306 μm	0.180
212 μm	No. 70	0.0083	±10 μm	242 μm	263 μm	0.152
180 μm	No. 80	0.0070	±9 μm	207 μm	227 μm	0.131
150 μm	No. 100	0.0059	±8 μm	174 μm	192 μm	0.110
125 μm	No. 120	0.0049	±7 μm	147 μm	163 μm	0.091
106 μm	No. 140	0.0041	±6 μm	126 μm	141 μm	0.076
90 μm	No. 170	0.0035	±5 μm	108 μm	122 μm	0.064
75 μm	No. 200	0.0029	±5 μm	91 μm	103 μm	0.053

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Table 3.4.2D (continued)

Sieve Designation		Nominal Sieve Opening, in. ^c	Permissible Variation of Average Opening from the Standard Sieve Designation	Maximum Opening Size for Not More than 5% of Openings	Maximum Individual Opening	Nominal Wire diameter, mm ^a
Standard ^b	Alternative					
(1)	(2)	(3)	(4)	(5)	(6)	(7)
63 μm	No. 230	0.0025	$\pm 4 \mu\text{m}$	77 μm	89 μm	0.044
53 μm	No. 270	0.0021	$\pm 4 \mu\text{m}$	66 μm	76 μm	0.037
45 μm	No. 325	0.0017	$\pm 3 \mu\text{m}$	57 μm	66 μm	0.030
38 μm	No. 400	0.0015	$\pm 3 \mu\text{m}$	48 μm	57 μm	0.025

^a The average diameter of the warp and of the shoot wires, taken separately, of the cloth of any sieve shall not deviate from the nominal values by more than the following:

Sieves coarser than 600 μm 5%

Sieve 600 to 125 μm 7½%

Sieves finer than 125 μm 10%

^b These standard designations correspond to the values for test sieve apertures recommended by the International Standards Organization, Geneva, Switzerland.

^c Only approximately equivalent to the metric values in Column 1.

^d These sieves are not in the standard series, but they have been included because they are in common usage.

^e These numbers (3½ to 400) are the approximate number of openings per linear inch, but it is preferred that the sieve be identified by the standard designation in millimeters or μm .

^f 1000 μm = 1 mm.

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Table 3.4.3
Guide to base metal gritblasting rates
for NACE* No. 1, white metal finish

Equipment	Rate, ft ² /h	
	minimum	maximum
Syphon type	10	20
Pressure type	20	40
Manual abrasive return room	30	60
Automatic abrasive return room	50	100
Wheel type airless (per wheel)	150	400

Notes:

The minimum rate indicates the output on small work heavily corroded requiring considerable handling.

The maximum rate is for large surfaces in semi-bright or lightly corroded conditions.

*National Association of Corrosion Engineers

NACE No. 1, White Metal Blast Cleaned Surface Finish is a surface with a gray white (uniform metallic) color that has been roughened to form a suitable anchor pattern for coatings. This surface is free of oil, grease, dirt, mill scale, rust, corrosion products, oxides, paint, and other foreign matter. (Comparable to SSPC-SP 5-63, *White Metal Blast Cleaning*.)

The surface roughness adequate for most spray coatings is 100 $\mu\text{in.}$ (2.5 μm) to 500 $\mu\text{in.}$ (13 μm) AA. For some critical applications, especially on thin metal parts, it may be necessary to use a roughness value of 50 $\mu\text{in.}$ (1.3 μm) AA. For plastic parts coated with low melting point

materials and alloys, such as zinc, the roughness should be 250 $\mu\text{in.}$ (6 μm) AA, minimum.

Adhesion bond strength normally increases with surface roughness, although the rate of improvement decreases above 400 $\mu\text{in.}$ (10 μm) AA. The best adhesion bond strength is associated with a roughness dimension comparable to three-fourths of the diameter of the particles sprayed.

3.4.4 Blasting Procedures. In addition to the abrasive grit type and size, other process variables of importance are air pressure, blast angle, distance, and time (Table 3.4.4).

Table 3.4.4
General conditions frequently used to produce the
required roughness on steel substrates

Grit size (mesh)	Grit material	Blast pressure		Nozzle bore dia.		Machine type	Substrate	Roughness AA	
		psi	(kPa)	in.	(mm)			in.	(μm)
24	Aluminum oxide	60	(414)	5/16	(7.9)	Pressure	Steel	500	(13)
60	Silicon carbide or aluminum oxide	60	(414)	5/16	(7.9)	Suction	Stainless	250	(μ6)
80	Aluminum oxide	60	(414)	5/16	(7.9)	Pressure	Plastic	250	(μ6)

All substrate areas that can be damaged by the blast operation, or are to be coated, must be protected by suitable masking. Dust or grit adhering to the substrate surface must be removed by air blast before starting a spraying operation.

Air pressures for blasting are in the range of 30 to 100 psi (34 to 88 kg/sq cm), depending on the substrate material; the required surface finish; the flow, weight, and size of abrasive particles; and the machine and nozzle type used.

Low blasting air pressures and soft or fine grit should be used for substrates, such as aluminum and copper alloys, bronzes, and plastics, to minimize the likelihood of embedding the grit. High air pressures, in addition to causing rapid breakdown of the grit, produce compressive stresses which can distort thin substrates.

With pressure type blasting equipment, the following pressures at the nozzle should be used:

(1) With aluminum oxide, silicon carbide, flint or slag - 50 psi (345 kPa) minimum and 60 psi (414 kPa) maximum

(2) With sand, garnet, or crushed chilled iron grit - 75 psi (517 kPa) minimum

These are not the pressures at the blast machine tank, but at the blast nozzle as measured with a needle probe gauge.

When syphon blasting (suction blasting), the maximum nozzle pressure should be

(1) With aluminum oxide, silicon carbide, flint or slag - 75 psi (517 kPa)

(2) With sand, garnet, or crushed chilled iron grit - 90 psi (621 kPa)

The abrasive stream should be directed onto the substrate surface at a spray angle of 75° to 90°, and moved from side to side.

Nozzle to substrate distance varies from 4 to 12 in.

(102-304 mm), depending upon the size and type of abrasive used, nozzle opening size, and capacity of the blast machine.

Visual inspection for uniform coverage and surface texture determines the required time for producing a grit-blasted surface suitable for spraying (3.4.3, NACE No. 1). Excessive blasting time may result in an undesirable surface texture.

3.4.5 Blasting Speeds and Costs. Blasting speeds and costs depend on several factors including the type, size, and loading capacity of the blasting equipment as well as the substrate material. Table 3.4.3 shows the typical performance of various blasting devices.

Blast machine nozzles having large diameter orifices will cover more area per hour than nozzles having smaller orifices. However, the size of the nozzle orifice to be chosen is limited by the amount of compressed air available. Table 3.4.5 shows the square feet (square meters) of blast cleaned surface that can be obtained for various surface conditions with a given size nozzle, using a continuous pressure type blaster with an air pressure of 100 psi (0.03 kg/m²).

The type and size of the abrasive also influences blasting rates. Generally, the larger the abrasive particle size, the slower the operation. Approximately 15 lb (6.8 kg) of aluminum oxide or 25 lb (11.3 kg) of chilled iron grit are required per square foot of blasted surface.

3.4.6 Grit Recycling. Abrasives used in shop or production applications may be recycled, cleaned, and screened so that they can be used again. Angular chilled iron grit and aluminum oxide are most commonly used in such operations. When an abrasive is reused, it should be cleaned of dust and resized, with a minimum of 80% conforming to the original size requirements. Con-

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Table 3.4.5
Pressure blast cleaning rates on semi-bright or lightly
corroded steel substrate using 925 iron grit

Surface condition and type blasted	Nozzle size, in. (mm)		
	¼ (6.4)	⅝ (7.9)	¾ (9.5)
	Blasting rate, ft²/h (m²/h)		
Surface condition No. 1			
White	75 (7.0)	117 (10.9)	168 (15.6)
Commercial	112 (10.4)	175 (16.3)	252 (23.4)
Brush-off	299 (27.8)	467 (43.4)	672 (62.4)
Surface condition No. 2			
White	96 (8.9)	150 (13.9)	216 (20.1)
Commercial	144 (13.4)	225 (20.9)	321 (29.8)
Brush-off	381 (35.4)	600 (55.7)	851 (79.1)
Surface condition No. 3			
White	85 (7.9)	133 (12.4)	192 (17.8)
Commercial	128 (11.9)	200 (18.6)	288 (26.8)
Brush-off	341 (31.7)	533 (49.5)	768 (71.4)

taminated abrasive grains, or those of questionable quality, should not be reused. Failure to remove broken down grit (fines) from the abrasive can be detrimental to the proper bonding of a coating.

Table 3.4.6 shows frequently used materials evaluated under controlled conditions. There are many variables that can alter these data, but the table gives a relative idea of the number of times different types of material can be recycled through a blast machine.

Table 3.4.6
Abrasive life

Material	No. of recycles
Aluminum oxide	10
Chilled iron	15
Steel	100
Garnet	7

Single-use abrasives are employed in on-site or field applications, where it is usually not economical to reclaim and reuse abrasives.

3.4.7 Compressed Air Supply. The compressed air supply should be adequate to furnish the necessary

pressure and volume to sustain the proper blast quality. The air should be free from oil, water, and other contaminants. In addition to clogging the system, oil or water in the compressed air can adversely affect surface preparation and subsequent bonding.

3.5 Macroroughening

Macroroughening is another surface preparation method usually accomplished by machining or grinding, and is performed in conjunction with grit blasting, the use of bond coatings, or both.

3.5.1 Undercutting. Undercutting is the operation of machining or grinding away surface to provide space for the thermal spray deposit. This is necessary on mechanical parts that are to be rebuilt.

Undercutting is also done to provide a uniform thickness of finished coating or to remove metal from a surface due to work hardening, chemical contamination, oxidation, or previously applied sprayed material. Since undercutting reduces the cross-sectional area of the components, it can adversely affect the tensile and fatigue strength of the part.

Shoulders and Undercut Sections. At each undercut section on a cylindrical part, the shoulders should be cut square or at a slight obtuse angle (15°). The use of acute angle dovetails is detrimental and not recommended. A radius of 0.015 to 0.020 in. (0.38 to 0.50 mm) should be made at each corner of the undercut. The undercut section should not extend to the end of a shaft. The proper and improper ways to terminate the thermal sprayed inlay at the end of a shaft are illustrated in Fig. 3.5.1. Leave a shoulder at end of the undercut section wherever possible.

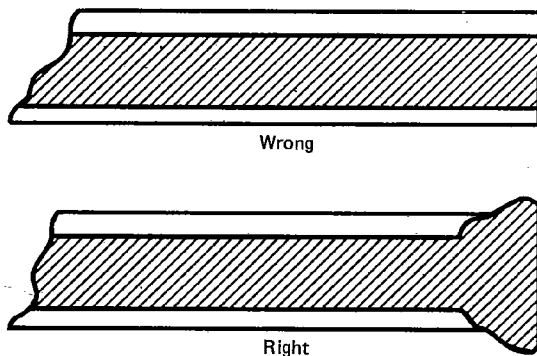


Fig. 3.5.1—Shaft with proper and improper undercut section

On cylindrical surfaces (such as pump plungers) where the coating is exposed to pressure from the end, it is recommended that a weld be deposited circumferentially around the pressure end. The welded bead should then be machined to a 1/8 in. (3.2 mm) minimum shoulder. The diameter of the shoulder should be greater than the final finish size of the shaft. The welded bead can withstand the pressure of operation better than an exposed thermal sprayed layer. It is important to note that welding can affect base metal properties; this must be considered in salvage or repair applications.

3.5.2 Grooving. Grooving pertains to the operation of cutting deep, closely spaced striations in the substrate. Grooving (or threading) is performed primarily for the following purposes:

- (1) restrict the shrinkage stresses
- (2) increase the bond surface area
- (3) produce folds in the layers of the coating to limit internal stresses

Internal stresses from shrinkage develop in coatings, which can result in bond failure. The stresses increase with increased coating thickness, and are more severe in

hard metals or ceramics. Grooving is a method of reducing the stresses by dividing the internal stresses into smaller components. Figure 3.5.2 shows sections of two shafts. One is undercut without threading, and the internal stresses are in a straight line across the full length of the undercut. In the threaded shaft, stresses have been broken into smaller components, along each side of each thread, and can cancel each other. All corners at the root of each thread should be radiused to reduce the notch effect. A second method is to use U-shaped grooves instead of conventional V-shaped threads which may act as points of stress concentration in heavily loaded machine parts.

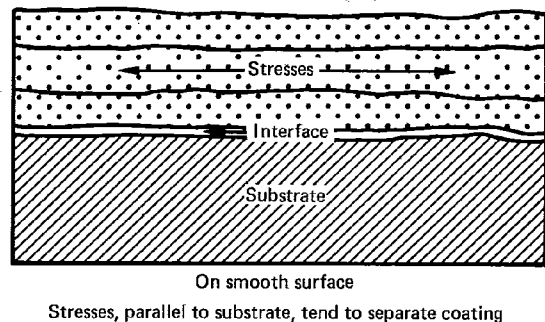
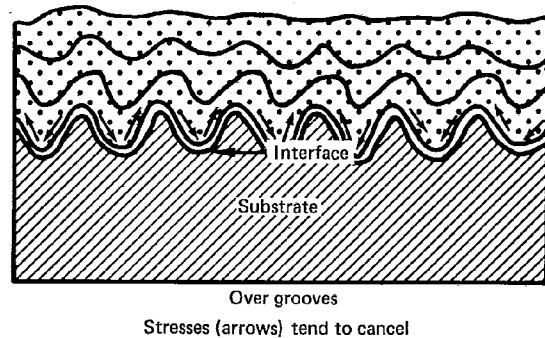


Fig. 3.5.2 — Sprayed metal

Since thermal sprayed coatings consist of laminations or layers of flattened particles, much like a piece of straight grained wood, the strength of the coating is lower in the direction perpendicular to the layers than in the parallel direction. As the laminations are folded up and down over relatively large grooves, the coating strength is improved, and there is less tendency for layer separation to occur.

Grooving should be considered in the following situations:

- (1) for all coatings over 0.050 in. (1.27 mm) thickness wherever there is an edge
- (2) for high-shrink coatings over 0.030 in. (0.76 mm)

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thickness wherever there is an edge

(3) for coatings that do not have edges, such as continuous coatings on cylindrical surfaces, when severe service conditions exist, or when there is danger of cracking due to thick buildups or high shrink materials

3.5.3 Studs or Slots on Flat Surfaces. Hard metallic coatings on flat surfaces present special problems. If the substrate is of a harder metal, the depth of the blast profile is reduced, and the adhesion of the thermal sprayed coating is decreased. In addition, hard metal coatings are usually applied thicker than soft coatings such as aluminum or zinc. Consequently, the total amount of coating shrinkage during cooling is much greater.

On such applications, it is often necessary to stud the surface. This consists of drilling and tapping holes at 1 in. (25 mm) intervals and inserting unplated flat-head screws which match the composition of the substrate. Screw diameters vary from 0.125 to 0.25 in. (3 to 6 mm). After attachment, the surfaces and screws are blasted.

3.5.4 Coarse Grit Blasting. For some types of work where grooving is not practical, but where macroroughening is desired, extremely coarse grit blasting can produce similar results (see 3.4). Coarse grit blasting is used in place of grooving methods for many applications to take advantage of lower costs and higher production. SAE² G-14 chilled iron grit will provide adequate roughness for a strong adhesive bond and cause sufficient folds in the laminations to effectively perform the function of fine grooves. This method may also be used for undercutting.

3.6 Roughening Applications

3.6.1 Corrosion Resistant Coatings. Where zinc coatings up to and including 0.009 in. (0.23 mm) thick or aluminum coatings up to and including 0.007 in. (0.18 mm) thick are to be applied, the following abrasive grits are recommended for use with pressure blast equipment to produce a 300 μ in. (7.5 μ m) AA anchor tooth pattern.

- (1) Aluminum oxide or silicon carbide
mesh size: SAE G-25 to SAE G-40
- (2) Hardened steel grit
mesh size: SAE G-25 to SAE G-40
- (3) Angular silica sand, garnet, flint, or crushed slag
mesh size: SAE G-25 to SAE G-50

2. Refer to SAE J444, *Cast Shot and Grit Size Specifications for Peening and Cleaning*, Rev. A, Society of Automotive Engineers, November 1, 1976.

To prepare surfaces for zinc coatings greater than 0.010 in. (0.25 mm) thick or aluminum coatings in excess of 0.008 in. (0.20 mm), the following abrasives are recommended for use in pressure type blast machines to provide a 500 μ in. (13 μ m) AA anchor tooth pattern:

- (1) Aluminum oxide or silicon carbide
mesh size: SAE G-18 to SAE G-25
- (2) Hardened steel grit
mesh size: SAE G-18 to SAE G-25
- (3) Angular silica sand, garnet, flint, or crushed slag
mesh size: SAE G-18 to SAE G-25

3.6.2 Fused Coatings. For the application of self-fluxing alloys, the surface preparation must be sufficient to hold the coating until the fusing operation is accomplished. Self-fluxing alloy applications receive the greatest stress during the fusing operation at temperatures of 1800 to 2100°F (982 to 1149°C).

When preparing the surfaces, SAE G-25 chilled iron grit is normally used. Grit size may vary according to substrate hardness, etc. However, grit such as aluminum oxide tends to embed in the surface and impair the coating adhesion.

On cylindrical surfaces that are to be precision finished, undercutting is necessary. The depth of the undercut is determined by service conditions. If the maximum allowable wear is 0.020 in. (0.5 mm), an undercut of an additional 0.015 in. (0.38 mm) minimum is recommended so that some coating will remain after maximum wear has taken place.

Shoulders at the end of the undercut section should be opened to about a 40° to 45° angle. For coatings, greater than 0.040 in. (1.0 mm) thick, threading the undercut surface is advisable prior to grit blasting.

3.6.3 Stainless Steel Coatings. For stainless steel coatings on hardened steel, an SAE G-20 aluminum oxide grit provides a surface roughness with a 500 μ in. (13 μ m) AA anchor tooth pattern. For stainless steel coatings on mild steel or cast iron, an SAE G-25 chilled iron grit is recommended.

3.6.4 Plastic Substrates. Soft substrates, such as plastics, require a finer mesh size and lower blasting pressure. Aluminum oxide, size SAE G-50 to SAE G-80, will provide a 250 μ in. (6 μ m) AA surface roughness.

3.7 Cleanliness After Roughening

When blast roughening is employed, the freshly exposed substrate is extremely susceptible to contamination. Hand contact should be avoided because deposited oil or finger

prints may adversely affect the coating bond. Spray coatings should be completed before oxidation occurs on the cleaned surface. Clean roughened surfaces are degraded by moisture or condensate; even slight corrosion is an indication of moisture. Where possible, humidity should be maintained at 60% or less in the spray and preparation area. In some instances, a mild preheat prior to blasting may be helpful.

3.7.1 Coverings. Freshly prepared surfaces, that are not to be coated immediately can be protected by covering them with clean plastic sheet. For extended periods, all prepared parts may be stored in a clean heated cabinet or oven, or a sealed bag with a desiccant. Heated storage can facilitate preheating for spraying.

3.7.2 Handling. Work pieces that have been prepared for spraying should be handled with clean, lint free gloves or the equivalent until the thermal sprayed coating is applied.

3.8 Bond Coatings

The use of bond coatings is another method of surface preparation. Certain materials adhere to clean, smooth surfaces forming strong coating-to-substrate bonds, over a wide range of conditions. A thin layer of bonding material serves as an anchoring subcoat for subsequently applied coating layers. For best results, the substrate should be grit blasted before applying the bond or intermediate coating. A top coat applied to a grit blasted, bond-coated surface normally will produce a higher bond strength than that obtained without a bond coating.

Bond coatings are particularly applicable for substrates that are too thin or too hard to be prepared by abrasive grit blasting or macroroughening. They are also applicable when size or configuration make blasting or roughening difficult. Frequently, bond coating is selected to provide protection to the substrate as well as to provide a good bond to it.

3.8.1 General Considerations. Certain general rules should be observed in using a bond coating. The decision to use a bond coating must take into account the conditions under which the coating will be used, particularly if the coating will be exposed to corrosive or oxidizing conditions. Molybdenum has poor oxidation resistance, and would not be suitable for use in air at temperatures above 600°F (316°C). Nickel-aluminum coatings are susceptible to corrosion in aqueous salt solutions. Where the coating will be exposed in electrolytic solution, the bond coating may be cathodic to the substrate material, resulting in increased rate of corrosion and delamination.

3.8.2 Bond Coat Thickness. The use of a bond coat sometimes limits the thickness of subsequently applied top coats. Unless the substrate has first been treated, the bond coat may not be able to absorb the shrinkage stresses produced by thick, hard metallic deposits. The bonding material should be applied sufficiently thick to cover the substrate, usually 0.003 to 0.007 in. (0.08 to 0.18 mm). There is no practical economic or engineering advantage in a thick bond coating, except when used as the entire coating.

3.8.3 Bond Coat Materials. Commercially available bonding materials include molybdenum and nickel-aluminum composites and alloys which produce some metallurgical interaction with the substrate during spraying. Table 3.8.3 lists common bond coating materials and their service temperatures. Nickel-aluminum is used for many applications because of its good high temperature properties and ease of application to various substrates.

Materials such as aluminum, tin, and zinc aid the bonding of sprayed coatings to materials, such as plastics, that are resistant to low temperature.

Nickel-chromium alloys or other metal-chromium-aluminum alloy (MCrAlY) materials resist thermal shock better than other bonding materials. They are particularly suited for thermal barrier coatings in high temperature environments, 2300° to 2400°F (1260° to 1316°C).

Table 3.8.3
Approximate maximum service temperature limits for bond coatings

Coating	°F	°C
Molybdenum	600	315
80 Ni-20 Al	1150	620
95 Ni- 5 Al	1850	1010
80 Ni-20 Cr	2300	1260
94 NiCr-6 Al	1800	980

3.8.4 Ceramic Top Coatings. Surface preparations for ceramic coatings are the same as those used for metallic coatings. Bond coatings are used extensively, and vary with the composition and characteristics of the substrate. The environment in which the coating is to operate dictates the type of bond coating material.

Bond coatings of nickel, chromium, stainless steel, or other corrosion resistant alloys, such as MCrAlY, are often applied (80 nickel-20 chromium being especially good) in thicknesses of 0.002 to 0.013 in. (0.05 to 0.33 mm) or more. They provide flexible and adherent coatings for ceramic deposits. Ceramic coatings are often subject to thermal cycling, high temperatures, and chemical cor-

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rosion. Relatively thicker bond coatings promote longer life under these conditions.

3.8.5 Arc, Combustion, and Plasma

Arc. The inherently high adhesive bond strengths achieved with the electric arc process make it possible to eliminate surface roughening for certain applications by using a bond coating of nickel-aluminum alloy. This, however, should be the exception rather than the rule. Surface roughening as described previously is always recommended.

High bond strengths may be obtained with arc spray coatings applied to a prepared surface by making the first pass as hot as possible to produce large particles [low air pressure and a 2 in. (50 mm) spray distance.] This

establishes conditions for the superheated spray particles to adhere tightly. Three materials, 90 aluminum-10 copper alloy (aluminum-bronze), 80 nickel-20 chromium alloy, and 95 nickel-5 aluminum alloy, have excellent bonding properties. The adhesion and the ability to produce a rough profile with the first pass makes these materials ideally suited for subsequent coating buildup.

Combustion (Wire and Powder Flame Spraying). With flame spraying (see 1.4.3), grit blasting and bond coatings are usually required for most applications because of the low heat of combustion and low particle velocities.

Plasma. The surface preparation and bond coatings required for subsequent plasma sprayed deposits are as outlined in this chapter.

Chapter 4

Coating Characteristics

4.1 Introduction

4.2 Formation and Structure of Coatings

4.2.1 Form of the Spray

4.2.2 Particle Deposition

4.2.3 Substrate Surface Influence on the Molten Particle

4.3 Coating Properties

4.3.1 Visual

4.3.2 Tensile Strength

4.3.3 Residual Stress

4.3.4 Hardness

4.3.5 Compression

4.3.6 Wear Resistance

4.3.7 Fatigue

4.3.8 Ductility

4.3.9 Corrosion Resistance

4.4 Coatings Produced Under Controlled Atmospheres

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Chapter 4

Coating Characteristics

4.1 Introduction

To understand the characteristics of the sprayed deposit, knowledge of the various deposition processes and the associated fuels, raw materials, and kinetics is important.

In addition to the operating conditions associated with the thermal spray process, raw material characteristics must also be considered. This is especially true of powdered materials. Particle shape, size, density, oxide content, all contribute to the quality of the end product. The melting and vaporization temperatures of the coating material are important because they restrict the use of a material and dictate the spraying conditions. For example, the liquid-vapor temperature range for pure alumina is narrow, and vaporization may occur under conditions of superheating, and produce a sponge-like coating structure.

The basic criterion is that the particles should melt completely without excessive vaporization, and remain molten until they impinge onto the substrate. Although smaller particle size will ensure more complete melting, there are usually serious difficulties in proper injection of fine particles [$<200\mu$ in. (5μ m)] into the heat system. In the case of oxyfuel flame spraying, consideration should be given to the dust content in the powder. The use of powders containing sizeable quantities of fines (dust) will lead to excessive coating oxidation and voids.

In externally fed plasma spraying systems, the velocity gradient of the high energy plasma stream restricts entry of fine particles into the hot zone. Therefore, some of the particles are transported on the periphery of the stream and do not melt sufficiently prior to impact. Further, fine particles cool more rapidly and, therefore, can partially solidify before impact. Only properly aligned particles melt completely by absorption of radiation from the surrounding hot gases.

Some simplified models have been proposed to describe the melting of solid particles in a heated gas effluent. Material related variables, such as the heat transfer coefficient, conductivity, and melting temperature, have been combined in equations for gas flow dynamics and heat conduction yielding the following equation:

$$\frac{S(K\Delta T)^2}{V\mu} \geq \frac{L^2 D^2}{16p} \quad (\text{Eq 1})$$

effluent particle

where:

- S = particle travel distance (spray distance)
- K = mean boundary layer thermal conductivity
- ΔT = mean boundary layer temperature gradient
- V = mean effluent velocity
- μ = mean effluent viscosity
- L = particle heat content per unit volume at melting temperature
- D = mean particle diameter
- p = particle density

According to equation (1), there is a critical particle residence time and a critical particle size for which complete melting is achieved. The residence time is determined mainly by gas velocity, energy, and spray distance. The physical attributes of the particle, which are given by the term on the right of equation (1), depend on the material under consideration.

To measure particle temperature, T, a model was suggested by Plunkett which assumes that the surface temperature of a particle with a radius, R, is instantaneously brought to a constant temperature, T_s , while the interior temperature is raised by conduction during the dwell time, such that

$$\frac{T}{T_s} = \left\{ 1 - \frac{2R}{\pi R} \sum \frac{(-1)^n}{n} \sin \frac{n\pi r}{R} \cdot \frac{(\alpha n\pi)^2 t}{R} \right\} \quad (\text{Eq 2})$$

where:

- n = 1
- T = Particle temperature
- T_s = Constant temperature
- R = Radius of particle (particle size in microns)

Σ = Symbol for summation of all terms, in brackets
 r = Distance from particle center to R
 t = Residence time for particle
 α = Thermal diffusivity

Wire and rod feedstock vary in size from 20 gauge (0.88 mm) to 1/4 in. (6.35 mm). Powdered spray materials have a size range of 5 to 45 microns for refractory oxides and 45 to 106 microns (-140 to 325 mesh) for metallic powders with melting ranges lower than 3500°F (1927°C).

4.2 Formation and Structure of Coatings

4.2.1 Form of the Spray. Observation of the coating material exiting a thermal spray gun will reveal a conical shape, with the spray concentrated in the central zone and more sparse in the outer portions. The central zone is comparatively narrow and the material content highly concentrated. This may be demonstrated by spraying a single pass and then examining under a microscope a transverse section of the structure at 90 degrees to the direction of application. Figure 4.2.1A shows such a section in sequence A-B, B-C, C-D where A was at periphery of the deposit and D at the center.

The particles in the outer periphery (A) of the deposit, are widely spaced and poorly adhered to the substrate. The spray deposit density ratio is largely dependent on the particles within the peripheral zone.

Figure 4.2.1B schematically illustrates the actual spray form shape. A circular or oval central zone, within which the densest and thickest coating is deposited, is between C and C. Between B and C, the spray stream is luminous, and coating deposition of a marginal nature occurs, (point B). The deposited coating in the zone identified as AB is extremely porous.

The final sprayed coating contains a mixture of material from each zone, because the gun and the substrate are moved relative to each other during coating application.

4.2.2 Particle Deposition. During the spraying process, particles are superheated and impinge on the substrate with varying velocities. The porous "pancake" morphology generally produced by spraying results from the rapid flattening of superheated liquid particles impinging, essentially independently, on the substrate of previously deposited layers. This is referred to as *splat-cooling*.

It is important to accurately represent the rate of cooling in a typical spray process. Some of the factors which must be taken into consideration are the size variation of the particles, their location within the heat zone, and, in the case of metal particles, the formation of an oxide film.

Ballard and Gerdeman/Hecht (see Bibliography) have studied the splash effects of molten droplets onto glass. In these experiments, glass slides were passed under the spray stream. The molten particles impinged on the glass, solidified, and were studied with a microscope. While somewhat idealized, the investigations indicated the ef-

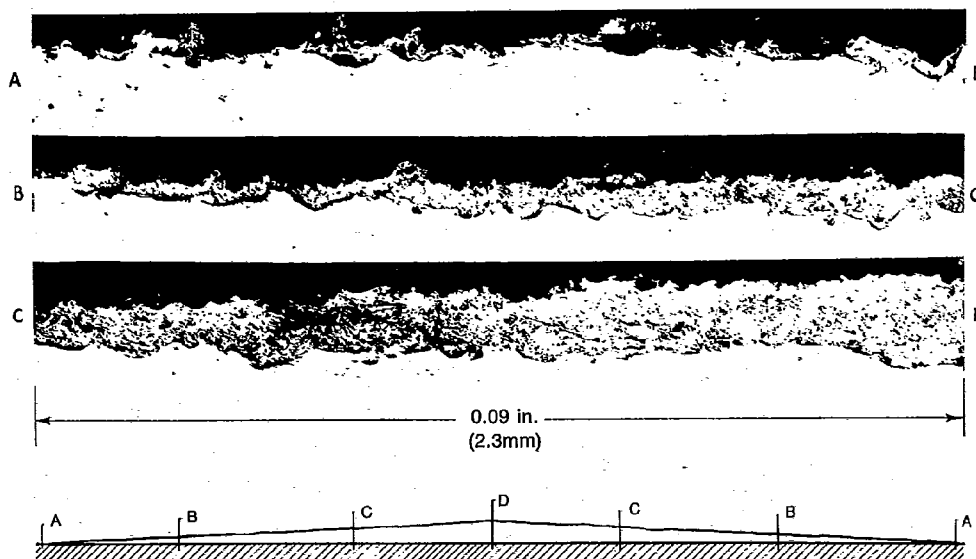
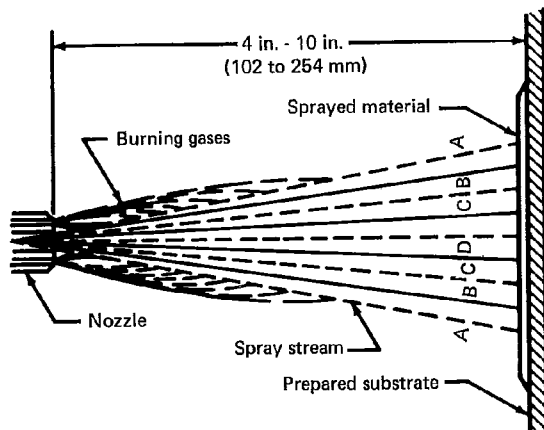


Fig. 4.2.1A — Typical transverse section of spray deposit from one pass of the thermal spray gun

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**Fig. 4.2.1B—Development of spray pattern**

fects of operating conditions upon final splat configuration.

Gerdeman and Hecht considered the technique useful for rapidly determining optimum standoff distance. Figure 4.2.2A illustrates properly melted ceramic particles. The particle splash, or wetting, resulting from improper standoff distances are shown in Fig. 4.2.2B as being too close and in Fig. 4.2.2C as being too far.

In Figure 4.2.2B, where gun-to-work standoff distance was too close, the particle has not become completely molten, and the solid center core has rebounded away from the glass surface, resulting in a void.

Figure 4.2.2D shows two particles which began to solidify while in transit.

A molten drop, arriving at the surface which it does not wet, will first spread out in a thin layer and will, if surface tension does not operate, continue to spread until the layer becomes of unimolecular thickness or until it solidifies. The spreading is helped if the drop arrives at high velocity, but after a short interval, surface tension restrains this spreading. The edge of the drop becomes thickened, and tends to break and form a ring of small spherical drops, leaving a spherical drop in the center, smaller than the original. This action of retraction also causes a number of radial splashes, as shown in Fig. 4.2.2E.

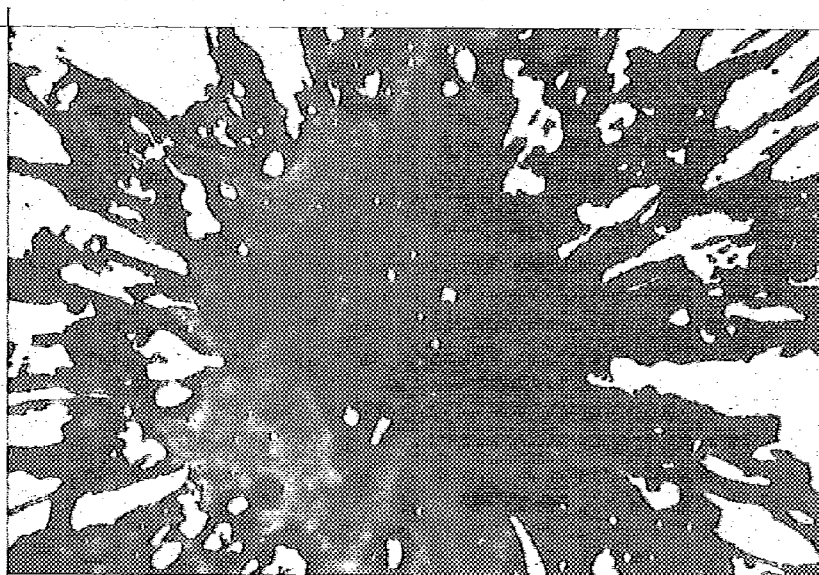
In the case of the sprayed drop, solidification may take place at any instant in the cycle of events. It is apparent, therefore, that in considering the formation of sprayed coatings, retraction of individual drops, or aggregates of drops as a result of surface tension, must be taken into account. Oxide films on the splats or aggregates also cause modifications to the splash effect, as they tend to interfere with the distribution of surface energy. In some metals, most of the splats become frozen in the first stages of spreading and retraction, and they then appear roughly circular in shape, with serrated edges. This general effect is shown by cadmium, lead, tin, and zinc, which have

**correct standoff distance****Fig. 4.2.2A — Fully melted ceramic particle (2000 x)**



close standoff distance

Fig. 4.2.2B — Partially melted metallic particle (2000 x)



far standoff distance

Fig. 4.2.2C — Fully melted metallic particle (2000 x)

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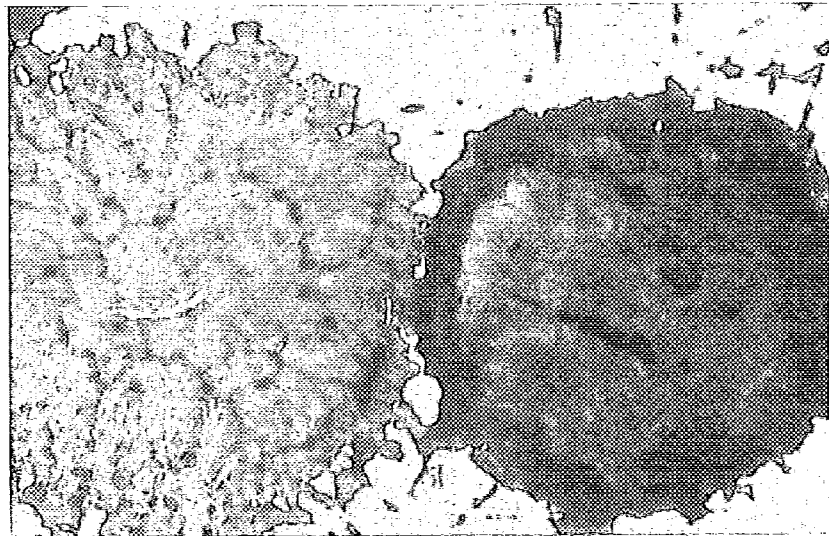


Fig. 4.2.2D — Recoiled metallic particles (2000 x)

a comparatively low heat content. Conversely, aluminum, iron, nickel, and copper have high heat content, and show more variation in the pattern of splats.

One aspect of this difference may be illustrated. Consider the case when all particles are molten on impact. Droplets of metals with high heat content will have pronounced splash effect, and the patterns will be broken up. Surface tension will have produced many small spheres, not connected if the layer is one particle in thickness. If the metal has low heat content, the drops will have frozen when the surface tension was at its maximum value, considering the flattened splat as a whole.

Sprayed coatings are generally examined metallographically in transverse or longitudinal sections through the thickness of the coating. In these sections, the most characteristic features of the deposit is the lamellae — the undulating contours of the individual sprayed particles. These particles, at the moment of impact, flatten out into elongated lenticular splats. Typical coatings applied in an air environment are a heterogenous mixture of sprayed material, oxide inclusions, and porosity (Fig. 4.2.2F). The deposit is bonded to the substrate by adhesive forces and to itself by cohesion.

A face view or the front of a sample taken parallel to the surface shows the structure to be an emulsification of oxides and round metallic flakes grouped in irregular superposition (Fig. 4.2.2G).

As-sprayed self-fluxing alloy coatings exhibit microstructure and properties similar to any typical thermally sprayed coating. It is only after heating to 1900° to 2200°F (1040° to 1200°C), that they assume their characteristic fused, homogenous appearance (Fig. 4.2.2H).

Generally, the grain orientation in as-sprayed deposits is determined by the heat flow pattern within the individual particles. Microstructural examination of thick, sprayed deposits reveals directionally oriented, columnar grains near the interface where rapid cooling occurs through the substrate.

Examination by scanning electron microscopy (SEM) has verified the light microscopy observations (Fig. 4.2.2I).

The columnar orientation gradually decreases as the thickness of the sprayed coating increases. The change from columnar to random grain morphology is believed to be produced by the effective lowering of the cooling rate, because of the evolved heat of fusion, which gives the grains time to reform and change shape.

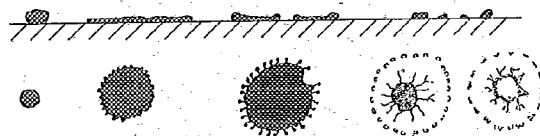


Fig. 4.2.2E—Splash forms of mercury on glass

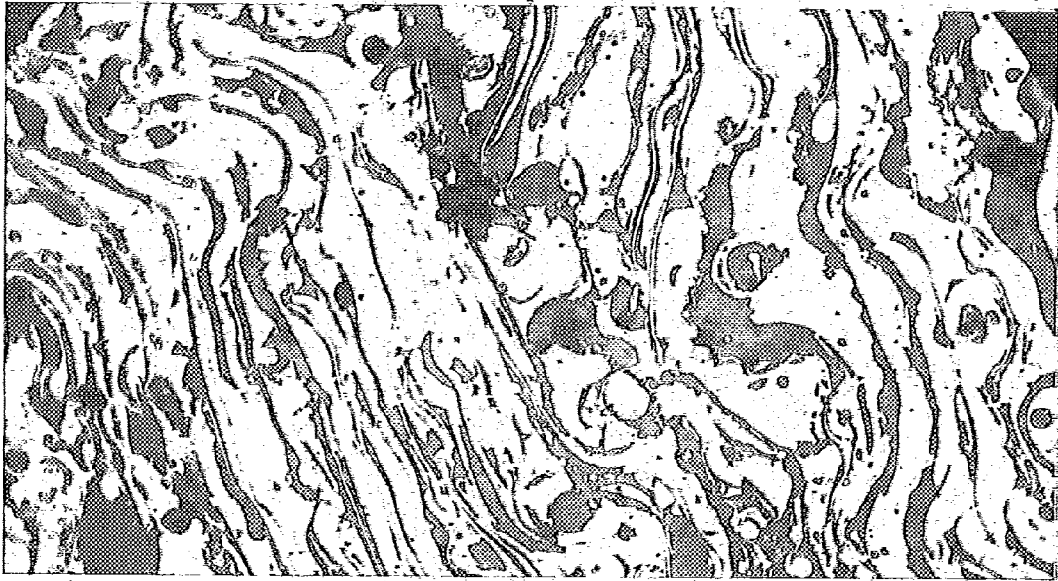


Fig. 4.2.2F — Transverse section through 0.8C (carbon) steel wire flame sprayed coating (250 x)

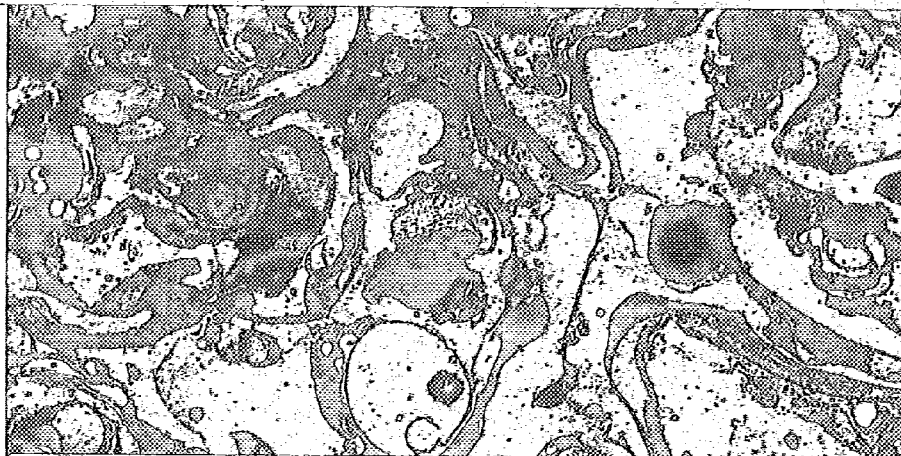
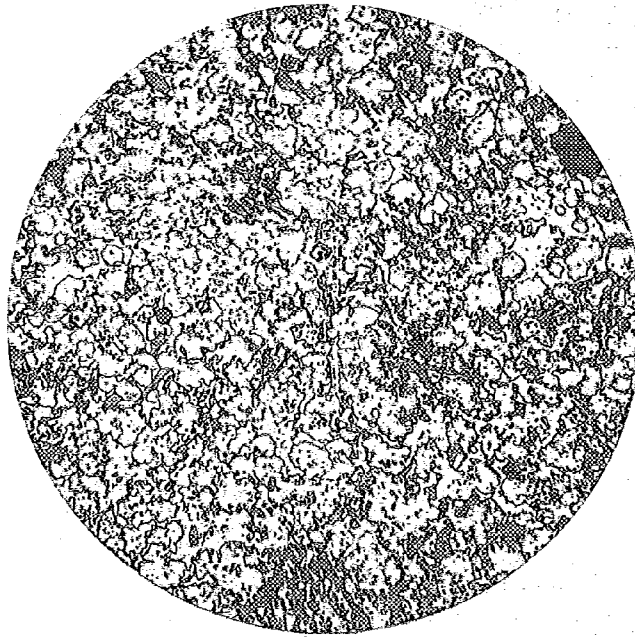


Fig. 4.2.2G Frontal section of 0.8C steel wire sprayed coating. Light areas are steel, gray areas are iron oxide, and black areas are voids (250 x)

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**Fig.4.2.2H — Fused NiCrBSi brazing alloy (250 x)
(Aerospace Materials Specification 4775)**



**Fig. 4.2.2I — Scanning electron micrograph of an
alumina plasma sprayed coating showing the
columnar structure**

4.2.3 Substrate Surface Influence on the Molten Particle. The substrate surface influences the formation of metastable phases in the fluid particle, resulting from rapid solidification of the molten particles. This will, to some extent, depend on substrate surface topography and on the influence of the surface on particle spreading at impact (i.e., wetting).

Transmission electron microscopy (TEM) has been utilized to determine the solidification morphology of particles as affected by the surface topography of the substrate. Because of the high kinetic energy of the molten particles, considerable liquid flow and radial sliding occur upon particle impact. Two different grain morphologies were observed. Figure 4.2.3 shows a schematic of the planar morphology of a solidified particle.

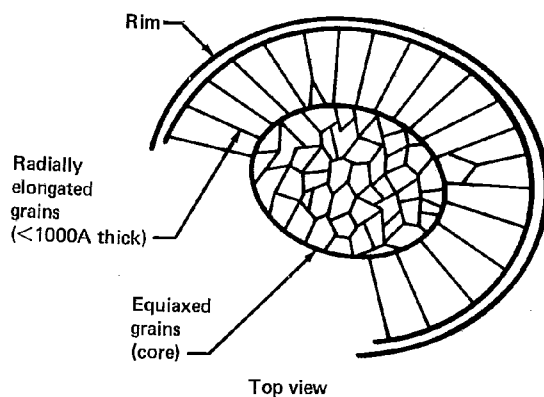


Fig. 4.2.3 — Planar morphology of a solidified particle

In the central core region, where the particle first comes into contact with the surface, heat is extracted through the substrate, and the solid-liquid interface moves away from the substrate. This area is generally too thick to be examined by TEM in the as-sprayed condition. However, in the peripheral areas, heat is not extracted through the substrate but rather back through the core region. This is indicated by the radially elongated grains which propagate from the core and terminate at the rim. Furthermore, the virtually defect free and regularly patterned grains suggest that these thin regions are not in full contact with the substrate. Similar arguments have been given for the splat quenching of metal alloys.

The assumption of one dimensional heat flow perpendicular to the substrate was shown to be unreasonable. TEM observations of plasma sprayed aluminum particles strongly support experimental results regarding heat flow parallel to the substrate in thin regions of the liquid-quenched particles.

This solidification process for the individual droplets appears common to virtually all observed microstructures in sprayed metals. Columnar grains can be found in

regions far from the substrate. Due to the limited liquid flow on the rough surfaces of the previously deposited layers, radially elongated grains are rarely observed in thick coatings. This is due to the high thermal conductivity of metals. In addition, thin regions under the impact of the subsequently arriving molten droplets probably recrystallize into randomly oriented grains.

The gradual transformation of the grains from highly oriented to larger, randomly shaped structures in metal coatings is attributed to several factors. Although these metals have very high thermal conductivity, they can resolidify and undergo rapid grain growth at relatively low temperatures. Therefore, substrate temperature and cooling rate are of great importance and should be controlled in order to deposit a more homogeneous metal coating.

Another feature of the rapid solidification in thermal spraying is the formation of structural defects, especially with copper, where significant twinning occurs. With liquid quenched aluminum, defects such as vacancy coagulation and dislocations are observed. However, the structure depends heavily on quench rate. Aluminum samples quenched from high temperatures, do not exhibit dislocation loops, clusters, or concentrations of dislocation and subgrain boundaries. This is important in TEM studies. Even when spray conditions are selected so that most particles are heated to barely above the melting point, some particles may be superheated to very high temperatures, $>2200^{\circ}\text{F}$ (1200°C).

In summary, a number of microstructural similarities are found between the liquid quenched metals formed by conventional techniques and those prepared by thermal spraying. For thin layers, or the first few layers of the thick deposits, the grain structure reveals rapid cooling rates essentially identical with those observed for amorphous cooling techniques. However, hot particles impinging onto the surface can result in annealing and recrystallization of the lamellae during spray deposition. For pure metals, such as aluminum and copper, annealing is rather extensive. Defect annihilation and grain reorientation, especially in thick layers, readily occur.

4.3 Coating Properties

The chief advantage of thermal spraying is the ability to tailor coating properties to suit the application. A particular material may be sprayed to form a hard or soft, porous or dense coating. This versatility presents difficulties when attempts are made to compare reported properties of coatings. These effects are compounded when different testing techniques are employed. The values presented in this section and Tables 4.3A, 4.3B, 4.3C, 4.3D, 4.3E, and 4.3F should, therefore, be regarded only as general information.

