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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).

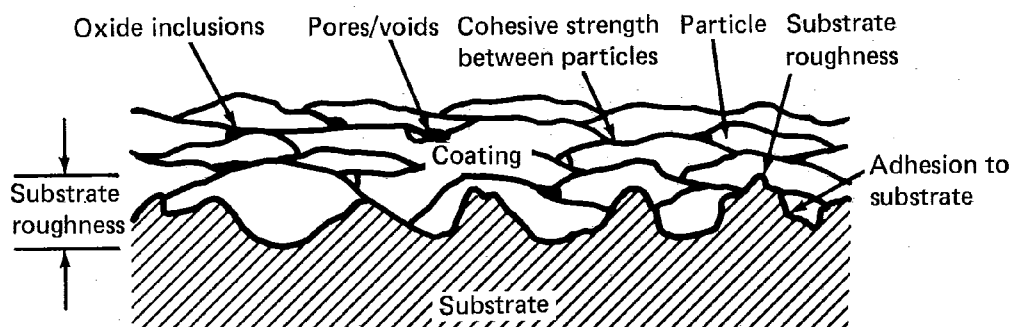


Fig. 1.4.3A — Typical coating cross section to illustrate lamellar structure of oxides and inclusions

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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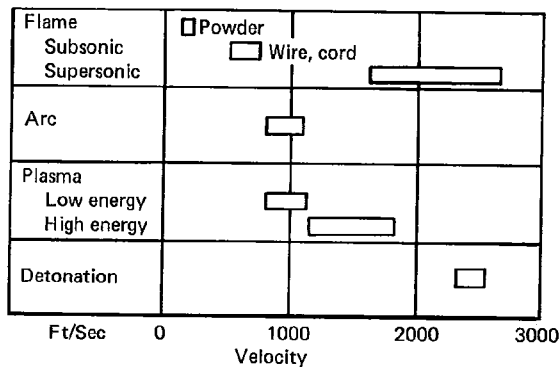


Fig.1.4.3B—Average particle impact velocities

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.

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 Combustion

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

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.