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Table 4.3A
Physical properties of ceramic rod coatings

Type of coating	Crystal form	Average bulk density (gm/cc)	Knoop microhardness	Porosity, percent
Aluminum oxide	Gamma type	3.3	2000	8 (7% open)
Barium zirconate	Cubic	5.25	--	10.0 (5.1% open)
Calcium zirconate	Cubic	4.414	--	5.7 (4.5% open)
Chromium oxide	Hexagonal	4.6	1900	4 (2% open)
Magnesium aluminate	Cubic	3.3	--	6 (4% open)
Magnesium zirconate	Cubic	4.52	--	4.8 (4.5% open)
Strontium zirconate	Orthorhombic	4.71	--	9.8 (7.8% open)
Zirconium oxide	Cubic	5.2	1000	8 (7% open)
Zirconium silicate	Cubic ZrO ₂ in siliceous glass	3.8	1000	8 (4% open)

Table 4.3B
Electrical properties of ceramic rod coatings

Type of coating	Electrical resistivity (Ohm-inch)	Dielectric strength, ac volts per 0.001 in.	Dielectric constant at 0°-600°F	Dissipation factor at 0°-600°F	Loss factor
Aluminum oxide	4.5 x 10 ⁶ @ 500°F 1.2 x 10 ⁵ @ 800°F	0.005 in. thk-160 0.010 in. thk-120 0.020 in. thk- 65 0.030 in. thk- 48+	10	.05	0.5
Barium zirconate	—	140	—	—	—
Calcium zirconate	—	70	—	—	—
Magnesium zirconate	—	150	—	—	—
Strontium zirconate	—	130	—	—	—
Zirconium oxide	2.7 x 10 ⁴ @ 500°F 2.1 x 10 ² @ 800°F	—	35	0.15	5.25
Zirconium silicate	1.1 x 10 ⁶ @ 500°F 4 x 10 ² @ 800°F	—	15	0.08	1.20

S.I. Soft Conversion
Table 4.3B
Electrical properties of ceramic rod coatings

Type of coating	Electrical resistivity (Ohm-meter)	Dielectric strength ac volts V/0.025 mm	Dielectric constant at -18° to 315°C	Dissipation factor at -18° to 315°C	Loss factor
Aluminum oxide	1.14 x 10 ⁵ @ 260°C 3.0 x 10 ³ @ 427°C	160 @ 0.13 mm thk 120 @ 0.25 mm thk 65 @ 0.51 mm thk 48 + @ 0.76 mm thk	10	0.05	0.5
Barium zirconate	—	140	—	—	—
Calcium zirconate	—	70	—	—	—
Magnesium zirconate	—	150	—	—	—
Strontium zirconate	—	130	—	—	—
Zirconium oxide	6.9 x 10 ³ @ 260°C 5.3 x 10 ² @ 427°C	—	35	0.15	5.25
Zirconium silicate	2.8 x 10 ⁴ @ 260°C 10 @ 427°C	—	15	0.08	1.20

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Table 4.3C
Thermal and chemical properties of ceramic rod coatings

Type of coating	Melt temp. °F	Mean specific heat Btu/lb/°F	Coefficient of expansion, in./in./°F	Conductivity, Btu/hr/ft ² in./°F (coating only)	Total emittance (200-1000°C)	Thermal shock resistance	Chemical composition, percent	Resistance to acids	Resistance to alkalis
Aluminum oxide	3600	.28 (90-3100°F)	4.1.10 ⁻⁶ (70-2250°F)	19 (1000-2000°F)	0.8-0.4 (200-1000°C)	Good	Pure aluminum oxide	Good	—
Barium zirconate	4870	—	3.5.10 ⁻⁶ (70-2012°F)	—	—	—	98.6 Al ₂ O ₃	—	Good (except hot)
Calcium zirconate	4245	—	4.6.10 ⁻⁶ (70-2012°F)	—	—	—	—	—	—
Chromite oxide	3000	.2 (60-2700°F)	5.0.10 ⁻⁶ (70-2000°F)	18 (est) (1000-2000°F)	0.8-0.9 (100-1200°C)	Moderate	85 Cr ₂ O ₃	Good (except HF)	Good (except hot)
Magnesium aluminum	3500	.25 (70-1832°F)	4.5.10 ⁻⁶ (70-2000°F)	18 (100-1200°C)	0.7-0.3 (100-1200°C)	Good	98 MgO-Al ₂ O ₃	Good (except HF)	Good (except hot)
Magnesium zirconate	3880	—	4.0.10 ⁻⁶ (70-2012°F)	—	—	—	—	—	—
Strontium zirconate	5070	—	4.7.10 ⁻⁶ (70-2012°F)	—	—	—	—	—	—
Zirconium oxide	4500	.175 (80-2550°F)	5.4.10 ⁻⁶ (70-2250°F)	8 (1000-2000°F)	0.7-0.3 (200-1000°C)	Very good	ZrO ₂ + 2% HfO ₂ + 3.5-5% CaO	Good (except HF)	Good
Zirconium silicate	3000	.15 est.	4.2.10 ⁻⁶ (70-1100°F)	15 (1000-2000°F)	0.7-0.3 (200-1000°C)	Good	65 ZrO ₂ 34 SiO ₂	Fair (except HF)	Good (except hot)

S. I. Soft Conversion
Table 4.3C
Thermal and chemical properties of ceramic rod coatings

Type of coating	Melt temp. °C	Mean specific heat J/(kg.K)	Coefficient of expansion, m/m °C	Conductivity, coating only W/(m.K)	Total emittance	Thermal shock resistance	Chemical composition, percent	Resistance to acids	Resistance to alkalis
Aluminum oxide	1982	0.067 (32-1700°C)	2.3.10 ⁻⁶ (21-1230°C)	2.7 (540-1090°C)	0.8-0.4 (200-1000°C)	Good	Pure aluminum oxide	Good	—
Barium zirconate	2688	—	1.9.10 ⁻⁶ (21-1100°C)	—	—	—	98.6 Al ₂ O ₃	—	Good (except hot)
Calcium zirconate	2340	—	2.6.10 ⁻⁶ (21-1100°C)	—	—	—	—	—	—
Chrome oxide	1649	0.048 (16-1480°C)	2.8.10 ⁻⁶ (21-1090°C)	2.6 (540-1090°C)	0.8-0.9 (100-1200°C)	Moderate	85 Cr ₂ O ₃	Good (except HF)	Good (except hot)
Magnesium aluminum	1927	0.06 (21-1000°C)	2.5.10 ⁻⁶ (21-1090°C)	2.6 (540-1090°C)	0.7-0.3 (100-1200°C)	Good	98 MgO-Al ₂ O ₃	Good (except HF)	Good (except hot)
Magnesium zirconate	2138	—	2.2.10 ⁻⁶ (21-1100°C)	—	—	—	—	—	—
Strontium zirconate	2799	—	2.6.10 ⁻⁶ (21-1100°C)	—	—	—	—	—	—
Zirconium oxide	2482	0.042 (27-1400°C)	2.7.10 ⁻⁶ (21-1230°C)	1.15 (540-1090°C)	0.7-0.3 (200-1000°C)	Very good	ZrO ₂ + 2% HfO ₂ + 3.5-5% CaO	Good	Good
Zirconium silicate	1648	0.04 est.	2.3.10 ⁻⁶ (21-590°C)	2.2 (540-1090°C)	0.7-0.3 (200-1000°C)	Good	65 ZrO ₂ 34 SiO ₂	Fair (except HF)	Good (except hot)

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Table 4.3D
Mechanical properties of ceramic rod coatings

Type of coating	Compressive strength at ambient temperature		Adherence to steel (approx.)		Minimum profilometer surface finish AA range	Coefficient of friction	Strain % elongation per unit of lgth. (0.020 in. thk. coat)
	ksi	(MPa)	psi	(MPa)			
Aluminum oxide	37	(255)	1000	(6.89)	****	0.10**	0.7
Barium zirconate	—	—	1153	(9.5)	—	—	—
Calcium zirconate	—	—	1125	(7.76)	—	—	—
Chrome oxide	105	(724)	—	—	****	0.11***	1.3
Magnesium aluminate	—	—	—	—	****	—	—
Magnesium zirconate	—	—	1000	(6.89)	—	—	—
Strontium zirconate	—	—	1129	(7.78)	—	—	—
Zirconium oxide	21	(145)	1000*	(6.89)	****	0.10**	1.4
Zirconium silicate	—	—	1000*	(6.89)	****	0.10**	0.7

Notes:

* Nonferrous substrate 600 psi (4KPa)

** Against 440 stainless steel

*** Against brass

**** As coated 200-300 μ in. (5.1-7.6 nm)As ground 50- 60 μ in. (760-1270 μ m)As lapped 25- 45 μ in. (435-1143 μ m)

Table 4.3E
Specific gravity of flame sprayed wire coatings

Metal	Specific gravity weight relative to water
Aluminum	
2.35	
Aluminum 12% silicon	2.32
Aluminum 5% magnesium	2.32
Copper	7.56
Copper 10 aluminum	6.92
Copper 10 zinc	7.57
Copper 40 zinc	7.38
Copper 42 zinc	7.41
Copper 30 zinc	7.45
Copper 5 tin	7.65
Iron	6.50
Lead	10.00
Magnesium	1.52
Molybdenum	9.05
Nickel	7.58
Nickel 20 chromium	7.28
Silver	9.10
Steel 0.1 chromium or carbon	6.67
Steel 0.25 carbon	6.77
Steel 0.40 carbon	6.94
Steel 0.80 carbon	6.35
Steel 1.20 carbon	6.74
Steel 18 Nickel 8 chromium	6.98
Tin	6.83
Zinc	6.35

4.3.1 Visual. As-sprayed coatings present a dull matte finish. In some instances, the surfaces are rougher than the original grit blasted surface. Profilometer measurements taken on these surfaces range from less than 100 to greater than 1500 μ in. (2.5 to 38 μ m). High energy plasma and detonation sprayed coatings will average 60 to 90 μ in. (1.5 to 2.2 μ m) AA; standard plasma coatings range from 100 to 500 μ in. (2.5 to 12.5 μ m) AA. This is dependent on the size of the powder, in that fine powder yields a smoother coating than one produced from coarse powder. Wire and rod coatings are coarser, with typical values of 300 to 1000 μ in. (7.5 to 25 μ m) AA. Coatings applied by powder flame spraying, especially those applied for gas path seals, have been measured in excess of 1000 μ in. (25 μ m) AA with some readings exceeding 1500 μ in. (38 μ m) AA. This roughness is typical of a porous and loose structure. The arc gun, when operated at low atomizing pressures, can produce coating roughness profiles as great as 1/8 in. (3.2 mm).

4.3.2 Tensile Strength. The tensile strength of a thermal sprayed deposit consists of the bond between the deposit and the substrate (adhesion) and interparticle attraction (cohesion).

The adhesion of the coating to the substrate is the relationship of particle to surface interactions. The bonding mechanisms fall into three categories: mechanical, metallurgical-chemical, and physical. The adhesion is a combination of all three mechanisms. A molten particle

Table 4.3F
Typical mechanical properties of plasma
sprayed coatings*

Material	Bond tensile strength	Hardness		Density	
	psi (MPa)*	macro/micro	Rockwell	lb/ft ³	(g/cc)
Pure metals					
Aluminum	1200 (8.3)	R _H	45/58	155	(2.48)
Copper	3100 (21.4)	R _B	65/142	449	(7.20)
Molybdenum (fine)	8300 (57.2)	R _{15N}	70/1450	618	(9.90)
Molybdenum (coarse)	8000 (55.2)	R _A	65/1448	559	(8.96)
Nickel (fine)	3400 (23.4)	R _{15T}	84/--	496	(7.95)
Nickel (coarse)	4800 (33.1)	R _{15T}	81/--	467	(7.48)
Niobium	7900 (54.5)	R _C	61/1344	441	(7.06)
Tantalum	6800 (46.9)	R _A	65/1585	883	(14.15)
Titanium	6000 (41.4)	R _{15N}	78/	260	(4.17)
Tungsten	5800 (40.0)	R _A	50/500	1055	(16.90)
Alloy metals					
304 Stainless	2550 (17.6)	R _{15T}	88/--	451	(7.22)
316 Stainless	3400 (23.4)	R _{30T}	70/--	425	(6.80)
431 Stainless	4500 (31.0)	R _C	35/--	390	(6.25)
80Ni 20Cr (fine)	4500 (31.0)	R ₁₅	90/--	467	(7.48)
80Ni 20Cr (coarse)	4200 (29.0)	R _{15T}	90/--	449	(7.19)
40Ni 60Cu	3500 (24.1)	R _B	72/--	493	(7.89)
35Ni 5In 60Cu	3500 (24.1)	R _{15T}	83/--	496	(7.94)
10A1 90Cu (fine)	4100 (28.3)	R _{15T}	88/--	418	(6.73)
10A1 90Cu (coarse)	3200 (22.1)	R _{15T}	81/--	393	(6.30)
Hastelloy 31 (fine)	6000 (41.4)	R _{15T}	79/--	478	(7.65)
Hastelloy 31 (coarse)	3400 (23.4)	R _{15T}	79/--	489	(7.83)
5A1 95Ni	9900 (68.3)	R _B	80/490	469	(7.51)
20A1 80Ni	6900 (47.6)	R _B	80/510	432	(6.92)
6A1 19Cr 75Ni	7200 (49.6)	R _B	90/250	469	(7.51)
12Si 88A1	2400 (16.5)	R _{15T}	78/60	155	(2.49)
5A1 5Mo 90Ni	5500 (37.9)	R _B	80/200	464	(7.43)
Hastelloy X	6200 (42.7)	R _{15T}	89/--	478	(7.65)
Hastelloy C	6100 (42.1)	R _{15T}	90/--	515	(8.25)
420 Stainless	3200 (22.1)	R _{15N}	70/--	443	(7.10)
0.9C Steel	4900 (33.8)	R _C	35/--	440	(7.05)
Cast Iron	5200 (35.9)	R _C	28/--	437	(7.00)
Ti 6A1 4V	4800 (33.1)	R _C	35/--	268	(4.30)
Monel	6500 (44.8)	R _{15N}	35/--	531	(8.50)
0.2 C Steel	3200 (22.1)	R _B	95/--	431	(6.90)
Metal composites					
95Ni 5A1	4900 (33.8)	R _{15T}	80/500	461	(7.39)
80Ni 20A1	4700 (32.4)	R _{15T}	86/500	438	(7.02)
65Ni 35Ti	4650 (32.1)	R _{15N}	72/660	413	(6.62)
75Ni 19Cr 6A1	6200 (42.7)	R _{15T}	92/250	481	(7.71)
75Ni 9Cr 7A1 5Mo 5Fe	4000 (27.6)	R _B	80/250	431	(6.90)
90Ni 5A1 5Mo	7000 (48.3)	R _B	80/200	462	(7.40)
Carbide powders & blends					
88WC 12Co (cast, fine)	6500 (44.8)	R _{15N}	88/--	858	(13.75)
88WC 12Co (cast, coarse)	6500 (44.8)	R _{15N}	81/--	775	(12.41)
88WC 12Co (sintered)	8000 (55.2)	R _{15N}	85/--	908	(14.55)
83WC 17Co	10000 (68.9)	R _{15N}	85/950	693	(11.10)
75Cr ₃ C ₂ 25NiCr (fine)	6000 (41.4)	R _{15N}	84/950	400	(6.41)
75Cr ₃ C ₂ 25NiCr (coarse)	5000 (34.5)	R _{15N}	80/1850	389	(6.23)
75Cr ₃ C ₂ 25NiCr (composite)	—	R _{15N}	--/1850	—	—
85Cr ₃ C ₂ 15NiCr	—	R _{15N}	80/1850	362	(5.80)

(Continued)

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Table 4.3F (continued)

Material	Bond tensile strength	Hardness		Density	
	psi (MPa)*	macro/micro	Rockwell	lb/ft ³	(g/cc)
Ceramic oxides					
Zirconia (calcinated)	6500 (44.8)	R ₁₅ N	70/--	331	(5.30)
Chromium Oxide	6500 (44.8)	R ₁₅ N	90/--	300	(4.80)
80 Zirconia 20 Yttria	2200 (15.2)	R ₁₅ N	80/--	312	(5.00)
Titanium Oxide	—	R ₁₅ N	87/--	256	(4.10)
Aluminum Oxide (white)	6500 (44.8)	—	—	—	—
87 Alumina 13 Titania	2250 (15.5)	R ₁₅ N	90/--	218	(3.50)
60 Alumina 40 Titania	4000 (27.6)	R ₁₅ N	90/850	218	(3.50)
50 Alumina 50 Titania	—	R ₁₅ N	85/--	250	(4.0)
Alumina-Grey (fine)	1000 (6.9)	R ₁₅ N	87/--	187	(3.30)
Alumina-Grey (coarse)	—	R ₁₅ N	85/--	187	(3.30)
Magnesium Zirconate	2500 (17.2)	R ₁₅ N	75/--	262	(4.20)

Note:

*Over a grit blasted surface roughened to 100 to 160 μ in. (2.5 to 4.1 μ m) AA.

impinging on a suitably prepared surface will flatten and conform to the undulating surface, and mechanically key itself to the asperities thereon. When diffusion or alloying occurs, including the formation of intermetallic compounds and solid solutions, the adhesion mechanism is metallurgical-chemical. The particle adhesion to the substrate by van der Waals forces or secondary valence bonds is physical bonding.

Particle to substrate adhesion is generally mechanical and emphasizes the importance of proper surface preparation to achieve bonding.

Self-bonding materials (molybdenum, columbium, tantalum, nickel-aluminum alloys, and nickel aluminum composites) exhibit bond strengths in excess of 2500 psi (17.2 MPa). For this reason, they are used as bond coats for subsequent coatings. The overall adhesion of the system is improved. The adhesion of self-bonding materials occurs as localized fusion and alloying with the substrate. The heat of reaction comes from the striking molten particle. The degree of fusion-diffusion is governed by the particle quench rate.

Zones of interaction are located primarily at the center of the particle or that portion containing the greatest mass.

Cohesive bonding, that is particle to particle bonding, operates on the same principles governing particle to substrate adhesion. For adhesive bonding, the mating relies on particle characteristics such as mass, quench rate, and heat content.

4.3.3 Residual Stress. As in other types of deposits, thermal sprayed coatings contain residual stresses that result from contraction during cooling and solidification. They can cause cracking and spalling (separation).

Residual stresses are stresses existing within a body not resulting from external forces. They exist either as micro forces acting within the structural elements ("textural" stresses) or as forces affecting the mass ("body" stresses). Both forms are often interrelated, although from a practical standpoint, only mass effects are of direct interest to the user. The magnitude of the stresses depends upon the coefficient of thermal expansion of the coating material. Thin coatings seldom cause residual stress problems, but thick deposits having coatings with high coefficients of expansion may cause problems.

Methods which reduce residual tensile stress in the coating, and hence reduce shear stress on the bond are

- (1) expanding the substrate before spraying, by preheating
- (2) selecting a coating material with low shrinkage properties
- (3) macroroughening (3.5) to limit the magnitude of stresses
- (4) building up part way with a low shrinkage material

When a sprayed coating is applied to only one side of a thin plate, the tensile forces in the deposit produce compressive forces in the underlying metal near the interface. These forces cause concave deformation of the plate. To some extent, this relieves the tensile stresses in the deposit, but the remaining stresses are still predominantly tensile. Greater distortion occurs in deposits which have been separated from their supporting plates, since the deposit is then free from restraint at the interface. Deformation of the mass occurs until finally the tensile stresses developed in the inner layers are equal to those in the outer layers.

Coating tensile stresses occur through the contraction of individual particles as they solidify on the substrate. Momentarily, the molten particles are in intimate contact with cooled solid particles. They all contract in the same proportion, but in the time pause between depositions, an accumulation of tensile forces arises. In a bimetallic strip, longitudinal compressive and tensile forces are in equilibrium so long as the strip is free to deflect. In sprayed coatings, however, the deposit is entirely under tensile stress.

Contraction stresses due to thermal variations result in dimensional changes and are largely responsible for residual stresses set up in casting and fusion welds. Thermal spraying is a related process, and its products are similarly affected.

The interface is subject to shearing stresses. For a given adhesion strength, only a tensile force up to the bond strength can be tolerated in the coating; otherwise, failure of the bond results. This limits the maximum thickness of any deposit, since the tensile force is proportional to the deposit thickness.

4.3.4 Hardness. Thermal spray coatings possess a heterogeneous structure consisting of the coating material, oxides and voids. As a result, the macrohardness values are less than those of equivalent material in either a cast or a wrought form.

The hardness of sprayed deposits are determined by macro or micro hardness tests. Macrohardness is a measurement of the resistance of the total deposit to

penetration, and is measured with either the Brinell or the Rockwell hardness test. The hardness of individual particles is measured by a microhardness test. Under light loads of 50 to 100 grams, a Knoop hardness impression may be confined to a single particle, as shown in Fig. 4.3.4. Values are reported as KHN.

A standard diamond pyramid (Vickers) is also frequently used for microhardness determination, especially for tungsten carbide coatings, with a 300 gram load. The values are expressed as DPH_{300} .

Macrohardness values are not a true indication of the coating hardness but are a general indication of coating quality for a given material. The hardest coating in a trial spray run often indicates application by optimum conditions. However, in the case of metal coatings, high hardness may indicate a very oxidized coating.

In addition to indentation hardness tests, scratch hardness testing of sprayed coatings is also utilized. Scratch hardness testing of abrasion clearance control coatings is a measure of their resistance to rubbing. The wider and deeper a scratch, the more abrasion is a deposit.

4.3.5 Compression. Thermal sprayed coatings possess compressive strengths greater than their tensile strengths, often from three to four times greater than the ultimate cohesive tensile strengths. Compressive strength is an important property when considering bearing loads on shafts, flanges, and rabbet diameters. The compressive strengths of several ceramic materials are listed in Table 4.3D. Operating environments, especially temperatures, should



Fig. 4.3.4 — Rhomboidal Knoop indentation (arrow) in electric arc sprayed Ni₃Al

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always be considered. High temperature usage coupled with load will cause plastic flow and consequently dimensional loss.

Thin coatings are better suited to transmit compressive loads than thick deposits. Spray coatings do not fracture when suddenly subjected to compression loading.

4.3.6 Wear Resistance. Thermal spray coatings are used to increase the wear resistance of soft or worn substrates. Types of wear, the deterioration of a surface through use, include (1) erosion through gas flow or solid particle impingement, (2) non-intended motion or fretting wear, (3) sliding wear, (4) combined impact-sliding wear, (5) cavitation, and (6) galling.

There are many tests for evaluating wear including Alpha LFW-1, Falex, Tabor, (Reference¹ ASTM Sections 5 and 15) simulated service tests, and others. The test results are useful as a guide in coating selection, since various factors have to be individually selected and evaluated. Simulated service results are limited in practical application, because there may be other critical factors in actual service. In defining the wear characteristics of thermal sprayed deposits, it is necessary to define the service environment.

Sprayed coatings are generally more wear resistant than the parent material in wrought or cast form. This is attributed to particle quench rate, resulting structure, porosity, and in the case of metallic coatings, oxide content. Porosity in a coating enables it to maintain a film of lubricant. An advantage of porosity is to contain debris generated during wearing, thus exposing clean contact surfaces.

4.3.7 Fatigue. Limited specific data exist concerning the endurance limits of sprayed coatings. Sprayed coatings should not be used under tensile loading or under bending flexing motion. The laminar structure of the product and its inherent propensity is sensitive to crack propagation when exposed to these conditions.

Substrate preparation for a thermal spray deposit affects the fatigue properties of the coating. Grit blasting or intentional roughening of a smoothly machined surface will lower the endurance limit of aluminum, iron, nickel, cobalt and nickel alloys in low cycle fatigue (LCF) and high cycle fatigue (HCF). The loss will depend upon

the degree and severity of roughening. However, the effects of roughening can be offset by shot peening prior to blasting.

All self bonding materials, such as molybdenum, tantalum, columbium, nickel-aluminum alloys, and composites, significantly reduce both the low and high cycle fatigue life of high strength alloys. Similar reductions in endurance limit may be expected with carbide coatings produced by the detonation or high energy plasma processes. Loss in fatigue properties is attributed to fusion or diffusion of the coating particles with the substrate. Each point of attachment is a minute notch from which cracking can propagate. The substrate surface is blanketed with notches, any of which may initiate a crack under the proper conditions. Finish grinding of the spray coating does not significantly improve fatigue life of as-sprayed coatings.

4.3.8 Ductility. The ductility of metallic thermal spray coatings is slightly better than cast iron, but less than most cast metal structures. This is related to the mechanical bond of each sprayed and unfused layer and to the cohesion strength between particles. Once the cohesive bond between particles is broken, the coating will disintegrate and fail. The ductility of sprayed coatings rarely exceeds 2%.

4.3.9 Corrosion Resistance. Corrosion protection of iron and steel is an important use of thermal spray coatings. There are guidelines which the trained, knowledgeable applicator follows. These are based upon experience, asking the right questions, and a familiarity with the theories of chemistry and electro-chemistry. Section 5.7.3 and AWS publication C2.14-74, *Corrosion Tests of Flame-Sprayed Coated Steel, 19-year Report*, contains additional information.

4.4 Coatings Produced Under Controlled Atmospheres

Arc or plasma generators may be operated with an inert gas shroud or in an inert gas chamber.

Shielding of the spray cone by an inert gas shroud significantly decreases oxygen, nitrogen, or hydrogen contamination while providing higher particle temperatures and velocities for better bond strengths. Microscopic examination reveals shrouded coatings strongly resemble those applied in the air; there is an accumulation of residual stresses.

1. Standard tests for wear and wear life may be found in the *Annual Book of ASTM Standards*, Section 5 and 15, published by the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

For a controlled spray environment, atmospheric chambers are utilized. The chambers are evacuated to a pressure of less than 20 Torr (2.7 kPa) and then back-filled with an inert gas to a specific pressure under which the spraying is to be done. After the chamber has been evacuated and back-filled with inert gas, the only gases entering the system are the plasma and the atomizing gases that are usually inert. The workpiece can be heated without dangers of oxidation, and the substrate surface will not be contaminated. The resulting nascent surface substantially enhances coating adherence (Fig. 4.4A).

Lack of intersplat oxides improves particle-to-particle cohesion and overall coating density. Porosity in as-sprayed metallic overlays is usually less than 1%. This is true even in coatings that are applied at impingement angles of 45 degrees or less.

The operation of a plasma or arc gun in a low pressure environment permits attainment of higher temperatures at the workpiece, without detrimental oxidation. The lengthened effluent produces longer residence times for the spray particles. A greater percentage of particles are plasticized and deposited onto the substrate surface. Elevated substrate preheat temperatures reduce particle rebounding, and promote wetting by the impinging powdered materials.

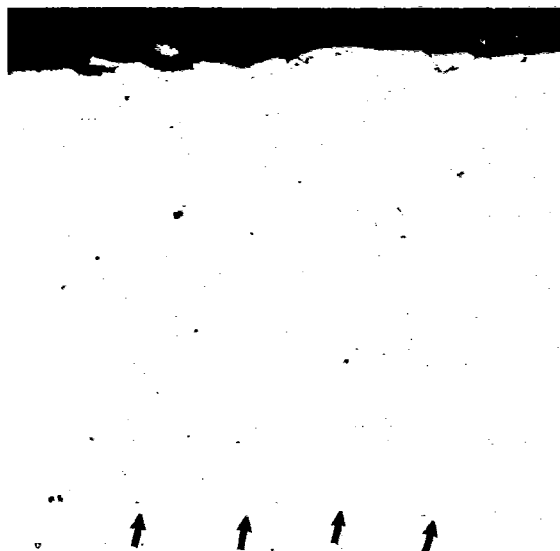


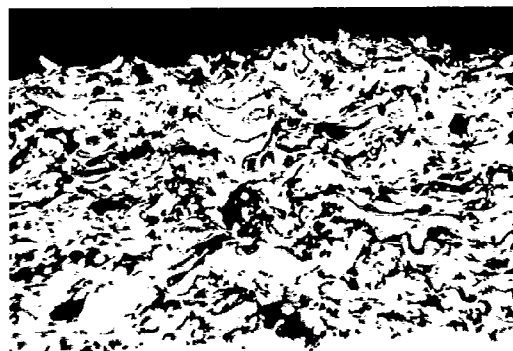
Fig. 4.4A — Metallic coating as applied utilizing the low pressure plasma coating process. Note intimate coating to substrate interface (arrows) (500 x)

The effluent velocities are much greater in vacuum than in an air environment or one atmosphere inert gas environment. Since the gas stream is moving at high speeds, exceeding 3000 fps (900m/s), it may be concluded that the entrained particles will travel at rates greater than during atmospheric pressure spraying. Oxide-free splats, deposited at high velocities, wet and flatten to a higher degree than those applied at atmospheric pressure. This also increases process density.

The low pressure spraying process deposits coatings with low stress levels. It also permits the fabrication of free standing structures suitable for engineering components, such as those used in gas turbines.

The chemical integrity of coatings applied under partial pressures has been found to be equal to the input material. Elemental losses were not readily evident, nor was the formation of oxides, nitrides or hydrides. Metallographic examination of these metallic coatings reveals a homogeneous, relatively pore free and oxide free, coalescent structure (Fig. 4.4B).

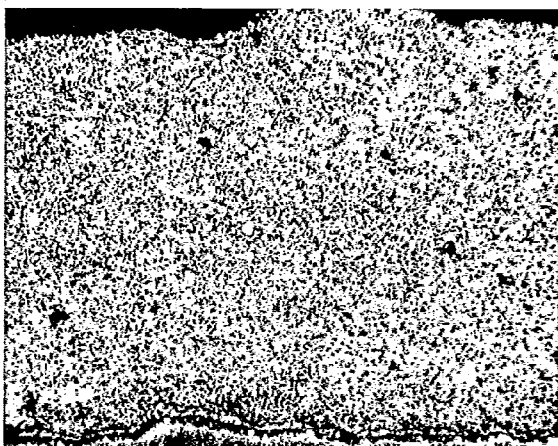
The intersplat oxide lattice normally obtained in the lamellar structure, typical of air or gas shrouded deposits, is absent. The interface is clean and void of oxides or residual surface preparation media. This is akin to evaporative Physical Vapor Deposited (PVD) coatings, but without the columnar structure and leaders often observed in those overlays (Fig. 4.4C). Similar coatings have been obtained utilizing the arc spray process operating in a controlled argon atmosphere.



Cobalt, chromium, aluminum, yttrium deposit plasma sprayed in air

Fig. 4.4B — Plasma Sprayed Deposit

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Same material applied under partial pressure conditions. Note absence of oxide stringers and overall coating homogeneity

Fig. 4.4B (continued)—Plasma Sprayed Deposit

Leaders



Fig. 4.4C — Typical metallic coating material as applied by the EB vacuum evaporative (PVD) process. Note numerous, deep leaders

Chapter 5

Coating Selection and Application

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- 5.3.2 Circuits, Panels, and Switches
- 5.3.3 Shielding
- 5.3.4 Electronics

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5.5 Reclamation

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5.7 Environment

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Chapter 5

Coating Selection and Application

5.1 Introduction

The selection of a proper coating material involves more than choosing the desired properties of a deposit. It should be approached as an engineering problem by considering items such as coating function and service environment, in addition to the physical and chemical properties of both the coating and the substrate. Choosing a thermal spray material for an application is more complex than selecting a wrought or cast material for the same application. The properties of conventional materials are well understood, and their service performance is predictable. This is not true of thermal spray coatings. The mechanical and corrosion resistant properties of sprayed materials differ from solid or powder metal parts of the same chemistry (see Chapter 4).

The total operational environment should be evaluated prior to choosing a candidate material. Although the primary function of a coating may be wear protection, the operating temperature, and service environment — such as corrosive media — should all be taken into account. Coating material selection should be based on properties and related to end use and service environment, plus factors involving its compatibility with the substrate.

It is not difficult to select the proper coating for a given function after all the pertinent factors are taken into consideration.

Information is presented in two forms: (1) the broad function of coatings, and (2) a study of applications. Bond coat materials and applications are discussed according to their basic function (mechanism). This is followed by an extensive listing of materials (powders, wires, and rods) classified according to well known metallurgical definitions and modified by thermal spray industry requirements. Each material is coded for cross referencing to a listing of applications. Applications (case histories) are treated primarily by function and, where appropriate, by industry. For each application, the working thermal spray coating is called out by code number and a generic description.

5.2 Bonding (see 3.8)

Predominantly successful bonding agents are refractory metals such as molybdenum, columbium, tantalum, nickel-aluminum composites, and nickel-aluminum, nickel-chromium, and aluminum-bronze alloys (see Table 5.2). Bond coats are thin [.003 to .007 in. (.08 to .18 mm)], with the overlay coating material comprising the bulk of the deposit. They have the ability to adhere to smooth substrates by metallurgical and mechanical interaction. This is called *self-bonding*, and grit blasting is not required for adhesion. However, industry practice is to grit blast or otherwise roughen the substrate, where practical, for good bond strength and integrity.

Table 5.2
Commonly used bonding materials and method of application

Bond coating	Powder flame spray	Powder plasma spray	Wire arc	Wire flame spray
Molybdenum		X		X
Columbium		X		
Tantalum		X		
80/20 Nickel/Aluminum	X	X	X	X
83/17 Nickel/Aluminum	X		X	X
95/5 Nickel/Aluminum	X	X	X	X
Nickel Chromium Aluminum		X	X	X
80/20 Nickel Chromium			X	X
Aluminum Bronze	X	X	X	
90/5/5 Ni/Al/Mo	X	X		

5.3 Electrical Applications

Thermal spray deposits are used extensively in the electrical industry for a number of applications including electrically conductive coatings and resistance type heating circuits.

5.3.1 Condensers, Resistors, and Brushes. One application is the production of electrolytic condensers. Automatic wire flame spray equipment is used to apply aluminum onto a gauze-like fabric. Special air caps are employed to provide uniform spray patterns at high velocities.

Carbon and ceramic resistors and carbon brushes are sprayed with a thin film of copper to provide an electrical connection of high conductivity. Pigtailed may be soldered to the copper layers on the carbon brushes. Ceramic resistors are also coated. Surface preparation is unnecessary, because the copper particles readily adhere to the relatively porous surface of the carbon or ceramic parts.

5.3.2 Circuits, Panels, and Switches. Thermal spraying is a useful method of producing thick film electrical circuits. These circuits can carry higher currents than the printed type, yet are more flexible than stampings. Circuits are produced by spraying the metal onto a nonconductive substrate — usually plastic, ceramic, or glass. The bond to plastics is obtained by grit blasting the surface. Unglazed ceramics are sprayed without surface preparation. The circuit patterns are produced by spraying through masks and etching away unwanted material afterward, or by molding the patterns into the plastic. After the entire surface has been coated, the molded circuits are revealed by grinding away the excess coating to the plastic substrate.

The most commonly used metals for thick film applications are copper, aluminum, zinc, and silver. Materials which may make thermal spraying even more attractive to the electrical industry are being developed for stable resistors, capacitors, and inductors. Heater panels have been produced by spraying onto thermally treated glass. Aluminum is the preferred metal for use on glass. Silver is used in the contact areas of large knife switches to provide good electrical contact.

5.3.3 Shielding. Shielding material is used to eliminate electromagnetic and radio frequency interference (EMI/RFI) and to dissipate static discharge sparks. Applications include computer terminals, electronic office equipment, medical monitoring devices, and sensitive electronic equipment. Housings constructed of temperature sensitive plastics do not offer shielding. Zinc coatings provide protection, are inexpensive, and easily applied. Adhe-

sion is excellent, as is electrical conductivity, which provides high levels of attenuation in the range of 60-120 dB.

5.3.4 Electronics. In electronic applications that require wear resistance with a high dielectric factor, pure aluminum oxide is applied by wire flame spraying.

5.4 Antifretting and Wear

Wear may be caused by fretting, sliding, impact, abrasion, erosion, and other service conditions. Consequently, wear resistant coatings are generally hard and exhibit resistance to heat and chemical attack. The self-fluxing alloys of iron, nickel, or cobalt, discussed in other sections of this manual, offer such properties. When the substrate cannot tolerate high fusing temperatures, carbides, ceramics, and Laves phase alloys (cobalt and molybdenum based) offer excellent protection.

Laves phase is a "size factor compound" where one atom is 20 to 30% smaller than the other, enabling them to pack together in crystal structures more efficiently than if they were the same size.

Tungsten carbides are best used at temperatures less than 900°F (480°C). Between 900°F (480°C) and 1200°F (650°C), titanium carbide and chromium carbide are preferred. Above 1200°F (650°C), chromium carbide or ceramics are best. Laves phase alloys may be used to resist both fretting and sliding wear at temperatures to 1800°F (980°C). Highly lubricious materials, such as aluminum bronze, copper-nickel-indium, and even polyesters, afford resistance to fretting type wear. High carbon steels, cast iron, martensitic stainless steels, molybdenum, nickel chromium alloys, and other materials have been utilized to protect against sliding wear. In any situation where protection is required, it is best to select a material and evaluate it under actual service conditions prior to committing a large quantity of parts. See the applications chart for case histories and coating recommendations in this chapter.

5.5 Reclamation

Thermal spraying is a cost effective means for dimensional restoration. Whether the component is undersize due to service induced wear or manufacturing errors, new surfaces may be provided without the distortion of welding or the expense of special plating techniques. Furthermore, the new surface may be constructed from wear or corrosion resistant materials, or even the same material as the base metal.

5.5.1 Applications. Typical applications include machine shafts and spindles, rotating and reciprocating

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shafts, automotive and machine crankshafts, roller faces and journals, hydraulic rams, dryer drums for paper making, pump plungers, sleeves, and impeller blades and housings for chemical and petrochemical industries.

5.5.2 Wear. The coatings required to combat wear or corrosion, or both, will include carbon steel, stainless steel, nickel-chromium steels, low alloy steels, nickel, bronze, and other alloys. The mating diameters of components such as bores for roller races and fly wheels, which require shrink or interference fits, may be sprayed with steel, nickel-aluminum, or molybdenum.

While molybdenum coatings are not recommended for use with the arc spray process, most other iron and nickel based wire arc coatings are suitable for machine element reclamation, when chosen for the excellent adhesion and high cohesive strength of the coating.

The carbon steel tubes that form a wall in coal fired power plant boilers are subject to fireside corrosion, sometimes coupled with abrasion or erosion, or both. Thermal spray coatings applied to a nominal thickness of 0.030 in. (0.75 mm) are considered to be effective in protecting water walls, slope tubes, economizers, superheaters, and cyclones from fireside wastage. Coatings selected for use in coal fired boilers should combine self bonding, high density, high bond strength, technique independence, and the ability to apply a new coating over an old one.

Spray coatings allow restoration of worn, steam heated drums used in the drying of paper. Before the original wall thickness is reduced to where lower steam pressure is necessary, restoration can be performed. Coatings of 400 series stainless steel have successfully provided bond strength and wear resistance, with moderate loss in thermal conductivity. Pulp and paper mills have achieved improvements in both production and quality through use of such coatings.

5.6 Clearance Control Coatings

5.6.1 Abradables. Abradable coatings wear preferentially when contact is made with the mating part. This makes it possible for the mating elements to establish the necessary clearances automatically, providing optimum seals. Abradable or sacrificial materials have been successfully employed to reduce the rotor to shroud clearance for aircraft engine applications. The coating is sacrificial in the event of an incursion by an opposing member, and the abradable material will be rubbed away. A series of sprayed abradable coatings have been developed for sealing the gas path areas of jet engines. Significant improvements in efficiency have been achieved when these materials are applied to the outer air seal locations, be-

tween compressor or turbine blade tips and the metallic superstructure or shrouds. Sacrificial materials are also used in the labyrinth seal locations, where they are used to channel cooling air, to minimize loss of pressurized air from the engine, and to maintain a pressure balance on the rotor shaft.

Pure aluminum flame spray coatings were initially used for clearance control applications in the high pressure compressor. Today, high technology abradable coatings consist of two powders blended or agglomerated and applied using the combustion or plasma spray processes. A common abradable coating consists of a metal matrix and a nonmetallic filler such as graphite, polyester, polyimide, boron nitride, or a friable mineral. The filler serves to weaken the integrity of the matrix and thereby enhance abrasability.

Plasma and flame sprayed abradables are applied directly onto aircraft engine hardware. By eliminating the need for a secondary brazing operation, the sprayed abradables are economical in both initial engine manufacture and overhaul.

5.6.2 Abrasives. Gas path seals of the type used in aircraft engines are meant to be sacrificial when rubbed by rotating components such as compressor and turbine blades or labyrinth seal teeth. In areas of high erosion, potential clearance control coatings of high integrity are required. These erosion-resistant coatings often result in rotor wear. To solve this problem, abrasive, wear resistant coatings are applied to blade tips and labyrinth seal teeth. Coatings recommended for this application include alumina, alumina titania, nickel-aluminum cermet, and an 80% nickel 20% chromium alloy blended with chromium carbide.

5.7 Environment

5.7.1 Thermal Barrier Coatings. Thermal barrier coatings (TBC), which are usually used on diesel engine pistons, gas turbine combustion chambers, vanes, and flame holders, are generally two component systems consisting of a metallic layer overcoated with a ceramic material or mixture. These coatings protect base metals from high operating temperatures, thus allowing more efficient operation of the machinery. They lower the operating temperature of the base metal from 50° to 150°F (10° to 65°C).

Typically, thermal barrier coatings are duplex or triplex layered. Duplex coatings consist of a metallic bond coat overlaid with a ceramic. Triplex coatings include a transitional cermet layer or layers between the bond and ceramic layers. The metallic component may be a cobalt

or nickel plus chromium-aluminum-yttrium material, but nickel-aluminum and nickel-chromium-aluminum alloys have also been utilized. Zirconia, stabilized with either yttria or magnesia, is preferred as the ceramic constituent.

Thermal barrier coatings may be used to protect dies and mandrels used in the fabrication of high temperature extrusions. A hardened tool steel die or mandrel is coated with calcia-stabilized zirconium oxide over an 80% nickel-20% chromium undercoat. The advantage of this system for extruding refractory materials, such as molybdenum, tungsten, and tantalum, is that the mandrel or die can be recoated after multiple extrusions.

Other applications involving the use of zirconium oxide as a thermal barrier include protection against hot gases in exhaust systems, thus increasing the efficiency of pistons. There are many applications in the fabrication of steel equipment, including transfer rolls and oxygen lances. Magnesium zirconate is used as a nonwetting thermal barrier. Its principle applications are in vessels and handling equipment for molten material.

5.7.2 High Temperature and Oxidation Resistant Coatings. Aluminum coatings are suitable for the protection of iron and steel against corrosion or oxidation, or both, at temperatures between 250°F (120°C) and 1600°F (870°C), and for short term protection to 2100°F (1150°C). For working temperatures up to 1000°F (535°C), sealing with a suitable silicone type sealer is the only additional treatment required.

For higher working temperatures, combustion sprayed aluminum coatings should be covered with a bituminous or other carbonaceous sealer. The treated component is then heated to some temperature above the melting point of aluminum. During the heating cycle, compounds of iron and aluminum are formed on the substrate surfaces. These provide excellent resistance to high temperature attack under service conditions. Arc sprayed aluminum coatings do not require a special thermal treatment, because they form compounds by diffusion during elevated temperature service.

5.7.3 Corrosion Protection. Thermal spray coatings are used for protection of iron and steel in a range of corrosive environments. Long term effectiveness (over 20 years) in both industrial and marine locations has been documented.

Austenitic stainless steels, aluminum bronze, and cobalt and nickel base alloys, when sealed, offer varying degrees of atmospheric protection. The particular environment will dictate the appropriate alloy selection.

Zinc and aluminum provide the broadest atmospheric protection, and the choice in their use is often based on the relative ease of application and comparative costs for the specific case. They are more corrosion resistant than steel, and hence form an effective atmospheric barrier.

Zinc and aluminum are anodic to steel. They also protect the ferrous substrate in electrolytic solutions. The coating serves as a sacrificial anode and is consumed in time. This reserve cathodic protection acts to prevent corrosion of the substrate even when the coating coverage is incomplete or suffers mechanical damage. Aluminum corrodes less rapidly than zinc in highly acidic conditions, while zinc performs better than aluminum in alkaline conditions.

For the protection of steel in gas and chemical plants, or for other applications where the temperature is in excess of 390°F (200°C), aluminum is used. Spraying of aluminum coatings should be avoided whenever there is a fire or explosion hazard, as in the case of mines or oil rigs, because of the possibility of impact sparking. Consequently, sprayed zinc is always used in coal mines. Zinc is the preferred metal for the protection of steel in fresh cold waters, while above 150°F (65°C), aluminum is used.

Where zinc is alloyed with aluminum, the zinc-rich spray material forms a highly effective corrosion-resistant coating, having the attributes of both elemental components. The zinc affords sufficient electrochemical activity, enabling it to protect cathodically; the aluminum strengthens the coating, providing abrasion and erosion resistance.

Flame and arc spraying give rapid, uniform coverage at economical spray rates, and are replacing painting for reasons of effectiveness and economics. Coatings have a predictable life, require but a single application, need no drying time, protect damaged areas cathodically, and have good abrasion resistance. Thermal spraying complements hot-dip galvanizing, and should be considered for coating existing structures when the fabrications are excessively large or otherwise cannot be hot-dip galvanized.

The size or shape of the structure to be protected is not a limiting factor. Components may be sprayed either in plant or on site. Automation is practical for long runs of repetitive work. The coating thickness can be controlled according to the degree of protection required. The life of a metal coating is proportional to the coating weight per unit area. For very long service life or in highly corrosive conditions, it is possible to increase the thickness to obtain enhanced corrosion protection. Zinc coatings can be applied in thicknesses from 0.002 in. (0.05 mm) to over 0.020 in. (0.50 mm); sprayed aluminum coatings range from 0.004 in. (0.10 mm) to 0.010 in. (0.25 mm) thick.

Surfaces which are not to be coated are masked before spraying. Areas of discontinuity or of insufficient thickness can be rectified by additional spraying. Aluminum and zinc coatings both have good adhesion to grit-blasted steel. Because spraying does not cause excessive heating of the substrate, there is no effect on the mechanical properties.

Porosity is an inherent feature of thermal sprayed coatings. In the case of active metal coatings, porosity is

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not detrimental, since porous passages through the thickness will not give rise to substrate attack because of the galvanic protection. The natural surface texture provides an excellent base for sealers or paint top coats.

There is a history of corrosion protection by metal spraying for structural steel work. Included are buildings, bridges, towers, radio and TV antenna masts, steel gantry structures, high power search radar aerials, overhead walkways, railroad overhead line support columns, electrification masts, tower cranes, traffic island posts, and street and bridge railings. On a smaller scale, zinc spraying has been used successfully to protect outdoor wrought iron furniture in corrosive environments.

The sulphurous and oxidizing atmospheres of chemical industries provide many applications, including storage tanks for fuels, alcohol, acetate, toluene, glycerine, molasses, and pump sleeves, mechanical seals, and impellers. Parts subjected to severe chemically corrosive environments require testing and evaluation of the coating before being placed in service.

Wellhead assemblies, for offshore use, have been coated for salt atmosphere corrosion protection since the 1950's. The process has been used for flare stacks, refinery columns, and for external protection of oil and propane gas storage tanks.

The interiors of fluid cargo railcars are thermal sprayed to control fluid purity and guard against iron contamination. The coating also aids in avoiding the discoloration of the cargo. Steel railroad cars are zinc sprayed for corrosion protection. These coatings should last the lifetime of the cars, thus eliminating the need of removal from service for painting (approximately every five years).

Spraying has been used to protect pipelines against many other environments. Lengths up to 40 feet (12 m) have been successfully coated internally. Pipe couplings, manhole covers, and other small industrial items are coated. Zinc spraying can restore corrosion protection to areas of products where galvanizing is inadvertently removed during fabrication. This can occur on the threaded ends of electrical conduit, or along the welded seams inside galvanized barrels and drums. Here, spraying is particularly advantageous because it ensures uniformity and reproducibility of coating thickness.

Sprayed zinc coatings have protected fresh water pipelines, the interiors of water towers, and sluice and canal lock gates in irrigation systems. These coated components have required virtually no maintenance for decades.

Sealed zinc coatings improve the resistance to corrosion of steel bridgework and railings from de-icing salts.

Furthermore, the rebars in reinforced concrete can be zinc sprayed to retard corrosion. Reinforced concrete bridges and highways, especially in marine environments, commonly suffer damage caused by road salting (de-icing). There is evidence that the rate of corrosion of the reinforcing steel is substantially reduced if the steel is coated with zinc prior to embedding in the concrete.

In marine applications, hulls, deck sections, and concrete portions of barge, scow, tug, and fishing vessel superstructures have been sprayed with excellent long term results. Lifeboats and floating caissons have also been coated, as well as smaller items such as ship rudders and the axles of boat trailers. A common usage of metal spray is on piers, pilings, and ferry berths.

The U. S. Navy, in a major effort to combat shipboard corrosion, has developed a comprehensive program of thermal spray metallization. A number of above deck and steam room ferrous metal components have been sprayed with aluminum and subsequently sealed. Tests to date are encouraging and have led the Navy to introduce specifications for a wide range of thermal spray applications.

5.8 Decorative Coatings

Thermal spraying has not been widely adapted for decorative coatings. The most common and notable decorative effect occurs when bridges, water towers, masts, chimneys, above ground pipes, and other large structures are sprayed with aluminum or zinc for corrosion protection. Such structures are left unsealed or are clear sealed without further surface treatment. Zinc and aluminum are used for corrosion protection, but they also provide a cosmetic, improved appearance.

Plain and colored sealers, available for corrosion protection, add an aesthetically pleasing appearance to coated structures. For these applications, a choice is made based on economical and practical values. It must be decided whether to apply thin coatings of painting or sealing, or to apply a thick unpainted coating. An example would be: a fresh water tank sprayed internally with a 0.010 in. (0.25 mm) coating of zinc with no subsequent treatment; the exterior sprayed with a 0.004 in. (0.10 mm) coating of zinc that is sealed with aluminum vinyl.

Some work has been done in thermal spraying concrete brick and block products with glazing materials for decorative value. In many applications, thermal spraying has replaced hard or industrial type chromium plating. However, it cannot compete with decorative chromium plating whose primary function is aesthetic appeal.

5.9 Materials Classification

5.9.1 Oxide Ceramics^a

Available form					
Code	Composition weight — percent	Powder		Wire, rod, cord	Comments
		Type	Particle size		
1 ^a	Al ₂ O ₃ 94.0, TiO ₂ 2.5, SiO ₂ 2.0, FeO ₃ 1.0, other oxides bal.	Compound	-2100+590 μ in. (-53+15 μ m)	3/16 (4.8) cord 1/8 (3.2) rod	
2 ^a	TiO ₂ 99.0+	Neat*	-2100+400 μ in. (-53+10 μ m)	3/16 (4.8) cord	
3 ^a	Al ₂ O ₃ 98.0, SiO ₂ 0.5, other oxides bal.	Neat	-2100+400 μ in. (-53+10 μ m)	3/16 (4.8) cord 1/8 (3.2) rod	
4 ^a	Cr ₂ O ₃ 98.0	Neat	-3500+590 μ in. (-90+15 μ m)	1/8 (3.2) cord 1/8 (3.2) rod	
5 ^a	Al ₂ O ₃ 50.0, TiO ₂ 50.0	Blend	-2100+400 μ in. (-53+10 μ m)	—	
6 ^a	TiO ₂ 55.0, Cr ₂ O ₃ 45.0	Blend	-4200+400 μ in. (-106+10 μ m)	—	
7 ^a	Al ₂ O ₃ 87.0, TiO ₂ 13.0	Composite	-1200+200 μ in. (-30+5 μ m) -2100+400 μ in. (-53+10 μ m)	—	Composite of TiO ₂ plus Al ₂ O ₃
8 ^a	Al ₂ O ₃ 60.0, TiO ₂ 40.0	Composite	-1800+200 μ in. (-45+5 μ m)	—	Composite of TiO ₂ plus Al ₂ plus Al ₂ O ₃
9 ^a	SiO ₂ 5-9, others 3-5, Cr ₂ O ₃ bal.	Composite	-2100+590 μ in. (-53+15 μ m)	—	SiO ₂ clad Cr ₂ O ₃ composite
10 ^a	ZrO ₂ 93.0, CaO 1-5, Al ₂ O ₃ 0.5, SiO ₂ 0.4	Composite	-2100+400 μ in. (-53+10 μ m) -2100+400 μ in. (-53+10 μ m)	1/8 (3.2) rod 1/8 (3.2) and 3/16 (4.8) cord	Calcia stabilized zirconia

*Neat means undiluted

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5.9 Materials Classification (Continued)

5.9.1 Oxide Ceramics^a

		Available form			
		Powder		Wire, rod, cord	
Code	Composition weight — percent	Type	Particle size	Diameter in. (mm)	Comments
11 ^a	ZrO ₂ 80.0, Y ₂ O ₃ 20.0	Composite or compound	-3500+400 μ in. (-90+10 μ m)	—	Composite or fused yttria stabilized zirconia
12 ^a	MgO 24, ZrO ₂ bal.	Compound	-2100+400 μ in. (-53+10 μ m)	—	Magnesia stabilized zirconia
13 ^a	CaO 31.0, ZrO ₂ bal.	Blend	-2100+400 μ in. (-53+10 μ m)	—	
14 ^a	ZrO ₂ 88, Y ₂ O ₃ 12	Compound	-2100+400 μ in. (-53+10 μ m)	—	Yttria stabilized zirconia
15 ^a	ZrO ₂ Y ₂ O ₃ 6-8	Compound	-2100+400 μ in. (-53+10 μ m) -2800+1700 μ in. (-70+44 μ m)	—	Yttria stabilized zirconia
16 ^a	Cr ₂ O ₃ 40-50, MgO 1-10, Fe ₂ O ₃ 2-10, TiO ₂ 1-10, Al ₂ O ₃ 5-40, SiO ₂ 0-8	Compound	-1800+200 μ in. (-44+5 μ m)	—	
17 ^a	Cu ₂ O ₃ 82-85, SiO ₂ 7-9, TiO ₂ 3-4, Al ₂ O ₃ 3-5, MgO 2-3, CuO 0.2-0.5	Compound	-1800+200 μ in. (-44+5 μ m)	—	
18 ^a	Cr ₂ O ₃ 95, TiO ₂ 5	Compound	-1800+590 μ in. (-44+15 μ m)	—	
19 ^a	Al ₂ O ₃ 91.0, Fe ₂ O ₃ 6, TiO ₂ 3	Compound	-2100+400 μ in. (-53+10 μ m)	—	

5.9 Materials Classification (Continued)

5.9.2 Iron Based Alloys^b

	Available form				
	Powder		Wire, rod, cord		
Code	Composition weight — percent	Type	Particle size	Diameter gage, in. (mm)	Comments
1 ^b	Mn .5, C .10, Fe bal.	Alloy	—4200+1800 μ in. (—106+45 μ m)	11 (3.05) 1/8 (3.2) 3/16 (4.8)	Low carbon steel
2 ^b	Al 10.0, Mo 1.0, C .2, Fe bal.	Composite	—4900+1800 μ in. (—125+45 μ m)	—	Low carbon “steel” composite
3 ^b	Al 3.0, Mo 3.0, C 3.0, Fe bal.	Composite	—4900+1800 μ in. (—125+45 μ m)	—	High carbon iron “steel” composite
4 ^b	C .35, P .02, S .02, Mn .5, Cr 13.0, Si .5, Fe bal.	Alloy	—2900+1700 μ in. (—74+44 μ m)	14 (2.03) 11 (3.05) 1/8 (3.2) 3/16 (4.8)	Type 420 stainless steel
5 ^b	C .15, P .06, S .03, Mn 8.5, Ni 5.10, Cr 18.0, Si 1.0, Fe bal.	Alloy	—	14 (2.03) 11 (3.05) 1/8 (3.2) 3/16 (4.8)	Type 202 stainless steel
6 ^b	C .80, P .04, S .04, Mn .7, Fe bal.	Alloy	—	14 (2.03) 11 (3.05) 1/8 (3.2) 3/16 (4.8)	High carbon steel
7 ^b	C .04, P .03, S .03, Mn 2.0, Ni 4.0, Cr 1.5, Mo 1.5, Fe bal.	Alloy	—	14 (2.03) 11 (3.05) 1/8 (3.2) 3/16 (4.8)	
8 ^b	Cr 17.0, Ni 12.0, Mo 2.5, Si 1.0, C .1, Fe bal.	Alloy	—2100+400 μ in. (—53+10 μ m)	—	Type 316 stainless steel

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5.9 Materials Classification (Continued)

5.9.2 Iron Based Alloys^b

	Available form				
	Powder		Wire, rod, cord		
	Type	Particle size	Diameter gage, in. (mm)	Comments	
9 ^b	Cr 16.0, Ni 2.0, C .2, Fe bal.	Alloy	-4200+1800 μ in. (-106+45 μ m)	14 (2.03)	Type 431 stainless steel
10 ^b	Mo 15.0, C 3.0, Mn .25, Fe bal.	Composite	-3500+400 μ in. (-90+10 μ m)	---	High carbon molybdenum composite
11 ^b	C 3.50, Mn .35, Fe bal.	Alloy	-2100+400 μ in. (-53+10 μ m)	14 (2.03) 11 (3.05) 1/8 (3.2) 3/16 (4.8)	High carbon iron
12 ^b	Cr 19.0, Ni 9.5, Mn 2.0, Si 1.0, Fe bal.	Alloy	-3500+400 μ in. (-90+10 μ m)	---	Type 304 stainless steel

5.9 Materials Classification (Continued)

5.9.3 Nickel Based Materials and Cobalt^c

Code	Composition weight — percent	Available form			Comments
		Powder	Wire, rod, cord	Diameter gage, in. (mm)	
1 ^c	Ni 99.5	Element —3000+1800 μ in. (—75+45 μ m)	15 (1.83) wire 1/8 (3.2) wire 3/16 (4.8) wire	Nickel	
2 ^c	Al 20, Ni bal.	Composite —3500+2100 μ in. (—90+53 μ m)	—	“Nickel clad” aluminum	
3 ^c	Cr 8.5, Al 7.5, Mo 5.0, Si 2.0, Fe 2.0, B 2.0, Ni bal.	Composite —4900+1800 μ in. (—125+45 μ m)	—	Stainless composite for bonding	
4 ^c	Al 6.0, NiCr bal.	Composite —4700+1800 μ in. (—120+45 μ m)	—	Nickel chromium/ Al composite	
5 ^c	Cr 9.0, Al 7.0, Mo 5.5, Fe 5.0, Ni bal.	Composite —4900+1800 μ in. (—125+45 μ m)	—	Self-bonding composite	
6 ^c	Ni 60.0, Cr 16.0, Si 1.15, Fe bal.	Alloy —4700+1800 μ in. (—120+45 μ m)	14 (2.03) wire 1/8 (3.2) wire 3/16 (4.8) wire		
7 ^c	Al 4.5, Ni bal.	Composite Alloy —3500+1800 μ in. (—90+45 μ m)	14 (2.03) wire 1/8 (3.2) wire	Aluminum/nickel for bonding	
8 ^c	Cr 9.5, Si 2.5, B 1.5, Al .5, Ni bal.	Blend —4200+1800 μ in. (—106+45 μ m)	—	Nickel/chromium aluminum	
9 ^c	Ni 80.0, Al 20.0	—	1/8 (3.2) wire	Composite nickel/ aluminum wire bond coat	

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5.9 Materials Classification (Continued)

5.9.3 Nickel Based Materials and Cobalt

	Available form				Comments
	Composition weight — percent	Powder		Wire, rod, cord	
Code	Type	Particle size	Diameter gage, in. (mm)		
10 ^c	Ni 80.0, Cr 20.0	Alloy	-4200+1800 μ in. (-106+45 μ m)	14 (2.03) wire	
11 ^c	Ni 67.0, C .15, Fe 1.5, Mn 1.0, Si .1, Al .1, Cu bal.	Alloy	-2900+1700 μ in. (-74+44 μ m)	14 (2.03) wire 1/8 (3.2) wire 3/16 (4.8) wire	
12 ^c	Cr 25.5, Ni 10.5, W 7.5, CO 0.5, Co bal.	Alloy	-1800+200 μ in. (-45+5 μ m)	—	
13 ^c	Ni 95, Al 5	Alloy	-3500+1500 μ in. (-88+37 μ m)	—	—
14 ^c	Cr 9.0, Al 7.0, Mo 5.5, Fe 5.0, Ni bal.	Alloy	-3500+1500 μ in. (-88+37 μ m)	—	—
15 ^c	Cr 22.0, Al 10.0, Y 1.0, Ni bal.	Alloy	-1800+200 μ in. (-45+5 μ m)	—	Ni, Cr, Al, Y
16 ^c	Mo 28, Cr 8.0, Si 2.5, Fe 1.0, Co bal.	Alloy	-1800+790 μ in. (-45+20 μ m)	—	—
17 ^c	60 Ni, 40 Ti	Alloy	-1800+790 μ in. (-45+20 μ m)	—	—
18 ^c	Ni 32.0, Cr 21.0, Al 8.0, Y 0.5, Co bal.	Alloy	-1800+200 μ in. (-45+5 μ m)	—	Ni, Co, Cr, Al, Y

5.9 Materials Classification (Continued)

5.9.4 Nonferrous Materials^d

Code	Composition weight — percent	Available form			Comments
		Type	Particle size	Wire, rod, cord gage, in. (mm)	
1 ^d	Al 9.5, Fe 1.0, Cu bal.	Alloy	-4900+1800 μ in. (-125+45 μ m)	14 (2.03) wire 11 (3.05) wire 1/8 (3.2) wire 3/16 (4.8) wire	Aluminum bronze
2 ^d	Si 12.0, Al bal.	Alloy	-4200+1800 μ in. (-106+45 μ m)	14 (2.03) wire 11 (3.05) wire 1/8 (3.2) wire 3/16 (4.8) wire	Silicon aluminum alloy
3 ^d	Al 99.0+	Element	-3500+1800 μ in. (-90+45 μ m)	14 (2.03) wire 11 (3.05) wire 1/8 (3.2) wire 3/16 (4.8) wire	Aluminum
4 ^d	Cu 99.0+	Element	-3500+1800 μ in. (-90+45 μ m)	14 (2.03) wire 11 (3.05) wire 1/8 (3.2) wire 3/16 (4.8) wire	Copper
5 ^d	Ni 38.0, Cu bal.	Alloy	-3000+1800 μ in. (-75+45 μ m)	14 (2.03) wire	Copper-nickel alloy
6 ^d	Ni 36.5, In 5.0, Cu bal.	Alloy	-3000+1800 μ in. (-75+45 μ m)	—	Copper-nickel indium alloy
7 ^d	Zn 99.9+	Element	—	14 (2.03) wire 11 (3.05) wire 1/8 (3.2) wire 3/16 (4.8) wire	Zinc
8 ^d	Cu 66, Zn 34	Alloy	—	14 (2.03) wire 11 (3.05) wire 1/8 (3.2) wire 3/16 (4.8) wire	Brass

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5.9 Materials Classification (Continued)

5.9.4 Nonferrous Materials^d

Code	Composition weight — percent	Available form			Comments
		Type	Particle size	Wire, rod, cord Diameter gage. in. (mm)	
9 ^d	Cu 90, Zn 10	Alloy	—	15 (1.83) wire 14 (2.03) wire 1/8 (3.2) wire 3/16 (4.8) wire	Brass
10 ^d	Cu 95, Sn 5	Alloy	—	1/8 (3.2) wire 3/16 (4.8) wire	Brass
11 ^d	Cu 58.2, Sn .8, Fe .75, Mn .25, Zn bal.	Alloy	—	1/8 (3.2) wire 3/16 (4.8) wire	—
12 ^d	Cu/SiC	Composite	—	1/8 (3.2) wire	Cu tubing with SiC composite filler
13 ^d	Zn 80, Tin 20	Alloy	—	14 (2.03) wire 11 (3.05) wire 1/8 (3.2) wire	—
14 ^d	90 Tin, 7 Antimony, 3 Copper	Alloy	—	11 (3.05) wire 1/8 (3.2) wire	Babbitt
15 ^d	85 Zn, 15 Al	Alloy	—	14 (2.03) wire 11 (3.05) wire 1/8 (3.2) wire	—
16 ^d	Tin	Element	—	11 (3.05) wire 1/8 (3.2) wire	—
17 ^d	Lead	Element	—	11 (3.05) wire 1/8 (3.2) wire	Caution: lead is hazardous. See Chapter 11
18 ^d	85 Pb Sn	Alloy	—	11 (3.05) wire 1/8 (3.2) wire	Caution: see above SAE 6A solder

5.9 Materials Classification (Continued)

5.9.5 Other Carbides*

Code	Composition weight — percent	Available form			Comments
		Powder	Wire, rod, cord	Diameter gage, in. (mm)	
1 ^e	Cr ₃ C ₂ 99.0	Type Compound	Particle size -5500+1200 μ in. (-140+30 μ m)	---	AMS 7875
2 ^e	Cr ₃ C ₂ 75, Ni 20, Cr 5	Blend	-1800+200 μ in. (-45+5 μ m)	---	Chromium carbide + Ni chromium alloy blend
3 ^e	Cr ₃ C ₂ 85, Ni 12, Cr 3	Blend	-5500+400 μ in. (-140+10 μ m)	---	Chromium carbide + Ni chromium alloy blend
4 ^e	Cr 48, Ni 28, C 6, Al 2, Mo 2, B 1, Si 1, Co bal.	Blend	-3000+400 μ in. (-75+10 μ m)	---	Chromium carbide "Ni aluminide" blend
5 ^e	TiC 55, Co 45	Composite	-1700+400 μ in. (-44+10 μ m)	---	Fine TiC particles clad with Co
6 ^e	TiC 55, Ni 45	Composite	-1700+400 μ in. (-44+10 μ m)	---	Fine TiC particles clad with Ni
7 ^e	WC 67, NiCrB33	Composite + Blend	-1700+400 μ in. (-44+10 μ m)	---	Fine WC particles clad with Co and blended with Ni

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5.9 Materials Classification (Continued)

5.9.6 Refractory Metals and Alloys^f

	Available form			
	Composition weight — percent	Powder		Wire, rod, cord
		Type	Particle size	
Code			Diameter gage, in. (mm)	Comments
1 ^f	W 99.5	Element	—7900 + 1200 _μ in. (—200 + 30 _μ m)	—
2 ^f	Ta 99.5	Element	—3500 + 1700 _μ in. (—90 + 44 _μ m)	—
3 ^f	Mo 99	Element	—7900 + 1200 _μ in. (—200 + 30 _μ m)	—
4 ^f	Mo 99.5	Element	—3500 + 1700 _μ in. (—90 + 44 _μ m)	—
5 ^f	Mo 75.0, Cr 4.25, B 0.8, Si 1.0, Fe 1.0, C 0.2, Ni bal.	Blend	—3500 + 590 _μ in. (—90 + 15 _μ m)	Self-fluxing alloy plus molybdenum blend

5.9 Materials Classification (Continued)

5.9.7 Self-Fluxing Alloys^g

Available form					Comments
Code	Composition weight — percent	Powder		Wire, rod, cord	
		Type	Particle size	Diameter gage, in. (mm)	
1 ^g	Cr 10.0, B 2.5, Fe 2.5, Si 2.5, C .15, Ni bal.	Alloy blend	—4900+1800 μ in. (—125+45 μ m)	1/8 (3.2) cord	—
2 ^g	Cr 17.0, Fe 4.0, Si 4.0, B 3.5, C 1.0, Ni bal.	Alloy	—4200+1800 μ in. (—106+45 μ m) —2100+590 μ in. (—53+15 μ m)	1/8 (3.2) cord	—
3 ^g	Co 40.0, Cr 18.0, Mo 6.0, Si 3.5, B 3.0, Fe 2.5, C 0.2, Ni bal.	Alloy	—4900+2100 μ in. (—125+53 μ m)	—	—
4 ^g	Cr 16.0, Si 4.0, B 4.0, Fe 4.0, Cu 2.4, Mo 2.4, W 2.4, Co 0.5, Ni bal.	Alloy	—4200+1800 μ in. (—106+45 μ m)	—	—
5 ^g	Ni 46.0, WC/Co 35.0, Cr 11.0, Fe 2.5, Si 2.5, B 2.5, C 0.5	Blend	—4900+1800 μ in. (—125+45 μ m) blend	—	Blend of WC/Co powder plus self-fluxing alloy
6 ^g	WC/Co 80.0, Ni 14.0, Cr 3.5, B 0.8, Fe 0.8, Si 0.8, C 0.1	Blend	—4900+1800 μ in. (—125+45 μ m) blend	—	Blend of WC/Co powder plus self-fluxing alloy
7 ^g	WC/Co 50.0, Ni 33.0, Cr 9.0, Fe 3.5, Si 2.0, B 2.0, C 0.5	Blend	—2100+590 μ in. (—53+15 μ m)	—	Blend of WC/Co powder plus self-fluxing alloy

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5.9 Materials Classification (Continued)

5.9.7 Self-Fluxing Alloys^g

	Available form			
	Powder	Wire, rod, cord		Comments
		Type	Particle size	
8 ^g	WC/Co 3.0, Co 28.0, Ni 19.0, Cr 12.5, Mo 4.2, Si 2.5, B 2.0, Fe 1.9, C 0.1	Blend	-4900 + 1800 μ in. (- 125 + 45 μ m)	Blend of WC/Co powder plus self-fluxing alloy
9 ^g	Wc/C 35, Cr 11.0, B 2.5, Fe 2.5, Si 2.5, C 0.5, Ni bal.	Blend	-5900 + 1800 μ in. (- 150 + 45 μ m)	Blend of WC/Co powder plus self-fluxing alloy
10 ^g	Si 1.6, B 2.4, Cr 19, Co .06, Ni 2.7, W 4.5, Co bal.	---	---	---

5.9 Materials Classification (Continued)

5.9.8 Tungsten Carbides^h

Available form					
Code	Composition weight — percent	Powder		Wire, rod, cord	
		Type	Particle size	Diameter gage, in. (mm)	Comments
1 ^h	Co 12, C 4, Fe 1, WC bal.	Composite	—1800+200 μ in. (—45+5 μ m)	—	Full sintered and crushed powder meets AMS 7879
2 ^h	Co 12, WC bal.	Composite	—1800+590 μ in. (—45+15 μ m)	—	Partial sintered and crushed powder meets AMS 7880
3 ^h	Co 17, WC bal.	Composite	—2100+400 μ in. (—53+10 m)	—	Composited plus sintered powder
4 ^h	Co 12, WC bal.	Composite	—1200+200 μ in. (—30+5 μ m)	—	Composited plus without sinter
5 ^h	C 0.5, Si 1.5, Cr 6.0, B 1.0, Fe 1.5, Al 0.7, WC 12, Co 50, Ni bal.	Blend	—6700+590 μ in. (—170+15 μ m)	—	Blend of WC/Co (Code 120) plus nickel-aluminum
6 ^h	WC 12, Co 75.0, Cr 3.0, Al 1.5, Fe 0.8, Si 0.8, B 0.5, C 0.15, Ni bal.	Blend	—3500+550 μ in. (—90+14 μ m)	—	Blend of WC/Co (Code 120) plus nickel-aluminum
7 ^h	Co 20, WC 80	Composite	—1700+400 μ in. (—44+10 μ m)	—	Fine WC particles clad with Co
8 ^h	Co 12, WC 88	Composite	—1700+400 μ in. (—44+10 m)	—	Fine WC particles clad with Co

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5.9 Materials Classification (Continued)

5.9.9 Abradable Coatings¹

Available form					
Powder			Wire, rod, cord		
Code	Composition weight — percent	Type	Particle size	Diameter gage, in. (mm)	Comments
1 ⁱ	BN 5.5, Al 3.5, Fe 8, Cr 14, Ni bal.	Composite	—4900+1800 μ in. (—125+45 μ m)	—	Boron nitride plus Ni alloy composite
2 ⁱ	Ni 75, C 25	Composite	—3500+1200 μ in. (—90+30 μ m)	—	Nickel plus graphite composites
3 ⁱ	Ni 85, C 15	Composite	—3500+1200 μ in. (—90+30 μ m)	—	Nickel plus graphite composites
4 ⁱ	Al 57, C 35, Si 8	Composite	—4900+590 μ in. (—125+15 μ m)	—	Silicon aluminum graphite composite
5 ⁱ	Al Si 55, C 45	Composite	—4900+590 μ in. (—125+15 μ m)	—	Silicon aluminum plus graphite composite
6 ⁱ	Al (12 Si) 60 polyester bal.	Blend	—5500+400 μ in. (—140+10 μ m)	—	Aluminum plus polyester blend
7 ⁱ	Al Si 60, PI 40	Composite	—5500+400 μ in. (—140+10 μ m)	—	Silicon aluminum polyimide composite
8 ⁱ	Cu 9.5 Al, 1.0 Fe, BN 7	Composite	—3000+400 μ in. (—75+10 μ m)	—	Aluminum bronze plus boron nitride cermet powder
9 ⁱ	Ni 80, C 20	Composite	—3500+1200 μ in. (—90+30 μ m)	—	Nickel plus graphite composite

5.10 Applications

5.10.1 Machine Element — Salvage and Restoration of Dimension

Part by name	Material code no.	Thermal spray system	Comments
Heavy duty bearing surfaces, where corrosion is not critical: Rolls surfaces Journals Crankshafts Papermill dryer drums	4b, 10b, 11b, 6b	Wire, combustion, or arc Powder, combustion, or plasma	Finished by grinding
Heavy duty bearing surfaces, good corrosion resistance is required: Pump plungers Hydraulic rams Impellers Shafts	4b, 3c, 8c	Wire, combustion, or arc Powder, combustion, or plasma	Finished by grinding
Load bearing applications, under marine or caustic environments	11c	Wire, combustion, or arc Powder, combustion, or plasma	—
Repair: Printing roller surfaces, Electric grounding conductors, Railway carriage axles, conductor rolls in electric plating plants	4d	Wire, combustion, or arc Powder, combustion, or plasma	For electrical conductivity

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5.10 Applications (Continued)**5.10.2 Antifretting and Wear**

Part by name	Material code no.	Thermal spray system	Comments
Fan blade interlocks	1h, 2h, 3h	Detonation, plasma	Wear and impact resistance
Compressor blade interlocks	1h, 2h, 3h	Detonation, plasma	Wear and impact resistance
Exhaust nozzle flaps	16c, 2e, 3e, 3h	Plasma	Rub and wear resistance
Exhaust nozzle seal	16c, 2e, 2h	Plasma	Fretting resistance
Miscellaneous brackets	5d, 6d, 2h, 7h, 8h	Plasma	Fretting resistance
Miscellaneous clips	5d, 6d, 2h, 3h, 7h, 8h	Plasma	Fretting resistance
Landing gear struts	2d	Plasma wire-arc	Rebuild struts
Helicopter pulleys	6b	Wire combustion	Rebuild pulleys
LPTV interlocks	16c, 2e	Plasma detonation	High temperature resistance to fretting
Exhaust nozzle	16c, 2e	Plasma	
Stator seal	2e	Plasma	High temperature resistance to fretting
Nozzle diaphragm	16c, 2e, 2g	Plasma	
Seal mate faces	16c, 5d	Plasma	Fretting wear
Compressor vane dovetail	16c, 5d, 6d	Plasma detonation	Fretting wear
Fan disc pressure faces	5d, 6d	Plasma	Soft antifretting
Fan blade dovetails	16c, 5d, 6d	Plasma	---
Blade retainer rings	16c, 5d	Plasma	---
Bearing housing	3f	Plasma	---
Tail engine adaptors	2h	Plasma	Fretting wear
Cam and cam followers	16c, 2h	Plasma	Sliding wear
Wire drawing capstans	4a, 17a, 18a, 19a	Plasma	Sliding wear
Wire drawing pullies	4a, 18a, 19a	Plasma	Sliding wear
Oil flangers	4a, 11b	Plasma	---
Seals	16a, 17a, 5d, 6d	Plasma	Sliding wear

5.10 Applications (Continued)**5.10.3 Clearance Control**

Part by name	Material code no.	Thermal spray system	Comments
Fan tip seals	2d, 6i	Wire arc Wire combustion Plasma	
Low pressure compressor (inner and outer seals)	2d, 2i, 3i, 6i	Wire combustion Wire arc Powder combustion Plasma	
Intermediate compressor case (Rolls Royce)	6i	Plasma	
High pressure compressor (inner and outer seals)	2d 1i, 2i, 3i, 6i	Wire combustion Wire arc Powder combustion Plasma	
Centripetal compressors (small engines)	6i	Plasma	
Low pressure turbine shrouds [below 1500°F (815°C)]	7c, 1i, 8i	Wire arc Powder combustion	Open structure
High pressure turbine shrouds*	11a	Plasma	Intermediate cermet is required
Fuel nozzle valve seal	1i	Powder combustion	
Low pressure turbine nozzle	8i	Powder combustion	
Labyrinth seals (including oil seals)	1i, 2i, 3i, 4i, NiAl + Ag 6i NiAl-1	Powder combustion Plasma	

* Bond coat code — 1007

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5.10 Applications (Continued)

5.10.4 Petrochemical and Paper

Part by name	Material code no.	Thermal spray system	Comments
Yankee dryer rolls	4b	Wire combustion Wire arc Plasma	Paper industry
Corrugated rolls — Sleeve Journal fits	4b	Wire combustion Wire arc Plasma	Paper industry
Pressure rolls — Sleeve Journal fits	4b	Wire combustion Wire arc Plasma	Paper industry
Compressor cylinders Hydraulic and power	4b	Wire combustion Wire arc Plasma	Oil industry
Swivel joints for underwater securing	11c	Wire combustion Wire arc Plasma	Oil industry
Compressor pistons — all types	4b, 1d, 11d, 12d	Wire combustion Powder combustion	Oil industry
Compressor piston rods	7a, 4b, 3h	Wire combustion Plasma	Oil industry
Turbine runners	4b	Wire combustion	Oil industry
Turbine runners — Bearing seal and carbon areas	4b	Wire combustion	Oil industry
Burner nozzle	10a, 12a, 15a	Plasma Flame (rod)	Thermal barrier coating
Rotary valve	1a	Flame (rod)	Resist wear by particle erosion
Boiler tubes	4b, 5c, 14c, 3d	Wire arc plasma	Resist corrosion
Packing journals — Sleeves	7a, 14a, 15a, 16a	Plasma	Slurry pumps — paper industry
Pump housings	14a, 15a, 16a, 17a	Plasma	Resist wear by particle erosion
Extrusion screws	16a, 17a	Plasma	Resist wear by particle erosion

5.10 Applications (Continued)**5.10.5 Atmosphere and Sea Corrosion**

Part by name	Material code no.	Thermal spray system	Comments
Winches	3d, 7d	Wire, arc, or combustion	Coatings should be primed, and sealed for maximum life
Booms	3d, 7d	Wire, arc, or combustion	Coatings should be primed, and sealed for maximum life
Piping	3d, 7d	Wire, arc, or combustion	Coatings should be primed, and sealed for maximum life
Stanchions	3d, 7d	Wire, arc, or combustion	Coatings should be primed, and sealed for maximum life
Tie downs	3d, 7d	Wire, arc, or combustion	Coatings should be primed, and sealed for maximum life
Steam riser valves	3d, 7d	Wire, arc, or combustion	Coatings should be primed, and sealed for maximum life
Exhaust stacks	3d, 7d	Wire, arc, or combustion	Coatings should be primed, and sealed for maximum life
Bridges	3d, 7d	Wire, arc, or combustion	Coatings should be primed, and sealed for maximum life

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5.10 Applications (Continued)

5.10.6 Electrical

Part by name	Material code no.	Thermal spray system	Comments
Capacitors	13d, 4d, 16d, 7d, 3d	Wire combustion Wire arc	---
Ceramic resistors	3d, 4d, 7d	Wire combustion Wire arc	---
Graphite electrodes	3d, 4d	Wire combustion Wire arc	---
Varistors	3d, 7d	Wire combustion Wire arc	---
Oxides (special)	3d, 7d	Wire combustion Wire arc	---
Glass	3d, 4d	Wire combustion Wire arc	---
Shielding	3d, 7d	Wire combustion Wire arc	---

Chapter 6

Training, Testing, and Quality Control

6.1 Introduction

6.2 Operator

- 6.2.1 Certification
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- 6.5.2 Nondestructive Evaluation

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Chapter 6

Training, Testing, and Quality Control

6.1 Introduction

W. E. Ballard has written, "When applying coatings, the pistol is used as a hand tool, and the ultimate behavior of the deposit will therefore depend to some extent on the operator. One of the standard criticisms of the metal spraying process is its dependability on the human element, and it is therefore necessary to consider how best to avoid unsatisfactory work." Meters and controllers have been added since 1926, when the author first made this observation, but the operator is still relied upon to produce a quality product. This applies not only to the deposition process but also to the preparatory processes, and ultimately, the end product. Controls must be applied to all phases of the operation to assure a consistently dependable end product. This chapter identifies existing controls and alerts readers to measures they may want to take.

6.2 Operator

6.2.1 Certification. The United States Navy has issued an Operator Certification Requirement in DOD-STD-2138, *Metal Spray Coatings for Corrosion Control on Naval Ships*, and certain other industries also require certification acknowledging proficiency with the degree of compliance determined by the user.

6.2.2 Training. Before operators handle or use any thermal spray equipment, they should be trained in basic safety, equipment and tool handling, and have a good familiarity with manuals and instructions. These include, but are not limited to

Safety Tools*

- Safety glasses, clear
- Safety glasses, number 3, 4, and 5 lens
- Welder's helmet, number 9 lens
- Work gloves
- Aluminized gloves
- Aluminized bib or apron
- Hearing protection
- Breathing respirator

* Consult Chapter 11 Safety for proper usage.

Publications - (see Bibliography)

- AWS C2.1-73, *Recommended Safety Practices for Thermal Spraying*
- AWS A3.0, *Welding Terms and Definitions*
- Background information on various spray processes and practices
- Equipment manufacturers recommendations

Instruction

- Presentation of safety precautions and process procedures that yield acceptable quality deposits
- Equipment/process description including discussion and demonstrations by qualified personnel
- Trainee self-study period on previously supplied manuals and processing instructions
- Supervised process operation on-the-job training with qualified personnel
- Maintenance/repair of equipment
- Solo process operation with frequent performance review by qualified personnel
- Performance evaluation

Generally, a **THOROUGH** training period, encompassing all processes, may require as much as ten to twelve weeks, with the final week devoted to solo on-the-job operation and testing. The training period should be divided into segments; for example:

Safety

- Demonstration of safety devices
- Demonstration of operating equipment
- Self-study (reading)
- Testing (written/oral/performance)

Surface Preparation

- Process description
- Demonstration of safety practices
- Demonstration of operating equipment
- Solo
- Testing (performance)

Wire Flame and Arc Spraying

- Process description

- Demonstration of safety practices
- Demonstration of operating and control equipment
- Self-study (reading/hands-on)
- Equipment construction and assembly
- Trouble shooting
- Testing (written/oral/performance)

Powder Flame Spraying

- Process description
- Demonstration of safety practices
- Demonstration of gun and control equipment
- Self-study (reading/hands-on)
- Equipment construction and assembly
- Trouble shooting
- Testing (written/oral/performance)

Plasma Spraying

- Process description
- Demonstration of safety practices
- Demonstration of gun and control equipment
- Self-study (reading/hands-on)
- The feed system
- Equipment construction and assembly
- Trouble shooting
- Testing (written/oral/performance)

6.2.3 Testing. Upon completion of the required training, the proficiency of the candidate for thermal spray operator should be evaluated. Testing may be either written or oral, and a hands-on demonstration of skills. A combination of these is preferred. The written or oral test should contain questions directly related to the text or subject material. True-or-false or multiple choice are best. Plans for retesting and additional training should be established. The actual tests should be direct and to the point. Individual tests should be provided for each subject; i. e., Safety, Surface Preparation, Plasma Spraying, Wire and Powder Flame Spraying, Wire Arc Spraying, and Detonation. It would be inappropriate to test candidates for proficiencies in areas of expertise that they would never be expected to perform. A typical written/oral test on two subjects is presented in Exhibit 6.2.3 (A & B). Such tests should be prepared for each process. Spray tests should be on a pre-established schedule and should be conducted on actual or simulated hardware. Each may be accompanied by companion panels suitable for physical testing. These tests may include hardness, tensile strength, and microstructure. The purpose of the spray test is to enable the candidate to demonstrate required skills as a craftsman. Hence, the coating visual appearance, thickness control, temperature during application, and amount of overspray all should be evaluated.

Exhibit 6.2.3
Thermal Spray Operators Test

This example could be used to certify trainees as they complete the program as well as for operator recertification.

A. Plasma Spraying	True	False
1. Spraying should follow grit blasting after four hours exposure.	<u>X</u>	___
2. All parts need not be cleaned and grit blasted before spraying.	___	<u>X</u>
3. Dry powder should be poured directly from the can to the hopper "as is."	___	<u>X</u>
4. Spilled powder should be replaced in the can immediately.	___	<u>X</u>
5. Dirt in small amounts in the powder is not critical since it will be consumed in the arc.	___	<u>X</u>
6. If there is any doubt as to the dryness of the powder, it should be dried in an oven before use.	<u>X</u>	___
7. Nitrogen and hydrogen are used as carrier gases.	___	<u>X</u>
8. The exhaust system should always be turned on before entering the spray booth.	<u>X</u>	___
9. If the gas or cooling water pressure fails, the system shuts down automatically.	<u>X</u>	___
10. To rid the gun body of water the "Purge" button should be pushed as long as necessary.	<u>X</u>	___
11. Internal gun and control valve units can be cleaned with ordinary compressed air.	___	<u>X</u>
12. Powder feed unit "O" rings should be changed daily.	___	<u>X</u>
13. "O" rings should be lubricated before assembly into the gun.	<u>X</u>	___
14. A green color in the plasma stream indicates trouble.	<u>X</u>	___
15. The gap between the nozzle and the electrode should be kept completely dry.	<u>X</u>	___
16. The electrode nozzle arc should always be adjusted with the special tool provided.	___	<u>X</u>

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A. Plasma Spraying (cont'd.)

	<u>True</u>	<u>False</u>
17. A welding helmet is sufficient eye protection.	—	<u>X</u>
18. Gloves, ear plugs or muffs, or both, and long sleeves need only be worn when spraying certain materials.	—	<u>X</u>
19. Respiratory equipment should be worn when spraying toxic materials, but need not be worn otherwise unless felt necessary by the operator.	—	<u>X</u>
20. No spraying should be performed without a procedure.	<u>X</u>	—
21. Part temperature can be controlled by reducing amperage.	—	<u>X</u>
22. The secondary gas should be turned off when the ammeter drops to 250-300 amps.	—	<u>X</u>
23. The "Run-Off" button should be pushed when the ammeter shows about 100 amps.	<u>X</u>	—
24. It is necessary to check the electrode for replacement whenever replacing the nozzle.	<u>X</u>	—

B. Powder and Wire Combustion Spraying

	<u>True</u>	<u>False</u>
1. Structure of sprayed steel is different from cast, rolled, or drawn steel.	<u>X</u>	—
2. A coating sprayed at 45° to the surface is just as good as one sprayed at 90°.	—	<u>X</u>
3. When heating I.D.'s to improve bond, 600° F (315° C) is an approximate temperature to use.	—	<u>X</u>
4. If small light blue streamers appear in the flame, the oxygen pressure is too high.	<u>X</u>	—
5. The melting end of all wires should always be even with the front of the air cap.	—	<u>X</u>
6. When spraying dual coatings, the thickness of the first coat is not critical.	—	<u>X</u>
7. When spraying molybdenum for a bond coat, the initial passes are put on at 6-8 in. (152-203 mm),		

after which the gun is moved into 2-3 in. (51-76 mm).	—	<u>X</u>
8. As a general rule of thumb, the travel speed of the work piece in surface feet per minute should be fifty or higher.	—	<u>X</u>
9. Maintenance of the guns is not so important as spray technique.	—	<u>X</u>
10. A small flame or noise at the nozzle after the gun has been shut off shows a leak in the gas valve.	<u>X</u>	—
11. Wire gun valves should be lubricated after every 500 hours of use.	<u>X</u>	—
12. Oil in small amounts on the wire is not critical since it will be consumed in the flame.	—	<u>X</u>
13. Kinky wire will cause sticking in the gun.	<u>X</u>	—
14. Low spraying speeds increase the oxide content in the deposit.	<u>X</u>	—
15. Cracking can be minimized on heavy coatings by interrupted spraying.	<u>X</u>	—
16. After grit blasting, the area to be sprayed must not be touched or contaminated.	<u>X</u>	—
17. No wire should be in the gun when adjusting the settings.	—	<u>X</u>
18. Molybdenum is a stainless steel wire.	—	<u>X</u>
19. If something happens to sprayed coatings during the process, the defect can be covered over with added spray.	—	<u>X</u>
20. Ceramic rods can be sprayed using the same gun as that for wire coatings.	—	<u>X</u>
21. Poorly bonded coatings can usually be traced to contaminated gases.	—	<u>X</u>
22. Thick coatings can be deposited faster by increasing wire feed speed.	—	<u>X</u>
23. A "flashback" will result when wire feed is too fast.	—	<u>X</u>
24. Compressed air should be turned on after the wire gun is ignited.	—	<u>X</u>

6.3 Consumables

6.3.1 Spray Materials

Metal Wires and Rods. The wire and rods used in spraying should always be certified for coating applications. Some of the requirements are

- Chemical composition
- Physical dimensions
- Surface appearance
- Physical condition/strength
- Camber or cast

Though not covered by universal industry standards, the chemical composition of metallic wires and rods is determined by utilizing standard procedures. Chemical limits for most of these products are listed in military specification MIL-W-6712, Rev. B, *Metallizing Wire*. Materials for spraying should meet this or other industrial specifications.

ASTM - American Society for Testing and Materials
- *Annual Book of ASTM Standards* covers the general requirements for conventional wire types under Section 1 and 2, in the appropriate volume for the metal involved.

AWS - American Welding Society - *Filler Metals Specifications*, A5 series, give such data as classifications, composition, details of manufacture, certification, test methods, marking, and packaging.

SAE - Society of Automotive Engineers - *Aerospace Materials Specifications* covers metals according to product form and temper.

SAE also publishes a reference guide with a cross index of chemically similar specifications - *Metals and Alloys in the Unified Numbering System*.

The roundness and diameter of wires has a direct effect on sprayability and feed. Oversized wires may not feed. Oval shaped or loose fitting wires permit combustion gases to flow backwards, behind the nozzle, into the drive rolls. This could result in a fire, explosion, or both. Wire or rod should be $+0 - 0.004$ in. ($+0$ mm - 0.10 mm) of the indicated nozzle bore diameter.

Wrought spray stock should be clean, have a smooth surface, be free of shavings, nicks, or kinks which may cause binding within the nozzle. The material should not be oxidized, corroded, or contain sulfides and other contamination which may affect the quality of the spray deposit. This includes drawing/extruding lubricants such as grease, oils, or graphite.

Wires are provided in coils or on spools. Wire/rod sized 1/8 to 3/16 in. (3.2 to 4.8 mm) is used for combustion

spraying. Material of 6 to 13 gauge (4.1 to 1.8 mm) is used for arc spraying. The wire should not overlap itself, so it can be freely fed to the gun without knotting. The cast or curvature of the wire should not be tight. Wire with a tight cast, if not properly straightened, may cause binding within the spray head or wandering of the electric arc. The wire should possess sufficient ductility and strength that, on bending or pulling, it does not break. Materials, such as tin and zinc, should be sufficiently hard to resist flattening or gouging by drive rolls. Wire should be properly packaged, some with dessicants, for protection during storage and shipping.

Powders. Wires are wrought products, produced by either drawing or extruding, and providing a consistent, homogenous product. In contrast, powders, while consistent in method of manufacture, are different from lot to lot. These differences are in particle configuration and size distribution.

The quality of powders for thermal spray coatings depends upon several basics. Many methods can be employed to manufacture powders, but only two have any commercial significance:

Mechanical processing of solid materials

Atomization of liquid materials

Mechanical processing of solids involves pulverizing and milling. Liquid metal may be atomized by techniques using gas, water, centrifugal force, or mechanical means. Particle sizes and shapes may vary both within and between methods of manufacture. All powder particles of similar chemical composition may not behave in the thermal spray gun in a manner identical to differently sized particles. It is necessary to characterize each powder in detail for successful reproduction. Materials should be spray tested using the thermal spray devices intended for their deposition.

Particle Size Distribution. Powders are a specific blend of various, predetermined sizes. The greater the sieve number the smaller the openings in the screen. A 20 mesh sieve has a standard opening of 850 microns (22 μ m), a 400 sieve is 38 microns (1.1 μ m).

Consider a powder designated -140 + 325 mesh; that is, containing particles within the range of 106 microns (2.7 μ m) to 45 microns (1.1 μ m). A powder this broadly classified should be more fully characterized in terms of the several intermediate screens. Between the 140 and 325 screens are four others: 170, 200, 230 and 270. Particle sizes may have to be tailored to improve coating properties or deposit efficiency.

Standard methods exist for evaluating powders, such as ASTM specifications B214, *Sieve Analysis of Granular Metal Powders* and E11, *Wire-cloth Sieves for Testing Purposes*.

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For powders finer than 50 microns (1.25 μm), a variety of procedures is available. Many are time consuming if absolute values are required. Approximate or empirical methods which give changes or trends are usually adequate.

Test methods which can be employed to test fine particle sizes are

- (1) Direct measurement and counting, using an optical or electron microscope
- (2) Automatic counting, using a "flying spot" microscope
- (3) Methods based on settling or transport rates in still or moving currents of liquids or gases
- (4) Methods dependent upon permeability to gases or to air
- (5) Methods of measurement of specific surface, as for example by absorption of gases, liquids, or dyes
- (6) Methods based upon centrifugal forces
- (7) X-ray line-broadening techniques

In these methods of measurement, reproducible results are preferred even when they do not represent absolute values. Reference ASTM standard methods include B293, *Subsieve Analysis of Granular Metal Powders by Air Classification*, B212, *Apparent Density of Free-Flowing Metal Powders*, and *Special Technical Publications* No. 140 and No. 234 on Particle Size Measurement.

Apparent Density. Apparent powder density is an indication of particle size distribution and shape. Determinations are made by weighing the powder that occupies a specified volume either after it has fallen from a specified height from an orifice, or after being subjected to a specified method of tapping, shaking, or vibration. ASTM B212 covers the subject in detail. Although laboratory determination of apparent density provides essential information, it does not necessarily indicate powder flowability from a hopper through a feed tube to the spray nozzle.

Rate of Flow. Powder flow rates can be determined in the laboratory by measuring the rate at which a specific weight or volume of powder flows through a small orifice at the base of a funnel. Most instruments of this type are based upon the Hall flowmeter, and are specified in ASTM B213, *Flow Rate of Metal Powders*.

In determining powder flow properties, the equipment should be free of magnetic or static electrical fields which may influence the powder or the instrument.

When evaluating powders, it is imperative that they be dry. Drying may be accomplished using heat or desiccants. Whichever method is used, care should be exercised to avoid damaging the powder.

Sprayability. Testing of thermal spray materials includes determining the chemical and physical properties

of each material and its behavior in the thermal spray gun. This sprayability testing includes feed and deposition characteristics, plus an evaluation of the deposited product.

Powders should be free flowing to prevent clogging of powder feeders, injectors, gun nozzles, or feed lines. Feed rate or spray rate is the measure of flowability. This is expressed as pounds per hour (lbs/hr) or grams per minute (g/min). When determining spray rate, equipment configuration and gas pressures and flows should be specified, as they would for the actual spray operation. To begin a deposit efficiency test, powder flow should first be started, and the powder feeder should reach full speed (rpm), achieving a smooth flow rate. Conditions should stabilize within ten to twenty seconds; powder then is collected in a clean container for a prescribed period, such as one or two minutes.

Efficiency may vary with target configuration, size, and amount of overspray. Deposition efficiency is the ratio of sprayed material adhering on a large flat surface compared to the amount of material sprayed. Material counted is confined within the borders of that surface. Deposit efficiency, expressed as a percentage, is the ratio of coating weight to the weight of powder sprayed.

Example:

A coated panel, minus the weight of that panel, weighs 1.4 ounces (40 grams). The time duration for deposition was two minutes; spray rate was 0.88 ounces (25 grams) per minute. Deposit efficiency is 80 percent, computed as follows:

$$\frac{1.4 \text{ oz.} \times 100}{0.88 \text{ oz./min} \times 2 \text{ min}} \text{ or } \frac{40 \text{ g} \times 100}{25 \text{ g/min} \times 2 \text{ min}} = 80\%$$

Ceramic rods are inspected for characteristics similar to wires; i.e., size, surface condition, roundness, and chemical integrity. Rods that are curved can break in the drive rolls causing binding or damage to the spray gun.

Rods are usually 3/16 or 1/4 in. (4.8 or 6.4 mm) in diameter, and are generally supplied in lengths from 18 to 24 in. (460 to 610 mm). Color varies with composition, as follows:

Refractory	Color
Aluminum Oxide	White
Magnesium Aluminate	White
Zirconium Oxide	Tan
Zirconium Silicate	Tan
Chromium Oxide	Dark Green/Black

Contaminated rods, especially when short or curved, should not be used since defective coatings or lowered productivity, or both, may result.

6.3.2 Gases

Compressed Air. Compressed air is the single most widely used gas in thermal spray coating applications. The compressed air utilized should be of proper quality to assure a reliable end product.

The Compressed Gas Association (CGA) *Commodity Specification for Air* (CGA No. G-7.1) presents limits on the impurities for atmospheric air (see Table 6.3.2A), and for air synthesized by blending oxygen and nitrogen. Atmospheric air contains a wide variety of trace contaminants such as water and oil.

Typical operating systems include in-line water and oil filters located between the compressor and the spray device. These should be inspected and cleaned periodically to assure uncontaminated dry air. This should be an established in-house **STANDARD PRACTICE**. Where greater control is required, techniques and instruments are available to determine dewpoint.

Oxygen. Four grades of gaseous oxygen, E through H, Table 6.3.2B, are satisfactory for flame spray applications. These tables are a digest of Compressed Gas Association (CGA) data as it applies to thermal spraying. Water content and dewpoint both affect coating quality. The user should establish in-house standard practices to

maintain oxygen quality. Water content is determined as outlined under compressed air, Table 6.3.2A - Note 2, and by using a dewpoint analyzer, in which the temperature of a viewed surface is measured at the time frost first begins to form.

Fuel Gases. Refers to combustible gases used in the gas flame spray process. The more common gases are acetylene, hydrogen, propane, and methylacetylene propadiene. These gases should have a minimum purity of 99.6%. Acetylene should not have an excess of acetone vapors, because they lower the flame temperature and propagation rate. Acetylene should not be drawn off at a rate greater than 1.5% of the total gas available in the cylinder or at pressures greater than 15 psi (103 kPa).

Plasma Gases. Plasma forming gases include argon (A), nitrogen (N₂), and hydrogen (H₂). These gases are described in CGA specifications G-11.1 Commodity Specification for Argon, G-10.1 Commodity Specification for Nitrogen, and G-5.3 Commodity Specification for Hydrogen.

Argon. Table 6.3.2C lists the various commercial grades of argon, Grades D through H which are suitable for plasma spray applications. Gas constituents most often scrutinized are water content, dewpoint, and oxygen/nitrogen level.

Table 6.3.2A
Grades of compressed air for thermal spray use

Limiting characteristics	Type I (Gaseous)		Grade C	Grade D	Grade F
	Grade A	Grade B			
Contamination limits (Note 1)	atm	atm	atm/ 19-23	atm/ 19-23	atm/ 19-23
Water vapor		none condensed	(Note 2)	(Note 2)	(Note 2)
Hydrocarbons (condensed) in mg/m ³ of gas at Ntp (Note 3) ppm		none	5	5	5
Carbon monoxide ppm			50	20	10
Carbon dioxide ppm				1000	500

Note 1. The term "atm" (atmospheric) denotes the oxygen content (21%) normally present in atmospheric air. The numerical values denote oxygen limits for synthesized air (% by volume).

Note 2. The water content of compressed air required for any particular grade may vary with the intended use from saturated to very dry. If a specific water limit is required, it should be specified as a limiting dewpoint or concentration in ppm. Dewpoint is expressed at one atmosphere absolute pressure in temperature °F (760 mmHg) or in temperature °C (101.3 kPa).

Note 3. Ntp=normal temperature and pressure. Other than major constituents, all gas limits are in parts per million (ppm).

Note 4. Grade B or better air, less than 50% relative humidity and oil free, is strongly recommended for cooling and the operation of equipment. Grade D or better is required for breathing apparatus. The user should insist on the driest, cleanest air obtainable with the available equipment when operated per manufacturer's recommendations.

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Table 6.3.2B
Grades of gaseous oxygen for flame spray use

Limiting characteristics*	Grade E	Grade F	Grade G	Grade H
Oxygen min. %	99.5	99.99	99.995	99.995
Inert gases, ppm		45	30	Balance
Odor	none		none	
Water vapor, ppm	6.3	10	3.0	1.0
Dewpoint °F (°C)	-83 (-64)	-77 (-61)	-92 (-69)	-104 (-76)
Total hydrocarbons (as methane)		20	14	1.0
Methane	40		10	
Ethane (and higher)	3.0		3	
Ethylene	0.2			
Acetylene	0.05		0.05	0.05
Carbon dioxide	5.0	10	1.0	1.0
Carbon monoxide		10	1.0	1.0
Nitrous oxide	1.0		1.0	0.1
Halogenated refrigerants	1.0		1.0	
Solvents	0.1			
By infrared	0.1			
Permanent particulates	Type II 1.0 mg/L and none >1 mm		Type II (requires filtering)	
Fibers (<40 units dia.)	Type II none >6 mm in length			

* Except for oxygen, all gas limits are in parts per million (ppm).

Table 6.3.2C
Grades of argon gas for plasma spray use

Limiting characteristics*	Grade D	Grade E	Grade F	Grade G	Grade H
Argon min. %	99.996	99.997	99.9975	99.998	99.999
Water vapor, ppm	14.3	10.5	5.3	3.5	1.5
Dewpoint °F (°C)	-72 (-58)	-76 (-60)	-85 (-65)	-90 (-68)	-100 (-73)
Oxygen	7	5	3	2	1
Nitrogen	15	20	15	10	5
Hydrogen	1	1	1	1	1
Total hydrocarbons (as methane)	5	3	1	0.5	0.5
Carbon dioxide			1	0.5	0.5

* Except for argon, all gas limits are in parts per million (ppm).

Nitrogen. The various grades of nitrogen used in plasma spraying are listed in Table 6.3.2D. Major impurities to be ascertained are water content, dew point, and oxygen. The nitrogen gas grade nominally used is H or better.

Hydrogen. Hydrogen grades are listed in Table 6.3.2E. Gases equivalent to Type I grades F to K, or Type II grades A thru D, are employed for plasma arc spraying. Of concern are water content/dewpoint and oxygen level.

6.3.3 Miscellaneous Consumables. This category includes such items as masking aids, grit blast media, inks, paints, and sealers.

Masking Aids. Masking aids are divided into two groups - temporary and permanent. Permanent masking (generally hard tooling) is constructed to perform a singular task. Materials are hard rubber, silicon rubbers, and various metals including steel, brass, and copper. Metal masks should be bright, clean, and smooth. Chrome plate on steel helps to reduce overspray build-up. All masking should be inspected periodically for fit-up, dimensional correctness, and overspray build-up. This last check should assure that adherent overspray from a previous operation does not interfere with the deposition process.

Temporary masking includes tapes, inks, and paints. Tapes should be sufficiently resistant to both the roughening and spray operations. They should lie flat and not exhibit degradation during use. Paints and inks, usually applied to areas outside the roughened zone, should be capable of being easily removed, while not emitting fumes or vapors during the coating process.

Grit Blast Media. Abrasives for surface preparation and cleaning or roughening or both, are defined in military specification MIL-A-21380, *Abrasives for Blasting*, (see 3.2.6). Properties to be characterized and controlled are sharpness (angularity), size, and cleanliness.

Blast media should be recycled when practical due to their cost. Before reuse, the abrasive particles should be examined for sharpness with a 10 power magnifier. Inspect the media to assure that particles exhibit sharp, angular cutting edges. While refractory oxides will usually cleave along crystallographic planes, chilled iron grit will dull. This usually occurs after three to five cycles of use. Dulled blasting media should be discarded.

Since refractory oxide grains fracture along crystallographic planes and constantly present sharp cutting edges, the breaking down of the particles results in a finer media, eventually attaining the consistency of dust.

Table 6.3.2D
Grades of nitrogen gas for plasma spray use

Limiting characteristics*	Grade H	Grade J	Grade K	Grade L	Grade M	Grade N	Grade P
Nitrogen min. % (Note 1)	99.99	99.99	99.995	99.998	99.999	99.9985	99.999
Water vapor, ppm	11.4	3.5	16.2	3.5	1.5	1.5	1.5
Dewpoint °F (°C)	-75(-59)	-90(-68)	-70(-57)	-90(-68)	-100(-73)	-100(-73)	-100(-73)
Hydrocarbons condensed		0.1 (wt/wt)					
Total hydrocarbons (as methane)	5	3				1	
Oxygen	50	50	20	10	5	1	1
Hydrogen						1	
Argon, neon, helium						5	
Carbon monoxide						1	
Permanent particulates	Less than 1.0 mg/L	Less than 1.0 mg/L requires filtering					

Note 1: Unless shown otherwise, %N₂ includes trace quantities of neon and helium and small amounts of argon.

* Except for nitrogen, all gas limits are in parts per million (ppm).

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Table 6.3.2E
Grades of hydrogen gas for plasma spray use

Limiting characteristics*	Type I (gaseous) grades					Type II (liquefied) grades			
	F	G	H	J	K	A	B	C	D
Min %H ₂	99.95	99.95	99.99	99.995	99.995 (Note 1)	99.995	99.995	99.9995	99.9997 (Note 1)
Water vapor	32.0	7.8	3.5	3.5	1.5				
Dewpoint °F (°C)	-60(-51)	-80(-62)	-90(-68)	-90(-68)	-100(-73)				
Oxygen	10	10	5.0	5.0	1.0	1.0	1.0	1.0	1.0
Argon						9.0			
Nitrogen	400	400	25	20	20		2.0		2.0
Total hydrocarbons (as methane)	10	10	5.0	1.0	0.5		2.0	9.0 (Note 2)	
Neon									
Helium								39	
CO dioxide	10	10		0.5		1.0		1.0	
CO monoxide	10	10	10	1.0			.5		
Inorganic and organic sulfur compounds			2.0						
Hg vapor, ppb		4							

Note 1: May include up to 50 ppm neon and helium.

Note 2: Includes water.

*Except for hydrogen, gas limits are in parts per million (ppm). Mercury vapor is in parts per billion (ppb).

This is satisfactory for cleaning applications, but is unsuitable for roughening. Materials finer than 120 Mesh (125 μ m) should be discarded. Inspection should be performed in accordance with ASTM B 214, *Standard Test Method for Sieve Analysis of Granular Metal Powders*.

The test for powder cleanliness is visual inspection. Grit should be examined for contaminants such as grease, oil, water, scale, and masking residues. If the contaminants cannot be removed, the blasting medium should be discarded. Blasting equipment with built-in sizing control features (cyclones, screens, fans) is preferred.

Paints and Sealers. Paints and sealers used with thermal spray coatings are of organic or inorganic base. Their uses are many and their compositions complex.

It is strongly recommended that the primary manufacturer be consulted for application and evaluation techniques.

6.4 Equipment

The certification or verification of equipment to apply coatings may be through calibration of meters and gages, or through demonstration of coating application. A combination of these methods proves most suitable.

Electrical meters are easy to calibrate. Remove the instrument from its mounting, install it in a test rig, and evaluate its performance against a known standard. Gas flow and pressure gages are similarly calibrated to a known standard.

6.5 Quality Control of Coatings

6.5.1 Destructive Test Methods. Adhesion is the most desirable property of a thermal spray deposit. Consequently, this section will concentrate heavily on that attribute. Also presented will be test methods for the determination of other coating properties which may be of interest.

Standard Method of Adhesive/Tensile Strength Determination. The adhesion of a thermal spray coating to a substrate is the principal property for determining its quality and application. Coatings on metal substrates are tested in a manner similar to that described by ASTM C633-79, *Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings*. The test consists of coating one face of the substrate and then bonding a loading fixture to the coating with a suitable adhesive. The coating is then ground around the base of the loading fix-

ture so that shear stresses are avoided during the tensile test of the assembly. The test is performed at room temperature due to high temperature limitations of the adhesives. The coatings should have greater than 0.015 in. (0.38 mm) thickness because of adhesive penetration into the coating. The tensile adhesion test is easy to perform and is useful in quality control for providing a ranking of various types of spray systems and resulting coatings. The mode of coating failure, shown in Fig. 6.5.1A, will be either adhesive or cohesive. An adhesive failure occurs when the entire coating separates from the substrate. True adhesive failure rarely occurs because of the rough nature of the substrate surface. Failure in this case takes place near the interface where the fracture surface exhibits areas devoid of coating. A fracture occurring entirely within the coating is of a cohesive nature.

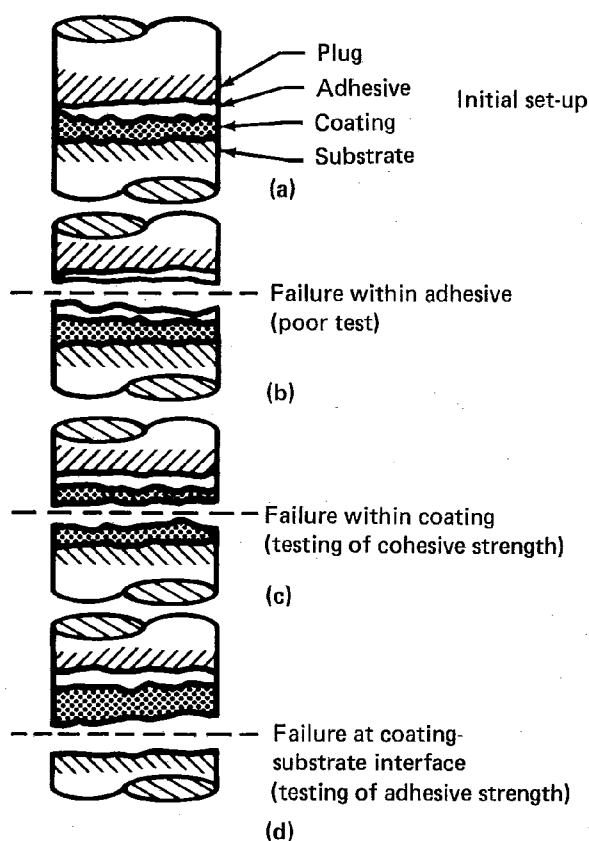


Fig. 6.5.1A — Modes of coating failure

The strength is found from the simple relation

$$UTS = L/A$$

Where UTS = cohesive or adhesive strength - force per unit of surface area

L = load to failure - force

A = cross-sectional area of specimen

Many other techniques (see Bibliography) have been devised based on this test method; they all suffer from the possibility of test error and disadvantages such as the following:

(1) If failure occurs within the adhesive only, the area within the coating is used in the calculation to find the stress at failure. This method is inaccurate because the test result has indicated either defective bonding of the sample or askew loading of the sample.

(2) The manner in which the coating is loaded is not typical of stresses observed during its service life.

(3) The value of the measurement is influenced by the symmetry of the experimental setup, and by the penetration of epoxy into pores of the coating.

(4) The adhesive must have a greater tensile strength than the coating.

(5) The elevated curing temperature of the adhesive may affect the adhesion of the coating, since the residual stress distribution may be altered.

(6) The fracture surface of a test specimen may exhibit both adhesive and cohesive failure. In this case, the tensile adhesion test yields only an average value when both of these failure modes act together. It does not establish which failure mode limits the strength of the coating.

(7) The mechanism by which the coating structure contributes to the adhesion is not readily ascertained without a quantitative assessment of the various modes of adhesion. The tensile adhesion test does not readily permit such mechanistic studies.

(8) Flaws in the form of microcracks, porosity, and second phase inclusions within the coating will affect adhesion. The role of these microstructural features of the coating cannot be examined by the tensile adhesion test.

Shear Strength. Figure 6.5.1B shows experimental arrangements used to carry out shear tests. For example, (a) and (b) show how bushings transmit a shear load applied perpendicular to the specimen surface. The applied force causes the deposited splats to slide over the substrate surface so that an additional frictional force must be overcome. If this force exceeds that of particle adhesion, then the rupture of the deposit will appear to be cohesive. The results of the shear test are influenced by the machining of the test specimens, and a certain clearance must be maintained between the specimen and the bushings.

Figure 6.5.1B illustrates a method not affected by these problems, i.e., the coating is sheared in the as-sprayed condition.

Compressive Strength of Coatings. Samples are sprayed to a thickness of 0.33 in. (8.4 mm). From the

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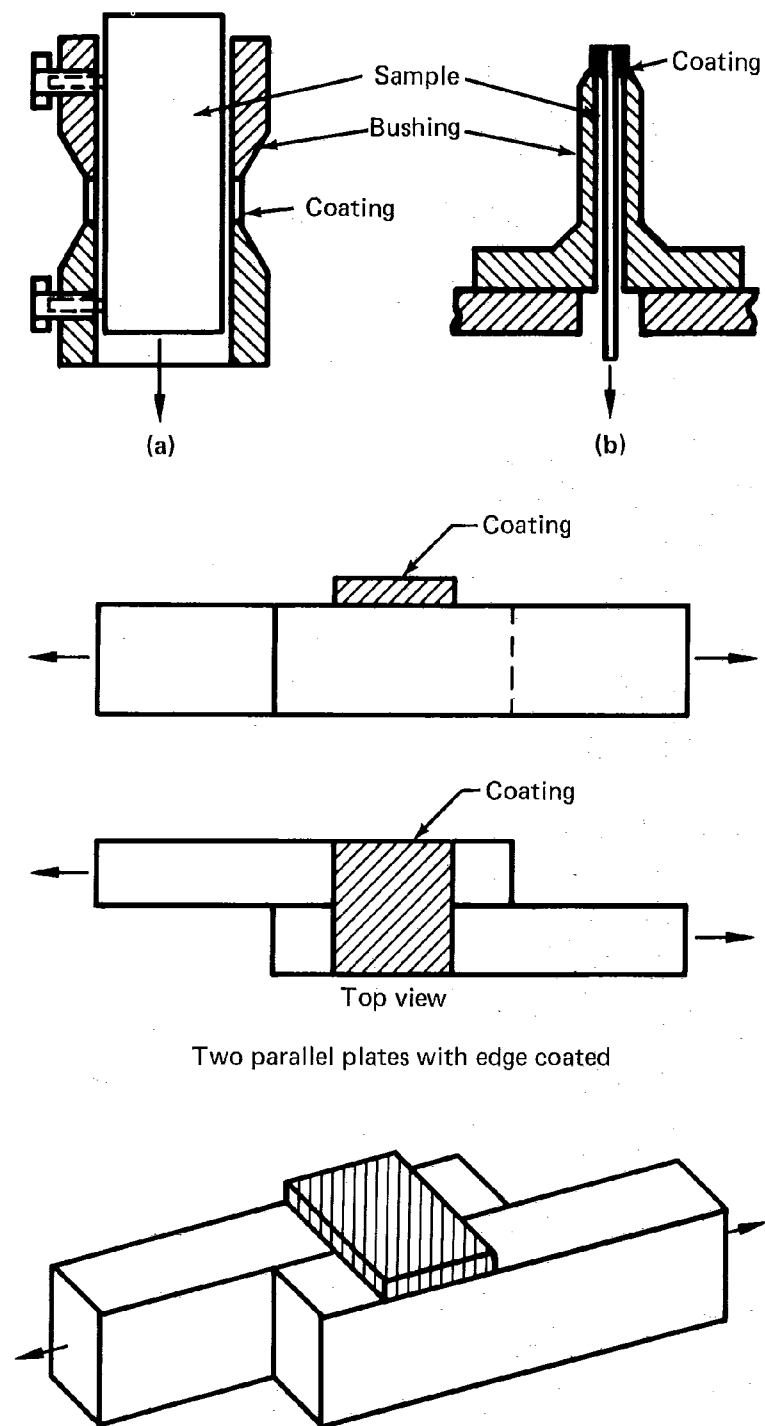


Fig. 6.5.1B — Specimens for shear tests

sprayed layer, minus the substrate, the individual specimens are machined. Specimen size is approximately 0.33 in. (8.5 mm) diameter by 0.20 in. (5 mm) thick. The sample is placed between a male and female die, and loaded in compression in a tensile machine. Compressive strength is given by the formula

$$G_d = F_d/A$$

where G_d = compressive strength, psi (kPa)

F_d = maximum compressive force, pounds (kg)

A = initial area, sq. in. (mm²)

In addition to the compressive strength, the percentage yield, Y , may be determined from

$$Y = (h_1 - h_2)/h_1$$

where h_1 = height of specimen before the test

h_2 = height of specimen after the test

Evaluation is by comparison of the results with each other and published data.

Nonstandard Tests for Adhesion. The resonance test is applied to coating deposits 0.040 in. (1 mm) or thicker that are sprayed onto shafts, or machine ways. The procedure involves tapping the deposit with a steel rod. The rod should be 3/8 to 1/2 in. (9.5 to 12.7 mm) in diameter and 4-3/4 in. (120 mm) long. The workpiece should be able to vibrate freely. A metallic sound represents a good bond, while a dull sound indicates that the coating deposit is partially adherent or totally detached.

The chisel test is used for spray deposits to determine whether base metal roughness is sufficient to ensure bonding. The chisel is placed with its bevelled edge at the interface of the coating and the substrate, and the head is struck. With a satisfactory bond, only small pieces of the coating are loosened, and there is no further separation of the deposit. With an inadequate bond, large sections of coating will come loose. A chisel test is also used for thin deposits; for example, 0.02 in. (.5 mm) or thinner corrosion-protection coatings. It is especially suitable as an in-process test. If random samples are taken from the workpiece, it is necessary to respray these areas after testing. The test involves cutting a 3/4 x 3/4 in. (19 x 19 mm) square in the deposit with a chisel having a bevelled, ground, sharp edge. The chisel is held in an angular position, 30 to 60 degrees to the work, so that damage is limited outside the square. The coating deposit is cut through until the substrate is exposed. The goal is to lift the spray deposit in the form of a square. The bond is adequate if the section is crumbly - smaller than 1/4 in. square (6 x 6 mm); it is inadequate if larger than 1/4 in. square (6 x 6 mm) pieces readily lift.

There are two adhesion tests of coated plastics. Plastics require different testing because of lower bond strengths [200-1000 psi (1.4-6.9 MPa)] and softer substrates. The first resembles the tensile test described, but uses a small hand operated pull tester (Fig. 6.5.1C).

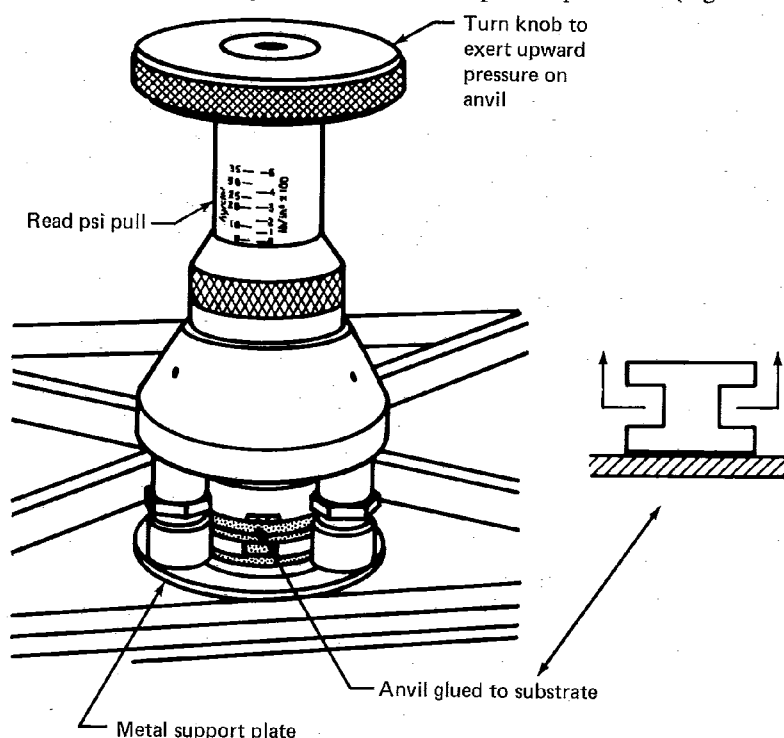


Fig. 6.5.1C — Pull tester for adhesion tests of coated plastics

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A premachined anvil, 3/4 in. (19 mm) diameter, is epoxied to the coating and encased with a pressure ring to distribute stresses. The pull tester is then positioned and secured, exerting upward pressure against the anvil. The unit contains a calibrated spring and indicator which returns to its home position when the anvil is removed. A direct reading of the adhesive strength is the result. Failure of coated plastics is generally adhesive.

A scratch test, ASTM D3359-78, *Standard Methods for Measuring Adhesion by Tape Test*, is also used. It consists of scoring a cross hatch pattern on the sprayed surface, overlaying it with adhesive tape and then pulling the tape away (Fig. 6.5.1D). Examination under a 10x pocket microscope indicates the percentage of the coating that has been lifted.

In many plastic coating applications, such as shielding, 200 psi (1.4 MPa) or better is deemed satisfactory, and if it meets the requirements of ASTM D3359-Method B, acceptance is assured.

Both the tape and scratch tests may be spray repaired and thus, are considered nondestructive. An additional advantage of these tests is that they may be performed on actual hardware, not sample coupons.

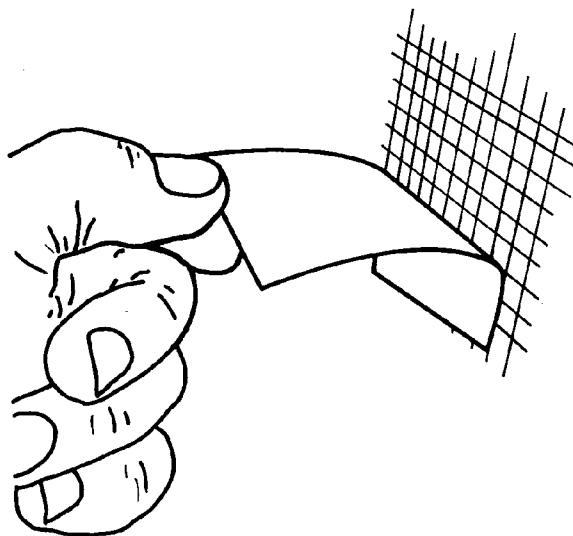


Fig. 6.5.1D — Scratch test, ASTM D3359-78, Method B, Standard Methods for Measuring Adhesion by Tape Test

Cohesive Strength. Cohesive strength is a measure of interparticle attraction. It is determined by using a free standing, sprayed specimen; that is, a sample of coating deposit detached from its substrate. This sprayed deposit is machined to a standard tensile specimen size and tested in a conventional manner.

The heterogenous structure of sprayed coatings causes them to be less hard than cast or wrought stock. The hardness of individual particles that compose the coating is higher than the overall coating. Hardness of the coating is referred to as its macrohardness; whereas particle hardness, accomplished using light loads and magnifiers to read the impressions left by those loads, is the microhardness.

Macrohardness Testing. The macrohardness test generally utilized is the Rockwell Superficial Hardness Test. Indentor loads are light and spread over the largest area possible. The Rockwell 15Y and 15W scales are recommended for softer materials.

In determining macrohardness values, coating thickness is of the utmost importance. Table 6.5.1 is provided as a guide. All thicknesses are after grinding or machining.

**Table 6.5.1
Minimum thickness requirements for
Rockwell hardnesses determination**

Rockwell Scale	Thickness (in.)	(mm)
15N	0.015	0.40
30N	0.025	0.64
45N	0.035	0.90
A	0.040	1.0
B	0.060	1.6
C	0.070	1.8
D	0.050	1.3
15Y	0.070	1.8
15W	0.070	1.8

The scleroscope (rebound) test is used for measuring steel coatings with thicknesses greater than 0.040 in. (1 mm). The tester is brought into contact with the machined finish coating. Release of a lock causes a small rebounding hammer to contact the test specimen. Rebound of the hammer actuates the pointer on a scale. The values indicated by the pointer may be converted into Rockwell or Brinell hardness values. This test is used for comparison and verification only.

Microhardness Testing. Two types of microhardness testing are the Knoop test and the Vickers or Diamond Pyramid Hardness (DPH) test. The Knoop Hardness Number (KHN) is measured with a rhomboid diamond indenter under loads from 10 to 1000 grams. A 50 gram load is preferred for determining the hardness of single particles, as the light load aids in confining the impression within the boundaries of the splat.

The Diamond Pyramid Hardness (DPH) or Vickers Test finds application in evaluating deposits of hard materials, especially carbides. The load used is 300 grams. The impression is spread over several particles, and the hardness is the ratio of the load to the area of the impres-

sion, computed from the length of the diagonals of the square impression.

The **Hoffman Scratch Hardness Test** is a tool for evaluating the abrasability of clearance control coatings. A loaded stylus is drawn across an as-coated surface, minimum thickness 0.035 in. (0.89 mm), to scratch its surface. The width of the scratch indicates abrasability; the wider the scratch, the less cohesive the coating and the greater the abrasability.

A **file scratch test** is another indicator for estimating the relative hardness of sprayed steel deposits. A sharp flat file should be used. It is helpful to make direct comparison with test bars of known hardness. Evaluation is based upon the fact that, with extremely hard coatings, the file fails to bite, but it easily bites on moderately hard coatings.

Wear Tests. The types of wear tests usually performed on industrial sprayed coatings are metal-to-metal lubricated sliding wear, dry sand rubber wheel abrasion, and solid particle erosion tests.

Sliding wear tests are useful for determining metal-to-metal wear of various mating combinations. Figure 6.5.1E shows the principle of operation of a typical test machine. The test specimen, a 0.80 in. x 2.33 in. (20 x 60 mm) sample, is machined from a spray coating of 1/4 in. (6 mm) thickness. The specimen surfaces are ground parallel to each other. Evaluation is by comparison with homogenous cast or wrought materials such as aluminum and steel. The same set-up without lubrication may be used for dry sliding wear.

Abrasion tests provide information on the ability of materials to resist erosion by hard particles. In the standard dry sand rubber wheel test, shown in Fig. 6.5.1F, an abrasive of specific grit size is applied between the test specimen and a rotating wheel, with a rubber rim of specified hardness.¹ Specimens are weighed before and after the test. The weight loss is converted to volume loss in cubic inches.

Erosion tests utilize a small grit blaster with an alumina nozzle of known diameter. A predetermined quantity of 50 micron (1.25 μ m) alumina powder is blasted against the specimen, using an air flow of 25 CFH (12 L/min) until the powder is consumed. The elapsed time is nominally 100 seconds. The depth of erosion is measured. Erosivity is calculated from

$$E = t/D$$

where E = erosivity

t = time in seconds to spray the measured amount of alumina

D = depth of erosion

1. Refer to ASTM G65-1981, *Practice for Conducting Dry Sand/Rubber Wheel Abrasion Test*, Philadelphia: American Society for Testing Materials.

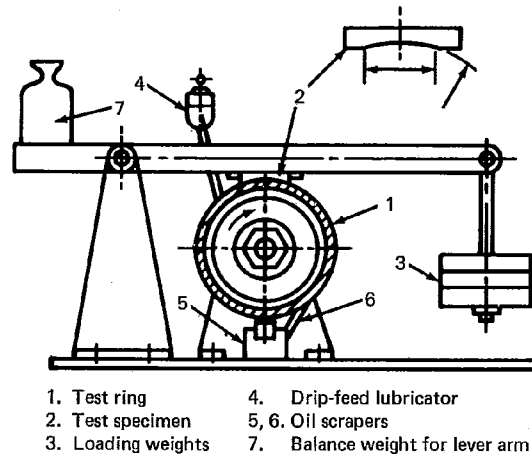


Fig. 6.5.1E — Principle of operation of the metal-to-metal lubricated surfaces sliding wear testing machine

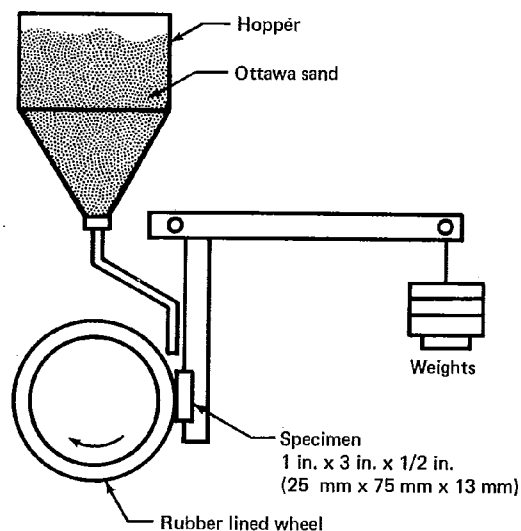


Fig. 6.5.1F — Schematic diagram of test apparatus for dry sand rubber wheel abrasion test

Fatigue Tests. Fatigue tests are used to determine the effects of

- new methods of surface preparation
- new materials
- application process changes

The coatings or processing should be applied to standard base metal test specimens, whether for high or low cycle fatigue (HCF, LCF). Evaluation is based upon previously established fatigue curves and data.

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Corrosion and Oxidation Tests. Resistance to corrosion and oxidation is tested to estimate the life of a particular coating in a given working environment. These are accelerated tests, such as ASTM B117, *Salt Spray (Fog) Testing*. The test environment contains an anticipated contaminant, such as hydrocarbons, salts, sulfur, etc. Test temperature is controlled. In most cases, these are in-house tests designed for a particular product which is engineered to perform under specific conditions.

Thermal Shock. Two simple tests for thermal shock are as follows:

(1) A coated sample is heated and rapidly quenched into cold water.

(2) One side of a coated sample is heated while the opposite side is cooled.

The former is an empirical test to evaluate differences in coefficient of thermal expansion; the latter is excellent for ascertaining spalling characteristics of sprayed ceramic coatings, especially thermal barriers. Test temperatures, times, and cycles will vary with testing site, coating, and use.

Metallographic Evaluation. The subject of preparation of samples for metallographic evaluation is well documented, but there are some special considerations required for thermal spray coatings. All efforts are directed to preventing the formation of artifacts and producing a sample suitable for studying the degree of microporosity, oxide inclusions, oxide layers, structural composition, coalescence, the effect of surface roughening, and diffusion layers. Micrographs of thermal spray deposits reveal the effects of such spraying conditions as energy setting, spray distance, and atomization.

To determine the level of oxide inclusions and degree of porosity, it is necessary to study both transverse sections and surface samples from segments of the spray deposit. Examination is at a magnification of 100x or greater. The junctions of the spray deposit and base metal are also examined at high magnification. For the examination of diffusion layers, very high magnifications, usually 1000x, are used. Evaluations of the roughened substrate are simplified by etching the spray deposit immediately prior to viewing. Delayed examination gives false indications, as it is not possible to completely remove the etchant from coating pores, and the section tends to be altered with time as the etch leeches out. The same undesirable reactions follow electrolytic polishing. Avoid ultrasonic cleaning, as it causes severe particle pull-out.

Preparation time for grinding and polishing of sections should be as short as possible. This applies particularly to soft materials (e.g., lead, zinc, aluminum, and copper). For hard materials, diamond polishing abrasives are recommended.

In addition to visual inspection at low magnifications of 10x to 50x, it is possible to make quantitative evalua-

tions of voids, oxide inclusions, and other discontinuities. Measurements of particle sizes, thickness, and diffusion layers may be made with a high degree of accuracy. The quantitative television microscope (QTM) is particularly suited for determining percentages of oxides and porosity.

Coating Density. Coating density is determined by machining a measurable volume of sprayed coating so that all surfaces are flat and parallel. The volume is calculated and the weight recorded. Coating density is as follows:

$$D = W/V$$

where:

D = density

W = weight

V = volume

To ascertain how coating density compares with the density of the original material, the actual density is divided by the theoretical values, and expressed as a percent.

Miscellaneous Physical Tests. Included in miscellaneous physical tests are thermal expansion, electrical resistivity, shrinkage, residual stress, and thermal conductivity. Testing in these areas has been relatively limited.

6.5.2 Nondestructive Evaluation. The nondestructive evaluation (NDE) of thermal spray coatings is primarily confined to studies of thickness, roughness, visual appearance, and liquid penetrant tests. Well established procedures use calipers, micrometers, height and thickness gages, profilometers and replica techniques, magnifiers, stereoptic microscopes, and liquid penetrants. Sophisticated techniques for detecting thermal spray properties are currently being evaluated. Many of these NDE concepts are being pursued in laboratories, and they will eventually play an important role in the application of new examination technology. These fall into several major groups, based on thermal, light, sound, magnetic, and electrical measurements.

Thickness Gages. The thermal spray industrial standard is the magnetic thickness gage. This is a direct reading gage that measures the thickness of any nonmagnetic coating on an iron or steel base. It is held against the work, and the thickness of the nonmagnetic coating appears on a dial. The gage reports the distance that has interrupted its magnetic circuit.

Coating thickness on nonconductive surfaces can be measured using sensitive resistance measuring equipment. The instrument reads directly in milliohms, which are converted to coating thickness. Care must be taken when operating within 1/2 in. (12.7 mm) of sharp angles and edges; these drastically affect readings. A calibration curve can be generated using samples of known thicknesses. Zinc on plastic yields typical values (Table 6.5.2).

Table 6.5.2
Resistance vs. thickness for
zinc coatings on plastic

Thickness		Resistance
mils	(mm)	milliohms
1	(0.025)	6.08
5	(0.127)	4.98
10	(0.25)	2.51
18	(0.20)	1.98
30	(0.76)	.094
100	(2.5)	.054
200	(5.1)	.041
300	(7.6)	.033

Thermal Methods to Observe Lack of Bond. The rate at which the coating surface loses heat depends on two principle factors: (1) the conductivity of the coating, and (2) its thermal contact with the substrate. Any physical differences between one part of the coating and the next, or any change in the bonding, will therefore affect the surface temperature and be detectable. There are three methods of detecting small changes of surface temperature: infrared (IR) camera, liquid crystals, and thermographic paints. They presently are being applied to laminates, honeycombs, and adhesive bonds.

Infrared cameras are based on liquid nitrogen-cooled indium antimonide IR detectors. They display a television-type picture with sensitivity of 3°F (1.6°C) at 86°F (30°C). Picture storage and slow playback facilities for the analysis of rapid events are available, as are various lens systems for distant or close-up work. Success depends upon the rapid response and storage capability of the camera system. A pulse of heat may be applied to the coating, and the development of the resultant temperature pattern may be observed; or a temperature gradient may be maintained through the depth or across the face of a coating. Unbonded surfaces heat up more rapidly than bonded areas. Nevertheless, small variations in surface temperature are transient, and too fast for the eye to follow; hence, the necessity for system storage and slow playback. Temperatures both above and below room ambient and different geometries are being studied. The tests are relative and not diagnostic because nonstandard patterns of heat flow could result from a number of different causes. Using different heat injection positions, an experienced operator will come to associate certain patterns with certain defects. The best use of thermal methods for analysis is in repetitive work.

Liquid crystals are long chained organic compounds

which display a degree of order in their molecular arrangement. The ordered state exhibits various optical properties not shown by a disordered state. The order/disorder change is brought about by thermal stress. Liquid crystals are available as paints or in tape form. This NDE method is presently applied only in examining thermal insulation coatings on low mass components.

Thermographic paints are phosphors activated by ultraviolet light. The phosphorescence is subsequently quenched by heat, over a narrow range of temperature, and the range of operation can be tailored to suit a particular requirement. They offer the possibility of direct application to a coating so that spatial and thermal resolution can be achieved.

Light Methods to Observe Lack of Bond. The application of interferometry and holography to sprayed coatings on metal components is in the laboratory stage. They are capable of detecting very small changes in the surface of an object, such as a faulty section of a coating. Light methods require more extensive development before they can detect the subtle defects that can cause a poor bond.

Sound Measurements. Acoustic methods generate information relating to mechanical properties. The transmission of sound through a solid is closely linked with its soundness. Ultrasonic pulse-echo techniques can successfully detect areas of poor bonding. The method is under development.

Acoustic resonance instruments scan through a range of frequencies and pick up the resonance levels, yielding information regarding unbonded areas or other flaws. Relatively thin layers of coatings sprayed onto thicker and denser metallic substrates are insensitive to this technique.

Release of strain energy in a solid, resulting in acoustic emissions, may be detected by a transducer at the surface. Application to sprayed coatings will require comparing emitted noises with those of an established standard.

Other NDE Methods. Eddy Current Testing is an electromagnetic method in which small currents are induced in a material. The flow patterns indicate inhomogeneities to a nearby coil for subsequent electronic processing. Eddy currents in ground-finished surfaces can reveal coating flaws.

Magnetic Flux Analysis employs alternating field and search coils to perform a complex analysis of the stray flux field. This method is useful only on ferromagnetic surfaces. It is a non-contacting method and does not rely on surface smoothness.

Chapter 7

Finishing of Coatings

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Chapter 7

Finishing of Coatings

7.1 Introduction

The means of finishing thermal sprayed metals, ceramics, and cermets is an area of varied opinion and practices. The many methods of finishing coatings have produced the 'proper' methods, procedures, and techniques that should be used to yield specific results. This information refers to surfaces that need further finishing. In many instances, as in corrosion applications, no additional operation is necessary. Plasma transferred arc and fused coatings have more strength and are more homogeneous, and thus may not require the degree of special precautions outlined here.

The machining of coatings is troublesome for the inexperienced operator. Materials, that are abrasion resistant, are difficult to grind. The structure of the sprayed mass is porous; highly reflective finishes are difficult to achieve. The bond between the particles is primarily mechanical; therefore, individual particles can pull out if cutting pressures are excessive. Spray coatings are composed of well defined particles and have poor thermal conductivity compared to the same material in wrought form. Heat transfer away from the point of grinding is slow. The accepted methods, practices, and techniques used to grind and polish materials in their wrought form do not apply to the same materials when sprayed.

7.2 Finishing Methods

Thermal spray coating deposits can be ground and finished in many ways. The method chosen can range from simple hand polishing operations, to hand grinding with coated abrasive belts, or to more complex machining, such as the use of precision grinders. Factors which influence the choice of finishing method include type of material to be ground, shape of part, finish and tolerance required, type of equipment available, and economics. Generally, with most spray applications, the finer and more uniform the material applied the better the final finish.

7.2.1 Hand Stoning, Buffing, Polishing. Hand stoning, buffing, and polishing can be accomplished with an abrasive stone, stick, wheel, or paper. The surface finish of an as-sprayed deposit can be greatly improved in smoothness and appearance with minimal stock removal.

Hand stoning and buffing develop the most improved surface finish on soft metals. These metals, in addition to aluminum and zinc, are readily polished to a bright finish. The abrasive device is rapidly loaded, which requires frequent dressing. A coarse abrasive should be used initially, followed by progressively finer abrasives until the desired smooth finish is achieved. The type of material involved will largely dictate the specific sizes.

Carbon and stainless steel coating deposits are very difficult to hand stone or buff to a good finish.

Ceramics and cermets are hand stoned to a light finish with the proper choice of abrasives. This method is ideally suited for parts with unusual contours that otherwise would be difficult to finish.

While these are the easiest methods of finishing, care should be taken to avoid breaking through coating edges and, consequently, it may be difficult to maintain a uniform thickness.

7.2.2 Tumbling and Burnishing. When smooth finishes are required on a large quantity of very small parts or on parts with unusual contours, a tumbling or burnishing procedure can be cost effective. In tumbling, the parts are placed in a vibrating or rotating tub containing an abrasive medium and water. The interaction of the abrasive and parts polishes the coating. By selecting the proper abrasive and vibratory time cycle, specific finishes can be attained. Burnishing is accomplished in much the same manner as tumbling. Instead of trying to abrade the surface, hard metal balls are used to compress the surface. The smoothness of the resultant coating is a function of pressure and frequency of ball-to-part contacts.

7.2.3 Abrasive Belt Grinding and Polishing. Sprayed metals and ceramic coatings can be effectively ground and polished with coated abrasive belts. Abrasive belts are used to improve the surface produced by a prior operation

such as single point turning. Coated abrasive belts are used to perform the entire grinding and finishing operation. Developments in backing materials and in grain design have produced strong waterproof belts which are sharp and durable. Belts made from these materials produce excellent finishes with high stock removal rates. Abrasive belts provide several advantages over other grinding media; they cut without overheating, do not require dressing, and can be rapidly changed when worn. Belt costs are lower than comparable machining costs.

When grinding and polishing with coated abrasive belts, the part is fixtured or positioned in a lathe. The part is either traversed or rotated under the belt head. Belt speeds are generally 6,000 to 7,000 sfpm (30 to 35 m/sec). Part speeds range from 25 to 200 sfpm (0.13 to 1.0 m/sec), depending on part size, type coating, and type and size abrasive. Coarse grit belts are used for rapid stock removal; whereas, finer belts are used to improve finishes. Out-of-roundness in the coating is very difficult to remove by belt polishing, and alternate methods should be employed.

7.2.4 Machining

Shafts, Tubing, and Cylindrical Shapes. Machining of a sprayed coating involves special techniques. Advances in the cutting tool industry, together with faster, more precise, rigid machinery has, in recent years, opened up a new era of machining. This is particularly true of the harder tool materials such as ceramics, carbides, and cermets.

Carbide tools are generally used on machinable thermal spray coatings. Tool angles, and surface speeds and feeds are critical in the success of machining these coatings. Improper tool angles and tool pressure can result in excessive particle pull-out and destruction of the coating substrate bond. Properly sharpened tools can machine hard fused coatings with relative ease.

Machining of a spray coating starts with removal of the heavy overspray at the end of the coated area. Rough machining of the coating can be accomplished at the same or slightly slower speeds (surface feet per minute) and with approximately twice the amount of feed (inches per revolution) of finish machining. The depth of cut can range up to 0.030 in. (0.76 mm) thickness. Approximately 0.005-0.010 in. (0.13 - 0.25 mm) on the radius should be left for finishing. Removal may require multiple passes. See Tables and Figs. 7.2.4A and 7.2.4B for recommendations concerning carbide and high speed tools.

A properly sharpened cutting tool will wear flat at the contact point. This flattening has the effect of smearing the metal and can actually provide a better finish than would result with a sharp tool with a radius. However, should this flattening become excessive, heat buildup in-

creases rapidly, and particle pull-out occurs. Excessive heat buildup can result in catastrophic coating failure.

The newer cutting tool materials, such as boron nitride, oxide coated carbides, ceramics, and diamonds enable very hard metals to be successfully machined at very fast metal removal rates. For optimum results, when using these cutters, the use of rigid machinery is mandatory.

Flat Surfaces and Other Shapes. Not all machining is performed on cylindrical parts in lathes. Machining of flat surfaces demands close attention to the use of a cutting tool, especially at the corners or edges of a coating. It is possible to lift a coating at an edge if care is not exercised. Minimal amounts of stock should be removed with each cut.

7.2.5 Grinding. Material finish and tolerance requirements may dictate grinding as the only practical means of finishing thermal sprayed parts. Machines commonly used are outside diameter grinders (cylindrical and centerless), surface grinders (horizontal and vertical spindle), and internal grinders.

When using any abrasive medium to grind and polish, it is important to realize that thermal sprayed coatings are vastly different from the same material in wrought or cast form. If wheels of excessive hardness are used, or if they do not cut freely, individual particles can be pulled from the coating surface; or worse, the entire deposit can delaminate from the substrate. Because the ductility of sprayed materials is low, excessive grinding pressure may cause the surface particles to shift or be displaced. With a mechanical bond, heat conduction away from the point of tool contact is not as efficient as when grinding similar wrought materials. Unsatisfactory conditions will result if improper wheels and grinding techniques are used.

7.3 Grinding Wheel Selection

The selection of a grinding wheel involves the coating, its hardness and structure, the amount of stock removal, the size of the part, surface finish specifications, and the type, condition and capabilities of the grinding machine. Table 7.3 gives grinding wheel recommendations for selected thermal spray materials. Four rules will aid in grinding wheel selection.

Rule I. ALWAYS USE THE SHARPEST WHEEL POSSIBLE. SHARP WHEELS CUT RAPIDLY WITHOUT OVERHEATING. Wheel sharpness is governed by several factors, among which are the type of abrasive grain and the grit size.

Grain Type. Four major grain types are used in the manufacture of grinding wheels; the two most commonly used for grinding thermal sprayed surfaces are silicon carbide and diamond. Silicon carbide is chosen for its

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Table 7.2.4A
Carbide tools — machining recommendations

Code no. (Chapter 5)	Material	Speed (Surface ft/min)		Feed (in./rev.)	
		Rough	Finish	Rough	Finish
Iron Base					
1b	Mn .5; C.10; Fe bal.	75-100	75-100	.006	.003
	Mn .6; C.23; Fe bal.	50-75	50-75	.004	.003
4b	C.35; Mn .5; Cr 13.0; Si .5; Fe bal.	30-40	30-40	.004	.003
5b	C.15; Mn 8.5; Ni 5.10; Cr 18.0; Si 1.0; Fe bal.	100-125	125-175	.006	.003
6b	C.80; Mn .7; Fe bal.	30-40	30-40	.004	.003
7b	C.04; Mn 2.0; Ni 4.0; Cr 1.5; Mo 1.5, Fe bal.				
Aluminum Base					
3d	99.0+Al	250-300	300-350	.004	.002
Copper Base					
1d	Al 9.5; Fe 1.0; Cu bal.	250-300	300-350	.006	.003
4d	99.0+C	250-300	300-350	.006	.003
8d	Cu 66; Zn 34	250-300	300-350	.006	.002
9d	Cu 90; Zn 10	250-300	300-350	.006	.002
10d	Cu 95; Sn 5	250-300	300-350	.006	.003
11d	Cu 58.2; Sn .8; Fe .75 Mn .25; Zn bal.	250-300	300-350	.006	.003
Nickel Base					
1c	Ni 99.5	200-250	250-300	.004	.002
11c	Ni 67; C.15; Si .1; Fe 1.5; Mn 1.0; Si .1 Al .1, Cu bal.	200-250	250-300	.004	.002

**S.I. Soft Conversion
Table 7.2.4A
Carbide tools — machining recommendations**

Code no. (Chapter 5)	Material	Speed (Surface m/s)		Feed (mm/rev.)	
		Rough	Finish	Rough	Finish
Iron Base					
1b	Mn .5; C.10; Fe bal.	0.38-0.51	0.38-0.51	0.15	0.08
	Mn .6; C.23; Fe bal.	0.25-0.38	0.25-0.38	0.10	0.08
4b	C.35; Mn .5; Cr 13.0; Si .5; Fe bal.	0.15-0.20	0.15-0.20	0.10	0.08
5b	C.15; Mn 8.5; Ni 5.10; Cr 18.0; Si 1.0; Fe bal.	0.51-1.5	0.63-0.89	0.15	0.08
6b	C.80; Mn .7; Fe bal.	0.15-0.20	0.15-0.20	0.10	0.03
7b	C.04; Mn 2.0; Ni 4.0; Cr 1.5; Mo 1.5, Fe bal.				
Aluminum Base					
3d	99.0+Al	1.3-1.5	1.5-1.8	0.10	0.05
Copper Base					
1d	Al 9.5; Fe 1.0; Cu bal.	1.3-1.5	1.5-1.8	0.15	0.08
4d	99.0+C	1.3-1.5	1.5-1.8	0.15	0.08
8d	Cu 66; Zn 34	1.3-1.5	1.5-1.8	0.15	0.05
9d	Cu 90; Zn 10	1.3-1.5	1.5-1.8	0.15	0.05
10d	Cu 95; Sn 5	1.3-1.5	1.5-1.8	0.15	0.08
11d	Cu 58.2; Sn .8; Fe .75 Mn .25; Zn bal.	1.3-1.5	1.5-1.8	0.15	0.08
Nickel Base					
1c	Ni 99.5	1.0-1.3	1.3-1.5	0.10	0.05
11c	Ni 67; C.15; Si .1; Fe 1.5; Mn 1.0; Si .1 Al .1, Cu bal.	1.0-1.3	1.3-1.5	0.10	0.05

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Table 7.2.4B
High speed steel tools — machining recommendations

Code no. (Chapters)	Material	Tool no. (Fig. 7.2.4B)	Speed (surface ft) per min.	Feed (in./rev.)
Iron Base				
1b	Mn .5; C.10; Fe bal.	3	75-100	.003 - .005
	Mn .6; C.23; Fe bal.	2	50-75	.003 - .005
5b	C.15; Mn 8.5; Ni 5.10 Cr 18; Si 1.0; Fe bal.	3	100-125	.003 - .005
7b	C.04; Mn 2.0; Ni 4.0; Cr 1.5; Mo 1.5; Fe bal.	2	50-75	.003 - .005
Copper Base				
1d	Al 9.5; Fe 1.0; Cu bal.	3	100-125	.003 - .005
4d	99.0 + Cu	3	100-125	.003 - .005
8d	Cu 66; Zn 34	2	100-125	.003 - .005
9d	Cu 90; Zn 10	3	100-125	.003 - .005
10d	Cu 95; Sn 5	1	100-125	.003 - .005
11d	Cu 58.2; Sn .8; Fe .75 Mn .25; Zn bal.	1	100-125	.003 - .005
Nickel Base				
1c	Ni 99.5	3	100-125	.003 - .005
11c	Ni 67; C.15; Fe 1.5; Mn 1.0; Si .1; Al .1 Cu bal.	3	100-125	.003 - .005
Miscellaneous				
3d	99.0 + Al	3	150-200	.003 - .005
7d	99.0 + Zn	3	150-250	.005 - .007
14d	90 Sn; 7Sb; 3 C	3	150-250	.005 - .007
16d	99.0 + Sn	3	150-250	.005 - .007

S.I. Soft Conversion
Table 7.2.4B
High speed steel tools — machining recommendations

Codc no. (Chapters)	Material	Tool no. (Fig. 7.2.4B)	Speed Surface m/s	Feed (mm/rev.)
Iron Base				
1b	Mn .5; C.10; Fe bal.	3	0.38-0.51	0.08-0.13
	Mn .6; C.23; Fe bal.	2	0.25-0.38	0.08-0.13
5b	C.15; Mn 8.5; Ni 5.10 Cr 18; Si 1.0; Fe bal.	3	0.51-0.20	0.08-0.13
7b	C.04; Mn 2.0; Ni 4.0; Cr 1.5; Mo 1.5; Fe bal.	2	0.25-0.38	0.08-0.13
Copper Base				
1d	Al 9.5; Fe 1.0; Cu bal.	3	0.51-0.20	0.08-0.13
4d	99.0 + Cu	3	0.51-0.20	0.08-0.13
8d	Cu 66; Zn 34	2	0.51-0.20	0.08-0.13
9d	Cu 90; Zn 10	3	0.51-0.20	0.08-0.13
10d	Cu 95; Sn 5	1	0.51-0.20	0.08-0.13
11d	Cu 58.2; Sn .8; Fe .75 Mn .25; Zn bal.	1	0.51-0.20	0.08-0.13
Nickel Base				
1c	Ni 99.5	3	0.51-0.20	0.08-0.13
11c	Ni 67; C.15; Fe 1.5; Mn 1.0; Si .1; Al .1 Cu bal.	3	0.51-0.20	0.08-0.13
Miscellaneous				
3d	99.0 + Al	3	0.76-1.0	0.08-0.13
7d	99.0 + Zn	3	0.76-1.0	0.13-0.18
14d	90 Sn; 7Sb; 3 C	3	0.76-1.0	0.13-0.18
16d	99.0 + Sn	3	0.76-1.0	0.13-0.18

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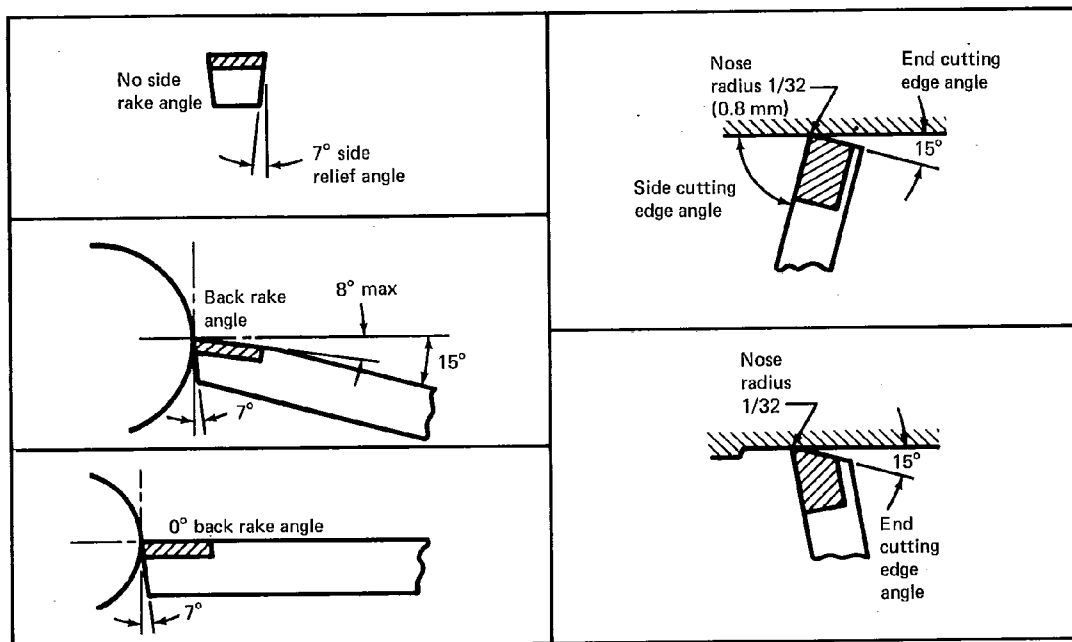


Fig. 7.2.4A — Tool angles for cemented carbide tools

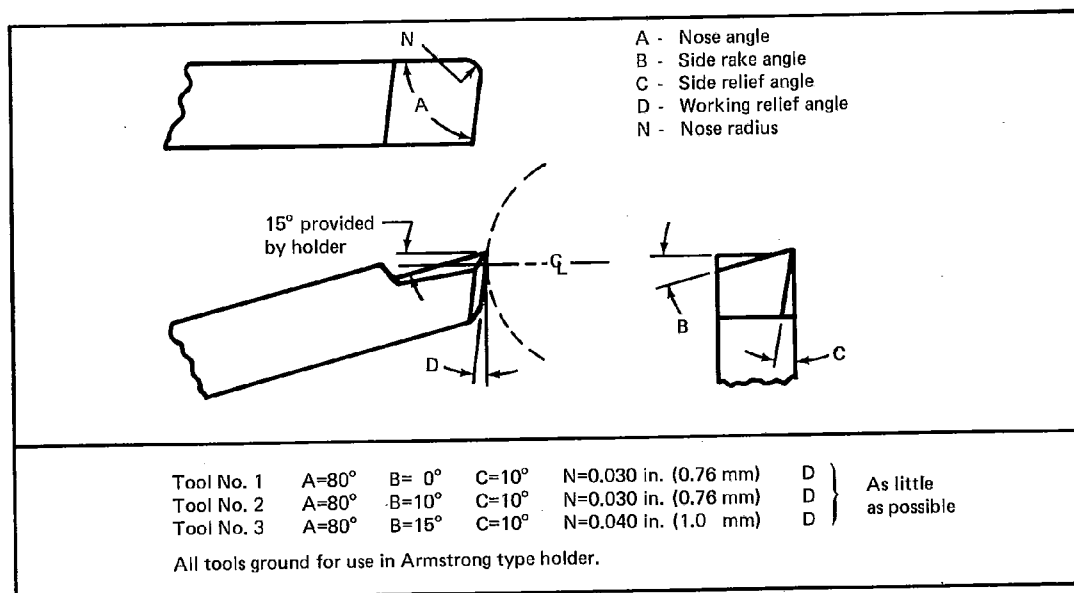


Fig. 7.2.4B — High speed tool bits ground at angles recommended for machining sprayed metal

Table 7.3
Grinding wheel recommendation

Material	Wheel specifications	Grinding application			
		Centerless	Cylindrical	Internal	Surface
Alumina Barium Titanate Boron Calcium Titanate Calcium Zirconate Chromium Disilicide Chromium Oxide Cobalt Zirconia Chromium Carbide Columbium Nickel Alumina Nickel Oxide Silicon Tantalum Titania Alumina	Abrasive type: Grit size: Grade: Bond:	C (Green) 80 (180 μm) G Vitrified	C (Green) 80 (180 μm) G Vitrified	C (Green) 80 (180 μm) J Vitrified	C (Green) 80 (180 μm) F Vitrified
Titanium Oxide Tungsten Tungsten Carbide Zirconia Zirconia Oxide Zirconia Silicate	Diamond type: Grit size: Grade: Concentration Bond:	Mfd Ni Clad 120 (125 μm) R 75 Resinoid	Mfd Ni Clad 120 (125 μm) R 75 Resinoid	Mfd Ni Clad 150/180 (100/83 μm) R/N 100 Resinoid	Mfd Ni Clad 120 (125 μm) R 75 Resinoid
Chromium Cobalt Nickel	Abrasive type: Grit size: Grade: Bond:	C/A 60 (250 μm) J Vitrified	C/A 60 (250 μm) J Vitrified	C/A 80 (180 μm) L Vitrified	C/A 46 (340 μm) H Vitrified
Iron	Abrasive type: Grit size: Grade: Bond:	C (Black) 46 (340 μm) J Vitrified	C (Black) 46 (340 μm) J Vitrified	C (Black) 60 (250 μm) M Vitrified	C (Black) 46 (340 μm) K Vitrified
Magnesium Zirconate	Abrasive type: Grit size: Grade: Bond:	C (Green) 80 (180 μm) G Vitrified	C (Green) 80 (180 μm) G Vitrified	C (Green) 80 (180 μm) L Vitrified	C (Green) 80 (180 μm) F Vitrified
	Diamond type: Grit size:	Mfg Ni Clad 120 (125 μm)	Mfg Ni Clad 120 (125 μm)	Mfg Ni Clad 150/180 (100/83 μm)	Mfg Ni Clad 120 (125 μm)
	Grade: Concentration: Bond:	R 75 Resinoid	R 75 Resinoid	R/N 100 Resinoid	R 75 Resinoid
Molybdenum	Abrasive type: Grit size: Grade: Bond:	C (Black) 60 (250 μm) I Vitrified	C (Black) 60 (250 μm) I Vitrified	C (Black) 80 (180 μm) N Vitrified	C (Black) 80 (180 μm) H Vitrified

(Continued)

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Table 7.3 (Continued)
Grinding wheel recommendations

Material	Wheel specifications	Grinding application			
		Centerless	Cylindrical	Internal	Surface
Molybdenum Disilicide Mullite	Abrasive type:	C (Green)	C (Green)	C (Green)	C (Green)
	Grit size:	80 (180 μm)	80 (180 μm)	80 (180 μm)	80 (180 μm)
	Grade:	G	G	J	F
	Bond:	Vitrified	Vitrified	Vitrified	Vitrified
	Diamond type:	Mfg Ni Clad	Mfg Ni Clad	Mfg Ni Clad	Mfg Ni Clad
	Grit size:	120 (125 μm)	120 (125 μm)	150/180 (100/83 μm)	120 (125 μm)
Stainless steel (400 series)	Grade size:	R	R	R/N	R
	Concentration:	75	75	100	75
	Bond:	Resinoid	Resinoid	Resinoid	Resinoid
High nickel, alloys and Stainless steel (300 series)	Abrasive type:	A	A	A	A
	Grit size:	60 (250 μm)	60 (250 μm)	80 (180 μm)	46 (340 μm)
	Grade:	J	J	L	H
	Bond:	Vitrified	Vitrified	Vitrified	Vitrified
	Abrasive type:	C/A	C/A	C/A	C/A
	Grit Size:	60 (250 μm)	60 (250 μm)	80 (180 μm)	46 (340 μm)
	Grade:	J	J	J/L	H
	Bond:	Vitrified	Vitrified	Vitrified	Vitrified

Abrasive Type: C=Silicon Carbide
A=Aluminum Oxide

Notes:

A diamond wheel should be selected first over silicon carbide or aluminum oxide.

The above grinding wheel recommendations are for wet grinding. When grinding dry, it may be necessary to select wheels 1 to 2 grades softer than those indicated.

Recommendations are suggested starting points only. Some adjustments in wheel grade and grit size may be required in order to accommodate such factors as machine conditions and operator technique.

Grit size shown on above charts will yield anywhere from 30 to 50 microinches.

(0.75 to 1.25 μm) microfinish. Finer finishes require finer grit sizes such as 80 or 100 grit in. (180 or 150 μm) for "A" or "C" abrasive.

ability to fracture and present sharp new cutting points during the grinding action. Diamonds are used for their durability and ability to cleanly cut hard alloys, metals, ceramics, and cermets. Aluminum oxide and cubic boron nitride (CBN) are used only on some steel alloys.

Grit Size. Because of their smaller surface area and sharper points, fine grit abrasives will penetrate hard materials easier than coarse grit abrasives. Grits normally used to grind sprayed deposits will range from 46 to 80 (37 to 180 μm), although smaller sizes may be used to generate finer finishes.

Rule II. CHOOSE WHEELS WITH STRUCTURES AND GRADES WHICH PROVIDE FREE CUTTING ACTION.

Wheel Structure. Structure, as it relates to the grinding wheel, is the spacing between the individual abrasive grains within the grinding wheel. Wheels with an open structure tend to cut more freely, since the additional spacing between the grains provide greater chip clearance. Wheel structures are designated numerically. For sprayed materials, structures ranging from 5 to 8 should be employed.

Wheel Grades. Grinding wheels can be manufactured in varying degrees of hardness. While harder wheels will last longer, they also tend to cut more slowly, generate more heat, and require more frequent dressing than softer wheels. Wheel grades are designated alphabetically in this system. When grinding sprayed materials, grades ranging between H and L are recommended. Softer grades are used on large areas of contact, when using light grinding pressures, or when attempting to achieve higher stock removal rates. Harder grade wheels are used on small areas of contact or with narrow wheels, and when using heavy grinding pressures, or producing finer finishes.

Rule III. CHOOSE THE BOND TYPE BEST SUITED TO THE OPERATION AND EQUIPMENT.

Vitrified Bond (inert glass-like materials). Vitrified bonds, because of their porosity, rigidity, and strength, can provide high stock removal rates and precision tolerances. They are not affected by water, acids, oils, or ordinary temperature variations. Most vitrified wheels, however, are limited to a safe operating speed of 6,500 sfpm (33 m/s). Although vitrified bonds are the most common type used for grinding sprayed materials, they should be used only after it has been established that the operating speed of the machine does not exceed the safe operating speed of the wheel.

Resinoid Bond (thermosetting plastic materials). Designed to operate at speeds of 9,500 sfpm (48 m/s), diamond resin bonded wheels are used for rapid stock removal and to generate fine finishes. Although resin bonded wheels operate safely at high speeds, the machine

speed should never exceed the indicated safe operating speed. Resinoid bonded diamond wheels should not exceed 6,500 sfpm (33m/s) for best grinding efficiencies.

Rule IV. KNOW THE EQUIPMENT — BOTH MACHINES AND WHEELS

Machines. It is important to know the machine being used for a particular grinding operation and to understand its limitations.

It is difficult to generate precision ground surfaces and fine finishes on equipment that is not properly maintained. Chucks should be clean and able to hold the work accurately. Gibs and ways should operate smoothly, and machine spindles should run concentric to the wheel face with a minimum of vibration.

Wheels. Attention to wheel mounting is important as any irregularity in grinding pressures can cause improper finishes, inaccurate tolerances or the destruction of the work piece. When mounting a wheel, ascertain that it is in balance, that the wheel center hole fits the arbor properly, and that the wheel runs true. Wheel sleeves, collets, and flanges should be carefully checked to assure that they are not worn or distorted. When using cup, diamond, or cubic boron nitride wheels, always maintain them on their own collet after use. This will facilitate remounting and reduce the need for retruing on subsequent operations.

American National Standard Grinding Wheel Markings. American National Standards Institute (ANSI) Standard B74.13, *Markings for Identifying Grinding Wheels and Other Bonded Abrasives*, applies to grinding wheels and other bonded abrasives, segments, bricks, sticks, hones, rubs, and other shapes, which are for removing material or producing a desired surface or dimension. It does not apply to diamond wheels or to specialties such as sharpening stones. The same standard markings, made by different manufacturers, may not produce exactly the same grinding action. The desired result cannot be accomplished, due to the impossibility of correlating measurable physical properties of various bonded abrasive products in terms of their grinding action.

The American National Standards Institute should be consulted for "Identification Code for Diamond Wheel Shapes."

Sequence of Markings. The accompanying excerpt from ANSI B74.13 illustrates the makeup of a typical wheel or bonded abrasive marking.

	1	2	3	4	5	6
Prefix	Abrasive type	Grain size	Grade	Structure	Bond type	Manufacturer's record
51	— A	— 36	— L	— 5	— V	— 23

The meaning of this and other markings is as follows:
(1) **Abrasive Letters.** The letter (A) is used for aluminum

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oxide and (C) for silicon carbide. The manufacturer may designate some particular type in either of these broad classes by using his own symbol as a prefix (for example, 51A).

(2) **Grain Size.** The grain sizes used vary from coarse to fine, indicated by the following numbers: 8, 10, 12, 14, 16, 20, 24, 30, 36, 46, 54, 60, 70, 80, 90, 100, 120, 150, 180, and 220. The following additional sizes are used occasionally: 240, 280, 320, 400, 500, and 600. The wheel manufacturer may add to the regular grain number an additional symbol to indicate a special grain combination.

(3) **Grade.** Grades are indicated by letters of the alphabet A to Z in all bonds or processes. Wheel grades from A to Z range from soft to hard.

(4) **Structure.** The use of a structure symbol is optional. The structure is indicated by Nos. 1 to 16 (or higher, if necessary) with progressively higher numbers. The higher the numbers, the finer the grit.

(5) **Bond or Process.** Bonds are indicated by the following letters: V, Vitrified; S, silicate; E, shellac or elastic; R, rubber; RF, rubber reinforced; B, resinoid (synthetic resins); BF, resinoid reinforced; O, oxychloride.

(6) **Manufacturer's Record.** The optional sixth position may be used for in-house manufacturing records.

Standard shapes and size ranges are listed in ANSI Standard B74.

Diamond Wheels. The following is an example of a designation for the composition of a diamond wheel:

1	2	3	4	5	6	7	8
Abrasive	Grit	Grade	Concen-	Bond	Bond	Depth of	Manufacturer's
	size		tration	type	modifi-	diamond	Identification
					cation	section	Symbol
ASD	— 100	— R	— 100	— B	— 56	— 1/8	— *

The meaning of each component in this symbol is below as follows:

(1) **Abrasive Type.** The letter D is used for natural diamond; SD or MD for manufactured diamond; CD for coated diamond; and ASD for armored diamond.

(2) **Grit Size.** The diamond grains of different sizes, referred to as grit, are expressed in numbers indicating screen mesh sizes. Commonly used grit sizes range from 24 to 500 (740 to 30 μm); for special applications finer grades may be employed.

(3) **Grade.** The grade designates the relative hardness and indicates the grain retaining strength of the bond. Letter symbols are used in alphabetical order from "soft" to "hard." Commonly used grades for various bond materials are as follows: for resinoid bond, from H to R; for metallic bond, from L to R; and for vitrified bond, from J to T.

(4) **Concentration.** The individual diamond grains are held in a bond material, and the proportion of diamond grains in terms of the unit volume of the abrasive conglomerate is termed concentration. The highest concentration, designated as 100 percent, contains 72 carats of diamond grains for each cubic in. ($164 \times 10^{-6} \text{m}^3$) of conglomerate. Other concentrations are 75, 50, and 25 per cent (low), indicating a proportionately reduced diamond content.

(5) **Bond.** Resinoid (B) bonds are used. For applications where stronger retention of the grains (i.e., greater hardness is needed), metallic (M), or vitrified (V) bonds may provide better service. (The letters in parenthesis are the respective identification symbols.)

(6) **Bond Modification.** Occasionally, numerals selected by individual manufacturers are used to designate a special bond modification. The example shows a resinoid — 56 bond.

(7) **Abrasive Layer.** The thickness of the abrasive layer applied to the core of the diamond wheel, also called the depth of impregnation or depth of diamond section, may vary for different wheel types. Thicknesses of commonly used sections are 1/32, 1/16, 1/8, and 1/4 in. (0.8, 1.6, 3.2, 6.4 mm). The thicker sections are specified for heavier stock removal rates.

(8) **Manufacturer's Identification Symbol.** This symbol, when used, appears in the eighth position.

Standard shapes and size ranges for diamond wheels can be found in ANSI Standard B74.1.

7.4 Grinding Variables

7.4.1 Wheel Speed. Wheel speed has an effect on wheel performance, finishing, and stock removal rates. Lower speeds will cause a wheel to behave softer, while high speeds will cause the same wheel to act harder. For example, a K grade wheel, normally operated at 5,000 sfpm (25 m/s), will act like an L grade wheel when operated at 6,500 sfpm (33 m/s). Ideally, the speed of the machine should be controllable, so that the effective operating speed is maintained at a constant rate as the wheel wears.

7.4.2 Work Speed. By varying the speed of the work, the cutting action of the wheel can also be altered. By increasing the speed of the work, the wheel will become more aggressive. Traversing the work slowly improves the surface finish.

7.4.3 Area of Contact. The basic principle in all types of grinding is pressure per unit area. The greater the pressure, the greater the depth of abrasive grain penetration. On a given machine of fixed horsepower, a narrow wheel, because of its smaller area of contact, will exert more units of pressure per units of area than will a wider wheel. Because of this, narrow wheels are more aggressive than wider wheels. Narrow wheels are very effective against hard materials, when rapid stock removal is required and when low horsepower machines are used.

7.4.4 Wet Grinding. Sprayed materials can be ground dry, if proper precautions are taken. However, the advantages of dry grinding are far outweighed by the benefits of wet grinding. When grinding wet, harder wheels may be used without increasing the incidence of blistering or heat checking. Pull-out of surface particles is minimized, and better finishes are obtained. Also, wheels do not load as fast, requiring less dressing. Wet grinding will also help flush out grinding residues that otherwise might become entrapped in the porous structure of the spray coating deposit.

Grinding fluid filtration and proper fluid concentration are as important to surface finish as fluid cleanliness. Water soluble oils with antiwelding agents are used. The

manufacturer's recommendation for fluid concentration should be followed.

7.4.5 Wheel Dressing. During use, the condition of the grinding wheel cutting face will change. After a period of time, either the abrasive grains on the face of the wheel will wear, so that the height of the grain will equal the height of the bond, or the wheel face will become loaded with the material being ground. When either of these conditions occurs, the cutting ability of the wheel will diminish, and more rubbing (burnishing) than cutting will take place. When this occurs, the wheel face should be reconditioned or dressed. When dressing a grinding wheel with a diamond tool, the rate at which the tool is traversed across the face of the wheel governs the final cutting action of the wheel. A fast traverse will open the wheel face, sharpen the abrasive grains, and allow the wheel to cut more freely. A slow traverse of the diamond tool will close the wheel face, dull the abrasive grains, and cause the wheel to act harder. While slow dressing rates can be used to produce finer finishes on conventional materials, they are not recommended for use on thermal sprayed materials. The use of sharp diamond tools is also important. Periodic rotation of the tool is recommended.

7.5 Superfinishing

Superfinishing is the process of improving the finish of a part. This is accomplished by movement of the part (rotation) as abrasive stones or laps oscillate and traverse the part.

In superfinishing, the choice of the lubricant or solvent is critical. The lubricant is a determining factor in the amount of cutting accomplished by the abrasive. To obtain the best finish, the viscosity of the lubricant should be increased. This reduces cutting action and produces finer finishes with minimal stock removal. This is generally a final step following another finishing method. Increased cutting speed is attained by lowering the viscosity of the lubricant. This is generally done by adding kerosene or linseed oil.

7.6 Honing

Honing follows the same general principles and results of superfinishing, whether internal or external.

7.7 Lapping

Lapping, like superfinishing and free abrasive tumbling, can readily improve the surface finish of thermal spray deposits. Lapping of flat parts can establish exact

degrees of flatness. Lapping cylindrical parts can yield high accuracies in size, finish, and straightness.

Lapping of a thermal sprayed coating may produce a certain amount of surface pull-out or pitting. This is the result of separation of coating particles during the lapping process. Generally, this is microscopic and is not visually detected. It lends the impression of a smooth surface appearance.

Lapping is accomplished using a lapping plate, which is usually serrated cast iron, or a cylindrical lap with a lapping compound comprised of abrasives and lubricants. Low speeds and high pressure produce the best results, where the lapping action shears or cuts the material, and particle pull-out is minimized. It is recommended that fused coatings be lapped dry.

7.8 Overall Guidelines

Good finishes can be generated on sprayed parts, provided care is exercised during the finishing process. Here is a checklist of grinding techniques:

- (1) Use softer, free cutting wheels. Chances of burnishing and pull-out will be greatly reduced.
 - (2) Maintain the wheel face in a clean and sharp condition.
 - (3) Observe proper dressing techniques.
 - (4) Use coarse grit wheels for maximum stock removal and fine grit wheels for finishing. Attempting to generate fine finishes with coarse grit wheels that have been dressed closed can result in particle pull-out, smearing, and burnishing.
 - (5) Use light cuts. Sprayed coatings are usually very thin. Excessive grinding pressure can cause delamination of the sprayed surface or pull-out of surface particles.
 - (6) Do not 'spark out' on the final pass; this tends to glaze or dull the wheel face.
 - (7) Grind wet whenever possible. Improved finishes, less chance of burnishing, and less contamination will result.
 - (8) Use finer grit wheels on dense, hard-to-penetrate, sprayed coatings.
 - (9) Use narrower wheels on machines with low horsepower and for more rapid stock removal of hard materials.
 - (10) Always keep the coating under compression. By cutting down through the sprayed surface towards the substrate, delamination and pull-out will be minimized.
 - (11) On encountering problems with a given wheel, experiment with wheel speeds, feed rates, work speeds, and dressing techniques. Changes in variables can have a significant effect on stock removal rates and finishes.
- To a great extent, the effectiveness of thermal spray coatings is dependent upon the finishing techniques employed. The fact that the coatings are not a homo-

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geneous mass, but rather many particles bonded together, dictates that sprayed coatings be finished with wheels and techniques not normally used on similar materials in wrought or cast form. By carefully observing the rules

governing wheel selection and by employing proper grinding techniques, the grinding of thermal spray coatings can become relatively trouble free.

Chapter 8

Post Treatment

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Chapter 8

Post Treatment

8.1 Sealers

8.1.1 Introduction. Thermal spray coatings are inherently porous. Porosity can range from less than 1% to greater than 15%. It may be interconnected and extend from the surface to the substrate. Sealers are used as a post treatment to fill such pores. Reasons for sealing sprayed coatings are

- (1) Prevention or retardation of corrosion at the coating/substrate interface
- (2) Life extension of aluminum and zinc corrosion preventive coatings
- (3) Prevention of fluid and pressure seal leakage in certain machine parts
- (4) Prevention of contaminants or grinding debris from entering the coating
- (5) Maintenance of dielectric constants of ceramic coatings

8.1.2 Types of Sealants. Many sealing materials are available. Properties required in a sealer material include:

- (1) Adequate penetration
- (2) Resistance to chemicals or solvents
- (3) Resistance to mechanical action on coating
- (4) Stability at operating temperature
- (5) Nondegrading to coating or base metal
- (6) Nontoxic (food applications)
- (7) Safe to apply

A list of sealant materials, classified according to their mechanism of formation, is presented in Table 8.1.2. Further information about performance, cost, and application procedures may be obtained from suppliers and manufacturers.

8.1.3 Corrosion Protection. The corrosion protection of iron or steel substrates by aluminum and zinc sprayed coatings is enhanced with low viscosity sealers. These are based on vinyl, phenolic, modified epoxy-phenolic, or polyurethane resins.

Following thermal spraying, coatings are prepared with a wash primer, generally phosphoric acid. This forms a thin film of complex metal phosphate compounds which aid in the adhesion of the sealer.

Table 8.1.2
List of sealer materials

(1) NonDrying	(3) Baking
(a) waxes, greases	(a) baking phenolics
(b) oils	(b) epoxy phenolics
(c) greases	(c) thinned epoxy resins
	(d) polyesters
(2) Air Drying	(e) polyimide
(a) paints, chlorinated rubber	
(b) air drying phenolics, epoxy phenolics	(4) Catalytic
(c) vinyls	(a) epoxy resins
(d) polyesters	(b) polyesters
(e) silicone resins	(c) polyurethanes
(f) linseed oil	(5) Others
(g) coal tars	(a) sodium silicates
(h) polyurethanes	(b) ethyl silicates
	(c) anaerobic methacrylates

It is sometimes possible to improve the role of the sealer by impregnating it with aluminum flake. The aluminum penetrates the coating pores and retards further aqueous penetration.

The American Welding Society 19 year report C2.14, *Corrosion Tests of Flame Sprayed Coated Steel*, demonstrated improved protection of vinyl sealed aluminum and zinc coatings. Chlorinated rubber is an unsatisfactory sealer for aluminum and zinc coatings.

Sealers are thinned to ensure good penetration, and may be applied by spraying or brushing. If maintenance is necessary, vinyl coatings are easily reapplied. The new coat softens and bonds with the original sealant, forming a solid layer. The maximum service temperature of vinyl coatings is 150°F (65°C).

Epoxy, epoxy-phenolic, and silicone resins may be used for certain corrosive conditions up to the temperature limits of their stability. Coal tar epoxy can be used for submerged applications in fresh or salt water.

For high-temperature, oxidizing atmospheres, aluminum

pigmented silicone resin sealers are satisfactory up to 900°F (480°C). Typical applications are exhaust stacks, mufflers, and exhaust manifolds. An aluminum containing coal tar sealer has been recommended for sealing sprayed aluminum and nickel chromium alloys operating at temperatures as high as 1600-1800°F (870-980°C). The carbon preserves the aluminum content of the coating during its reaction stage in the first heating cycle when protective iron aluminum compounds are being formed.

Sealers used on coatings involved in edible food production are required to be nontoxic and FDA approved.

8.1.4 Machine Parts. Sealers are used on thermally sprayed machine parts to prevent corrosive attack on parts such as high pressure hydraulic rams, and on pump shafts to prevent fluid seepage into the packing. They are also sealed to ensure a better and cleaner ground finish. Sealing before grinding prevents debris from entering the pores of the coating and facilitates wash cleaning after grinding.

There are several types of sealers commonly used today. Wax is an inert material used to prevent infiltration of liquids and to provide lubricity at low service temperatures. Supplied in stick form, it melts at approximately 200°F (93°C). It is applied by directly rubbing it onto the part upon completion of the spraying operation or after preheating the part to above the wax melting temperature. The wax is resistant to both salt and fresh water, most acids, and alkalis. It will not resist organic solvents or hydrocarbons, and when used in lubricated service will gradually be displaced from the coating pores by oils and greases. A wax sealer cannot be used for hydraulic rams with fluids which will dissolve it.

Wax has excellent high pressure lubricating properties and is used for "dry" applications such as bridge pressure pads which cannot be adequately lubricated in service. Since wax is inert, it is used for sealing and lubricating sprayed metal coatings on machine elements in the food and chemical industries where contamination by ordinary lubricants is a problem.

Phenolic resins in solution are widely used sealers. Composition variations are available in air drying and baking types. Service temperatures for these materials range from 300-500°F (150-260°C). When the resin is cured, it exhibits good resistance to organic solvents and weak acids. A typical use of air drying phenolics is the sealing of coatings applied to high pressure hydraulic rams [2000 psi (14 MPa) or greater]. Coating failure often occurs in unsealed parts when the pressure of fluid and air in the deposit lifts the sprayed structure from the substrate.

Generally, a baked phenolic system offers better protection than an air dried system, due to more complete polymerization. Other alternatives are catalytic sealers, which are epoxy or polyester resins that require the addi-

tion of a catalyst to produce polymerization. The catalyst should be compatible with the sprayed metal and the application. They are used to seal large areas or parts that cannot be oven baked.

For good penetration, vacuum impregnation is the most effective sealing method. The coated part is immersed in a container of resin, and both are placed in a vacuum chamber. The chamber is evacuated, pulling air from the coating pores. Capillary action draws the sealer into the vacated pores and voids.

Low viscosity methacrylate sealers that cure by anaerobic reaction have the advantage of deep penetration without vacuum. They remain liquid while exposed to air, but harden when confined in pores and deprived of oxygen. They are well suited for sealing coatings in pressurized hydraulic environments such as seal packing glands, hydraulic cylinders, and rams.

Methacrylate sealed coatings have been used in applications to 3000 psi (20 MPa) without leakage. These sealers are stable to 300°F (150°C) and resistant to water, oils, fuels, hydraulic fluids, and solvents. They are applied by brushing at room temperature, since higher temperature speeds curing. Curing occurs within the coating even though the surface remains wet. Penetration and curing times vary from thirty minutes to several hours, depending on coating thickness, type of material, porosity, and part temperature.

Generally, the sealer is applied after spraying and before finish grinding or machining operations. For some applications, sealing is done after finishing. This is because thermal spray coatings contain some isolated pores, not interconnected or extending to the surface, which may be opened by machining or grinding. However, the surface is less porous after machining, and measured penetration is significantly less.

In hydraulic cylinders, the presence of a filler in the surface pores could add some mechanical strength to the coating and reduce leakage along the surface. Grinding fluids or cutting oils should be removed after machining prior to sealing.

8.2 Fusing of Self-Fluxing Coatings

8.2.1 Introduction. Fusing as a post treatment is the second step in the application of self-fluxing alloy coatings. The first step, spray deposition, positions the powder in place. During spraying, the powder approaches its liquidus temperature, softens, and deforms upon impact. Still, a high degree of interparticle voids remain. The fusing step melts and densifies the coating, eliminating most of the pores. Wetting and coalescence are accomplished through the fluxing of the oxides on the powder and substrate surface. Fusing is required as a post treatment in traditional

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oxyfuel gas or plasma spraying with most hard, self-fluxing, facing alloys.

8.2.2 Fusion Process. The self-fluxing alloys all have wide melting ranges and exhibit very viscous behavior in their partially melted state. In fusing, the sprayed coating deposit is heated to a point between the solidus and liquidus where the surface attains a highly reflective, glassy appearance (called the "slick-up point"). This achieves an optimum combination of particle melting, closing of interparticle gaps, and fluxing of oxides; a shrinkage of about 20% takes place in the coating. The silicon and boron in the alloy form complex silicides and borides within the coating. These compounds remain dispersed through the coating. Wetting and bonding occur between powder particles and base metal, resulting in a dense deposit with low porosity levels.

Proper fusing technique is important in obtaining optimum coating characteristics. If a deposit is underheated, melting and fluxing will be incomplete, resulting in poor bonding and undesired porosity. Heating beyond the slick-up point will produce a liquid phase and induce shrinkage voids, distortion, running of the deposit, and base metal dilution. It is important to heat the coating and conclude the fusion rapidly. This avoids excessive fluxing, which depletes the alloy of silicon or boron, or both, and creates additional slag within the coating.

Fusing temperatures for various compositions of self-fluxing alloys are given in Table 8.2.2. Some alloys possess a wide viscous temperature range, along with a low surface tension. This allows for easier control of the fusing process and lessens the tendency to sag.

8.2.3 Torch Fusing. Fusing is most commonly performed with a torch. Single jet or multi-jet torches, us-

ing oxyacetylene or oxypropane flames, are employed. On very large components, five or six heavy duty multi-jet torches are used simultaneously. Fusing techniques vary with part size, shape, and base metal. A neutral flame is used for nickel alloys and a slightly reducing flame for cobalt alloys. A low velocity flame is used to prevent flowing of the molten surface. Cylindrical parts are rotated at a speed below that which would (1) cause loss of molten metal due to centrifugal force, and (2) prevent clear view of the surface condition. The entire mass, part and coating, is gradually and uniformly brought to a dull red color [about 1400-1600°F (760-870°C)]. Then the coating temperature is elevated to its fusing range by progressively heating a thin band of coating at a time, while moving the torch from one end to the other. The torch should be moved at a constant rate, slowly enough to heat the overlay, but fast enough to prevent sagging. Control of the temperature requires extensive operator experience, using the coating's color and sudden reflective appearance as a reliable indicator.

Semiautomatic equipment setups are often used for spraying and fusing very long cylindrical parts. The part rotates in a turning device. One or more spray guns, along with several fusing torches, are mounted on a common traverse mechanism. The speed of the traverse, position of the torches, and flow of powder and torch gases are controlled so that the proper coating buildup is achieved in one pass. The optimum fusing temperature is supplied by the last torch in the assembly.

Instrumented control systems have been developed for automatic torch fusing. Operation is by sensing the emissivity or reflectivity of the surface and translating it into an electrical signal which is used to govern the movement of the fusing torch.

Table 8.2.2
Approximate fusing temperatures of some typical self-fluxing alloys

Fusing temperature °F (°C)	Hardness (Rc)	Ni	Cr	B	Si	Fe	C	Co	Cu	Mo	W
2000 (1093)	21	Bal.	5.0	1.25	3.25	2.0	0.30				
1975 (1079)	30	Bal.		1.5	3.5	1.5	0.25				
1875 (1024)	35	82.9	10.0	2.5	2.5	2.0	0.10				
2012 (1100)	35-42	85.0	7.5	1.5	4.0	1.5					
1922 (1050)	49-52	77.0	10.0	1.5	4.0	4.0					
1868 (1020)	59-62	70.0	15.0	3.0	4.5	4.5					
1875 (1024)	58-61	67.0	16.0	4.0	4.0	2.5	0.50		3.0	3.0	
1875 (1024)	60-63	70.5	17.0	3.5	4.0	4.0	1.00				
2048 (1120)	43-46	13.0	19.0	1.5	2.5		1.00	50.0			8.0
2050 (1121)	50	27.0	19.0	3.0	4.0	1.0		40.0		6.0	
2057 (1125)	54-56	13.0	19.0	2.5	3.0		1.00	45.0			13.0
2200 (1204)	53-58	2.0	30.0	1.5	3.0		1.50	Bal.			14.0
1920 (1049)	60-62	13.0	19.0	3.0	3.0		1.50	42.0			15.0

8.2.4 Furnace Fusing. Furnace fusing offers the advantages of controlled heating, cooling, and atmosphere. Due to fairly stringent equipment requirements, furnace fusing is not as commonly used as torch fusing. It is more suitable for flat components, parts with irregular shapes and cross sections, very thin coatings, and high production items. It can also be used on large parts where the torch (or torches) cannot generate sufficient component heat to permit elevating the coating to fusing temperature. Since the heating and cooling rate can be precisely controlled, coating cracks due to expansion are minimized.

Furnace atmospheres of dry hydrogen, argon, or vacuum are necessary. Excellent temperature control and uniformity $\pm 5^\circ\text{F}$ ($\pm 3^\circ\text{C}$) over the entire furnace work space are requirements for proper results.

8.2.5 Induction Fusing. Induction fusing is becoming increasingly popular, due to the savings in fusion time and energy costs. For very large parts, this method has the advantage of reduced heat and noise levels, thus improving operator comfort. Automated induction fusing has been used on small parts such as sucker rod couplings for oilwell pumping, and on large parts such as steel mill conveyor rolls.

8.2.6 Precautions with Various Base Metals. Fusing of self-fluxing coatings to a wide variety of base metals is possible. These include carbon, alloy, and austenitic stainless steels, cast irons, and nickel-base and cobalt-base alloys. They cannot be applied to base metals containing elements whose oxides are not reduced by boron and silicon; e.g., alloy steels with greater than 1% aluminum and titanium. Difficulties will probably be encountered with sulphur or selenium free machining steels, due to the embrittling effects and the formation of porosity in the coating. This is particularly true of thin coatings.

Coefficient of expansion differences between coating and base metal should be compatible to avoid potential cracking problems. The high hardness ($> \text{Rc}40$) nickel base self-fluxing alloys are very brittle and have a high coefficient of expansion [8 to 9×10^{-6} in/in/ $^\circ\text{F}$ (14 to 16×10^{-6} m/m/ $^\circ\text{C}$)]. Preheating, other than warming, of carbon steels is not required prior to spraying. Austenitic stainless steels, to prevent coating cracking due to high coefficient of expansion (11×10^{-6}), require a 600°F (315°C) base metal preheat.

High carbon steels generally require heating to 600°F (315°C) after spraying, but before fusing, to avoid cracks in the fused overlay. In general, heating of the base metal must be thorough. Slow cooling after fusing is required to prevent cracking.

Hardenable steels, which undergo expansion during martensitic transformation, present a problem. Safe pro-

cedures involve placing the part in a heated furnace immediately after fusing, followed by an isothermal transformation treatment (normalizing).

8.2.7 Fusing Problems

Cracking. Cracking problems due to the fusing step stem from the alloy's brittle nature and high coefficient of expansion. They are minimized by uniform heating and very slow cooling of the parts. Slow cooling is effectively accomplished by burying the part in an insulating medium, such as vermiculite, or by cooling it in a preheated furnace. Special precautions should be taken with high hardenable steels.

Porosity. Excessive porosity in the final coating can result from many sources. Underfusing leaves large voids throughout the coating and interface due to incomplete melting, wetting, and fluxing of the powder particles. Overheating creates large voids, and a large amount of slag within the coating. Excessive porosity can also form in large parts, due to the extensive time required to reach the fusing temperature. High sulfur, selenium, and lead in the base metal, as in free-machining steels, cause porosity problems. Excessive metallic dust (fines) and contamination in the spray powder can result in entrapped oxides during spraying. These are manifested as porosity found during machining and grinding operations. Incorrect spray parameters may also result in porosity.

Sagging or Runoff. Sagging or runoff, or both, result from exceeding the optimum fusing temperature. These conditions are more likely to occur in parts that are hollow or vary in wall thickness. It is best to fuse from thin to thick areas to avoid overheated conditions.

Warpage. It is not always possible to completely eliminate warpage on irregular shapes or flat pieces which have been coated on one side.

Preheating or uniform heating during fusing also reduces warpage. Thin coatings cause fewer warpage problems than heavy coatings. Warpage can be minimized by choosing the closest match between the coefficient of expansion of the coating and base metal. Self-fluxing alloys incorporating tungsten carbide particles have lower expansion coefficients than the one component, self-fluxing alloys, and therefore can be used to advantage.

8.3 Other Post Treatments

8.3.1 Diffusion. Thin coatings of aluminum may be diffused into a steel or silicon bronze substrate to protect against the corrosive action of hot gases up to 1600°F (870°C). After being sprayed, the part is coated with a bituminous aluminum sealer or other suitable material to prevent oxidation of the sprayed deposit. The part is

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heated at 1450°F (788°C) and held at temperature for the required time for diffusion [typically 1 hour for each 1 in. (25.4 mm) of section thickness for large objects]. If the coating is for a service environment exceeding the melting point of aluminum, 1220°F (660°C), this step may be eliminated.

Diffusion heat treatments are often given to vacuum plasma-sprayed turbine engine parts such as blades, vanes, and duct segments (Chapter 4). Temperatures of about 1800°F (980°C) to 2000°F (1090°C) are used with vacuum, hydrogen, or argon atmospheres. Such treatments enhance coating integrity through formation of a metallurgical bond. They improve density, ductility, and resistance to oxidation and corrosion, as well as strength of the coating.

8.3.2 Impregnation. Impregnation of sprayed tungsten carbide coatings with solder improves strength and wear resistance. The process is carried out in vacuum at 1830°F (1000°C), or in hydrogen at 1470°F (800°C). At these temperatures, the solder flows to fill spaces between particles without melting the carbides. Capillary action occurs rapidly, permitting holding times of 1 to 2 minutes. It is claimed that most lead, tin, silver, and copper solders provide acceptable results.

8.3.3 Mechanical Treatments. Some metallic thermal sprayed coatings can be mechanically treated to close surface connected pores and to improve smoothness. Shot peening is used on some aircraft turbine parts. Peening and rolling can be used on active metal coatings for im-

provements in cavitation corrosion resistance. The improvement results from pore closure and residual compressive stresses. The cavitation corrosion resistance of a zinc coated steel plate in salt water has been shown to improve by rolling after spraying. No similar improvement, however, was seen in an 85 zinc-15 aluminum spray. Chapter 7 can be consulted for additional details.

8.3.4 Hot Isostatic Pressing (HIP). The use of hot isostatic pressing, that is, the simultaneous application of heat and pressure in an inert atmosphere, serves a two fold purpose: (1) it promotes diffusion at the substrate and coating interface, and (2) it serves to collapse the internal pores. Coating ductility, strength, and impact resistance are improved by this process. The expense associated with "HIPing" has limited its use to specialized applications.

8.3.5 Laser Heating. Laser treatment of sprayed coatings offers the possibility of performing highly controlled heating or melting. Because of the wide range of energy densities and shapes which can be produced with high power lasers, precise temperatures can be produced at specific depths in the coating. Development work has demonstrated feasibility of laser processing. Advantages include reduced porosity, increased bond strength, modified surface finish, and formation of unique metallurgical phases. Also, with coatings of high temperature materials on lower temperature substrates, the melting and infusion of a thin layer of the substrate at the bond line may be possible without melting of the surface coating.

Chapter 9

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Chapter 9

Ancillary Equipment

9.1 Introduction

The selection of equipment used in conjunction with the thermal spraying process is one of the key factors in obtaining quality coatings, reproducing them consistently, and in reducing application costs.

9.2 Blasting

The function of abrasive blasting equipment is to produce a surface receptive for coating. It is accomplished by cleaning or roughening, or both. Blasting equipment is available in sizes ranging from hand held guns, with a self contained grit canister, to large, totally enclosed, fully automated systems. Figure 9.2 shows such a fully automated system. Primary considerations in selecting blasting equipment are productivity, ability to keep grit clean, proper size, operator comfort, reproducibility of results, and protection of the operator and the surrounding area from environmental hazards. Another consideration is the efficient usage of the blasting materials.

9.2.1 Facilities. The type, size, and degree of automation of any system should be tailored to the part, environmental standards, and abrasive usage requirements. Blasting should always be performed in an enclosure designed for that purpose, and equipped with exhaust and dust collection facilities. Blast room designs vary with the application. To facilitate visibility and safety, all rooms should be equipped with an exhaust system to draw dust and contaminated material from the part and operator. Room dimensions depend on the size of the parts to be blasted. Abrasive recycling varies from manual shoveling to fully automated systems. In automated self-contained systems, the abrasive falls through a grated floor to either a vibratory plate or a conveyor which transfers it via an elevator to a holding area, where it is cleaned. Cleaning includes rescreening, sizing, and dust removal. Fines are removed, and reusable material is returned to the blasting tank. There are definite health hazards associated with silica dust. These are discussed in Chapter 11.

9.2.2 Machines. Blasting machines are available in three types. These are classified by the method of

transporting and projecting the abrasive particles: pressure, centrifugal, and suction. Pressure type blasting machines are applicable to large work requiring high production rates. They are more effective and efficient than other systems, since higher velocities are imparted to the abrasive, to afford greater cutting action. Pressure machines utilize a "Blast Generator" consisting of a closed hopper for the abrasive, a carrier base, and a blasting nozzle. The generator is pressurized and the abrasive is carried through the hose and nozzle to the workpiece. The blast generator must be periodically recharged with the abrasive. Pressure type machines are suitable for use with chilled cast iron, light oxides, and carbide abrasives.

When a part must be cleaned outdoors, and the abrasive media cannot be recovered, a lower cost grit may be selected if it is in accordance with local and federal regulations. Shielding should be used for this operation to protect the operator and the surrounding area. Disadvantages to this system are (1) degradation rate of the grit is high, causing the need for frequent replacement, (2) blasting particles cannot be reclaimed except in tank interiors, and (3) considerable care is required to prevent embedding grit in the substrate.

Centrifugal blasting is performed without air pressure. The resultant surface of the part is cleaner than that obtained through other methods. The shot or grit is fed on to a rapidly rotating vaned wheel designed to accelerate and propel the particles. The particles achieve a velocity equal to the tip speed of the vanes. The parts are loaded on a conveyor line which carries them through the blasting station to the discharge side of the machine. The blasting station may be robotized, allowing the part to be rotated, as required.

Centrifugal blasting machines have limited application, because economics require high volume conveyor line operation and that the part be large. Crushed cast iron grit should be used, as aluminum oxide and silicon carbide abrasives cause excessive wear to internal parts.

Suction type machines are convenient and versatile for preparing a large variety of components. The abrasive medium is dispensed from a hopper at the cabinet base and air propelled to the substrate. The grit drops through

a grate, returns to the hopper, and is recycled. Reuse continues until the abrasive loses its effectiveness. Suction type machines range from small, manually operated units to intermediate sized, and fully automated systems. They can be used with almost any type of abrasive with the exception of the larger sizes of crushed cast iron. Enclosure size and system efficiency are limiting factors.

9.2.3 Nozzles. Straight nozzles are commonly used for commercial work. There are many sizes (diameters), lengths, and configurations. Nozzle life depends on many factors including air pressure and type of abrasive. Inexpensive, short life, or expendable nozzles are manufactured from either cast iron or ceramic. Long wear nozzles are carbide or a carbide based composition. They are inserted into a steel or aluminum mounting which protects their hard, brittle, inner core. The internal configuration

and length govern the type of blast pattern received at a given distance. Long wear nozzles may give up to 100 times the life of a conventional ceramic or iron nozzle, but are subject to breakage if not handled properly. Table 9.2.3 provides air and sand flow rates, along with power requirements for nozzles of various sizes at various pressures.

The angle nozzle is made from carbide or carbide composition. The offset degree angle is designed for a specific application. They are manufactured with 15°, 45°, and 90° angles.

Centerblast nozzles are used for internal pipe cleaning. The nozzle employs a straight bore fixture that spreads the abrasive pattern 360°. Fixturing allows blasting of internal diameters ranging from 1 in. to 4 in. (25 to 100 mm). The angle of the target has a tendency to roughen in one direction. If sprayed in the opposite direction,

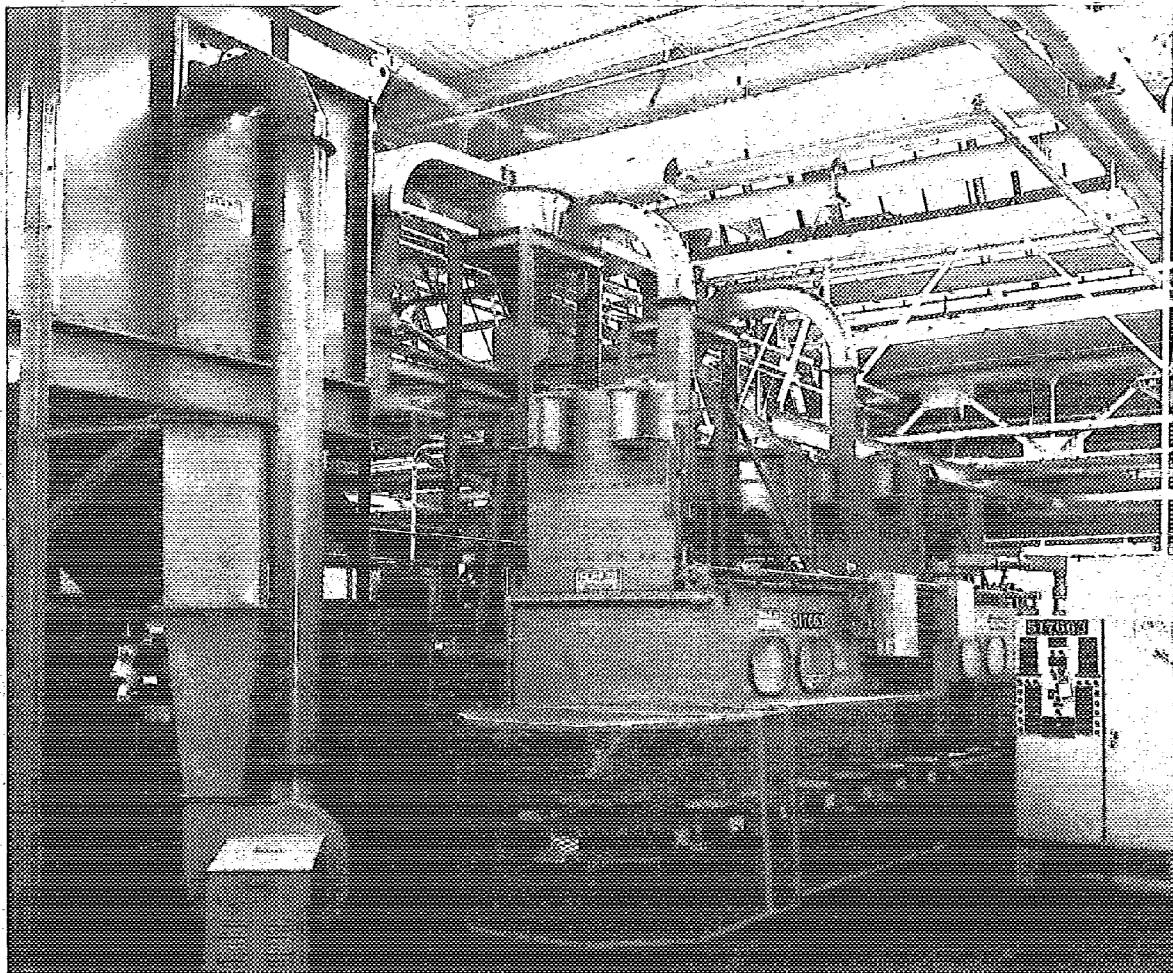


Fig. 9.2 — Fully automated, high production rate, grit blasting system

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Table 9.2.3
Air, sand flows, and energy requirements for various grit
blast nozzle sizes

Nozzle diameter in.		Nozzle pressure, psi					
		50	60	70	80	90	100
1/8	cfm air	11.3	13.2	15.1	17.0	18.5	20.3
	lb/hr	67.0	77.0	88.0	101.0	112.0	123.0
	hp required	1.6	2.1	2.5	3.1	3.5	4.2
3/16	cfm air	26.0	30.0	33.0	38.0	41.0	45.0
	lb/hr	150.0	171.0	196.0	216.0	238.0	264.0
	hp required	3.6	4.6	5.5	6.9	7.9	9.3
1/4	cfm air	47.0	54.0	61.0	68.0	74.0	81.0
	lb/hr	268.0	312.0	354.0	408.0	448.0	494.0
	hp required	6.4	8.3	10.2	12.4	14.2	16.8
5/16	cfm air	77.0	89.0	101.0	113.0	126.0	137.0
	lb/hr	468.0	534.0	604.0	572.0	740.0	812.0
	hp required	10.5	13.6	16.9	20.6	24.2	28.3
3/8	cfm air	103.0	126.0	143.0	161.0	173.0	196.0
	lb/hr	668.0	764.0	864.0	960.0	1052.0	1152.0
	hp required	14.8	19.3	23.9	29.3	33.2	40.6
7/16	cfm air	147.0	170.0	194.0	217.0	240.0	254.0
	lb/hr	896.0	1032.0	1176.0	1312.0	1448.0	1534.0
	hp required	20.1	26.0	32.4	39.5	46.1	52.6
1/2	cfm air	198.0	224.0	252.0	280.0	309.0	338.0
	lb/hr	1160.0	1336.0	1512.0	1680.0	1856.0	2024.0
	hp required	26.7	34.3	42.1	51.0	59.3	70.0
5/8	cfm air	308.0	356.0	404.0	452.0	504.0	548.0
	lb/hr	1875.0	2140.0	2690.0	2690.0	2960.0	3250.0
	hp required	42.4	54.4	68.0	82.0	96.8	115.6
3/4	cfm air	432.0	501.0	572.0	614.0	692.0	781.0
	lb/hr	2672.0	3056.0	3456.0	3810.0	4203.0	4608.0
	hp required	59.2	77.2	95.6	117.2	132.8	162.4

See Table 3.4.3 for cleaning rates

S. I. Soft Conversion Table 9.2.3 Air, sand flows, and energy requirements for various grit blast nozzle sizes							
Nozzle diameter mm		Nozzle pressure, ksi					
		34	41	48	55	62	69
3.175	Air, L/min	320	374	428	481	524	575
	Kg/h	30	35	40	46	51	56
	kW req'd	1.2	1.6	1.9	2.3	2.6	3.1
4.762	Air, L/min	736	850	934	1076	1161	1274
	Kg/h	68	78	89	98	108	120
	kW req'd	2.7	3.4	4.1	5.1	5.9	6.9
6.350	Air, kL/min	1.33	1.53	1.73	1.93	2.10	2.29
	Kg/h	122	142	161	185	203	224
	kW req'd	4.4	6.2	7.6	9.2	10.6	12.5
7.937	Air, kL/min	2.18	2.52	2.86	3.20	3.57	3.88
	Kg/h	212	242	274	259	336	368
	kW req'd	7.8	10.1	12.6	15.4	18.0	21.1
9.525	Air, kL/min	2.92	3.57	4.05	4.56	4.90	5.55
	Kg/h	303	347	392	435	477	523
	kW req'd	11.0	14.4	17.8	21.8	24.8	30.3
11.112	Air, kL/min	4.16	4.81	5.49	6.14	6.80	7.19
	Kg/h	406	468	533	595	657	696
	kW req'd	15.0	19.4	24.2	29.5	34.4	39.2
12.700	Air, kL/min	5.61	6.34	7.14	7.93	8.75	9.57
	Kg/h	526	606	686	762	842	918
	kW req'd	19.9	25.6	31.4	38.0	44.2	52.2
15.875	Air, kL/min	8.72	10.08	11.44	12.80	14.27	15.52
	Kg/h	850	971	1220	1220	1220	1474
	kW req'd	31.6	40.6	50.7	61.1	72.2	86.2
19.050	Air, kL/min	12.73	14.19	16.20	17.39	19.60	22.12
	Kg/h	1212	1386	1568	1728	1906	2090
	kW req'd	44.1	57.6	71.3	87.4	99.0	121.1

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voids, which form as the coating bridges over the anchor pattern, can yield an unsatisfactory bond.

Spinblast or rotary nozzles are used for internal blasting of larger diameters. This equipment consists of a pressurized, rotating head which carries the abrasive to the target. When the abrasive strikes the target, it is split between two carbide nozzles operating 180° apart. The nozzle is capable of blasting 36 in. (0.91 m) diameter substrates but, due to its weight, should be mounted on a lance with a mechanical traverse device.

9.3 Air

Clean, dry air can be used for drying cleaned parts, grit blasting, and air cooling during and after spraying, as well as in the operation of thermal spray equipment. The associated apparatus requires constant surveillance and maintenance. Numerous contaminants, such as water vapor, oil mist/vapor, and dust can be introduced to the air supply.

9.3.1 Supply Source. Dirty shop air contributes to interface contamination, poor bond strength, flaking, spalling, cracking, interlamellar oxides, and other defects. To ensure a clean air supply, in-line separators and filters should be located near the spray booth. There are systems that will clean and dry the air for an entire department or for the entire operation at its source. These should be used in conjunction with individual in-line filters.

Moisture should be eliminated to maintain coating quality, increase productivity, and decrease maintenance. Dryers are most efficient with an entering air temperature of 100°F (38°C). This is most economically accomplished by using an aftercooler. With the entering air temperature of 100°F, pressure dewpoints as low as -40°F (-40°C) can be achieved. Refrigerated dryers, unless interlocked with the air flow, consume energy regardless of work load, while deliquescent dryers incur only those costs directly related to the quantity of air being processed.

9.3.2 Compressors. Clean, dry air reduces maintenance and replacement costs, down time, and minimizes product rejection. All pneumatic equipment is designed for long life, maximum efficiency, and minimum maintenance, but only when operated with clean, dry air, and when lubricated according to the manufacturer's specifications. Thermal spray equipment does not contain built-in facilities for operation with wet air. The compressor raises the air temperature to 350°F (177°C). It drops to 300°F (149°C) prior to entering the aftercooler and is further lowered before entering the receiver. The saturation point is reached at 160°F (71°C), where water is condensed between 160°F (71°C) and 100°F (38°C). The saturated compressed air is stored in the receiver until

required. As air leaves the receiver, it passes through a dryer, lowering the dewpoint before entering the spray equipment.

Compression of air has one basic goal, to deliver air at a pressure and volume suitable to operate various components needed for thermal spraying and complimentary equipment. There are three types of compressors to consider in the selection of a system: Reciprocating, Vane Type Rotary, and Twin Screw Helical Lobe.

Reciprocating compressors are positive displacement machines, in which compression and displacement are accomplished by a piston with a reciprocating motion within a cylinder. The reciprocating compressor can be either a single cylinder compressing at one end of the stroke, or a double acting unit compressing at both ends of the stroke. Two stage reciprocating compressors are proportioned according to the total compression ratio. The second stage is smaller, since the air has already been partially compressed and cooled, occupying less volume than at the first stage inlet.

Vane type rotary compressor elements include the cylindrical casing, the heads, and the rotor assembly. The sliding vane unit has no valves. The inlet and discharge ports open at points in the cycle that are determined by the location of the ports over which the vanes pass. The inlet port is normally wide and is designed to admit air when the pocket between the two vanes is largest. It is closed when the following pocket vane passes the edge of the inlet port. The pocket is uncovered by the leading vane of each pocket. This type of system always compresses air to design values, regardless of the pressure in the receiver into which it is discharging.

Twin screw helical lobe compressors are positive displacement, constant volume, variable pressure machines similar to the vane type rotary. The most common helical screw compressor is the oil flooded single stage unit, which delivers air up to 125 psig (862 kPa). It is heavy duty and can operate at full load for extended periods. Operating economy is less than that of the reciprocating unit, but the lower initial cost offsets the reduced efficiency. It requires no lubrication within the compression chamber and thus delivers oil free air, with proper outlet filters. Inlet and discharge silencers reduce operating noise to acceptable limits.

When selecting a suitable compressor type, the following ratings can be used:

Type	Horsepower (kW)	Power range ft ³ /min. (m ³ /s)
Reciprocating	1/4 - 300 (0.2 - 224)	2 - 1500 (0.001 - 0.7)
Screw	2 - 75 (1.5 - 56)	6 - 350 (0.003 - 0.17)
Twin	5 - 500 (4 - 373)	20 - 2250 (0.01 - 1.1)

Additional information can be obtained from data issued by compressor manufacturers.

9.4 Furnaces and Handling

9.4.1 Furnaces. Furnace fusion of self-fluxing alloys provides an inexpensive, long wearing surface, but is not applicable to all parts or base metals. Success is predicated upon precise control of the temperature in the furnace and on the surface of the part. A tolerance of $\pm 10^\circ\text{F}$ ($\pm 5^\circ\text{C}$) is normal. Furnaces are classified by

(1) the method of heating or source of energy used (oil, gas, or electricity)

(2) atmosphere and salt furnaces, which can be heated by the same three heat sources

(3) operating temperature range: 225°F (107°C) to 1250°F (677°C) — low, 1250°F (677°C) to 1750°F (955°C) — intermediate, and 1750°F (955°C) to 2800°F (1538°C) — high. Each type has its specific use. Low temperature furnaces are used almost exclusively for preheating. The intermediate groups may be used for diffusion heat treating of sprayed coatings. The high tem-

perature group is for fusing self-fluxing coatings according to

(4) the method of operation; i.e., batch or continuous furnaces

(5) the methods of applying heat

9.4.2 Handling. Many manual spray operations are performed without the use of manipulating devices. For small pieces, a vertical stand with a heavy base and "C" clamps are satisfactory. They should be coated with an anti-bonding material to facilitate the removal of overspray. Semiautomatic spray operations are more complex, but higher production rates are possible. Manipulation of the part, rather than the spray gun, produces higher quality coatings. This is attributed to retention of the spray particles in the effluent and their continuous heating to impact. The success of this method is dependent upon part geometry and the areas to be coated. Areas and surfaces that are round or circular are the most readily adapted.

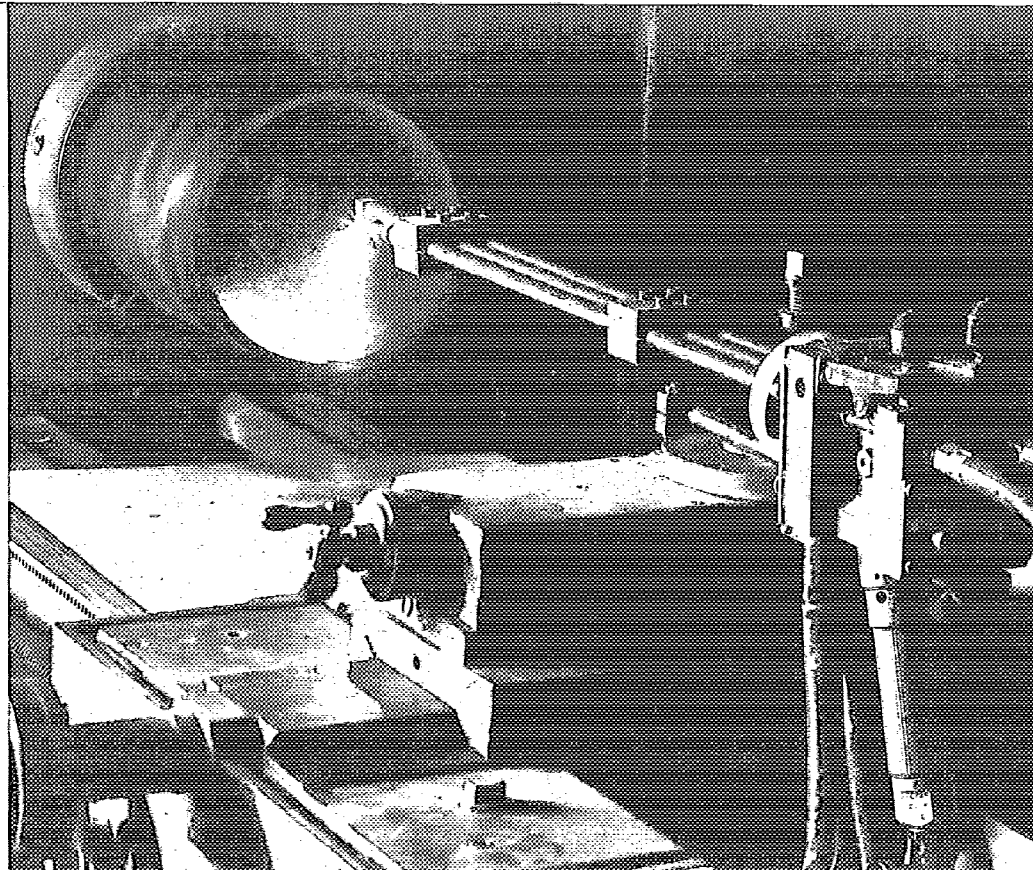


Fig. 9.4.2A — Use of a lathe to manipulate the part and the gun for spraying the inside surface of a cylinder

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Rotary Motion. A simple method of creating rotary motion incorporates a variable speed motor with a chuck. Electric motors should be sealed to prevent short circuits. Cylindrical parts can be sprayed manually or the gun mounted on the tool carriage of a lathe (Fig. 9.4.2A). The capability is limited by the size of the spray enclosure. Manipulation of large parts requires the use of a rotary table or positioner (Fig. 9.4.2B).

Rotational devices should be capable of a wide variety of speeds. The use of rotational velocities of less than 1 rpm, with high gun speeds, make a standard welding positioner practical (Fig. 9.4.2C).

Thermal spray coatings involving high production rates require the use of remotely controlled automated systems. The parts handling equipment is designed for specific operations including features such as batch loading, automatic stationing, multiple station conveying, and multiple station spraying. Spray gun manipulation synchronized with the part by numerical control (NC) or computer con-

trols becomes an integral part of a fully automated system (Fig. 9.4.2D).

Thermal spray manipulators automate gun movements which can reduce cost, improve coating quality and consistency, increase output, and improve operator environment. The complexity of the manipulator can vary from a homemade lathe or chain drive to a sophisticated computer controlled system which not only controls spray gun movement but interlocks, monitors, and controls other variables such as spray rate, pressures, and substrate temperature.

The basic semiautomatic system is the combination of a stationary gun stand and a rotary table. The gun stand consists of a heavy base, a vertical leg and a gun support. The gun is mounted rigidly on the stand, and the target structure is rotated on the table, creating a single band of coating circling the part. This procedure is satisfactory when only a narrow band of material is required.

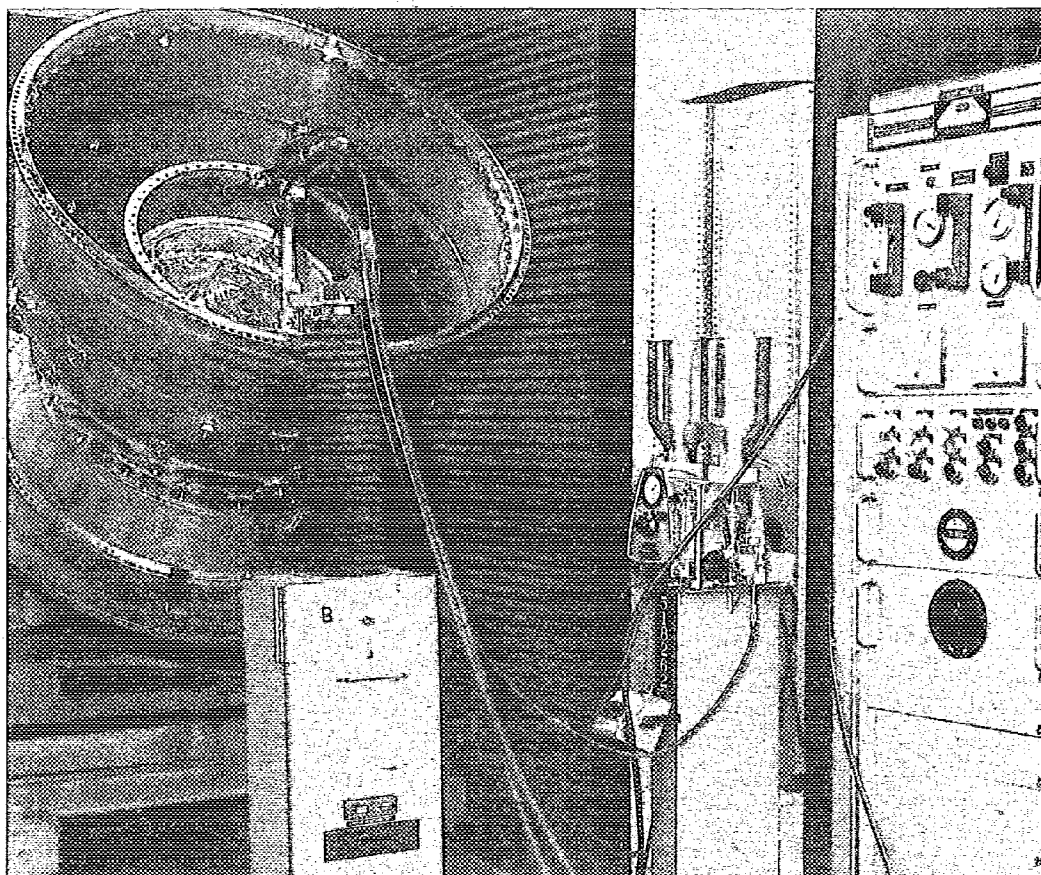


Fig. 9.4.2B — Use of a rotary table for part positioning and a verticle transverser for gun manipulation

The coating of complex structures requires additional handling equipment. Traverse units perform straight line movements along one or two axes (Fig. 9.4.2E).

The vertical traverse unit operates with a continuous motion along the "Y" axis only, whereas the horizontal traverse unit can operate along the "X" or "Z" axis, depending upon the orientation of the unit. The combination units operate along two axes simultaneously, with the horizontal axis having continuous motion and the vertical axis having either intermittent short steps or continuous motion. These motions will form a pattern on a flat surface. This combination also operates as a single axis unit in either "X" or "Y" direction. Current production models of these traverse units are controlled either by microprocessors or by electronic systems employing counters, microswitches, and relays.

Advanced design combination traverse units are also available that are microprocessor or numerical tape controlled, or both. These units are capable of multiple axes

manipulations plus initiation and control over attendant equipment (turntables, power feeders, etc.). Complete programs can be stored and recalled as required (Fig. 9.4.2F).

Another type of manipulator is a computer operated robot. Here the entire spray process, including the parts conveyor line, is controlled from the computer console. The motions of the robot are hydraulically or mechanically actuated with a wrist motion at the end of its arm. It is capable of rotational motion from stop to stop in a spherical pattern. Robots are used for atmospheric and vacuum plasma spraying operations. The use of these manipulators is economical where high production rates, a high degree of repeatability, or difficult geometric problems exist (Fig. 9.4.2G).

Robotics may also be required to meet OSHA regulations and to remove the operator from the spray environment.

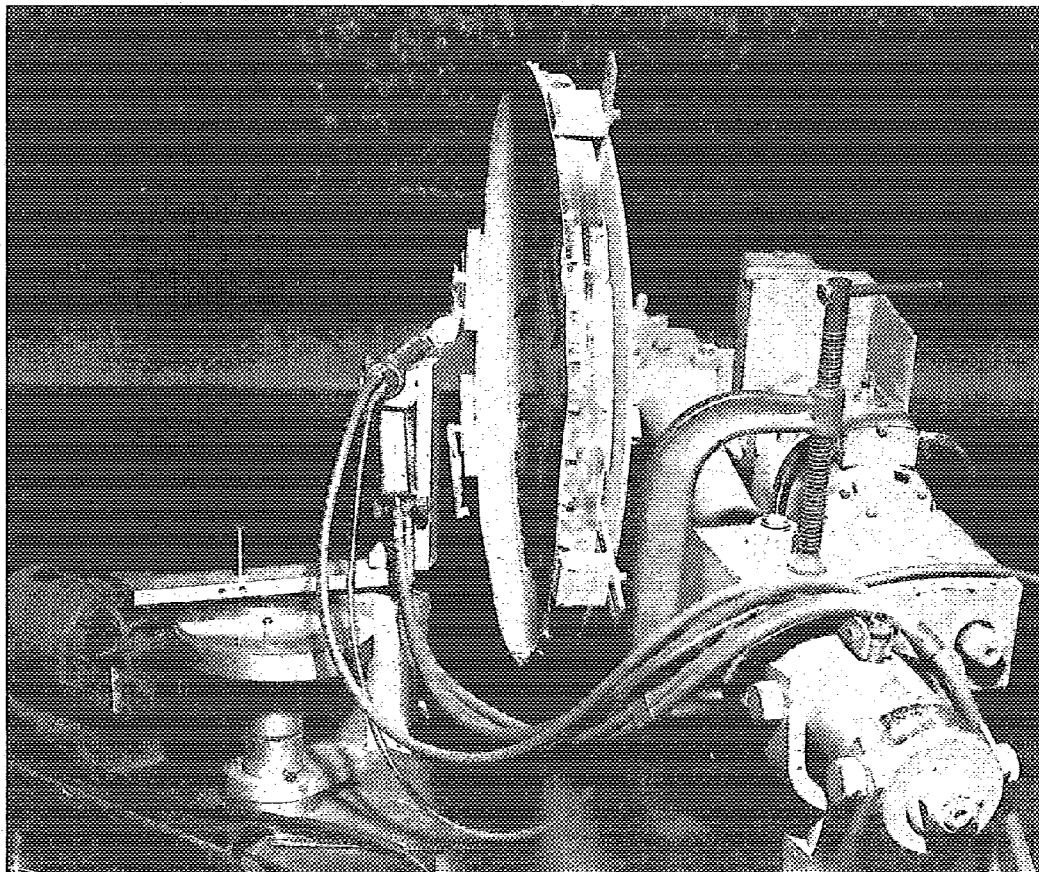


Fig. 9.4.2C — Use of a welding positioner to rotate parts oriented vertically or horizontally. A variable speed (zero-max) drive unit is being used to oscillate the flame spray gun

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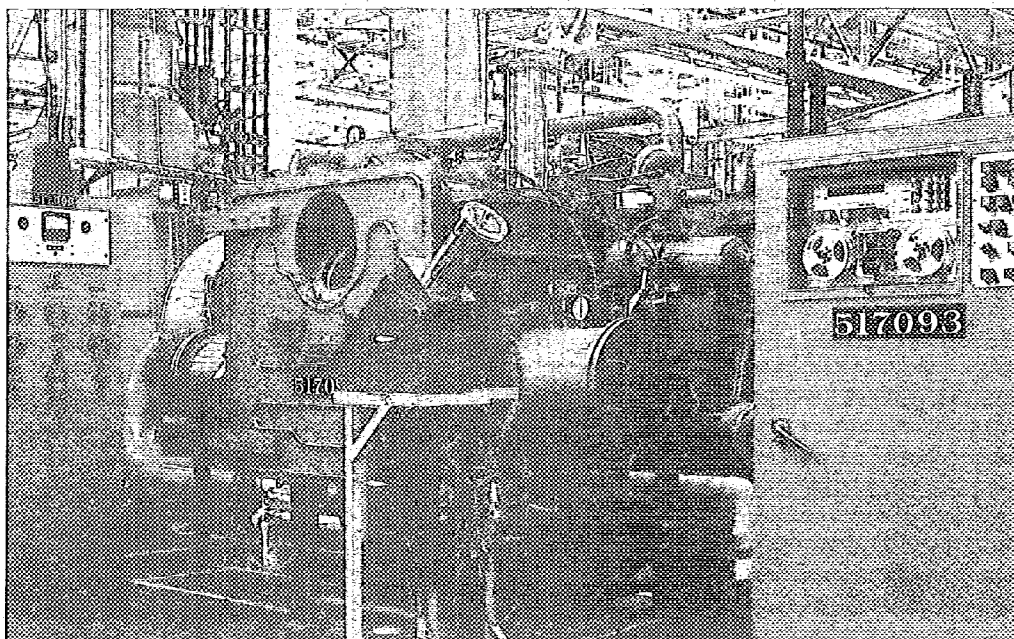


Fig. 9.4.2D — Inert spray chamber and 5 axis numerical control for coating turbine vanes

9.5 Spray Booths and Rooms

9.5.1 General Rules. General requirements to be considered when designing a fume-dust control system include

(1) When spraying in open booths with copper, aluminum, or aluminum bronze, a minimum air flow of 5,000 cfm (142m³/min) is required and 2,500 cfm (71m³/min) for other materials.

(2) Stagnant areas in the exhaust should be eliminated.

(3) The velocity of air in the gun area, sweeping fumes into the exhaust system, should be at least 300 linear ft/min (90m/min), and in more critical areas on automated systems at least 500 linear ft/min (150m/min).

(4) Transport ducts should be sized to 4,500 fpm (1400m/min) to keep particles airborne. This requires a 16 in. (406 mm) diameter duct operating at 5,000 cfm (142m³/min).

(5) State-of-the-art water wash cleaning systems provide the best overall cleaning efficiency, in the range of 99%. Fines less than 200 μ in. (5 μ m) in size are not completely removed and require higher pressure drop wet scrubbers.

(6) When spraying aluminum, hydrogen may be evolved when the collected powder remains submerged in water. It is important that the exhaust system be activated in advance of any spraying to assure purging of all gases from the exhaust system. Wet collectors should be self-venting.

(7) When spraying, a considerable amount of material

may be oversprayed with highest losses occurring with small parts.

(8) Bag filters have been used to collect some powders such as zinc. However, many spray powders are pyrophoric, and hazards exist relative to bag house fires. Bag houses are not recommended except in special situations where the value of the overspray warrants such collection and then only with very competent advice from safety, fire, and insurance experts.

Additional information may be obtained from the AWS

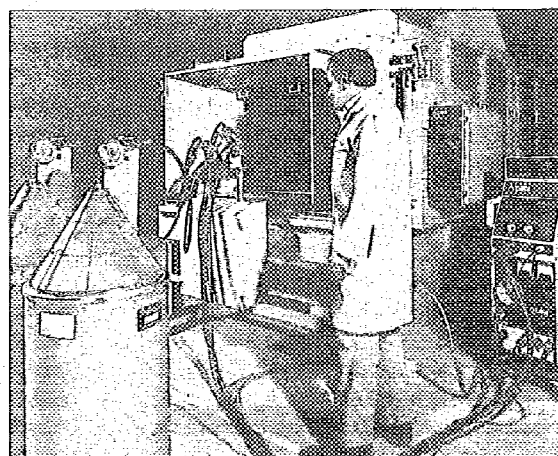


Fig. 9.4.2E — X-Y programmable movement

Research Committee on Safety and Health, equipment suppliers, and dust control equipment manufacturers.

Thermal spraying has a number of undesirable associated features. For environmental control and personnel safety, spraying operations are performed in enclosed areas. Dust and fume overspray must be removed from the work areas as rapidly as possible. Particles less than two microns (80μ in.) in size can constitute as much as 4 to 15% by weight of the overspray. Nearby personnel must be shielded from ultraviolet radiation, which may cause skin burns and conjunctivitis. Noise limits of 90 dBA or less, per eight hour period, and air flows of 300 linear ft/min (90m/min) or more, depending on the spray process, are necessary to maintain safe operating conditions. The most effective way to achieve these objectives is through the use of spray enclosures.

A limited number of spray enclosures have been specifically designed for thermal spraying operations. Most spray systems are a combination of equipment designed for other purposes. Some manufacturers of either paint

or thermal spraying equipment offer a number of basic units that can be built into a system tailored to the needs of the application (Figs. 9.5.1A, 9.5.1B, and 9.5.1C.)

This equipment is applicable to flame and arc spray operations, but is not always suitable for plasma spraying, particularly high energy operations, without an additional protective enclosure for noise control. All spray booths and rooms require an exhaust fan and a wet dust collector to minimize stack emissions. Acoustical treatment may be added or a "sound proof" room enclosure fabricated to enclose the work area. The control console and the operator are located outside the sound proof enclosure. The acoustical room contains the exhaust booth. Some automated applications use exit air velocities of 300 to 500 linear ft/min (90 to 150 m/min). In others, areas that are integral to the building structure are adapted for use as spray rooms. In any case, the specific spray process should be considered, since noise levels vary widely, thus influencing the amount of sound attenuation required.

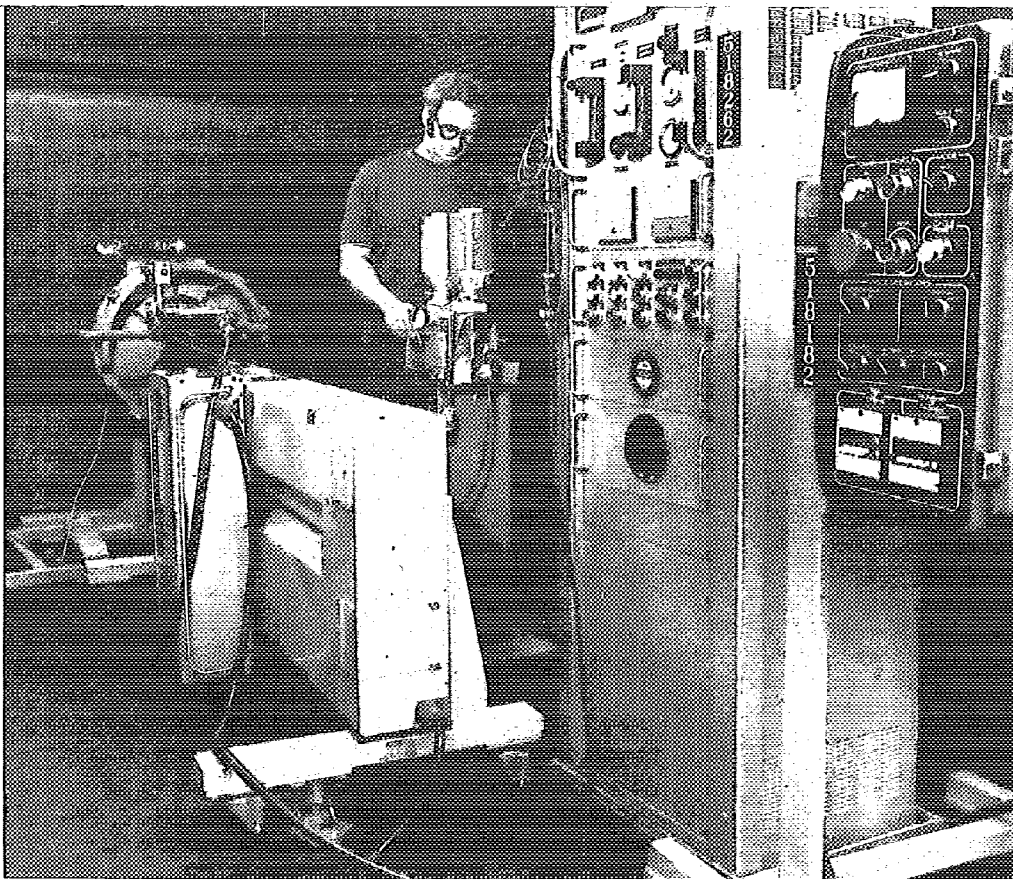


Fig. 9.4.2F — Numerical tape controlled traverse unit

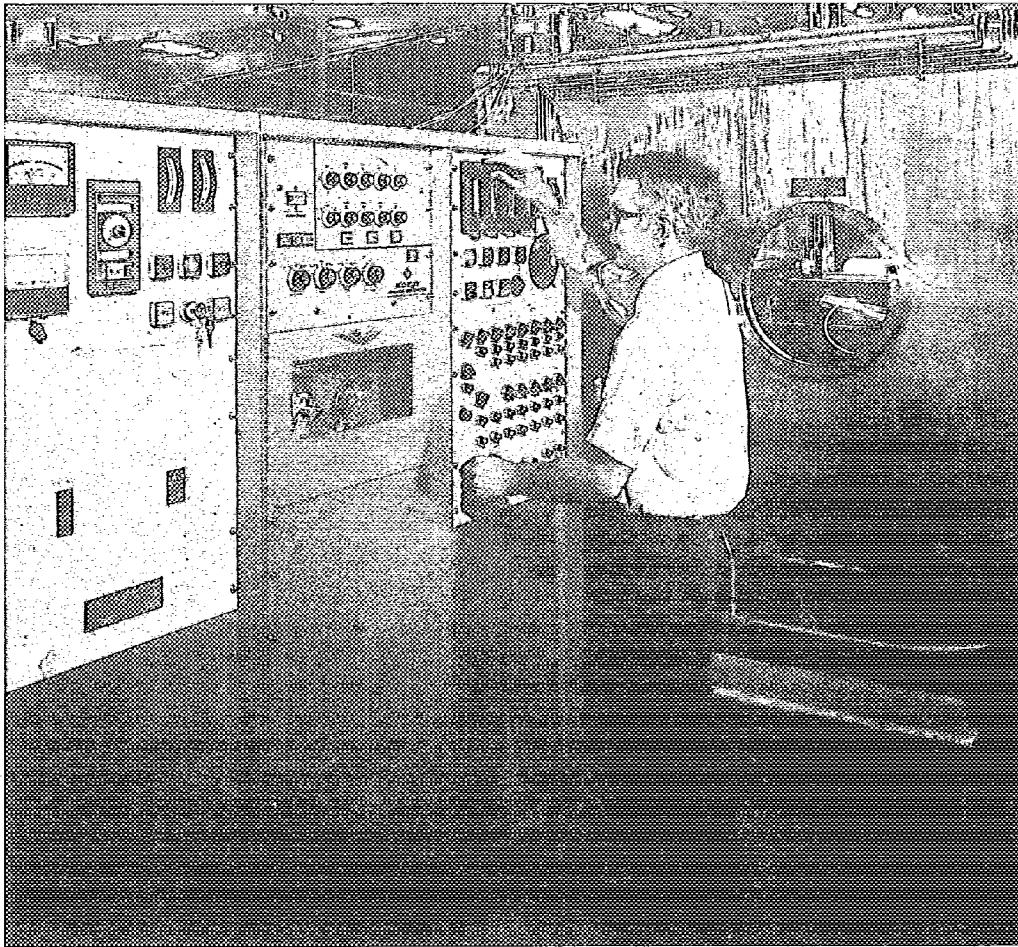


Figure 9.4.2G — Robotic manipulator controls

An alternative approach for providing satisfactory protection is the use of high velocity exhaust spray rooms lined with sound absorbent material. These have built-in facilities for water wash collection of airborne particles, air exhaust, and overhead lighting. They are constructed with three walls, and additional construction may be necessary. The sound absorbent room is constructed larger than the booth to allow for entry of air when the doors are closed. If the operator is working from a remote location, unbreakable windows should be provided for observation purposes.

In cases where the spraying operation must be performed on location, large portable fans and leaded curtains should be used.

The equipment manufacturer should be consulted if specific Environmental Protection Agency (EPA) or state regulations are required relative to stack emissions, since the amount of dust and fume generated depends on many

conditions including the type of spray equipment and material.

9.5.2 Exhaust systems. Exhaust systems and ventilation equipment complying with safety regulatory requirements are necessary for the protection of personnel. A side effect of thermal spraying is airborne contaminants, such as powder, smoke, and fumes. Dust collectors are required to dispose of these efficiently and quickly.

Wet collectors for thermal spraying are engineered and constructed to remove dust generated during the process. Units are constructed so that the dust laden air passes through a water tank and then through a water screen. Often, units are limited to an exhaust blower and a moisture eliminator (Fig. 9.5.2).

The preferred types of collectors use either the combination of a water pump and an exhaust blower, or a single fan and agitator water pump, to draw the con-

taminants through a wall of water. A float valve allows replacement of tank water lost through evaporation, and no overflow to area drains occurs.

Bag type collectors consist of a series of fabric filter bags mounted on frames in a dust tight casing. Collection hoppers are located at the casing's base. High velocity air blowers provide circulation. The screen frames are closed at the bottom and either side, leaving the top open for air passage. As dust laden air enters the casing, below the screens, it strikes a baffle plate. This sharp reduction in velocity causes the coarser dust particles to drop directly into the hoppers. Fine airborne dust particles are conveyed to and retained on the dust sides of the cloth screens. The cleaned air passes through the cloth and is discharged through the open top of the screen frames and the collector outlet. Electric or hand powered vibrators, or air pulses, are provided, as required, to dislodge and remove dust particles which adhere to the screens. The capacity of dust collecting equipment depends on the spray powder, the abrasiveness of the dust, and the character and condition of the work.

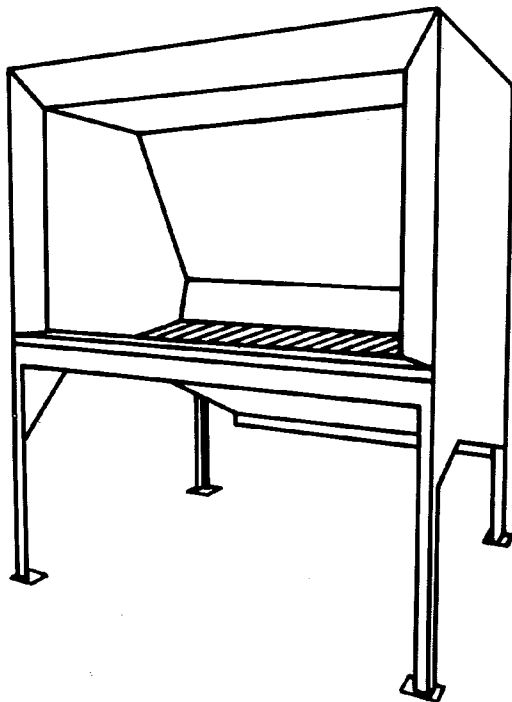


Figure 9.5.1A — Thermal spray booth (dry)

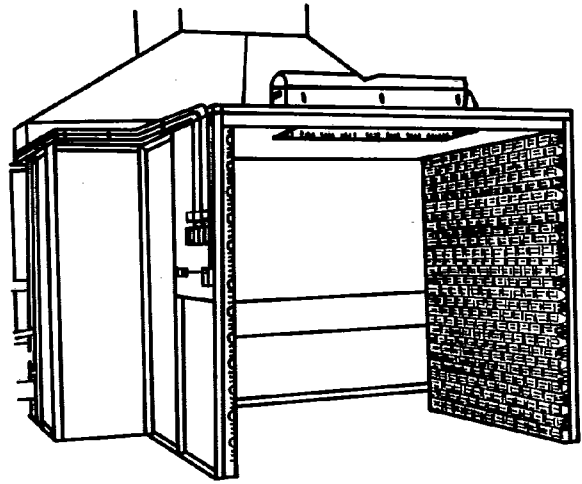


Fig. 9.5.1B — Tailored spray booth

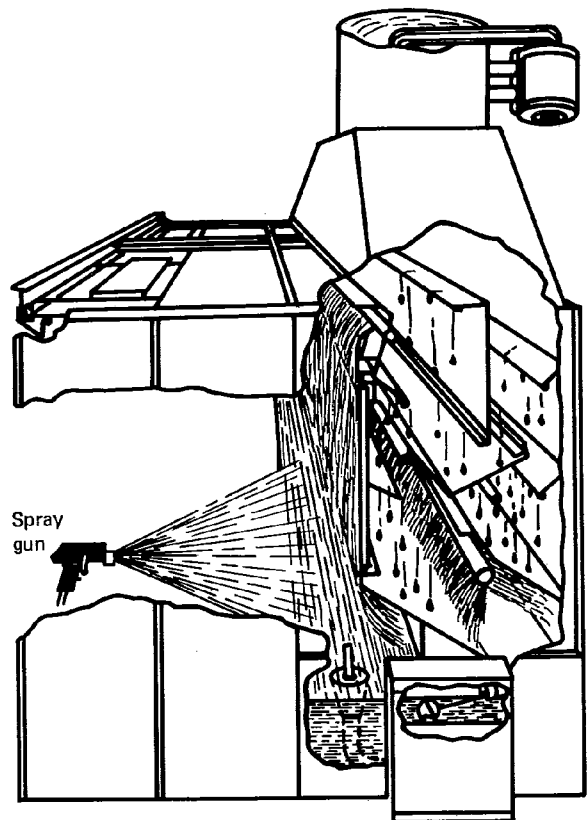


Fig. 9.5.1C — Integral spray water wash enclosure — basic unit

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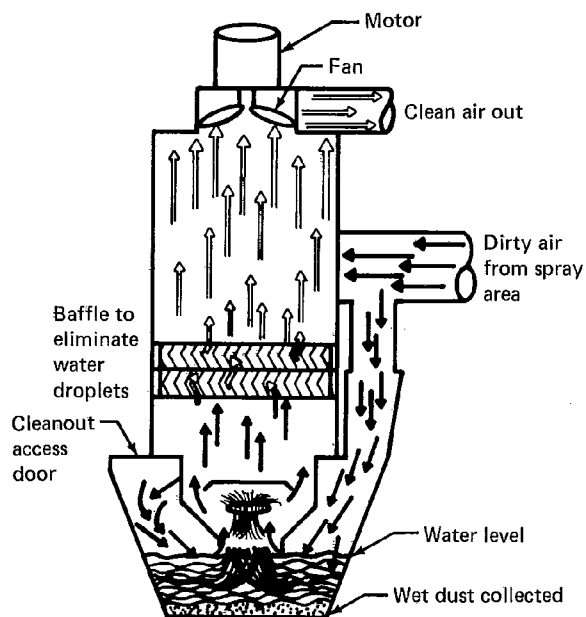


Fig. 9.5.2 — Wet collector

In cyclone collectors and centrifugal cyclone separators, air enters the inlet of these devices, creating a cyclone effect. The air is then drawn through a cone-shaped housing. The heavy particles are forced against the side walls and into the collector box. Clean air exhausts through the center of the turbulent cyclone. These collectors are ideal for controlling bulky particles at their source. All models exhaust outdoors or are equipped with after filters that can save on fuel costs by recirculating cleaned air indoors. This is done only where permitted by law. The self-cleaning material handling fans deliver high performance with low horsepower requirements.

Direct exhaust systems are used where it is permissible to exhaust dust and fumes into the atmosphere. Booths are available with powerful exhaust blowers. The air is circulated through the chamber to accumulate the contaminants and is passed into the atmosphere.

Traveling lathe exhaust units can be mounted on the traversing mechanism. A blower is attached by a flexible hose to the unit. The unit will suffice for short durations of spraying, but does little for actual entrapment of contaminants. A dry type filter can be used on the exhaust side. However, this arrangement hampers the volume of air flow and requires frequent cleaning.

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Chapter 10

Economics

10.1 Introduction

It is difficult to discuss the economics of thermal spraying without using specific examples and their related costs. Caution is urged in studying the various examples presented. Every proposed application should be recalculated, based on the specific conditions that will be met in the project under consideration. All the estimates suggested in this chapter are added for reference only. Cost will vary, depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material, and profit markup. The formats presented can be considered valid, however, and can be used as a basis for generating more exact cost figures.

This chapter considers the economics of various thermal spray processing methods. No comparison is made with other coating processes such as electroplating or welding. Moreover, the reader is cautioned that when this topic is discussed among experts, there are many differing opinions and approaches. For example, if three experienced spray shops were asked how to finish a thermal sprayed coating to obtain the same surface finish in each case, their specific approaches would no doubt differ relative to grinding vs. turning, types of tools, and the like, resulting in quite different cost figures for the finishing steps.

10.2 General Considerations

In each application, some or all of the following steps should be cost estimated.

- (1) Preparation: chemical cleaning, machining, blasting, and masking
- (2) Spray Equipment: process parts, spare parts, backup equipment, operator and safety equipment
- (3) Consumables: wire, powder, compressed air, gases, blast media, filters, maskants, sealers, electricity
- (4) Labor: preparation, spraying, finishing
- (5) Finishing Machinery: cutting tools, grinding wheels
- (6) Environmental Equipment: dust control, dust disposal, air cleaners, sound control

Many of the preceding costs are common to other operations and not specifically restricted to thermal spraying, such as machining and finishing. Information in this chapter will dwell on those items which are directly related to thermal spray operations. Health, safety, and environmental regulations are requirements to be fulfilled, and their impact on cost should be considered. The safety requirements, in Chapter 11, should be carefully followed. These costs primarily revolve around noise control, protection of the operator, and those working in adjacent areas. At times, soundproof rooms should be provided. In some states and localities, certification by regulating agencies is required. Costs are associated with the emissions from the exhaust. The user should be aware of such compliance requirements and be sure that the installation conforms to local ordinances.

With high volume spray applications, dust generation can be costly to control. Filters or scrubbers, or both, have to be installed, and in extreme cases, cost allowances made for the storage, handling, and disposal of dust or sludge.

Similarly, facilities should be available to properly store consumables prior to their use. Some powder materials require a dry, environmentally controlled atmosphere to maintain flowability. All consumables should be protected from excess humidity and kept clean to minimize feeding problems, which increase downtime and operating cost. Facilities should also be provided for safe gas storage and handling.

Adequate supervisory and quality control time should be budgeted to assure adherence to procedures and standards; otherwise, rejects and inefficient procedures can add to costs.

10.3 Installation

When contemplating a new thermal spray installation, consideration should be given to the location and the design of the facility. While this may add significantly to initial capital cost, the resultant positive influence on attitude and morale of personnel more than offsets the expense through improvements in productivity and reduced labor turnover. Thermal spray operations are inherently

dusty and noisy. If the facility is not properly designed to keep operator areas clean of fumes and dust, and to dispose of that dust, it will be difficult to maintain a staff of high quality, proficient workers. Turnover affects consistent quality and can add to such downstream costs as respraying, coating defects, increased equipment maintenance, and shortened equipment life.

In the case of original equipment manufacturers (OEM) and repetitive manufacturing type operations, the influence of the process on adjacent personnel dictates that spray systems be isolated from surrounding areas by sound insulating barriers or separate rooms. The separate room approach has many advantages in that it isolates odors, fumes, dust, and noise. Recommendations from thermal spray equipment suppliers and other experts should be solicited in these areas.

Different thermal spray processes generate different levels of noise and dust. In addition, the level of toxicity varies with materials. The level of fume generated can vary dramatically, and the design of the spray area should be tailored to specific conditions.

Floor space is a factor that is often ignored until it is unavailable, unsuitable, or inconvenient. Proper floor plans should be established at the outset.

10.4 Government Regulations

Government regulations impact both installation and operating costs, particularly in the area of safety procedures and equipment. The selection of proper goggles, fresh air equipment, and respirators contributes to lower costs through satisfied, enthusiastic, confident personnel operating at the highest productivity levels.

State and local environmental exhaust emission codes shall be observed. In extreme cases, the toxicity of the material being sprayed, such as lead, shall be considered. Where emission requirements are stringent, bag houses, electrostatic precipitators, or high energy consumption wet scrubbers may need to be added to the air cleaning system. In many states, maximum emissions are specified. These relate to the weight of dust included in each unit volume of exhaust air discharged from the facility. Typically, this is specified in grains per cubic foot (cubic meter); for example, 0.04 - 0.05 might be a typical number (there are 7,000 grains per pound (15430 grains/kg)).

Consider an exhaust stack that is emitting 5,000 cfm (142 m³/min) of air, with a spray rate of 20 lb/h (9 kg/h), the overspray is 10 lb/h (4.5 kg/h), and a wet scrubber, 95% efficient, is used to collect the dust. The system efficiency is calculated as follows: 5% of 10 lb/h (4.5 kg/h) overspray is not scrubbed from the air, thus 1/2 lb, 3,500 grains, (227 gm) of material per hour is being emitted from the building. This yields a loading of 0.012 grains

per standard cubic foot. Since this value is below the hypothetical acceptable emission level of 0.04 - 0.05 indicated above, the system should pass an emission sampling test. Should the system fail that test, it would be necessary to select a more efficient air cleaning system or pass significantly more dilution air through the collector.

The sample illustrates the need to study any new installation to be assured that environmental codes are met. Estimates for capital and operating costs must include properly sized emission control equipment and allowances for power consumption of associated fans, water pumps, and all related maintenance costs.

10.5 Capital and Operating Costs

10.5.1 Equipment Cost. The selection of specific thermal spray equipment for the job is treated elsewhere in this manual. Typical cost ranges for equipment at the time of this publication were

Technique	Equipment cost
Wire combustion	\$ 5,000 - \$ 6,000
Electric arc	\$ 8,000 - \$10,000
Plasma	\$15,000 - \$80,000
Powder combustion	\$ 3,000 - \$ 6,000
Rod combustion	\$ 4,000 - \$ 5,000

Replacement parts cost depends on the environment and application.

Support equipment such as exhaust systems, scrubbers, and soundproofing rooms can add from \$5,000 to \$50,000 or more to initial installation cost.

10.5.2 Gas and Energy Costs. A significant item in the operation of thermal spray devices is the cost of gas. Expenditures vary with volume usage, geographic location, and associated transportation and demurrage charges. Local gas charges should be verified for the anticipated usage. Table 10.5.2 suggests typical system gas and energy costs with assumed gas and electric rates. The data are presented only to serve as a guide for relative gas and energy outlays of the various systems. Material (feedstock) expenses vary widely. Gas and energy consumption charges are sometimes overshadowed by the higher prices of consumables. Also, some spray devices cannot be readily turned on and off, so that the actual energy consumption, whether gas or electricity, can be much higher than computed for the theoretical spray rates and gas consumptions during a given spraying time.

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Table 10.5.2
Example of hourly energy cost comparison*

Type	Air & Gas**	Electricity	Total/h
(1) Nontransferred plasma ^a	\$ 8.57	\$ 3.72	\$12.29
(2) Wire arc ^b	0.32	0.23	0.55
(3) Combustion wire ^c	4.75	0	4.75
(4) Powder combustion ^d	13.44	0	13.44

a. Nontransferred plasma 7 lb/h (3.2 kg/h)

Argon 75 ft³/h x 8¢/ft³ = \$ 6.00/h

Electricity 40 kWh x 6.5¢/kW = 2.60/h

Total \$ 8.60/h

To normalize to 10 lb/h: 8.6 x 10/7 = \$12.29/h

Nitrogen is cheaper than Argon, but nozzle cost is higher, resulting in similar costs.

b. Wire arc 10 lb/h

Electricity 3.5 kWh x 6.5¢/kW = \$0.23/h

Air 35 ft³/min x 60 min/h x 15¢/1000 ft³ = 0.23/h

Total \$0.55/h

c. Combustion wire 10 lb/h

Oxygen 90 ft³/h x \$0.0204/ft³ = \$1.84/h

Acetylene 32 ft³/h x \$0.081/ft³ = 2.59/h

Air 35 ft³/min x 60 min/h x 5¢/1000 ft³ = 0.32/h

Total \$4.75/h

d. Powder combustion 5 lb/h

Oxygen 95 ft³/h x \$0.0204/ft³ = \$1.94/h

Acetylene 59 ft³/h x \$0.081/ft³ = 4.78/h

Total \$6.72/h

To normalize to 10 lb/h: 6.72 x 2 = \$13.44/h

*For comparison purposes, costs are shown for the major types of equipment when spraying the same material (stainless steel) at 10 lb/h (4.5 kg/h). This table does not take into consideration the cost of materials. Costs of both energy and materials vary with location, usage, spray gun type, and materials form and size.

**Typical calculations (gas and air rates from Manufacturer's Handbook).

The importance of these various factors varies with the type of material sprayed. For example, when spraying a \$1/lb (\$2.20/kg) material such as zinc, energy charges are proportionately more significant than they would be when spraying a \$30/lb (\$66/kg) material. Note that material price can indeed be very high. For example, if a \$20/lb (\$44/kg) material is sprayed at 10 lb/h (4.5 kg/h), the materials consumption rate is \$200/h. Obviously, care should be taken to achieve the best deposition efficiencies consistent with the desired coating properties and production rates.

10.5.3 Job or Project Costing. Thermal spraying was used as a repair tool early in its history. Spare parts were often not available within the time frames required for replacement. Under such circumstances, the economics of thermal spraying were very attractive when compared

with the value of lost production and the effects on delivery time. As the technology evolved, usage became much broader. In current applications, specific coatings allow use of a less expensive substrate, or economically add properties to the product which are not achieved by other manufacturing techniques. Thus, the economic justification for repairs often is entirely different from the needs of the original equipment manufacturer (OEM). Savings can be so enormous in some repair applications, that the cost of equipment used, or the amount of materials consumed, is insignificant. Timeliness of repair and availability of coating equipment and applicator become more significant. This is not the case for an OEM manufacturer whose process is entirely automated, with a significant portion of the cost evolving from labor, operating cost of the thermal spray equipment, and the cost of consumables.

10.5.4 Materials. The cost of spray materials is calculated for known coating requirements; i.e., thickness, area, and deposit efficiency for the process used for each specific part. Some typical coating weights are listed in Table 10.5.4. These numbers can be used to calculate coating material requirements for a specific job or application.

For example, assume

Surface area to be coated = 400 ft² (37.2 m²)

Effective spray due to loss at holes and edges = 90%

Stainless steel feedstock requirement at 100% deposition efficiency (Table 10.5.4)

= 0.035 lb/ft² • 0.001 in. (0.17 kg/m² • 0.025 mm)

Deposit efficiency = 70%

Coating thickness = 0.100 in. (2.54 mm)

Spray rate = 60 lb/h (27.2 kg/h)

Amount of spray material required is equal to

Surface area x coating thickness x feedstock required (100% eff.)

Effective spray x deposit efficiency

$\frac{400 \text{ ft}^2 \times 0.100 \text{ in.} \times 0.035 \text{ lb/ft}^2 \cdot 0.001 \text{ in.}}{0.90 \times 0.70} = 2222 \text{ lb}$

or $\frac{37.2 \text{ m}^2 \times 2.54 \text{ mm} \times 0.17 \text{ kg/m}^2 \cdot 0.0254 \text{ mm}}{0.90 \times 0.70} = 1004 \text{ kg}$

Material cost can best be determined by obtaining a quoted cost per pound from the appropriate supplier. The same material will vary in cost with volume purchased and form of material; e.g., wire diameter, wire coating, powder size, and type of packaging.

10.5.5 Spray Time or Production Rate. Spray time can be calculated for the example just discussed as follows:

$$\begin{aligned} \text{Spray time} &= \frac{\text{amount of material to be sprayed}}{\text{spray rate}} \\ &= \frac{2222 \text{ lb}}{60 \text{ lb/h}} \quad \text{or} \quad \frac{100 \text{ kg}}{27.2 \text{ kg/h}} \\ &= 37 \text{ h} \end{aligned}$$

The following section of this chapter lists formulas required for job or project costing. Numerous examples are then given to illustrate computations using these varied

Table 10.5.4
Typical thermal spray
feedstock requirements lb/ft² • 0.001 in.

Material	Deposit efficiency, %			
	40	60	80	100
Aluminum	0.033	0.022	0.016	0.013
Aluminum bronze	0.083	0.055	0.042	0.033
Alumina (+2% titania)	0.043	0.028	0.021	0.017
Calcium zirconate	0.053	0.035	0.026	0.021
Chromic oxide	0.065	0.043	0.033	0.026
Copper	0.098	0.065	0.049	0.039
Molybdenum	0.115	0.077	0.058	0.046
Nickel	0.098	0.065	0.049	0.039
Nickel 20 chrome	0.095	0.063	0.048	0.038
Nickel chromium (16% chromium)	0.098	0.065	0.049	0.039
Stainless steel (17% chrome) (12% nickel)	0.088	0.058	0.044	0.035
Steel	0.090	0.060	0.045	0.036
Titania TiO ₂	0.053	0.035	0.026	0.021
Tungsten	0.220	0.147	0.110	0.088
Tungsten carbide (12% cobalt)	0.160	0.107	0.080	0.064
Tungsten carbide (17% cobalt)	0.143	0.095	0.071	0.057
Tungsten carbide (46% nickel) (35% tungsten/cobalt) (11% chromium)	0.108	0.072	0.054	0.043
Tungsten carbide (33% nickel) (50% tungsten/cobalt) (9% chromium)	0.120	0.080	0.060	0.048
Zinc	0.098	0.065	0.049	0.039
Zirconium oxide	0.070	0.047	0.035	0.028

1 kg/m² • 0.025 mm = 4.88 lb/ft² • 0.001 in.

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costing factors. The reader should select from the example segments which would be appropriate to the procedure and process being evaluated. Note that hourly labor costs are not the same in each example, since the skill required for a one-time job is greater than that needed on high production jobs.

10.6 Job or Project Costing Formulas

The following will provide guidelines for calculating the cost of a thermal spray coating:

10.6.1 How to Compute Sprayed Area. When estimating surface area, an allowance for loss at the edges needs to be made. A good rule is to add 1 in. (25 mm) to each dimension where there is an edge. This compensates for the edge loss. This also applies when estimating the cost of building up a shaft. In this case, add 2 in. (50 mm) to the length to be built up [(1 in. (25 mm) each end)].

Area formulae

Circumference of a circle = πd

Area of a circle = πr^2
 Area of a cylinder = $\pi d l$
 Area of a sphere = πd^2
 Area of a triangle = $bh \div 2$
 Area of a parallelogram = bh
 Area (lateral) of a cone = $\pi r \sqrt{r^2 + h^2}$
 Where $\pi = 3.1416$; b = base; d = diameter;
 h = altitude; r = radius of base; l = length

10.6.2 Calculating Costs. An important factor, when calculating costs, is the normal variation in coating thickness between the thinnest and the thickest area. The extent of this variation depends on the particular job and the manner in which it is coated. For all ordinary coatings, the average thickness should be used in calculating costs. However, if a minimum thickness is specified, be sure to apply an average thickness great enough that no area will be thinner than the specified minimum. If this correction cannot be determined from experience, spray a test area to determine the average thickness required (Table 10.6.2).

Table 10.6.2
Calculation of coating costs per square
foot for 0.001 inch average thickness

Symbol	Item	Units		Source
		U. S. Customary	(S.I)	
C	Cost of coating	\$ per sq ft for 0.001 in. thick	(\$/m ²) (0.25 mm)	Compute
P	Spray material cost	Dollars per pound	(\$/kg)	Supplier
S	Spray rate	Pounds per hour	(kg/h)	Supplier data or measure
E	Equipment operating cost per hour	Dollars per hour	(\$/h)	Section 10.6.3
d	Theoretical density of solid material	Pounds per cubic in.	(g/cc)	Handbook value
R	Ratio of coating density to theoretical density	Approximately 85 %	(0.85)	Average value
v	Vol. of 1 sq ft at 0.001 in. average thickness	0.144 cubic in./sq ft	(2.4 mm ³)	Compute
D	Deposit efficiency	Percent	(%)	Supplier data or measure
K	Cost of coating	Dollars per pound	(\$/kg)	Compute
(PxS) + E	Total operating cost	Dollars per hour	(\$/h)	Compute
v x R x d	Coating weight	Pounds/l sq ft 0.001 in. thick	(kg/m ²)	Compute or data bulletins
S x D	Spray material deposited	Pounds per hour	(kg/h)	Compute or data bulletins

Total cost of coating, \$/lb:

$$K = \frac{(PxS) + E}{S \times D}$$

Cost of coating, \$ per 0.001 in thickness =

$$C = \frac{[(PxS) + E] [v \times R \times d]}{S \times D} \quad \frac{[(PxS) + E] \times 0.122d}{S \times D}$$

10.6.3 Calculation of Equipment Operating Cost

(1) **Combustion Gas and Wire** (see Notes 1, 2, and 3)

Air cost per hour = air used x air cost

Fuel gas cost per hour = fuel gas used x fuel gas cost

Oxygen cost per hour = oxygen used x oxygen cost

$$E = \frac{\text{air cost}}{h} + \frac{\text{fuel cost}}{h} + \frac{\text{oxygen cost}}{h}$$

(2) **Electric Arc** (see Notes 1, 3, and 4)

Air cost per hour = air used x air cost

Electric cost per hour = power (kw/h) x power cost per hour

$$kw = \frac{\text{dc volts} \times \text{dc amperes}}{1000 \times 0.8 \text{ (see Note 4)}}$$

$$E = \frac{\text{air cost}}{h} + \frac{\text{electric cost}}{h}$$

(3) **Plasma** (see Notes 1, 2, 3, and 4)

Primary plasma gas cost per hour = gas used x gas cost

Secondary plasma gas cost per hour = gas used x gas cost

Carrier gas cost per hour = gas used x gas cost

Cooling air cost per hour = air used x air cost

Electric cost per hour = power used (kw/hr) x power cost per hour

$$kw = \frac{\text{dc volts} \times \text{dc amperes}}{1000 \times 0.8 \text{ (see Note 4)}}$$

Cooling water cost per hour = water lost or consumed (volume/hour) x water cost

$$E = \frac{\text{Primary gas cost}}{h} + \frac{\text{secondary gas cost}}{h} + \frac{\text{carrier gas cost}}{h} + \frac{\text{air cost}}{h} + \frac{\text{electric cost}}{h} + \frac{\text{water cost}}{h}$$

Notes:

(1) Air, gas, electric, and water consumption per hour can be obtained from the equipment supplier's operating manual.

(2) Gas used - volume/unit time.

(3) Include auxiliary items such as dust collectors, water cooling pumps, etc., when applicable.

(4) ac/dc conversion efficiency is approximately 0.8.

136/THERMAL SPRAYING: PRACTICE, THEORY, AND APPLICATION**10.6.4 Six Steps to Establish Cost of Coating**

- (1) Compute the area to be sprayed
- (2) Calculate the volume of the coating

$$\text{Coating volume} = \text{area} \times \text{coating thickness}$$
- (3) Calculate time required

$$\text{Time} = \frac{\text{coating volume}}{(\text{spray rate} \times \text{deposit efficiency}) / \text{coating density}}$$
- (4) Calculate weight of spray material required

$$\text{Weight} = \text{time required} \times \frac{\text{spray rate}}{\text{deposit efficiency}}$$
- (5) Calculate equipment operating cost
 See Section 10.6.3
- (6) Calculate total cost of spraying coating

$$\text{Total cost of spraying} = \text{spray material cost} + \text{equipment operating cost} + \text{labor cost}$$

$$\text{Spray material cost} = \text{weight used} \times \text{material cost}$$

$$\text{Equipment operating cost} = \text{values from 10.6.3} \times \text{time required}$$

$$\text{Labor cost} = \text{labor cost per hour} \times \text{time required}$$

Note:

The above information relates only to the cost of SPRAYING. The cost of the job also includes

- surface preparation before spraying
- fusing (if required)
- sealing (if required)
- machining, grinding, or other finishing needed after spraying.

Where finishing of the coating is required, include the material to be removed when calculating the thickness of coating to be sprayed.

10.7 Case History #1 — Small Spring Spraying

10.7.1 Background and Problems. A small AISI Type 302 stainless steel spring used to hold a ceramic ignitor on the gas control burner in clothes dryers required protection to continuous operating temperatures of 1200°F (650°C). Before the springs were coated, they would react with the ignitor and eventually corrode, allowing the ignitor to fall from its position. The coating resisted the reaction.

Tests determined that a 7 mil (0.18 mm) aluminum coating was best for this application. Because of part size and quantity to be processed, the optimum approach was through batch processing. There are 300 springs per pound (136/kg); they are 3/4 in. wide x 1 in. long x 1/32

in. thick (19 mm x 25 mm x .79 mm) and crimped longitudinally with a 5/32 in. (4 mm) bend on two corners which prevents them from adhering during processing. Batch quantities are between 15,000 and 50,000 pieces with a yearly quantity of 200,000 to 300,000 pieces.

10.7.2 Process. Initially all parts are vapor degreased to remove stamping oils, and the springs are tumble blasted, with aluminum oxide. After roughening, the parts are sprayed immediately in the same tumble mode. A combustion wire spray gun is used to apply a 0.007 in. (0.18 mm) coating of pure aluminum over all surfaces. The wire spray gun was selected, because it applies a very finely textured deposit and has the low spray rate necessary to prevent part sticking.

10.7.3 Costs. Aluminum consumption was 0.01 ounces (.28 g) per part. Because of the tumble spray operation, deposit efficiency was approximately 40%. Other measured costs were

Labor cost of preparation	\$0.005 per part
Labor cost of thermal spraying	\$0.005 per part

Initial cost of tumble blaster, turning fixture, and thermal spray unit amortized over one million parts	0.0109 per part
--	-----------------

Material cost including gas, oxygen, and wire	\$0.003 per part
Total cost	\$0.0239 per part

Finishing of the coating was not required.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

10.8 Case History #2 — Mandrel Repair

10.8.1 Background and Problems. Forming mandrels are used in manufacturing plastic pipe. Mandrel size varies with the range of plastic pipe manufactured. Mandrel diameter may be from 8 to 20 in. (0.20 to 0.50 m) and be as long as 23 ft (7 m). The majority of mandrels have a journal at each end that is 2-15/16 in. (75 mm) outside diameter by 16 in. (406 mm) long. Mandrel composition is low carbon steel. Due to a high replacement cost, a method was required to repair scored and worn mandrels.

10.8.2 Process. The arc process was selected for its cost effectiveness. A stainless steel (420) coating was chosen for its hardness, wear, and corrosion resistance. The mandrel repair consisted of the following steps:

- (1) Set up mandrel in a lathe or grinder, check for straightness.
- (2) Straighten mandrel, if required.
- (3) Pregrind mandrel, 0.040 in. (1 mm) undersize, using an outer diameter grinder.
- (4) Grit blast mandrel.
- (5) Coat mandrel, 0.050 in. (1.3 mm) oversize on diameter, for a total buildup of 0.090 in. (2.3 mm).
- (6) After spraying, finish grind the mandrel to a 16 microinch finish, and polish. Grinding costs are estimated in the total time per mandrel.

The deposition efficiency for this application at 20 lb/h (9.07 kg/h) is 80% with approximately 206 lb (93 kg) of wire consumed per mandrel, i.e.:

Coating area

U. S. = $3.1416 \times 8 \text{ in. minimum dia} \times 23 \text{ ft} \times 12 \text{ in./ft}$
 $= 6937 \text{ in.}^2$

S. I. = $3.1416 \times 0.203 \text{ m} \times 7 \text{ m} = 4.46 \text{ m}^2$
 lb metal/mandrel

U. S. = $6937 \text{ in.}^2 \times 0.33 \text{ lb wire/in.}^3 \times 0.090 \text{ in. thk}$
 $= 206 \text{ lb}$

S. I. = $4.46 \text{ m}^2 \times 0.150 \text{ kg/in.}^3 \times 61024 \text{ in.}^3 \times 0.00229$
 $\text{m} = 83.5 \text{ kg}$

(U.S.) time = $\frac{206}{20 \text{ lb/h} \times 0.80} = 12.9 \text{ hours}$

(S.I.) time = $\frac{93.5}{9.07 \text{ kg/h} \times 0.80} = 12.9 \text{ hours}$

10.8.3 Costs. The total time required per mandrel is 95 man hours.

Labor and overhead	95 h x \$50/h	\$4750
420 spray wire	270 lb x \$3/lb (122/kg x \$6.61/kg)	810
Electricity	8 kW x 12.9 h x \$0.10/kW	10
Spray air	35 cfm x 60 x 12.9 h x \$1.15/1000 ft ³ = (59,459 L/h x 12.9h x \$0.000052/L)	4
Blast air	Similar to spray	4
Abrasive	30 lbs Al ₂ O ₃ x \$0.50/lb (13.6 kg Al ₂ O ₃ x \$1.10/kg)	15
		\$5593

The replacement cost for an 8 in. (203 mm) diameter mandrel 23 ft (7 m) long is approximately \$13,000.00. Including profit, the repaired forming mandrel saved almost \$5,000 compared to a replacement unit.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

The two alternative approaches to repair of the mandrels are as follows:

(1) Manufacture a new mandrel - this would be twice as expensive as the repair process.

(2) The existing mandrel could be chrome plated. This is not economically practical because of the large buildup required per mandrel.

10.9 Case History #3 — EMI Shielding of Plastic Cabinets

10.9.1 Background and Problems. Manufacturers of small computers and word processors switched to plastic cabinets for cost and cosmetic purposes. Owing to Federal Communications Commission regulations on the amount of radiation permitted from such devices, and interference with circuits within the word processors from outside elec-

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trical radiation, the cabinet required coating with a conductive material.

Vacuum metallizing was attempted but deemed excessively expensive and required large capital investments. Available paints were insufficiently conductive, while coating with metal foils was costly and unreliable.

10.9.2 Process. Some plastics required grit blasting with 80 mesh aluminum oxide, to produce adequate zinc adhesion, while others merely required a clean surface. Manufacturers determined that 0.002 in. to 0.003 in. (0.05 mm to 0.08 mm) of sprayed zinc was the most economical and reliable way to shield cabinet interiors. Zinc was selected because of its excellent bond strength, ease of application, and low cost. Manual application procedures were selected due to the varied and complex cabinet shapes, and the short time required to enter into production.

10.9.3 Costs. Estimated application costs of the arc-spray zinc coating depend on the number of parts to be sprayed, their complexity, and size. It is difficult to arrive at a generalized cost number. However, the following data are presented which can be interpolated for a particular application. The amount of metal deposited depends on the complexity (ribs and pillars) of the surface sprayed. For such complex shapes, manipulation of the gun (to keep the spray stream at 45° to 90° to the surface and to assure a dense coating) may result in localized buildup.

Guidelines to estimate process costs will be indicated for a typical polycarbonate part of approximately 3 sq ft (0.28 m²) surface area with 2 in. (51 mm) high side walls, 2 structural ribs, and 6 support columns 1-1/2 in. (38 mm) high. Table 10.9.3 summarizes the cost that must be considered. An arbitrary labor rate of \$12/h has been used.

These figures include no profit and are based on a 200% overhead factor. Masking charges, special packaging, or unusual handling are not included in this example; add appropriate time and labor figures relating to the specific part processed. Again, the purpose of the example is to indicate a format for calculations and to demonstrate the increased productivity and the possibility of reducing spray time with automation. For example, automated installations have demonstrated a 20% reduction in materials costs and a 30% decrease in labor. If production were to be increased by 20% through faster spraying, the cost savings on the annual production rate of 138,240 units produced would be 16¢/ft² (1.72/m²) or \$66,355. This would amortize a typical automated system in one year.

The utilization rate on volume applications will depend

on the particular application. For automated systems, it may approach 70% to 90% and for manual operations 50% to 70%.

In making cost projections, note that the amount of metal spray varies with the complexity of the part. In addition, other factors such as surface preparation prior to spray vary greatly with different plastics. Likewise, masking of screw holes, support posts, and the like can increase costs. Masking costs are common to painting and thermal spraying.

The estimates in Table 10.9.3 are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

10.10 Case History #4 — Diesel Engine Connecting Rod Bearings

10.10.1 Background and Problems. Diesel engine crankshaft and wrist pin bearing areas of connecting rods are babbitt lined. This is an excellent bearing surface, sufficiently soft to prevent damage by seizure. It is capable of resisting galling without wearing the mating part. The traditional method of lining connecting rod bearings has been by casting over them with molten babbitt. After the babbitt has cooled, the parts are trimmed and machined to dimension.

Poured bearings present a number of costly and time consuming problems. Thin coatings are required for high load, high speed, and heavy duty bearings. It is technically difficult to pour high quality thin coatings because of porosity and crazing resulting during cooling. Thus, thick coatings must be poured and machined down to thinner dimension. Such a coating is spongy, weak, poorly bonded, and structurally inferior. The need for a bearing of greater integrity led to the testing of flame sprayed babbitt coatings.

Spraying proved to be the best method of constructing the preferred thin babbitt bearings. Laboratory and field tests demonstrated that sprayed bearings can withstand greater loads than can the more compressible poured bearings. This, coupled with the ease of application, has promoted the use of spray.

Users of sprayed bearings report that they outwear poured bearings 2 to 1. This is partly due to intersplat oxides and the retention of lubricants in the coating micropores.

Poured bearings suffer undesirable segregation of alloy constituents resulting in premature and costly failures. Reports indicate that this is not the case with flame sprayed bearings. Tin-antimony-copper babbitt wire is used for this application. The coating is machine finished.

Table 10.9.3
Arcspray zinc metal shielding cost using
2-3 mil (0.05 to 0.08 mm) thickness

Assumptions:

- Manual application
- 60% time utilization of equipment
- 3 shift operation 48 weeks/year = 240 days/year
- zinc wire cost — \$1.00/lb, (\$2.20/kg) 20,000 lb (9072 kg) per year quantity
- grit blasting required
- equipment to be amortized in 2 years
- 5 men required/shift
- labor plus overhead \$12/h
- air cost 15¢/1000 cf (28.3 m³), consumption 4032 cfh (114.2 m³/h), @ 90 psi (620 kPa)
- electric consumption 15 kva
- 3 sq ft surface/part

Equipment required:

arc spraying units	(2)	\$14,400
grit blasters	(2)	6,000
water wash booths	(2)	10,000
handling equipment, etc.	(2)	30,000
Total Capital		\$60,400

Measured items:

3 minute spraying time/part
0.5 lb (.23 kg) zinc/unit

Using the above data, the following costs were developed to produce 576 pieces per day:
 1728 ft² (160.5 m²)/day, or 414,720 ft²/year (38529 m²/year)

Summary Arcspray Coating Cost

Equipment amortization (2 years)	7¢/ft ²
Labor 5 men/shift x 3 shifts x 52 weeks x \$12/h	90¢/ft ²
Zinc	17¢/ft ²
Air, electricity, replacement parts	2¢/ft ²
Total Cost	\$1.16/ft²

10.10.2 Process. Manufacturing steps are as follows:

- (1) Melt out the existing babbitt in a furnace or with a hand torch, and clean the area to be coated with a stainless brush.
- (2) Disassemble the parts, shim as required, and mask to limit deposit areas.
- (3) Heat the bearing and tin the surface to improve the bond of the sprayed coating.
- (4) Use suitable spraying conditions to produce a coating [allowing 0.010 in. (0.25 mm) for fine finishing] which, when machined, will produce a long, continuous chip rather than a fine, broken chip.
- (5) Machine to finished dimensions.

10.10.3 Costs. Consumables per square foot of surface (0.09 m²) area coated to produce a 0.040 in. (1 mm) coating are 2.016 lb (0.914 kg) babbitt wire, 1.568 cu ft (0.044 m³) oxygen, and 0.898 cu ft (0.025 m³) acetylene. A combustion wire gun was used with a capital

cost of \$6000. Typical costs for 4 in. (102 mm) dia x 6 in. (152 mm) long bearing are

Labor 32 min x \$20.00/h	= \$10.66
Amortization — cost per spray time	= 1.54
Materials — babbitt [1/8 in. (3.2 mm)]	
2.016 lb x \$8.50/lb	= 17.14
Gases — Oxygen, Acetylene	= .30
Total cost/part	\$29.64

Cost by alternate process for new rod bearing is \$50 to \$75

This approach to bearing repair has reduced costs over conventional pouring methods by more than half, and permitted repair of large bearings with significantly less capital equipment.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

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10.11 Case History #5 — Farm Machine Blades

10.11.1 Background and Problems. Knives, blades, flails, and bars of crop harvesting machines encounter severe abrasive wear by soil impact and the produce they cut. This wear is compounded by the swinging, rotating, and cutting of the blades against cornstalks, wheat, barley, and hay. Some knives operate at 3600 rpm and provide 70,000 cutting strokes per minute. This causes damage and dulling of the cutting edges, resulting in reduced efficiency and productivity. Damaged parts have to be replaced, and worn parts sharpened. While replacement costs are a concern, the major problem is downtime. Any interruption in the harvesting cycle is very costly.

Research was conducted to determine a means of increasing part wear life to a full season's operation. Thermal spray hard facing was shown to be a solution. Sprayed cutting blades outwear the original hardened steel parts by up to 5 to 1. Market acceptance has been demonstrated by an increasing use of sprayed knives, flails, and bars. Since the cutting blades rotate at high speeds, balance and weight distribution are important to prevent vibration and wear of bearings. When spraying, the knife-to-bar clearances and other dimensions are readily maintained because of the ease of depositing any required coating thickness.

A tungsten carbide-containing self-fluxing alloy was selected for this application. The deposit is fused after spraying. Since the softer base metal wears first, leaving the hard tungsten carbide cutting edge exposed, it promotes a self-sharpening effect.

10.11.2 Process. Parts are stack coated, with 4 to 20 blades being sprayed at a time. They are prepared and coated on a semiautomatic production basis. Mechanical shielding and overlapping of parts in fixtures are generally used for blasting and spraying.

A blend of tungsten carbide plus cobalt with a cobalt base self-fluxing alloy is used on hardenable steel such as 4130, 4140, or the 400 series stainless steels. The hardness of the carbides in the coating is HRC75; the hardness of the matrix is HRC58-60. Both are harder, tougher, and more wear resistant than the original steel parts.

A blend of tungsten carbide plus cobalt-nickel with a nickel base self-fluxing alloy is used on mild steel parts. Both coatings are fused either by torch or by induction heating. The steps are as follows:

- (1) Degrease the part thoroughly.
- (2) Blast with coarse alumina.
- (3) Apply coating 0.008 in. (0.20 mm) to 0.015 in. (0.38 mm).
- (4) Fuse.
- (5) No finishing required.

10.11.3 Costs. Consumables per square foot (0.09 m²) of coating are 0.765 lb (.347 kg) powder, 2.295 cu ft (0.065 m³) oxygen, and 1.262 cu ft (0.036 m³) acetylene.

For a part with a dimension of 14 in. x 3 in. x 7/16 in. (356 mm x 76 mm x 11 mm) with 0.015 in. (0.38 mm) of material coating, costs are as follows:

Labor 20 min x \$50.00/h	= \$16.67
Amortization — auxiliary equipment and powder combustion system \$10,000	
2 year, 20 h/week	= 1.67
Tungsten carbide, cobalt powder	= 5.25
Gases — oxygen, acetylene	= .12
Total cost/part	\$23.71

This application extended part life 3-5 times over new, uncoated blades.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

10.12 Case History #6 — Gripping Fingers — Paper Bag Machines

10.12.1 Background and Problems. Finger grip assemblies are used in paper bag manufacturing machines. Generally, there are eight such assemblies per machine. Bags are made in stages: cutting, forming, gluing, and trimming. Conveying the bags from one stage to the next is automatic. At each stage of operation, the bag is pulled out of the jaws of the finger assembly, processed, and conveyed to the next stage.

Paper is abrasive, particularly recycled paper used for cement, charcoal, coke, sand, and grain. This abrasiveness rapidly wears the fingers, requiring maintenance and replacement. A method of reclaiming the worn fingers was needed. Welding and chrome plating were tested. Both proved unsatisfactory. Welding was rejected because of excessive heat and warpage. Chrome plating was costly and time consuming. Plasma spray was found to offer an alternative wear solution. Ease of application and extension of service life were the factors that led to the selection of a sprayed coating.

Plasma spraying with a tungsten carbide blend provides a surface more wear resistant than the original base material and has a hardness of HRC52 compared to HRC34 for the base part.

Sprayed parts outwear the original parts at least 4 to 1; one year compared to 90 days.

10.12.2 Process. Manufacturing steps are as follows:

- 1) Degrease.
- 2) Mask areas not to be coated.

- 3) Grit blast with coarse alumina.
- 4) Apply coating to a thickness of 0.015 in. (0.38 mm).
- 5) No finishing is required.

10.12.3 Costs. Consumables per square foot (0.09 m²) of coating to produce 0.015 in. (0.38 mm) thick coating are 1.320 lb (0.599 kg) tungsten carbide/cobalt powder, 4.693 kw electricity, 22 cu ft (0.622 m³) nitrogen, and 1.5 cu ft (0.042 m³) hydrogen.

For a part with a dimension of 14 in. x 3 in. x 7/16 in. (356 mm x 76 mm x 11 mm) costs are as follows:

Labor — 12 min x \$50.00/h	= \$10.00
Amortization — cost per spray time	= 3.30
Plasma system \$30,000 2 years, 20 h/week (4.5 parts/h)	
Material — tungsten carbide plus cobalt	= 5.57
Gases — nitrogen	= 0.53
— hydrogen	= 0.06
Electricity—0.39106 kWh x 0.12 kW/h	= 0.05

Total cost/part \$19.51

The cost of a new gripper finger: = \$62.00 ea.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

10.13 Case History #7 — Grinder Spindles

10.13.1 Background and Problems. Manufacturers of precision parts use grinders for close tolerance finishing operations. Working to tight dimensions [such as 15 millionths of an inch (0.38 μ m) on concentricity and tenths of thousandths (0.25 mm) on the diameter], spindle bearings must remain tight to prevent slight spindle play. Under such extreme conditions, shafts wore in several days. The combination of replacement cost plus downtime made the operation very expensive. Chrome plating proved unsatisfactory. Special tool steels were also evaluated, but the spindle journals continued to wear prematurely.

Technically and economically, thermal sprayed coatings proved to be best of all the processes evaluated. Various spray materials were tested. Some, such as molybdenum, were used successfully before the development of powder flame sprayed ceramic coatings. The ceramic coatings provided outstanding results on repaired parts and have been incorporated in original equipment manufacturing. Easily processed, lower priced steel base materials have replaced the earlier used special forgings. Low cost hardened steel base materials have replaced the costly bronze babbit originally used to make the mating bearings.

Flame sprayed spindles outwear the original forged spindles 24 to 1. The lower friction of a ceramic coated journal reduces wear on the mating bearing, and it is not corroded by grinding coolants.

10.13.2 Process. The powders used are a nickel aluminum bond coat, followed by a titania top coat. Alumina titania coatings may also be used for this application. Manufacturing steps are as follows:

- (1) Degrease.
- (2) Undercut 0.012 in. (0.30 mm) on the radius.
- (3) Mask areas not to be coated.
- (4) Preheat to 300°F (149°C) for one hour. This can be done in a furnace or oven.
- (5) Check temperature with pyrometer to assure that it is at least 250°F (121°C). If not, torch heat to 250°F (121°C).
- (6) Apply a 0.006 in. (0.15 mm) nickel-aluminum bond coat.
- (7) Apply titanium dioxide 0.25 in. (6.4 mm) thick. This allows 0.013 in. (0.33 mm) for finish grinding.
- (8) Seal with a room temperature curing phenolic. Air dry 30 to 60 minutes. Oven heating at 275°F (135°C) will dry the sealer in 15 to 30 minutes.
- (9) Grind, using either a diamond or a silicon carbide wheel.
- (10) Reseal as required.

Procedures for repair are the same as shown above, except that the worn coating must be removed.

10.13.3 Costs. Consumables per square foot (0.9 m²) of surface area coated are 0.006 in. (0.15 mm) nickel-aluminum bond or 0.252 lb (0.114 kg) powder, 1.470 cu ft (0.042 m³) oxygen, 1.050 cu ft (0.030 m³) acetylene, 0.025 in. (0.64 mm) titania coating or 0.900 lb (0.408 kg) titania powder, 21.15 cu ft (0.60 m³) oxygen, and 12.60 cu ft (0.36 m³) acetylene.

For a 2 in. (51 mm) diameter x 3 in. (76 mm) long part, the costs are as follows:

Labor — 25 min x \$20.00/h	= \$ 8.33
Amortization — cost per spray time	= 2.16
Powder combustion system \$4,500, lifetime 2 Years, 20 h week	
Material — nickel-aluminum bond	= 0.83
— titania	= 2.33
Gases — nickel-aluminum bond	
oxygen	= 0.07
acetylene	= 0.21
— titania bond	
oxygen	= 0.10
acetylene	= 0.21
Total cost/part	\$14.24

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The cost of a replacement spindle is \$1000.00.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material cost, and profit markup.

10.14 Case History #8 — Automotive Valve Seats

10.14.1 Background and Problems. An automotive cylinder valve controls the intake of fuel gases and the exhaust of the cylinder residue. In operation, the valve frets and traps hard carbon particles between mating valve seats, which tend to hold the valve open. This results in a gap which permits abrasive and corrosive particles to pass over the seats at high velocity and high temperature. This causes excessive wear.

To counter this problem, tests were conducted to identify a coating that would withstand the operating conditions.

On valves, a flame sprayed, fused coating of aluminum proved to be a good solution. It is used on many of the valves being produced. The process consists of applying a thin aluminum coating and fusing it. This forms intermetallic compounds which provide the required wear and corrosion resistance.

Prior to applying the sprayed aluminum coating, the valves were dipped in molten aluminum. This proved to be slow, inefficient and unsafe.

With more recent engine designs, the performance demands created a requirement for a coating other than aluminum. Special metals were evaluated, but they failed. Coating by hard chrome plating and brazing was also evaluated, but this proved ineffective.

Flame sprayed coatings of fused self-fluxing nickel-chromium alloys provided the best protection, and proved to be the most practical of all methods tested. It easily dovetails with automatic handling equipment, is lowest in cost, and is the least dependent on technique. The system offers consistent reproducibility, assuring quality, and production efficiency.

Sprayed valves outwear uncoated valves at least 2 to 1, resist wear by abrasive grains at high temperatures, and resist fretting, erosion, and corrosion at high temperatures.

10.14.2 Process

Aluminum Coating (Wire). By the combustion wire process, aluminum wire is sprayed and subsequently fused to form the desired coating. The process steps are as follows:

- (1) Grind valve seat to final dimensions.
- (2) Degrease.
- (3) Load onto conveyor stations.
- (4) Induction preheat to 450°F to 475°F (232°C to 246°C).
- (5) Using 15 gauge aluminum (1.45 mm), apply a "fog" coating 0.00075 in. (19 μ m) to 0.001 in. (25 μ m).
- (6) Induction fuse at 1450°F (787°C).
- (7) Finishing is not required.

Self-Fluxing nickel chromium coating. These alloys are applied by the combustion powder process. The process steps are as follows:

- (1) Degrease.
- (2) Grit blast with coarse alumina grit.
- (3) Preheat part to 250°F to 300°F (120°C to 150°C).
- (4) Apply a self-fluxing alloy 0.25 in. (6.4 mm) thick. This thickness allows for normal cooling shrinkage and for finishing. Use a concentrating nozzle for controlled high deposit efficiency.
- (5) Fuse coatings either by automatic torch or induction heating.
- (6) Grind to size.

10.14.3 Costs. Consumables per square foot (0.09 m²) of coating 0.001 in. (0.025 mm) thick are 0.014 lb (6.35 gm) aluminum wire, 0.108 cu ft (0.003 m³) oxygen, and 0.48 cu ft (0.0136 m³) acetylene.

For a part dimension of 1 3/4 in. (45 mm) diameter x 3/8 in. (9.5 mm) high, costs are as follows:

Labor — 15 min x \$20.00/h	= \$5.00
Amortization — cost per spray time	= 0.25
Wire combustion system \$6,000,	
lifetime 2 years, 20 h week (3 shifts)	
Materials — aluminum wire 1/8 in.	
(3.2 mm) diameter	= 0.0051
Gases — oxygen	= 0.004
acetylene	= 0.00076
Total cost/part	\$5.26

Cost of alternate dipping process was 50% higher.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

10.15 Case History #9 — Anti-Fretting Coatings on Jet Engine Stator Vanes

10.15.1 Background and Problems. The air flow within high pressure compressor military and commer-

cial jet engines is directed around and through stationary airfoils referred to as *vanes*. They are individually mounted in a circumferential dovetailed slot on the stator inner diameter. Quantity and size depend upon the engine's thrust, but normally may exceed 1000 and are larger than 1 in. (25 mm) long.

The purpose of a stator vane is to help orient air flow. Thus, as the air is compressed and forced back into the turbine, it exerts intermittent loads upon the vanes. This load is transmitted to vane footings within the stator dovetail slots. Vane footings are also of a dovetail configuration. The vane, as it rocks in the slot, causes fretting wear to both its upper surfaces and the outer diameter of the slot. To reduce metal loss, a lubricating wear coating is introduced onto the mating surfaces. Normal lubricants, such as colloidal graphite or molybdenum disulfide, when stressed under engine operating loads, rapidly extrude outward, leaving bare metal contact surfaces.

It has been determined that a 0.002 to 0.004 in. (0.05 to 0.10 mm) layer of plasma sprayed copper-nickel-indium alloy will afford wear protection and provide a reservoir for the lubricant. Indium provides lubricity, while coating pores and valleys retain the lubricant. Batch quantities are between 15,000 and 20,000 pieces, with an annual requirement of 500,000 pieces.

10.15.2 Process. All vanes are solvent washed to remove grease or oils remaining from machining and forming operations. After cleaning, the vanes are loaded into a fixture which protects them during both the blast and spray operations (Fig. 10.15.2).

A typical fixture is 48 in. (1.2 m) long and may hold 20 to 40 vanes. Thus, batch processing is possible. Once loaded, the vanes are grit blasted in an automatic machine; from there, the fixtured vanes are surfaced by a straight

line plasma gun manipulator. Four passes, two on each side of the vane, apply the CuNiIn alloy. After being sprayed, the vanes are taken from the fixtures, power wire brushed to remove loosely adherent particles, and given a final inspection.

10.15.3 Costs. The amount of CuNiIn deposited per part varies with part size. Use of a concentrating nozzle optimizes deposit efficiency at 65%. Typical costs per part are

<u>Labor</u>	
Degreasing	\$ 0.005
Fixturing	0.04
Grit blasting	0.02
Spraying	0.02
Clean-up	0.08
Inspection	0.10

<u>Consummables</u>	
Solvent	\$ 0.005
Gases	0.10
Powder CuNiIn	0.16
Total cost/part	\$ 0.53

<u>Amortization of equipment</u>	
Fixturing	\$ 5,000/set/stage
Plasma system	80,000
Gun manipulator	12,000

In this case there were no competitive costs for comparison.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

10.16 Case History #10 — Abradable Clearance Control Coatings for Gas Turbine Compressors

10.16.1 Background and Problems. Compressors for advanced turbine engines used to power jumbo jets are designed with higher pressure ratios, fewer stages, and higher tip speeds than employed in engines of simpler construction. Under these conditions, leakage over compressor blade tips can result in substantial performance losses. Attempts to reduce these losses by reducing tip clearances are often hindered by excessive tip rubs. A rub can lead to

- Blade wear and, hence, increased clearance
- Blade tip damage or failure

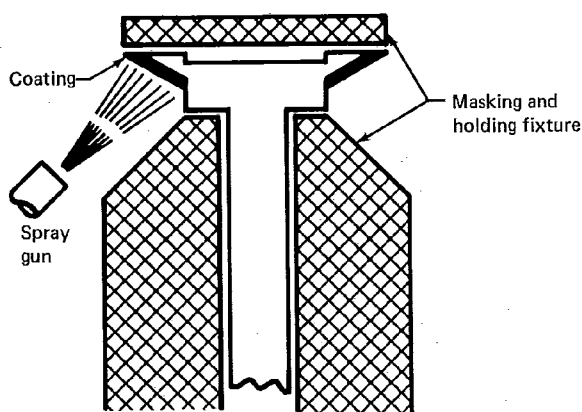


Fig. 10.15.2 — Vane loaded in fixture

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- Generation of debris which can stick to airfoils or clog cooling passages, and thus further reduce performance

Rub coatings sprayed on the blade tips are abrasible, thereby producing minimal damage to blade tips. They retain tight clearance and generate nonsticking, inert debris. These coatings can produce significant improvements in engine performance.

The application of abrasible-clearance control materials by thermal spraying techniques has proven to be a satisfactory means of producing acceptable sealing surfaces with excellent rub characteristics.

Typically, a large jet engine's front compressor case is slightly conical, measuring approximately 40 in. (1 m) high with a diameter varying from 28 to 32 in. (0.71 to 0.81 m). The unit may be constructed from titanium or a martensitic stainless steel.

10.16.2 Process. Casings are initially steam cleaned and solvent washed to remove dirt or oil residues. A combination of silicon rubber, teflon, and stainless steel masking is employed to protect areas not to be roughened, coated, or both. The entire inner diameter is then grit blasted with SAE 120 alumina, after which it is mounted on a turntable to be rotated during plasma spray application. The plasma spray process was selected owing to the high integrity of the coating.

The abrasible-clearance control coating is a duplex system comprised of a 95Ni/5Al barrier bond coat, 0.004 to 0.007 in. (0.10 mm to 0.18 mm) thick, overlaid with 0.022 to 0.027 in. (0.56 mm to 0.69 mm) of pure aluminum. The aluminum, to assure satisfactory aerodynamic air flow, is machined.

10.16.3 Costs. Typical costs per casing are as follows:

<u>Labor</u>	
Degrease	0.5 h
Mask	8.0
Grit blast	4.0
Spray	6.0
Clean-up/inspect	2.0
Total 20.5 h	
Labor and overhead-20.5 h x \$40	\$820.00
Machining	150.00
<u>Materials</u>	
Solvent	\$ 2.00
Masking tape	14.00
Powder	
9 lb NiAl @ \$20/lb	180.00
9 lb Al @ \$8/lb	72.00
Grit	45.00
Total	\$ 313.00

Total coating cost	\$1,283.00
Tooling/masking	\$8,000.00/set

Equipment

Typical spray cell with attendant equipment	\$150,000.00
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No competitive process is available; hence, the increase in engine performance and reliability pay for the coating costs in a fraction of a year's operations.

These estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

10.17 Case History #11 — Corrosion Protection

The economics of corrosion protection is a vital but complex issue. It has been estimated that on an annual basis, corrosion destroys the equivalent of one-fifth of the world's annual production of ferrous metals, and that in the United States 40% of all steel production goes to replace corroded parts and products. The total cost of corrosion damage in the United States was calculated to be \$70 billion (1975). Ten billion dollars of this was probably avoidable. These figures indicate the enormity of the problem.

The economic imperative should be to choose a corrosion protection system which will have a low initial cost and provide adequate protection to a structure throughout its projected lifetime, with a minimum of expensive maintenance. Unfortunately, there are many variables which should be considered when deciding what is an adequate protection system. Each system can be expected to last for varying lengths of time, depending on the specific environment. What will be adequate in one set of circumstances may prematurely fail in another. Moreover, it is difficult to compare specific costs, since these vary widely from job to job and from one geographical location to another. Even for a given structure in a given locality, cost estimates may vary considerably from one company to another, as well as from one system to another.

There are, however, certain general factors that should be considered in establishing and comparing the effective overall cost of different corrosion protection systems. First, it should be recognized that it is essential to take into account not only the initial cost of protection, but also maintenance costs over the design lifetime of the structure. While initial costs are a known factor, the cost of future maintenance is unpredictable and increasingly expensive. Each successive maintenance operation can be expected to cost more. Labor and material costs are con-

tinuously rising, and the quality of future maintenance cannot be guaranteed. Environmental considerations have led to government imposed regulations. The financial impact on maintenance operations is substantial. New regulations relating to toxic and noise hazards are likely to lead to still more stringent and costly restrictions in the future. While these expenses may lead to unacceptably high maintenance costs over the intended life of the structure, they cannot be easily planned or controlled. Maintenance is not always merely expensive; in many cases, due to geographical or other logistical constraints, it may be virtually impossible. Furthermore, the economic and social consequences of removing a structure from service, which is often necessary in order to carry out maintenance work, can not be ignored. This is especially true where, as in the case of the closing of a bridge or major roadway, the disruption becomes an economic disaster. It is therefore essential to choose a corrosion protection system which will minimize both maintenance costs and the number of maintenance operations.

On these counts, thermal spraying has outstanding economic advantages. Spraying a steel bridge with zinc can assure its essentially maintenance-free life for 20 or more years. When maintenance is eventually required, surface preparation for repair of sprayed zinc coatings, whether sealed or painted, is a simple matter of removing dirt and any loose sealer or paint, and then applying a new top coat. This is in sharp contrast to the extensive, and costly, surface preparation necessary to remove rust which frequently forms on structures protected by paint alone. The cost of building scaffolding, often required to carry out repair work on site, is extremely high, and the labor-intensive nature of such repair increases the costs still further. Moreover, material costs for maintaining a complex paint system containing a number of raw materials, often derived from petrochemicals, can be expected to rise far more steeply in the future than the material costs involved in maintaining a simple sprayed metal coating. Corrosion protection systems based on paint, which require frequent and regular maintenance in order to preclude early protection failure, also demand far more frequent, and hence more costly, inspection procedures than do protection schemes based on metal spraying.

Aluminum and zinc sprayed coatings have the further economic advantage of providing considerable flexibility in corrosion protection systems, since the thickness of sprayed coatings can be tailored to meet specific environmental requirements. In instances where maintenance can be expected to be unusually difficult or expensive, the thickness of the coating can be increased to give additional years of maintenance free life. In such cases, the extra corrosion protection afforded by the thicker

coating will add little to the total initial expense of the project and will be highly cost effective in the long run. Also, a sealer can be applied which, for a modest cost, will significantly extend the life of the coating.

On an overall cost basis, with the expense of future maintenance included in the calculations, metal spraying has long been competitive with most other corrosion protection systems. A 1971 British study of structural steel protection costs determined that spraying zinc or aluminum was approximately 10 to 20% more expensive than comparable paint schemes on an initial cost basis. However, the lifetime protection provided by these paint schemes, in the same environmental conditions, is a minimum of 5 to 15 years shorter than the maintenance free protection provided by metal spraying. Thus, with the expense of maintenance factored in, the apparent initial cost advantage of paint schemes is quickly eliminated. In long term use, metal spraying provides better protection at lower cost.

This experience is being confirmed in the United States. In a service evaluation program started in 1978, 22 of a fleet of railroad tank cars have been metal sprayed to evaluate the performance and economy of various thicknesses of zinc both with and without sealers. The cost of zinc coating an average tank car in this program was \$1042, or approximately two times the cost of an average paint job. However, the spraying cost could have been substantially reduced had the cars been treated during manufacture, where the benefits of automation would have been possible. Furthermore, it is anticipated that the zinc coatings will last the 20-year life of the cars, with only cosmetic touch-ups required. A painted tank car, on the other hand, is taken out of service and repainted approximately every 5 years over a 20-year lifetime. Thus, even without the lowered cost made possible by automation, thermal spraying will yield a substantial savings over the lifetime of the car. For example, in the program cited above, it has been projected that thermal spraying of a fleet of 1200 railroad tank cars will lead to an annual savings of \$80,000.

Cost estimates are added for reference only. Costs will vary depending on the type of installation, capital investment, individual overhead, labor cost in the area, stability of raw material costs, and profit markup.

It is important to note that more recent studies indicate that there is a trend towards metal spraying becoming cheaper than comparable paint schemes, even on a first cost basis alone. A survey, conducted in the United Kingdom during November 1977, of the comparative costs per square meter of surface for protecting different types of fabricated steelwork using various protection systems, found that unsealed sprayed zinc was approximately 20% cheaper on a first cost basis than comparable

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paint schemes. Sealed sprayed zinc was about the same or slightly cheaper than comparable paint schemes on a first cost basis.

Compared with high quality paint schemes, zinc or aluminum sprayed coatings are often completely competitive, even on an initial cost basis. When the increased maintenance costs and shorter protection times of paint systems are included in the economic calculations, the cost advantages of corrosion protection by metal spraying are obvious. Furthermore, inadequate corrosion protection may lead not merely to the need for extensive and expensive maintenance operations, but also to the premature failure of the structure as a whole. This will necessitate a replacement long before its planned lifetime. In an age

when conservation of the world's natural resources has financial as well as an environmental priority, corrosion protection methods should both last the life of the structure and even lengthen its life. Metal spraying accomplishes this and also avoids the waste of resources which would be required for their replacement and maintenance. The more reasons society has to perpetuate the life of existing or new steel structures, the more metal spraying is viewed as economically desirable.

Considerable promotion of metal spraying is underway in the United States at technical, governmental, and commercial levels. It is suggested that the reader contact various equipment suppliers and thermal spray contractors and investigate available literature for further information.

Chapter 11

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11.10 Safety Standards

Chapter Committee

J. O. Hayden, Chairman
Hayden Corporation

F. J. Wallace
Pratt & Whitney Aircraft

F. Kvaska, Jr.
Bender Machine Company

Contributor

P. F. Gerbosi
METCO, Incorporated

Chapter 11

Safety

11.1 Scope

The potential hazards associated with thermal spraying, including the preparation and finishing processes, and the safe practices applicable to those operations, are discussed in this chapter. The words *approved* or *approval* mean acceptable to the authority having jurisdiction.

11.1.1 Safety Guides. It is recommended that all personnel concerned with thermal spraying become familiar with these safe practices and the safety regulations contained in established standards. Such pertinent standards are listed in 11.10 at the end of this chapter.

Local, state, and federal health (OSHA Standards) should be thoroughly understood for proper compliance, especially when handling toxic materials.

11.1.2 Disposal of Toxic Wastes. Toxic materials may be generated by the thermal spraying process, during preparations for the process, the process itself, or subsequent finishing operations. Their disposal shall be in accordance with the regulations of EPA *Resource Conservation and Recovery ACT (RCRA)* governing the disposal of toxic wastes.

11.1.3 Flammable Solvents and Sealer Bases. Certain hydrocarbon degreasing solvents and sealer bases are flammable, and special handling precautions should be observed relative to their use, handling, and storage in and about the thermal spray area.

11.2 Fire Prevention and Protection

The basic precautions for thermal spraying are essentially the same as for welding and cutting. Consult *ANSI/AWS Z49.1, Safety in Welding and Cutting*; *NFPA 51B, Standard for Fire Prevention in Use of Cutting and Welding Processes*; and *NFPA 58, Standard for the Storage and Handling of Liquefied Petroleum Gases*.

Airborne metal dusts, finely divided solids, or accumulations should 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, except in special applications where the material to be collected is not explosive. Such collectors should only be used after consultation with those experienced and knowledgeable in the field. Further, when operational conditions do require these collectors, only the disposable type should be used. Reusable bag or filter-type collectors are difficult to clean of spray dust and so present an explosion or fire hazard.

Good housekeeping in the work area should be maintained to avoid accumulation of metal dusts, with particular attention given to inspecting for dust on rafters, tops of booths, and in floor cracks.

The extremely hot conditions of thermal spraying operations require additional precautions such as, not pointing thermal spray equipment at any person, or at material that will burn. Paper, wood, oily rags, and cleaning solvents can be ignited and should not be stored or contained within the spray room or enclosure.

11.3 Safe Operating Considerations

11.3.1 Storage, Handling, and Use of Compressed Gas Cylinders. Local, state, municipal, and federal regulations relative to the storage of cylinders should be investigated and their rules complied with.

Storage, handling, and use of oxygen and all fuel gas cylinders shall be in accordance with *ANSI/AWS Z49.1, Safety in Welding and Cutting*, and with *CGA Pamphlet P-1, Safe Handling of Compressed Gases*. The improper storage, handling, and use of gas cylinders constitute a safety hazard in the thermal spraying operation.

Oil or grease should never be used on oxygen equipment. Only special oxidation resistant lubricants may be used with oxygen equipment. When in doubt, a qualified dealer or the equipment manufacturers should be consulted.

Manifolding of cylinders is frequently required when spraying. This permits longer spray times before

changeover. These installations should be in accordance with ANSI/AWS Z49.1.

Pressure reducing regulators should be installed and used in accordance with ANSI/AWS Z49.1. Only the appropriate regulator for each gas cylinder should be used. Only acetylene regulators should be used on acetylene tanks or manifold systems. It is important to use the correct size wrench to connect the regulator to the cylinder valve outlet; never force or overtighten a connection. Oil or grease should never be used on a regulator.

11.3.2 Flow Meters. Flow meters should be installed and used in accordance with ANSI/AWS Z49.1. If a flow meter with glass tubes is used, a protective shield should be placed between the flow meter and the gun. In addition, backflow prevention devices should be used in conjunction with flow meters to avoid unsafe operating conditions and to ensure proper flame balance.

Hose and hose connections should be installed and used in accordance with ANSI/AWS Z49.1 and *Specification for Rubber Welding Hose*, published jointly by the Rubber Manufacturers Association and the Compressed Gas Association. Damage to hoses should be avoided. Hoses for applications for which they were not designed should never be used.

When connecting oxygen and fuel gas cylinders, pressure reducing regulators, and flow meters, the connecting nuts should be drawn up tight, but should never be overtightened. (Overtightening is likely to collapse the nose of the nipple.) If the fitting cannot be sealed without undue force, the fitting should be replaced.

Adequate ventilation of the work area should be provided before opening any of the gas valves.

The pressure reducing regulator should be drained of gas and the regulator adjusting screw fully released before opening the cylinder valves.

Cylinder valves should be opened slowly. One should stand to the side of the pressure reducing regulators when releasing the cylinder valves.

Regulator adjusting screws should be turned in slowly to prevent surges that may crack or burst flow meter tubes. Hoses should be blown out to remove any dust that may be present in them. Sources of ignition should be avoided.

The hoses to the thermal spray gun should be checked for leaks at all connections, with soapy water applied to each joint while the system is under pressure. A flame should never be used to check for gas leaks. Soapy water is safer and provides a more sensitive test than a flame.

When connections are found to leak, the following operations should be performed: depressurize, open the connection, wipe the sealing surfaces clean, see that the threads are clean, retighten, repressurize, and retest for leaks. If a leak persists, the system should be depressurized. Leaking thermal spray equipment should never

be used. A **Danger--Do Not Operate** tag should be placed on the defective equipment.

Obstructions in the gas lines caused by defective hoses, collapsed hose stems, or dirt in the gas passages of the gun head or the nozzle jets will require excessive pressure to obtain proper gas flow.

Acetylene pressures in excess of 15 psig (103 kPa) are dangerous and must not be used — the gas may detonate. When acetylene pressure of 15 psig (103 kPa) is insufficient, another fuel gas should be used. If both oxygen and fuel gas pressure required are more than 3 psi (21 kPa) over recommended pressures, a fouled nozzle or incorrect air cap adjustment is usually indicated. Pressures that are too low usually indicate a serious leak. Equipment should be shut down and the condition corrected before attempting to reuse the system.

11.3.3 Compressed Air. Compressed air should be referred to by its proper name to avoid confusing it with oxygen or fuel gas. Compressed air should never be used to clean clothing. Similarly, oxygen and fuel gas should not be used for this purpose.

Compressed air for thermal spraying or blasting operations should not be used at pressures other than those recommended by the equipment manufacturers. The air line should be free of oil and moisture. A qualified air compressor dealer or thermal spraying equipment manufacturer should be consulted for recommendations regarding filters and after coolers.

11.4 Flame Spray Equipment

Flame spraying guns should be maintained in accordance with the manufacturer's recommendations. Each thermal spraying operator should be familiar with the operation of the flame spraying gun. The gun instruction manual should be thoroughly read and understood before lighting the gun for the first time.

If a gun is equipped with valves, such as a taper valve for controlling the flow of oxygen, fuel gas, or compressed air, they should be properly seated and lubricated. This will enable the gun to operate freely and to be completely shut off.

Matches should not be used for lighting flame spraying guns. This may result in personal harm. A friction lighter, a pilot light, or arc ignition may be used.

When a gun has backfired, it should be extinguished as quickly as possible.

Reignition of a gun that has blown out or backfired during spraying should not be attempted without first determining the cause of the trouble.

A flame spraying gun or its hoses should not be hung

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on regulators or cylinder valves. A fire or explosion may result.

When spraying is terminated, or the equipment is shut down, left unattended, or taken down, all gas pressure should be released from the regulators and hoses. This is done in the following sequence: (1) close gun valves, (2) close cylinder valve, (3) open gun valves, (4) turn regulator screw out until free, (5) close gun valves, and (6) close tank valve or manifold valve ahead of regulator.

When cleaning flame spraying guns, oil should not be allowed to enter the gas mixing chambers.

The use of ordinary oils or greases should be avoided for lubricating the valves or other parts of a flame spraying gun that are in contact with oxygen or fuel gases. Only special oxidation resistant lubricants recommended by the equipment manufacturers should be used.

11.5 Plasma and Arc Equipment

The plasma and arc methods involve apparatus not used in other thermal spraying equipment. High voltages and amperages represent an electrical hazard. The operator should be thoroughly instructed and trained by qualified personnel in the operation of the equipment before use.

Familiarity with the operating and safety recommendations in the instruction manuals, and at the same time observing standard, safety precautions taken with electrical equipment, is imperative. All operations should be in accordance with ANSI/AWS Z49.1.

The plasma or arc equipment itself should be safe to operate. Heavy duty industrial push buttons, pilot lights, plugs, and cables should meet the standards of the ANSI/NFPA 70-1979, *National Electrical Code*. Exposed electrodes and cable connections of plasma guns should be grounded or adequately insulated.

On some handling equipment, the rotational speed for coating parts is high. In some cases, the parts should be fixtured and balanced. The equipment operator should be protected in the event a rotating part becomes airborne. The equipment should not be left unattended while in operation.

Periodic inspections of cables, insulation, hoses, and gas lines should be made. Faulty equipment should be repaired or replaced immediately.

No attempt should be made to adjust, clean, or repair any part of the power supply, console, or gun without first disengaging the entire system, including the power supply.

Arc guns and power supplies should be cleaned frequently to prevent the accumulation of metal dust which may cause shorts. Instructions contained in the manufacturer's operation manual should be followed. Wire control units used in conjunction with arc equipment should

be adequately grounded or insulated. If the plasma or arc gun is suspended, the suspension hook should be insulated or grounded.

Contact between any ungrounded portion of the plasma or arc gun and the spray booth or chamber should be avoided. In addition, all ground cables should be interconnected.

Plasma guns and nozzles should be electrically isolated from their support bracket to prevent stray high frequency currents from damaging other electrical equipment and controls.

11.6 Abrasive Blast Machines

Abrasive blast machines should be maintained and inspected according to the equipment manufacturer's recommendations. Worn parts should be removed and repaired or new parts installed as recommended by the manufacturer.

Blast hoses should be as straight as possible between the blast machine and blasting area. Sharp bends in the hose will cause excessive friction and wear, possibly resulting in a blowout at those areas. If a hose must be curved around an object, use long radius curves.

Blast hoses should be stored in cool dry areas to avoid rapid deterioration. A blast nozzle should never be pointed at the body, either your own or others. Air pressure in a blast tank should not exceed the pressure recommended by the equipment manufacturer.

Blast hose controls should require continuous pressure on the activating lever by the operator. When the pressure is released, the equipment should shut off (dead man control).

Most blasting operations require that the operator be provided with some form of respiratory protective device. The selection, operation, and maintenance of this device should be in accordance with ANSI Z88.2 *Standard Practices for Respiratory Protection*, and as described in the following section.

11.7 Protection of Personnel

The general requirements for the protection of thermal spraying operators are the same as for welders, as set forth in ANSI/AWS Z49.1, *Safety in Welding and Cutting*; ANSI Z87.1, *Standard Practices for Occupational and Educational Eye and Face Protection*; ANSI Z88.2, *Standard Practices for Respiratory Protection*; and ANSI Z89.1, *Standard Practices for Industrial Head Protection with Low Voltage Hazards*.

11.7.1 Eye Protection. Helmets, hand shields, face shields, or goggles are necessary to protect the eyes during

all spraying or blasting operations. These are described in ANSI Z87.1 and Z89.2. It is necessary for operators to use goggles for protection against infrared and ultraviolet radiation and flying particles. All helpers and adjacent operators should be provided with proper eye protection.

The helmet, hand shield, or goggles should be equipped with a suitable filter plate to protect the eyes from excessive ultraviolet, infrared, and intense visible light radiation (Table 11.7.1).

Table 11.7.1
Recommended shade numbers

Wire flame spraying (except Molybdenum).....	Shades 2-4
Molybdenum wire spraying.....	Shades 3-6
Flame spraying of metal powder.....	Shades 3-6
Flame spraying of exothermic ceramic powder or rod.....	Shades 4-8
Plasma and arc spraying.....	Shades 9-12
Plasma and arc spraying (when this equipment is provided with its own shield).....	Shades 3-6
Arc bonding.....	Shades 2-4
Fusing operations.....	Shades 4-6

When thermal spraying in an open area or at a lathe, where ventilation is adequate to eliminate the need for additional respiratory protection, goggles alone may be worn. These should be the eyecup type, fitted with lenses of about 2 in. (50 mm) diameter, or the covercup type for those wearing corrective lenses.

The goggles should have indirect ventilating fins to eliminate danger from flying particles and to reduce fogging. In plasma spraying, the goggles should be replaced by helmets or hand shields that provide face, chin, and neck protection from ultraviolet and infrared radiation.

While blasting, face shields or abrasive blasting helmets equipped with dust hoods are used to protect the eyes, face, chin, and neck. Respiratory protection should also be provided, as discussed in the following paragraphs.

11.7.2 Respiratory Protection. Most spray and blast operations require that respiratory protective devices be used by the operator. The nature, type, and magnitude of the fume and gas evolved determine which respiratory protection devices should be used. The selection of these devices should be in accordance with ANSI Z88.2. This standard contains descriptions, limitations, operational procedures, and maintenance requirements for standard respiratory protective devices. All devices selected should be of a type approved by the U. S. Bureau of Mines, National Institute of Occupational Safety and Health

(NIOSH), or other approved authority for the purpose intended. While the selection of these devices should follow the guidelines of ANSI Z88.2, those listed below are suggested for typical thermal spraying and blasting operations.

For blasting in the open, a mechanical filter respirator should be used in conjunction with the face shields and dust hoods cited above. Alternatively, an air line respirator may be used.

For blasting in confined or enclosed spaces, a continuous flow air line respirator for abrasive blasting is required. This consists of a standard continuous flow air line respirator, the full face piece or helmet and dust hood, which have been reinforced to protect the head and neck from rebounding abrasive. Minimum air flow to the respirator is 4 cfm (6.6 m³/h) at the face piece and 6 cu ft of air per minute (10 m³/h) entering the helmet or hood. Fresh air blowers are preferable to compressed air as a source of respirator air.

An in-line vortex cooler should be used when possible for operator comfort. The air supply line should contain a suitable filter to remove objectionable odors, oil or water mist (or both), and rust particles from air generated by the compressor blower. Care should be exercised in situating the air intake to ensure that the air supplied to the respirator is clean and dry. The air supply line filter will not provide protection against gaseous contaminants such as carbon monoxide unless a separate air purifier is used. In Table 6.3.2A, Grade D or better compressed air is considered breathable.

For thermal spraying in the open or at a well ventilated work area, additional respiratory protection may not be necessary. In borderline cases, such as for light work of short duration, with nontoxic materials, but with dust exposure, only approved mechanical filter respirators for protection against dust and metal fumes should be used. These are fitted with filter pads (and flutter valves) to remove dust.

When spraying in confined or semiconfined spaces, an air line respirator should be used. This is of the same design as the abrasive blasting air line respirator, except that it need not be reinforced on the helmet or face piece and hood for protection against rebounding abrasive. For this reason, an abrasive blasting continuous flow air line respirator may be used for both spraying and blasting.

Continuous flow air line respirators provide adequate respiratory protection for thermal spraying operations involving most commonly employed materials. If the air supply to the respirator fails, the operator may remove the supply line and return to respirable air, if the contaminant in the confined space is not immediately harmful to health. When applying highly toxic materials, the contaminated air should be considered immediately harm-

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ful. Since the operator should not remove the respirator in this situation, the air line respirator used should be equipped with an emergency auxiliary cylinder of respirable air.

In the event of a failure in the air supply, the operator should remove the air supply lines and use the auxiliary air supply while escaping.

Alternatively, when applying highly toxic materials, a hose mask with blower may be used to provide respiratory protection.

11.7.3 Noise Protection. All personnel in the vicinity of the thermal spraying operation should be provided with ear protection if the noise exposure exceeds the limitations established by OSHA in paragraph 1910.95 entitled "Occupational Noise Exposure" of the Occupational Safety and Health Standards.

The thermal spraying processes generate excessive noise levels. It is mandatory to limit employee exposure to excessive noise in accord with federally recognized standards as prescribed under the Occupational Safety and Health Act.

Background and Measurement. In the United States, the *Occupational Safety and Health Act of 1970* is administered by a division of the U. S. Department of Labor, the Occupational Safety and Health Administration (OSHA).

OSHA requires employers to provide employees with safe working conditions and requires employees to comply with all rules, regulations, and orders which apply to their own actions and conduct.

Even though OSHA is not specific on thermal spraying operations, it has established general rules for the control of unsafe and unhealthy elements.

The following paragraphs describe (1) The nature of noise and how it is measured; (2) noise levels created by thermal spraying equipment and OSHA limitations; and (3) general guides to the control of thermal spraying noise to facilitate compliance with OSHA rules.

Noise is sound which is unneeded and objectionable. Excess noise has a number of effects on people. It reduces productivity, causes tension, hearing impairment, nervousness, and slows reaction time.

Noise level is determined by measuring the energy (pressure) of the sound waves with a meter consisting of a microphone, amplifier, and read-out.

The human ear does not perceive an increase in sound energy as an equivalent increase in loudness, nor does it respond equally to all frequencies. To be useful, the instrument used to measure sound pressure level should simulate human hearing response. To accomplish this, "weighting" networks are used with characteristics based on international acoustical standards.

To match the response of the ear, a sound level meter "weights" sound measurements by frequency and uses a slow response to average out brief, high level noises such as the sound of hammering.

The meter is calibrated in decibels (dB). In perceiving loudness, the ear has a range of approximately 130 decibels.

Typical noise levels in various environments are indicated in Table 11.7.3A. Wherever there is the possibility of a problem, noise measurements should be made. Without an accurate sound level survey, there is no certainty a problem exists.

The physiological effect of noise is caused by its loudness and duration. The louder the noise, the shorter the permissible exposure to it. Table 11.7.3B indicates tolerable noise limits for various exposure times. An equal amount of additional noise raises the sound level by only 3 dBA. For example, two 80 dBA machines side-by-side produce a noise level of 83 dBA. Two more nearby 80 dBA machines will increase the noise from 83 to 86 dBA.

If an added noise is less than the existing noise, it has a negligible effect on the total noise. If the added noise is within 0 to 10 dBA louder, 3 dBA or less will be added to the total noise. If the added noise is more than 10 dBA louder than the existing noise, the total noise will be essentially the value of the added noise.

Noise and exposure should be controlled in three categories. These concern exposure of operators, nearby workers, and transient passers-by to thermal spray noise. Consideration should be given to protecting all three against the effects of the noise.

Noise can be controlled at the source, during its transmission, or at the receiver. Controlling any one of these items can solve the noise problem. However, there are so many variables in every noisy situation that each case should be treated individually. There is no simple solution for every noise problem, except isolation.

Both engineering and administrative controls can be used to reduce noise, or reduce exposure to noise.

Engineering controls include (1) redesign equipment, (2) relocate equipment, (3) change operating conditions, (4) isolate equipment acoustically, (5) insulate work area, and (6) provide operator hearing protection.

In the area of administrative controls, one can plan and schedule to reduce exposure time.

Redesign Equipment. Mufflers on thermal spraying equipment have proven to be impractical and ineffective. Simple baffles between the gun and nearby personnel are not effective because noise is scattered and reflected around the baffle.

Specially designed sound absorbent materials provide a 5 dB reduction to adjacent areas. Significant investment in such materials on walls and in hanging baffles also re-

Table 11.7.3A
Typical noise levels for thermal spraying equipment

Equipment	Set-up	dBA
Arc guns	Steel — 24 volts/200 amps	111
	32 volts/500 amps	116
Powder guns -Normal	Acetylene — w/o spray booth	89
	w/ spray booth	90
	w/ spray booth and air jet cooling	110
	Hydrogen — w/o spray booth	100
	w/ spray booth	101
	-High capacity	
Wire combustion guns 1/8 in. and 3/16 in. (3.2 and 4.8 mm) wire	Acetylene	114
	Propane	118
	Propane and nonload hardware	125
	Methylacetylene-propadiene gas	118
Plasma gun	Nitrogen — 600 amps	134
	Nitrogen/hydrogen — 600 amps	133
	Argon — 1000 amps	128
	Argon/hydrogen — 600 amps	132
	Argon/helium — 600 amps	127
	Argon/nitrogen — 1000 amps	131
Typical gritblasting equipment		80-85
Typical exhaust equipment		less than 90

Table 11.7.3B
Allowable noise level duration

dBA	H/day
90	8*
92	6
95	4
97	3
100	2
102	1.5
105	1
110	0.5
115	0.25 or less

duce nearby levels (but does not give much help to the operator).

Relocate Equipment. The greater the distance from the source of noise, the lower the sound pressure level. In a large room with no sound-reflecting surfaces, the sound pressure level decreases 6 dBA for each doubling of distance. In actual practice, which usually includes reflected surfaces, the reduction with distance will be somewhat less. Table 11.7.3C indicates typical decibel reduction with distance in a free field.

Table 11.7.3C
Typical decibel reduction

Distance from source	dBA reduction theoretical
3 ft (1 m)	0
10 ft (3 m)	10
30 ft (9 m)	20
90 ft (27 m)	28

Change Spray Gun Operating Conditions. The noise level of a thermal spraying gun can be reduced 3 to 5 dBA by reducing spray gun settings and spray rates to lower values.

A 3 to 5 dBA reduction in the noise of combustion wire and powder guns can be achieved by lowering the flow of gases and air flows. Less heat will be produced, so the spray rate can be reduced. The resulting coating, compared with a standard spray coating, is less dense, softer, and has a coarser texture.

With plasma, noise can be reduced by lowering the amperage. A corresponding reduction in spray rate is re-

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quired. Decreasing gas flows will reduce noise, make less heat available, and reduce coating quality.

Arc spray noise can be reduced by lowering the amperage (spray rate) or the flow of atomizing air, or both. If both are lowered, the effects on the coating will be similar to those described above. If the spray rate is lowered and the atomizing air flow is not lowered, the as-sprayed coating will have a finer texture, and the coating will be denser and, with some materials, contain more oxide.

Isolate Equipment. Noise can be isolated by moving it away from affected personnel, or placing the equipment in an acoustically insulated enclosure.

Standard booths are available which are designed to house spray operations and confine the noise. The noise level outside the room can be specified to be in full compliance with OSHA maximum limits for eight-hour exposure. In most instances involving flame or arc spray, a simple sheetrock enclosure will suffice.

If the user decides to design and construct an acoustically insulated area, it is recommended that it be done in consultation with a noise control expert.

Insulate Work Area. Very significant noise reduction can be obtained by blocking the path of transmission of the noise. This can be done by lining the work area with sound absorbing materials. High performance materials are available for such an installation. Recommendations should also be obtained from local services.

Provide Hearing Protection. Under the OSHA regulations, if engineering and administrative controls do not achieve acceptable limits of maximum noise and exposure duration, the law permits suitable personal protective equipment to be used. This also applies while engineering and administrative controls are being established to achieve those limits.

Plan and Schedule to Reduce Exposure Time. Engineering controls are intended to eliminate, reduce, or contain the noise hazard. Administrative controls are directed toward reducing exposure time.

Planning and scheduling can be used in maintenance departments and job shops where spraying is intermittent. Usually, spraying time is a small percentage of the total, compared with setup, surface preparation, and finishing.

If spraying time exceeds the permissible limits for noise exposure, jobs can be scheduled over more than one shift or day to hold the noise exposure within maximum limits. Jobs can be scheduled to be sprayed by more than one operator, to hold the exposure of any one person within limits. Off-hour spraying, outside day shift hours, can control the exposure of personnel in the vicinity of the operation. It is also possible to rotate the assignments of personnel in the vicinity of the thermal spraying operation to control exposure.

11.7.4 Protective Clothing. Appropriate protective clothing required for any spray or blast operation will vary with the size, nature, and location of the work to be performed.

When working in confined spaces, flame resistant clothing and leather or rubber gauntlet gloves should be worn. Clothing should be strapped tightly around the wrists and ankles to keep sprayed materials and abrasive dust away from the skin.

For work in the open, ordinary clothing, such as overalls, may be used. However, open shirt collars and unbuttoned pocket flaps are potential hazards.

High top shoes should be worn. Cuffless trousers should cover the shoe tops.

When spraying lead or other highly toxic materials in confined or partially open spaces, all clothing and respiratory protective devices worn should be changed each day and before any meal breaks. The used clothing and respiratory devices should be thoroughly washed or cleaned of all lead dust or other toxic materials before being reused.

The intense ultraviolet radiation of plasma spraying has been known to cause a "sunburn" through normal clothing. When using this process, clothing should be worn that will provide protection against radiation. Thick, tightly woven wool clothing is generally sufficient. For exposure to more intense radiation, leather capes or aluminized clothing is necessary. Exercise care so that radiation is not reflected from an aluminized bib into the inside of the face shield, causing face burns. This can be done by attaching the bib to the outside of the shield. Aluminized gloves should be used in conjunction with dark, fire retardant clothing. Aluminized clothing, however, may present a danger from electric shock.

Protection against radiation from arc spraying is similar to that used for electric arc welding and is outlined in detail in ANSI/AWS Z49.1. There is one definite difference, however; most arc spraying guns are equipped with an arc shield. With this in place, the operator is not exposed directly to the arc. Eye protection, in this case, can be reduced to a No. 3 or No. 6 shade lens, but a helmet should be used if parts of the body are exposed to direct arc radiation, or if exceptionally radiant materials or reflective substrates are sprayed.

11.7.5 Confined Spaces. Confined spaces are restricted spaces such as a closed tank, boiler, pressure vessel, or compartment of a ship. If the confined space has previously held combustible materials, it should be rendered safe for work before entering. AWS F4.1, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping That Have Held Hazardous Substances* should be consulted.

Ventilation is a prerequisite to work in confined spaces. Ventilation requirements are contained in 11.8.

When thermal spraying is in any confined space, the gas cylinders should remain external to the areas.

When thermal spraying or blasting operators must enter a confined space through a manhole or other small opening, means should be provided for quickly exiting in the event of an emergency. When safety belts and life lines are used for this purpose, they should be attached to the workman's body so that jamming in a small exit opening cannot occur. At least one attendant trained in rescue work should be stationed outside at all times, and proof of this person's ability to remove the operator from the confined space should be demonstrated before the operation begins.

In order to eliminate the possibility of gas escaping through leaks or improperly closed valves, the gun valve should be closed and the gas supply to the gun shut off at a point outside the confined area. Where practical, the gun and hose should be removed from the confined space. Potential oxygen deficiencies in the confined space should be evaluated with a standard miner's safety lamp.

11.8 Ventilation

A number of factors determine the amount of contamination to which the workman is exposed when performing blast and thermal spray operations. These include the following:

- (1) Volume of space in which the thermal spraying operation is to be done
- (2) Number of spray and grit blast operators
- (3) The evolution of hazardous fumes, gases, or dusts according to the abrasive used or material being sprayed
- (4) Heat generated by the spraying process
- (5) Presence of volatile solvents

All of the preceding should be considered in order to better protect the operators and to supply adequate ventilation to the spray room.

Local exhaust or general ventilation systems should be provided to control toxic fumes, gases, or dusts, and their removal from the work area.

Where thermal spraying operations are incidental to general operations, it is good practice to apply local exhaust ventilation to the spray areas. This prevents contamination of the general work area.

Individual respiratory protective devices should be well maintained. They should not be transferred from one employee to another without being cleaned and disinfected. Forced air respiratory devices require Grade D or better air, in accordance with Table 6.3.2A. (For methods of cleansing and disinfecting, ANSI Z88.2 should be consulted.)

Mechanical ventilation is required in spraying and blast-

ing operations that are not performed in the open or in a properly designed and ventilated room. Otherwise, the dust will rapidly fill a large tank, building, or semi-enclosed space.

The ventilation equipment for most field thermal spray and blast operations consists of engine or motor driven portable exhausters with flexible piping or ducts. This removes the dust rapidly and allows operators suitable visibility. Systems of this type have deficiencies, and operators should wear respiratory devices as described in 11.7.2.

When removing dust with portable exhausters, it is necessary to attach a dust collector to trap the dust and prevent contamination of the surrounding areas.

The use of bag or filter type collectors for gathering spray dust is not recommended (see 11.2). A wet collector of the water wash type is recommended. This limitation does not apply to dust from abrasive blasting operations. Dust bags should be replaced before entrapped dust seriously reduces the efficiency of the system.

If thermal spraying operations are performed on a machine tool such as a lathe, an exhaust hood should be mounted at the edge of the carriage so that it travels with the gun. This allows the dust and fumes to be exhausted into the dust collector. The gun is aimed so that the sprayed material enters the face area of the hood. The average size of the opening in a lathe hood is about 2 sq ft (0.2m²), and the velocity of the air entering the opening should be a minimum of 200 ft/min (1m/s). The hood opening should eliminate turbulence along the sides that could force the spray dust into the operator's breathing zone. In some permanent installations, the entire lathe, rotary table, or machine tool is enclosed except the front, and the velocity of the air entering the enclosure is approximately 300 ft/min (1.5 m/s). The top of the hood can be hinged, permitting use of a crane for loading or unloading. In automatic and production spraying, the entire mechanism is often totally enclosed, and the dust is exhausted into a water wash and collecting system. *Industrial Ventilation*, published by the American Conference of Governmental Industrial Hygienists, should be consulted.

During dry grinding or lapping operations on sprayed coatings, precautions should be taken to provide proper exhaust equipment. ANSI Z43.1, *Ventilation Control of Grinding, Polishing, and Buffing Metals*, should be consulted.

Spray cabinets used for spraying small and medium size parts should be equipped with exhaust ventilation, with an air velocity of 200 to 400 ft/min (1 to 2 m/s) entering the hood. The spray equipment should be operated within the face area of the hood and directed into it. Again, the design of the cabinet should be such that turbulent eddy

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currents are eliminated. When spraying toxic materials, minimum enclosure face velocity of 400 ft/min (2 m/s) should be used. *Industrial Ventilation*, published by the American Conference of Governmental Industrial Hygienists, should be consulted.

Blasting rooms should be designed to be well lighted and adequately ventilated. Ventilation should provide down draft and longitudinal air flow with a velocity of 80 to 100 ft/min (0.2 to 0.5 m/s).

The blasting room should be equipped with a dust collecting system. This is usually required by local ordinances. Further, local, state, and federal regulations should be investigated before exhausting directly into the atmosphere. The blasting room may also occasionally be used for spraying. This is not good practice and should be avoided whenever possible. Spray dust will quickly clog most cloth dust collectors used in the blasting rooms. Moreover, when spraying in a blasting room, the dust collector system will require more frequent maintenance to prevent fire or explosion due to accumulation of metallic dust (see 11.2). Workmen in the blasting room should be provided with respiratory protection as detailed in 11.7.2.

When ventilating confined spaces, all air replacing that withdrawn should be clean and respirable. Fans should be sized to give at least 10 air changes per minute. If portable gasoline or diesel engine driven ventilators or compressors are used, they should be located so that engine exhaust gases cannot be drawn into the ventilating system. This precaution will also prevent exhaust gases from entering the intake of the compressor. This is particularly critical if the air is to be used for respirators.

If dust collectors are used, closed type collectors should be provided with blowout holes or relief panels. Blowout panels should also be provided in ventilation piping.

All fans, pipes, dust arrestors, and motors should be grounded. Ground to piping that carries fuel gas or oxygen should not be used. Ventilating fans should be kept running when cleaning out booths, pipes, etc. This prevents the accumulation of dust or fumes in the system. Aluminum and magnesium dusts present an explosive hazard which requires special attention. Adequate wet collector systems should be used on either of these metals. Care should be exercised, since these metallic dusts may generate hydrogen gas in water. These systems should be designed to prevent hydrogen accumulation. Frequent clean-out operations should be performed to reduce residues.

When spraying on unusually large objects or in large confined spaces, such as encountered in boilers and tanks, it is imperative that fresh air helmets and protective clothing be worn.

No welding or cutting should be done in the repair of any ventilation or dust collecting equipment unless the equipment has been thoroughly cleaned.

11.9 Toxic Materials

All materials, in finely divided form, may be damaging to the respiratory system, and the precautions necessary for protecting the health of spray operators vary according to the type of material being sprayed. Careful attention to this health problem is particularly important because the damage does not cause an immediate sensory effect. In addition to respiratory requirements, extreme care should be exercised to maintain floors, work benches, and booths free from dusty residues for optimum health protection. Used clothing should be properly processed to remove dusts, or they should be discarded.

11.9.1 Beryllium. Beryllium and its compounds are highly toxic and potentially hazardous. Thermal spraying indoors, outdoors, or in confined spaces involving beryllium-containing alloys should be done only when using adequate local exhaust ventilation and air line respirators. The only exception occurs when atmospheric tests, under the most adverse conditions, have established that the operators exposure is within acceptable concentrations (defined by the American National Standards Institute or the American Conference of Governmental Industrial Hygienists).

The exhaust of the ventilation system shall be handled in a safe manner, and directed to a restricted area. In all cases, workers in the immediately vicinity of the thermal spray operations shall be protected as necessary by local exhaust ventilation or air line respirators (see 11.7.2 and 11.8).

When working with beryllium, expert advice should always be obtained. Such advice may be obtained from certified industrial hygienists, the Nuclear Regulatory Commission, insurance companies, state agencies, and the Occupational Safety and Health Administration (OSHA).

11.9.2 Cadmium. Cadmium is highly toxic and hazardous. Respiratory protective equipment, such as fume respirators approved by the U. S. Bureau of Mines, National Institute of Occupational Safety and Health (NIOSH), or other approving authority for these purposes should be used (see 11.7.2 and 11.8).

11.9.3 Lead, Lead Alloys, Cobalt, Chromium, and Tellurium. When spraying or blasting these materials, the principal hazard is from ingestion, inhalation, and subsequent absorption of fumes, dust, or vapors.

The fumes and dust of lead, lead alloys (such as solder and lead base babbitts), chromium alloys (such as stainless steels, nickel-chromium, and chromium oxide) and tellurium are toxic and potentially hazardous. When spray-

ing these metals and other highly toxic materials, respiratory protection and adequate ventilation should be provided wherever the fume and dust concentration is above the threshold limit value (see 11.7.2, 11.8, and 11.9.5).

11.9.4 Solvents. The radiation from an arc, such as encountered in plasma or arc spraying, causes rapid decomposition of chlorinated hydrocarbon solvent vapors into noxious and toxic gases. Solvents such as trichlorethylene and perchlorethylene decompose rapidly, even at considerable distance from the arc, and create phosgene gas. This problem can be reduced by slow extraction of the part from the solvent cleaning tank. Special precautions should be taken when spraying materials which have been vapor degreased to see that all the solvent has been removed prior to thermal spraying coating.

Liquid films or drops of solvent caught by pockets and crevices should be avoided. Solvent vapors should not be present in the spray area. The ultraviolet radiation from plasma and arc spraying generates ozone in the air. The amount of ozone produced may exceed the maximum allowable concentration value in confined spaces.

11.9.5 Threshold Limit Values. Threshold limit values (TLV) are air concentration levels of hazardous materials, which have been established for exposures not exceeding a total of eight hours daily. Threshold limit values, adopted by the American Conference of Governmental Industrial Hygienists (ACGIH), are published annually by the ACGIH under the title *Threshold Limit Values, Recommended and Tentative*. A current listing of the TLV should be consulted concerning the maximum allowable concentration of toxic material that may be encountered.

Air sampling should be conducted to determine the ventilation requirements for operations involving the above metals or solvents, or both. When less toxic metals are sprayed, the concentration of dust or fumes in the work area should never exceed the TLV for eight hour exposure. Respiratory protective devices and exhaust ventilation should be provided when the dust or fume concentration is sufficiently high to cause operator discomfort, even when the appropriate TLV is not exceeded.

11.9.6 Tin and Zinc. Tin and zinc, usually encountered in the forms of their oxides, may cause violent illness. However, all evidence indicates that tin and zinc are not toxic. The symptoms are coughing, headache, and particularly in the case of zinc oxide fumes, nausea, vomiting, chills, fever, pain in muscles and joints, and marked thirst. (In the case of zinc oxide, the effect has been known as "brass founder's ague," "brass chills," "zinc fever," or "metal fume fever"). Temporary short term immunity can be developed.

Preventive measures consist of adequate ventilation and proper respirators (see 11.7.2 and 11.8). Operators with pulmonary diseases or those who continue to suffer discomfort, even with proper ventilation and respirator measures, should be precluded from the work.

11.10 Safety Standards

Mandatory Federal Safety Regulations have been established by the Occupational Safety and Health Administration. For information on these regulations, refer to OSHA Standards, *Code of Federal Regulations, Title 29, Part 1910*.

Among the principal safety hazards associated with the thermal spraying process is the handling of compressed gases. In this publication, the safe handling of compressed gases is covered by reference to ANSI/AWS Z49.1, *Safety in Welding and Cutting*, and in accordance with the *Williams-Steiger Occupational Safety and Health Act of 1970* (84 Stat. 1943). More recently, the newly enacted *Resource Conservation and Recovery Act* (RCRA), dealing with the disposal of toxic wastes, has a potential for additional impact upon this industry and requires consultation as that legislation is clarified.

Where standards and other documents are referenced in this publication, they refer to the latest edition.

Occupational Safety and Health Act Standards (29CFR 1910), available from the Superintendent of Documents, U.S. Government Printing Office.

Ventilation Control of Grinding, Polishing and Buffing of Metals, ANSI Z43.1, available from the American National Standards Institute.

Safety in Welding and Cutting, ASC/ANSI Z49.1, available from the American Welding Society.

Standard Practices for Occupational and Educational Eye and Face Protection, ANSI Z87.1, available from the American National Standards Institute.

Standard Practices for Respiratory Protection, ANSI Z88.2, available from the American National Standards Institute.

Safety Requirements for Industrial Head Protection, ANSI Z89.1, available from the American National Standards Institute.

National Electrical Code, ANSI/NFPA 70-1979, available from the National Fire Protection Association, updated annually.

Safe Handling of Compressed Gases, CGA Pamphlet P-1, available from the Compressed Gas Association.

Oxygen, CGA Pamphlet G-4 available from the Compressed Gas Association.

Recommended Safe Practices for the Preparation for Welding and Cutting of Containers That Have Held Hazar-

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dous Substances, ANSI/AWS F4.1, available from the American Welding Society.

Safety Release Device Standards — Cylinders for Compressed Gases, CGA Pamphlet S1.1, available from the Compressed Gas Association.

Safety Release Device Standards — Cargo and Portable Tanks for Compressed Gases, CGA Pamphlet S1.2, available from the Compressed Gas Association.

Standard for Gaseous Hydrogen at Consumer Sites, CGA Pamphlet G5.1, available from the Compressed Gas Association.

Power Piping, ANSI B31.3, available from the

American National Standards Institute.

Acetylene, CGA Pamphlet G-1, available from the Compressed Gas Association.

Oxygen-Fuel Gas Systems for Welding and Cutting, ANSI/NFPA 51, available from the National Fire Protection Association.

Standard for Fire Prevention in Use of Cutting and Welding Processes, ANSI/NFPA 51B, available from the National Fire Protection Association.

Standard for the Storage and Handling of Liquefied Petroleum Gases, ANSI/NFPA 58, available from the National Fire Protection Association.

Appendix: Commonly Used Metric Conversions

Inch-millimeter conversion

1 in. = 25.4 mm exactly

To convert inches to millimeters, multiply the inch value by 25.4.

To convert millimeters to inches, divide the millimeter value by 25.4.

Inch and millimeter decimal equivalents of fractions of an inch

Inch			Inch		
Fraction	Decimal	Millimeter	Fraction	Decimal	Millimeter
1/64	0.015 625	0.396 875	33/64	0.515 625	13.096 875
1/32	0.031 250	0.793 750	17/32	0.531 250	13.493 750
3/64	0.046 875	1.190 625	35/64	0.546 875	13.890 625
1/16	0.062 500	1.587 500	9/16	0.562 500	14.287 500
5/64	0.078 125	1.984 375	37/64	0.578 125	14.684 375
3/32	0.093 750	2.381 250	19/32	0.593 750	15.081 250
7/64	0.109 375	2.778 125	39/64	0.609 375	15.478 125
1/8	0.125 000	3.175 000	5/8	0.625 000	15.875 000
9/64	0.140 625	3.571 875	41/64	0.640 625	16.271 875
5/32	0.156 250	3.968 750	21/32	0.656 250	16.668 750
11/64	0.171 875	4.365 625	43/64	0.671 875	17.065 625
3/16	0.187 500	4.762 500	11/16	0.687 500	17.462 500
13/64	0.203 125	5.159 375	45/64	0.703 125	17.859 375
7/32	0.218 750	5.556 250	23/32	0.718 750	18.256 250
15/64	0.234 375	5.953 125	47/64	0.734 375	18.653 125
1/4	0.250 000	6.350 000	3/4	0.750 000	19.050 000
17/64	0.265 625	6.746 875	49/64	0.765 625	19.446 875
9/32	0.281 250	7.143 750	25/32	0.781 250	19.843 750
19/64	0.296 875	7.540 625	51/64	0.796 875	20.240 625
5/16	0.312 500	7.937 500	13/16	0.812 500	20.637 500
21/64	0.328 125	8.334 375	53/64	0.828 125	21.034 375
11/32	0.343 750	8.731 250	27/32	0.843 750	21.431 250
23/64	0.359 375	9.128 125	55/64	0.859 375	21.828 125
3/8	0.375 000	9.525 000	7/8	0.875 000	22.225 000
25/64	0.390 625	9.921 875	57/64	0.890 625	22.621 875
13/32	0.406 250	10.318 750	29/32	0.906 250	23.018 750
27/64	0.421 875	10.715 625	59/64	0.921 875	23.415 625
7/16	0.437 500	11.112 500	15/16	0.937 500	23.812 500
29/64	0.453 125	11.509 375	61/64	0.953 125	24.209 375
15/32	0.468 750	11.906 250	31/32	0.968 750	24.606 250
31/64	0.484 375	12.303 125	63/64	0.984 375	25.003 125
1/2	0.500 000	12.700 000	1	1.000 000	25.400 000

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Conversions for Fahrenheit — Celsius temperature scales

Find number to be converted in center (bold face) column.

Converting Fahrenheit degrees, read Celsius equivalent.

Converting Celsius degrees, read Fahrenheit equivalent.

°C	°F	°C	°F	°C	°F	°C	°F	°C	°F				
-40	-40	132	270	518	543	1010	1850	932	1710	3110	1321	2410	4370
-34	-30	138	280	536	549	1020	1868	938	1720	3128	1327	2420	4388
-29	-20	143	290	554	554	1030	1886	943	1730	3146	1332	2430	4406
-23	-10	149	300	572	560	1040	1904	949	1740	3164	1338	2440	4434
-17.8	0	154	310	590	566	1050	1922	954	1750	3182	1343	2450	4442
-16.7	2	160	320	608	571	1060	1940	960	1760	3200	1349	2460	4469
-15.6	4	166	330	626	577	1070	1958	966	1770	3218	1354	2470	4478
-14.4	6	171	340	644	582	1080	1976	971	1780	3236	1360	2480	4496
-13.3	8	177	350	662	588	1090	1994	977	1790	3254	1366	2490	4514
-12.2	10	182	360	680	593	1100	2012	982	1800	3272	1371	2500	4532
-11.1	12	199	390	734	599	1110	2030	988	1810	3290	1377	2510	4550
-10.0	14	204	400	752	604	1120	2048	993	1820	3308	1382	2520	4568
- 8.9	16	210	410	770	610	1130	2066	999	1830	3326	1388	2530	4586
- 7.8	18	216	420	788	616	1140	2084	1004	1840	3344	1393	2540	4604
- 6.7	20	221	430	806	621	1150	2102	1010	1850	3362	1399	2550	4622
- 5.6	22	227	440	824	627	1160	2120	1016	1860	3380	1404	2560	4640
- 4.4	24	232	450	842	632	1170	2138	1021	1870	3398	1410	2570	4658
- 3.3	26	238	460	860	638	1180	2156	1027	1880	3416	1416	2580	4676
- 2.2	28	243	470	878	643	1190	2174	1032	1890	3434	1421	2590	4694
- 1.1	30	249	480	896	649	1200	2192	1038	1900	3452	1427	2600	4712
0.0	32	254	490	914	654	1210	2210	1043	1910	3470	1432	2610	4730
1.1	34	260	500	932	660	1220	2228	1049	1920	3488	1438	2620	4748
2.2	36	266	510	950	666	1230	2246	1054	1930	3506	1443	2630	4766
3.3	38	271	520	968	671	1240	2264	1060	1940	3524	1449	2640	4784
4.4	40	277	530	986	677	1250	2282	1066	1950	3542	1454	2650	4802
5.6	42	282	540	1004	682	1260	2300	1071	1960	3560	1460	2660	4820
6.7	44	288	550	1022	688	1270	2318	1077	1970	3578	1466	2670	4838
7.8	46	293	560	1040	693	1280	2336	1082	1980	3596	1471	2680	4856
8.9	48	299	570	1058	699	1290	2354	1088	1990	3614	1477	2690	4874
10.0	50	304	580	1076	704	1300	2372	1093	2000	3632	1482	2700	4892
11.1	52	310	590	1094	710	1310	2390	1099	2010	3650	1488	2710	4910
12.2	54	316	600	1112	716	1320	2408	1104	2020	3668	1493	2720	4928
13.3	56	321	610	1130	721	1330	2426	1110	2030	3686	1499	2730	4946
14.4	58	327	620	1148	727	1340	2444	1116	2040	3704	1504	2740	4964
15.6	60	332	630	1166	732	1350	2462	1121	2050	3722	1510	2750	4982
16.7	62	338	640	1184	738	1360	2480	1127	2060	3740	1516	2760	5000
17.8	64	343	650	1202	743	1370	2498	1132	2070	3758	1521	2770	5018
18.9	66	349	660	1220	749	1380	2516	1138	2080	3776	1527	2780	5036
20.0	68	354	670	1238	754	1390	2534	1143	2090	3794	1532	2790	5054
21.1	70	360	680	1256	760	1400	2552	1149	2100	3812	1538	2800	5072
24.4	76	366	690	1274	766	1410	2570	1154	2110	3830	1543	2810	5090
25.6	78	371	700	1292	771	1420	2588	1160	2120	3848	1549	2820	5108
26.7	80	377	710	1310	777	1430	2606	1166	2130	3866	1554	2830	5126
27.8	82	382	720	1328	782	1440	2624	1171	2140	3884	1560	2840	5144
28.9	84	388	730	1346	788	1450	2642	1177	2150	3902	1566	2850	5162
30.0	86	393	740	1364	793	1460	2660	1182	2160	3920	1571	2860	5180
31.1	88	399	750	1382	799	1470	2678	1188	2170	3938	1577	2870	5198
32.2	90	404	760	1400	804	1480	2696	1193	2180	3956	1582	2880	5216
33.3	92	410	770	1418	810	1490	2714	1199	2190	3974	1588	2890	5234
34.4	94	416	780	1436	816	1500	2732	1204	2200	3992	1593	2900	5252
35.6	96	432	810	1490	821	1510	2750	1210	2210	4010	1599	2910	5270
36.7	98	438	820	1508	827	1520	2768	1216	2220	4028	1604	2920	5288
37.8	100	443	830	1526	832	1530	2786	1221	2230	4046	1610	2930	5306
43	110	449	840	1544	838	1540	2804	1227	2240	4064	1616	2940	5324
49	120	454	850	1562	843	1550	2822	1232	2250	4082	1621	2950	5342

Conversions for Fahrenheit (Continued)

°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
54	130	266	460	860	1580	849	1560	2840	1238	2260	4100
60	140	284	466	870	1598	854	1570	2858	1243	2270	4118
66	150	302	471	880	1616	860	1580	2876	1249	2280	4136
71	160	320	477	890	1634	866	1590	2894	1254	2290	4154
77	170	338	482	900	1652	871	1600	2912	1260	2300	4172
82	180	356	488	910	1670	877	1610	2930	1266	2310	4190
88	190	374	493	920	1688	882	1620	2948	1271	2320	4208
93	200	392	499	930	1706	888	1630	2966	1277	2330	4226
99	210	410	504	940	1724	893	1640	2984	1282	2340	4244
100	212	414	510	950	1742	899	1650	3002	1288	2350	4262
104	220	428	516	960	1760	904	1660	3020	1293	2360	4280
110	230	446	521	970	1778	910	1670	3038	1299	2370	4298
116	240	464	527	980	1796	916	1680	3056	1304	2380	4316
121	250	482	532	990	1814	921	1690	3074	1310	2390	4334
127	260	500	538	1000	1832	927	1700	3092	1316	2400	4352

Abbreviations

ANSI	American National Standards Institute
ASP	Arc Spraying — See Glossary
BTU	British Thermal Units — See Glossary
CGA	Compressed Gas Association
FLSP	Flame Spraying — See Glossary
g/min	grams per minute
kPa	kilopascal, a unit of force equal to 1000 N/m ²
lb/h	pounds per hour
MPS	Methylacetylene-Propadiene Stabilized gas fuel
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
psi	pounds per square inch
psig	pounds per square inch — gage pressure
PSP	Plasma Spraying — See Glossary
RMS	Root Mean Square
SAE	Society of Automotive Engineers
scfh	Standard Cubic Feet per Hour
sfpn	Surface Feet per Minute — See Glossary
TBC	Thermal Barrier Coatings — See 5.6
THSP	Thermal Spraying — See Glossary
VPD	Vacuum Plasma Deposition — See Glossary

Glossary

A mixture of generic and popular terminology has been adopted by the thermal spraying industry. The compilation presented here includes (1) Standard Terms and Definitions (* starred items) from AWS A3.0 adapted for use in Thermal Spraying, and (2) terms and definitions judged to be of significant value in the understanding and application of the various processes.

A

abrasive. Material such as sand, crushed chilled cast iron, crushed steel grit, aluminum oxide, silicon carbide, flint, garnet, or crushed slag used for cleaning or surface roughening.

abrasive blasting. See preferred term **blasting**.

absorb. To take in and engulf wholly.

***absorptive lens (eye protection).** A filter lens designed to attenuate the effects of glare and reflected and stray light. See **filter plate**.

acoustical room. A soundproof enclosure, containing thermal spraying and sometimes related auxiliary equipment. Its design and construction prevent any unacceptable process noises from interfering with normal work in the environment surrounding the enclosure.

adhesion. A binding force that holds together molecules of substances whose surfaces are in contact or near proximity.

adhesive strength. The magnitude of attractive forces, generally physical in character, between a coating and substrate. Two principle interactions that contribute to the adhesion are van der Waals forces and permanent dipole bonds.

adsorb. To take in on the surface.

***air cap.** A device for forming, shaping and directing an air flow pattern for the atomization of wire or ceramic rod.

air cooler. See preferred term **workpiece cooler**.

***air feed.** A thermal spraying process variation in which an air stream carries the powdered surfacing material through the gun and into the heat source.

air filter. Mechanism for cleaning air of contaminants such as water, oil, and solid matter.

alumina. A chemical compound (aluminum oxide); a ceramic used in powder or rod form in thermal spraying operations. May also be a blasting medium.

anchoring. A supplemental method of locking the thermal spray deposit to the substrate by screw heads, studs, or similar means.

anode. The electrode maintained at a positive electrical potential. In typical plasma thermal spraying gun designs, this is the front electrode, constructed as a hollow nozzle and usually fabricated from copper. In electric arc thermal spraying guns, one feed wire is the positive electrode.

apparent density ratio. The ratio of the measured density of an object to the absolute density of a perfectly solid material of the same composition, usually expressed as a percentage.

arc. A luminous discharge of electrical current crossing the gap between two electrodes.

arc chamber. The confined space within the plasma thermal spraying gun enclosing the anode and cathode, in which the arc is struck.

***arc force.** The axial force developed by an arc plasma.

arc gas. The gas introduced into the arc chamber and ionized by the arc to form a plasma.

arc gas - primary. See preferred term **primary gas**.

arc gas - secondary. See preferred term **secondary gas**.

***arc plasma.** A gas that has been heated by an electric arc to at least a partially ionized condition, enabling it to conduct an electric current.

***arc spraying (ASP).** A thermal spraying process using an arc between two consumable electrodes of surfacing materials as a heat source and a compressed gas to atomize and propel the surfacing material to the substrate.

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***atomization.** (1) The division of molten material at the end of the wire or rod into fine particles. (2) The process used in the manufacture of powder.

auxiliary cooler. A device used to direct compressed air to prevent overheating of the thermal spraying deposit or the substrate.

B

***backfire.** The momentary recession of the flame into the spray gun, followed by immediate reappearance or complete extinction of the flame.

base material. See preferred term **substrate**.

base metal. See preferred term **substrate**.

berry formation. See preferred term **nozzle accumulation**.

***blasting.** A method of cleaning or surface roughening by a forcibly projected stream of sharp angular abrasive.

body stress. Residual stresses within an individual sprayed particle.

***bond.** See **mechanical bond** and **metallic bond**.

bond cap or bond bar. The test specimen on which a spray coating is applied for the purpose of determining adhesive-cohesive strength.

***bond coat.** A preliminary (or prime coat) of material that improves adherence of the subsequent spray deposit.

***bonding force.** The force that holds two atoms together; it results from a decrease in energy as two atoms are brought closer to one another.

***bond line.** The cross section of the interface between a thermal spraying deposit and substrate, or between adhesive and adherent in an adhesive bonded joint.

bond strength. The force required to pull a coating free of a substrate, usually expressed in psi (kPa).

BTU - British Thermal Unit, a unit of measure for heat (equal to 1055J).

***buildup.** A surfacing variation in which surfacing metal is deposited to achieve the required dimensions.

***burnoff rate.** A nonstandard term for **melting rate**.

C

cap. See preferred term **nozzle** or **air cap**.

carbide. A chemical compound formed between carbon and a metal or metals; examples are tungsten carbide, tantalum carbide, titanium carbide, chromium carbide.

***carburizing flame** — A nonstandard term for **reducing flame**.

***carrier gas.** The gas used to carry powdered material from the powder feeder or hopper to the gun.

cast. The twist warp or curvature of a metal wire.

cathode. The electrode maintained at a negative electric potential. In a plasma gun it is usually the rear electrode, conically shaped, and fabricated from tungsten or thoriated tungsten.

ceramic rod flame spray gun. A flame spraying device wherein an oxyfuel gas flame provides the heat, and the surfacing material to be sprayed is in ceramic rod form.

***ceramic rod flame spraying.** A thermal spraying process variation in which the material to be sprayed is in ceramic rod form. See **flame spraying (FLSP)**.

ceramic rod speed. The length of ceramic rod sprayed in a unit of time.

cermet. A physical mixture of ceramics and metals; examples are alumina plus nickel and zirconia plus nickel.

***cladding.** A surfacing variation that deposits or applies surfacing material, usually to improve corrosion or heat resistance.

***clad metal.** A laminar composite consisting of a metal, with a metal of different chemical composition applied to one or two sides.

clad powder. See preferred term **powder clad**.

coalesce. To grow or come together; fuse; unite.

coating. (1) The act of building a deposit on a substrate, (2) the spray deposit.

***coating density.** A nonstandard term for **spray deposit density ratio**.

coating strength. (1) A measure of the cohesive bond within a coating, as opposed to coating-to-substrate bond (adhesive strength), (2) the tensile strength of a coating, usually expressed in psi (kPa).

coating stress. The stresses in a coating resulting from rapid cooling of molten material or semimolten particles as they impact the substrate. Coating stresses are a combination of body and textural stresses.

coefficient of thermal expansion. The ratio of the change in length per degree rise in temperature to the length at a standard temperature such as 68°F (20°C).

cohesive strength. See **coating strength**.

***collaring.** Adding a shoulder to a shaft or similar component as a protective confining wall for the thermal spray deposit.

combination aftercooler/dryer. A deliquescent desiccant dryer with an integral aftercooler.

companion panel. A small tab coated concurrently with the workpiece, used for inspection.

composite coating. A coating consisting of two or more dissimilar spray materials which may or may not be layered.

composite powder. See preferred term **powder composite**.

compressed air mask. A force feed type of face mask with a suitable regulator worn by the thermal spraying operator to provide a fresh air supply.

***cone.** The conical part of an oxyfuel gas flame next to the orifice of the tip.

***contact tube.** A device which transfers current to a continuous electrode.

control console. The instrumented unit from which the gun is operated and operating variables are monitored and controlled.

controlled atmosphere chamber. An enclosure or cabinet either filled with an inert gas or evacuated to below atmospheric pressure in which thermal spraying can be performed to minimize, or prevent, oxidation of the coating or substrate.

cooler. See preferred term **workpiece cooler**.

cord. A plastic tube filled with powder, and extruded to form a compact, flexible layer level wound wire-like "cord."

critical resolved shearing stress. The shearing stress on the slip plane necessary to produce slip (threshold value).

cubicle. See preferred term **acoustical room**.

***cylinder.** See **gas cylinder**.

***cylinder manifold.** A multiple header for interconnection of gas or fluid sources with distribution points.

D

***defect.** A discontinuity or discontinuities that by nature or accumulated effect (for example, total crack length) render a part or product unable to meet minimum applicable acceptance standards or specifications. This term designates rejectability. See also **discontinuity** and **flaw**.

degrease. To remove oil or grease from the surface of the workpiece. See **solvent degreasing**.

deliquescent. The process of melting or becoming liquid by absorbing moisture from the air.

deliquescent desiccant dryer. A pressure vessel containing a collection chamber and a drying desiccant. It has no moving parts, and normally produces a 50°F (10°C) dewpoint or lower.

density. The mass or quantity of matter of a substance per unit volume, expressed as pounds per cubic inch, or grams per cubic centimeter.

density ratio. See **apparent density ratio**.

***deposit.** A nonstandard term for **thermal spraying deposit**.

***deposition efficiency.** The ratio, usually expressed in percent, of the weight of spray deposit to the weight of the material sprayed.

***deposition rate.** The weight of material deposited in a unit of time.

desiccant. A chemical used to attract and remove moisture from air or gas.

***detonation flame spraying.** A thermal spraying process variation in which the controlled explosion of a mixture of fuel gas and oxygen is utilized to melt and propel the material to the workpiece.

dewpoint. Temperature at which moisture will condense from humid vapors into a liquid state.

***discontinuity.** An interruption of the typical structure of a coating, such as a lack of homogeneity in the mechanical, metallurgical, or physical characteristics of

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the material. A discontinuity is not necessarily a defect. See also **defect** and **flaw**.

***dovetailing.** A method of surface roughening involving angular undercutting to interlock the spray deposit.

dwelt time. The length of time the spray material is exposed to the heat zone which produces and sustains a molten condition.

E

ear protection. OSHA or other safety agency approved devices for the reduction of sound audible to the outer ear.

edge effect. Loosening of the adhesional bond between the spray deposit and the substrate at the workpiece edges.

edge loss. Spray deposit lost as overspray resulting from spraying near the edge of the workpiece.

elastic modulus. The ratio of stress, within the proportional limit, to the corresponding strain.

***electric arc spraying.** A nonstandard term for arc spraying.

***electric bonding.** A nonstandard term for surfacing.

electrode. A component for the electrical circuit through which current is conducted to the arc. See **anode** and **cathode**.

enclosure. See preferred term **acoustical room**.

endothermic compounds. Beads and tablets which absorb moisture from the air and are consumed in the process. The action is termed deliquescence. Beads used are inorganic with absorption capability to reduce dewpoints 42°F (5.5°C) at an inlet temperature of 100°F (38°C), and 27°F (-2.8°C) at an inlet temperature of 70°F (21°C). Beads or tablets utilized are of two types: potassium carbonate and sodium chloride.

***exhaust booth.** A mechanically ventilated, semi-enclosed area in which air flow across the work area is used to remove fumes, gases, and solid particles.

eye protection. Proper helmets, face masks, or goggles which are required to be used to protect the eyes from ultraviolet and infrared radiation during thermal spraying operations.

F

***face shield (eye protection).** A device positioned in front of the eyes and over all or a portion of the face to protect the eyes and face. See also **hand shield** and **helmet**.

***feed rate.** A nonstandard term for **spray rate**.

***filter glass.** A nonstandard term for **filter plate**.

***filter lens (eye protection).** A round filter plate.

***filter plate (eye protection).** An optical material that protects the eyes against excessive ultraviolet, infrared, and visible radiation.

***fines.** A material finer than a particular mesh size under consideration.

***flame spraying (FLSP).** A thermal spraying process in which an oxyfuel gas flame is the source of heat for melting the surfacing material. Compressed gas may or may not be used for atomizing and propelling the surfacing material to the substrate.

***flashback.** A recession of the flame into or back of the mixing chamber of the thermal spraying gun.

***flashback arrester.** A device to limit damage from a flashback by preventing propagation of the flame front beyond the location of the arrester.

***flaw.** An undesirable discontinuity. See **defect**.

flow meter. A device for indicating the rate of gas flow in a system.

fretting. Surface damage resulting from relative motion between surfaces in contact under pressure.

***fuel gases.** Gases such as acetylene, natural gas, hydrogen, propane, stabilized methylacetylene propadiene, and other fuels, and hydrocarbons, usually used with oxygen for heating.

furnace fusing. The melting together of the spray deposit and the substrate which results in coalescence. The furnace offers the advantages of controlled heating, cooling, and protective atmosphere.

***fused spray deposit.** A self-fluxing spray deposit which is subsequently heated to coalescence within itself and with the substrate.

***fusion.** The melting together of filler metal and base metal (substrate), which results in coalescence.

fusion temperature. In thermal spraying, during the fusing of self-fluxing coatings, the narrow temperature range within which the coating surface exhibits a glassy or highly reflective appearance.

G

galvanic corrosion. Corrosion caused by spontaneous current between two dissimilar conductors in an electrolyte or between two dissimilar conductors in dissimilar electrolytes. If the two dissimilar metals are in contact, the reaction is referred to as **couple action**.

***gas cylinder.** A portable container used for transportation and storage of a compressed gas.

***gas pocket.** A nonstandard term for **porosity**.

***gas regulator.** A device for controlling the delivery of gas at some substantially constant pressure.

***graded coating.** A thermal spraying deposit composed of mixed materials in successive layers which progressively change in composition from the constituent material of the substrate to the surface of the sprayed deposit. Also referred to as **graduated** or **graded coating**.

gravity feed. A process by which powder is fed into a thermal spraying gun by gravity.

***grit.** See preferred term **abrasive**.

grit blasting. See preferred term **blasting**.

grit size. The particle size and distribution of abrasive blasting grains. Usually expressed by Society of Automotive Engineers numbers, such as SAE G25.

***groove and rotary roughening.** A method of surface roughening in which grooves are made and the original surface is roughened and spread.

***gun.** A nonstandard term for **thermal spraying gun**.

***gun extension.** The extension tube attached in front of the thermal spraying gun to permit spraying within confined areas or deep recesses.

H

***hand shield.** A protective device for shielding the eyes, face, and neck. A hand shield is equipped with a filter plate and is designed to be held by hand.

***hardfacing.** A surfacing variation in which surfacing metal is deposited to reduce wear.

***helmet.** A device designed to be worn on the head to protect eyes, face, and neck from arc radiation, radiated heat, spatter, or other harmful matter.

I

***inert gas.** A gas which does not normally combine chemically with the substrate or the deposit. Typical examples are argon and helium.

interface. The contact surface between the spray deposit and the substrate.

***interpass temperature.** In multiple pass thermal spraying, the temperature (minimum or maximum as specified) of the deposited spray coating before a subsequent pass is started.

ion. An atom or group of atoms forming a molecule that carries a positive or negative charge as a result of having lost or gained one or more electrons.

***ionic bond.** A primary bond arising from the electrostatic attraction between two oppositely charged ions.

K

***keying.** A nonstandard term for **mechanical bond**.

***knurling.** See **groove and rotary roughening, threading and knurling**.

L

lamella. A thin layer, as in the overlaid particles in a thermal spray deposit.

lamination. See preferred term **lamella**.

***lens.** See **filter lens**.

***locked-up stress.** A nonstandard term for **residual stress**.

low pressure plasma spray. See preferred term **vacuum plasma deposition**.

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M

***manifold.** See cylinder manifold.

***mask.** A device for protecting a substrate surface from the effects of blasting or adherence of a spray deposit.

matrix. The major continuous substance of a thermal spraying coating as opposed to inclusions or particles of materials having dissimilar characteristics.

***mechanical bond.** The adherence of a thermal spraying deposit to a roughened surface by the mechanism of particle interlocking.

melting rate. The weight or length of spray wire or rod melted in a unit of time.

***metallic bond.** The principal bond that holds metals together and is formed between base metals and filler metals in all processes. This is a primary bond arising from the increased spatial extension of the valence electron wave functions when an aggregate of metal atoms is brought close together. See also **bonding force**, and **ionic bond**.

***metallizing.** See preferred term for **thermal spraying**.

***metallurgical bond.** A nonstandard term for **metallic bond**.

molten metal flame spraying. A thermal spraying process variation in which the metallic material to be sprayed is in the molten condition. See **flame spraying (FLSP)**.

N

neat. Unadulterated.

***neutral flame.** An oxyfuel gas flame in which the portion used is neither oxidizing nor reducing. See also **oxidizing flame** and **reducing flame**.

***nontransferred arc.** An arc established between the electrode and the constricting nozzle. The workpiece is not in the electrical circuit.

***nozzle.** (1) A device which directs shielding media, (2) a device that atomizes air in an arc spray gun, (3) the anode in a plasma gun, (4) the gas burning jet in a rod or wire flame spray gun.

nozzle accumulation. Surfacing material deposited on the inner surface and on the exit end of the nozzle.

O

open circuit voltage. The potential difference applied between the anode and cathode prior to initiating the arc.

overspray. The excess spray material that is not deposited on the part being sprayed.

oxide. A chemical compound, the combination of oxygen with a metal forming a ceramic; examples — aluminum oxide, zirconium oxide.

***oxidizing flame.** An oxyfuel gas flame having an oxidizing effect (excess oxygen).

***oxyfuel gas spraying.** A nonstandard term for **flame spraying**.

P

parameter. A measurable factor relating to several variables; loosely used to mean a spraying variable, spraying condition, spray rate, spray distance, angle, gas pressure, gas flow, etc.

***parent metal.** A nonstandard term for **substrate**.

particle size. The average diameter of a given powder or grit granule.

particle size distribution. Classification of powdered materials as determined by various testing methods defining the particle sizes and quantities in a given sample.

particle size range. See preferred term **particle size distribution**.

pass. A single progression of the thermal spray device across the surface of the substrate.

physical bond. See preferred term **metallic bond**.

pistol. See preferred term **thermal spraying gun**.

***plasma.** See **arc plasma**.

plasma forming gas. See preferred term **arc gas**.

***plasma metallizing.** A nonstandard term for **plasma spraying**.

***plasma spraying (PSP).** A thermal spraying process in which a nontransferred arc is utilized as the source of heat that ionizes a gas which melts and propels the coating material to the workpiece.

***plenum.** See **plenum chamber**.

***plenum chamber.** The space between the inside wall of constricting nozzle and the electrode.

***porosity.** Cavity type discontinuities within a sprayed coating.

***postflow time.** The time interval from current shutoff to shutoff of shielding gas or cooling water, or both.

postheating. The application of heat to an assembly after a thermal spraying operation.

powder. Material manufactured into finely divided particles. When explicitly blended for thermal spraying, powder falls within a specific mesh range, usually finer than 120 mesh (125 microns). Fine powder is usually defined as having particles smaller than 325 mesh (44 microns).

powder alloy. Powder prepared from a homogeneous molten mixture of elements, and sometimes entrapped carbides or metal oxides. All of the particles have approximately the same composition.

powder blend. A heterogeneous mixture of two or more alloy powders.

powder clad (wire clad). Powder or wire wherein one alloy is encapsulated in another; a composite.

powder composite. Two or more independent materials, combined to form a single integrated unit. Maybe either chemically clad or mechanically agglomerated.

***powder feeder.** A device for conveying powdered materials to thermal spraying equipment.

powder feed gas. See preferred term **carrier gas**.

powder feed rate. The quantity of powder introduced into the hot, gaseous stream per unit of time.

***powder flame spraying.** A thermal spraying process variation in which the material to be sprayed is in powder form; all oxyfuel gas processes. See **flame spraying (FLSP)**.

***powder metallizing.** A nonstandard term for **powder flame spraying**.

***preflow time.** The time interval between start of shielding gas flow and arc or gas ignition.

***preheat.** The heat applied to the base metal or substrate immediately before spraying.

***preheat temperature.** A specified temperature that the substrate is required to attain immediately before material deposition.

primary gas. The major constituent of the arc gas fed to the gun to produce the plasma; usually argon or nitrogen.

***procedure.** The detailed elements of a process or method used to produce a specific result.

***protective atmosphere.** A gas envelope or vacuum surrounding the part to be thermally sprayed, with the gas composition controlled with respect to chemical composition; dewpoint, pressure, flow rate, etc. Examples are inert gases, combusted fuel gases, hydrogen and vacuum.

protective barriers. Curtains or portable fireproof canvas shields, sometimes required to enclose work areas, when there is a possibility of the spray stream being misdirected, or where the glare of the arc or flame could injure unprotected eyes.

protective clothing. Leather or metal coated articles designed to prevent burns from ultraviolet radiation or misdirected particles.

Q

quench rate. The speed at which a sprayed particle cools upon striking the surface of the substrate.

R

***rate of deposition.** See **deposition rate**.

***reducing flame.** A gas flame having a reducing effect (excess fuel gas).

refrigerated dryer. The application of a refrigeration cycle to physically lower the dewpoint.

regenerative dryer. A double column apparatus containing a drying medium for moisture absorption, which is automatically regenerated.

***regulator.** See **gas regulator**.

relative density. See preferred term **apparent density ratio**.

***residual stress.** Stress remaining in a structure or member as a result of thermal or mechanical treatment or both. See **coating stress**.

resonance time. See preferred term **dwell time**.

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root mean square (RMS). A method of defining the average roughness of a surface. It is the square root of the sum of all individual measurements divided by the number of measurements.

$$RMS = \sqrt{a^2 + b^2 + c^2 + d^2 + e^2 + \dots}$$

***rotary roughening.** A method of surface roughening in which a revolving roughening tool is pressed against the surface being prepared, while either the work or the tool, or both, move.

***rough threading.** A method of surface roughening which consists of cutting threads with the sides and tops of the threads jagged and torn.

S

saturated air. To reach 100 psi (690 kPa) air at 100% humidity, it is necessary to compress approximately 8 cu ft (0.23 m³) of free air, with its inherent moisture, into one cubic foot (0.028 m³), since atmospheric humidity is usually more than 12.5% at ambient. All undried compressed air systems at 100 psi (690 kPa) and ambient temperatures are at 100% relative humidity.

screen. One of a set of sieves, designated by the size of the openings, used to classify and sort powder to particle size.

***seal coat.** Material applied to infiltrate and close the pores of a thermal spraying deposit.

secondary gas. The minor or second constituent of the arc gas fed to the gun to produce plasma.

self-bonding materials. Those materials that exhibit the characteristics of forming a metallurgical bond with the substrate in the as-sprayed condition.

***self-fluxing alloys.** Surfacing materials that "wet" the substrate and coalesce when heated to their melting point, without the addition of an externally applied flux. These alloys contain boron or silicon, or both, as fluxing agents.

***shadow mask.** A protective device that partially shields an area of the work, thus permitting some overspray to produce a feathering at the coating edge.

***shear stress.** The stress on the slip plane produced by external loads tending to slide adjacent planes with respect to each other in the direction parallel to the planes.

***shielding gas.** Protective gas used to prevent or minimize atmospheric contamination. Also see **protective atmosphere**.

***shrinkage stress.** A nonstandard term for **residual stress**.

sieve. See preferred term **screen**.

***sieve analysis.** A method of determining particle size distribution, usually expressed as the weight percentage retained upon each of a series of standard screens of decreasing mesh size. Also see **particle size distribution**.

slick up. Point at which a self-fluxing alloy begins to shine during the fusing operation.

solvent degreasing. The removal of oil, grease, and other soluble contaminants from the surface of the workpiece by immersion in suitable cleaners.

spalling. The flaking or separation of a sprayed coating.

splat. A single thin flattened sprayed particle.

splat cooling. Extremely rapid, high rate of cooling, the effects of which can be observed in thermal spraying deposits leading to the formation of metastable phases and an amorphous microstructure.

spray. A moving mass of dispersed liquid droplets or heat softened particles.

spray angle. The angle of particle impingement, measured from the surface of the substrate to the axis of the spraying nozzle.

spray booth. See preferred term **exhaust booth**.

***spray deposit.** See **thermal spraying deposit**.

***spray deposit density ratio.** The ratio of the density of the spray deposit to the theoretical density of the surfacing material. Usually expressed as percent of theoretical density.

spray distance. The distance maintained between the thermal spraying gun nozzle tip and the surface of the workpiece during spraying.

***spray rate.** The rate at which surfacing material passes through the gun.

***spraying sequence.** The order in which different layers of similar or different materials are applied in a planned relationship, such as overlapped, superimposed, or at given angles.

stabilizing gas. The arc gas, ionized to form the plasma, is usually introduced into the arc chamber tangentially. The relatively cold gas chills the outer surface of the arc stream, tending to constrict the plasma, raise its

temperature, and force it out of the anode (nozzle) in a steady, relatively unfluctuating stream.

step mounting. The intentional overlapping of several workpieces in order that one protects or masks its neighbor during the blasting or spraying process.

sublime. To volatilize from the solid state to a gas.

***substrate.** Any material to which a thermal spraying deposit is applied.

superfines. Extra small, minute powder particles, usually less than five microns in size.

superheat. The difference between the higher actual temperature at the evaporator outlet and the lower theoretical temperature of the refrigerant at pressure.

surface feet per minute (SFPM). Linear velocity of the thermal spray gun as it traverses the length of the workpiece. Also, the circumferential velocity of the substrate.

***surface preparation.** The operations necessary to produce a desired or specified surface condition.

***surface roughening.** A group of methods for producing irregularities on a surface. See also **dovetailing**, **groove and rotary roughening**, **rotary roughening**, **rough threading**, and **threading and knurling**.

***surfacing.** The application by thermal spraying of a layer or layers of material to a surface to obtain desired properties or dimensions, as opposed to making a joint.

***surfacing material.** The material that is applied to a substrate during surfacing.

***surfacing metal.** The metal that is applied to a substrate during surfacing.

T

textural stress. The accumulated stress within an entire coating.

***thermal spraying (THSP).** 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 spray deposit. The surfacing material may be in the form of powder, rod, cord, or wire. See also **spraying**, **flame spraying**, and **plasma spraying**.

thermal spraying deposit. The coating or layer of surfacing material applied by a thermal spraying process.

***thermal spraying gun.** A device for heating, feeding, and directing the flow of a surfacing material.

***thermal stress.** Stress resulting from nonuniform temperature distribution.

***threading and knurling.** A method of surface roughening in which spiral threads are prepared, followed by upsetting with a knurling tool.

tons of refrigeration. A rate of heat exchange equal to 12,000 BTU/h.

torch. A device used for fusing sprayed coatings; it mixes and controls the flow of gases.

torch fusing. The use of a torch to heat and melt a fusible spraying deposit to produce coalescence.

***travel angle.** The angle that the gun makes with a reference line perpendicular to the axis of the deposit in the plane of its axis. This angle can be used to define the position of thermal spraying torches and thermal spraying guns.

traverse speed. The linear velocity at which the thermal spraying gun traverses across the workpiece during the spraying operation.

U

undercoat. A deposited coat of material which acts as a substrate for a subsequent thermal spraying deposit. See **bond coat**.

undercutting. A step in the sequence of surface preparation involving the removal of substrate material.

V

vacuum plasma deposition (VPD). A thermal spraying process variation utilizing a plasma gun confined to a solid enclosure. The enclosure is evacuated and the spraying performed under low pressure, usually below 10 Torr.

***van der Waals force.** A secondary force arising from the fluctuating dipole nature of an atom with all occupied electron shells filled.

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W

***water wash.** The forcing of exhaust air and fumes from a spraying booth through water so that the vented air is free of thermal sprayed particles or fumes.

***wire feed speed.** The rate of speed at which the wire is consumed.

***wire flame spraying.** A thermal spraying process variation in which the surfacing material is in wire form. See **flame spraying (FLSP)**.

wire metallizing. See preferred term **wire flame spraying**.

***wire straightener.** A device used for controlling the cast of coiled wire to enable it to be easily fed into the gun.

workpiece. The object or surface to be coated. See preferred term **substrate**.

workpiece cooler. See Auxiliary cooler.

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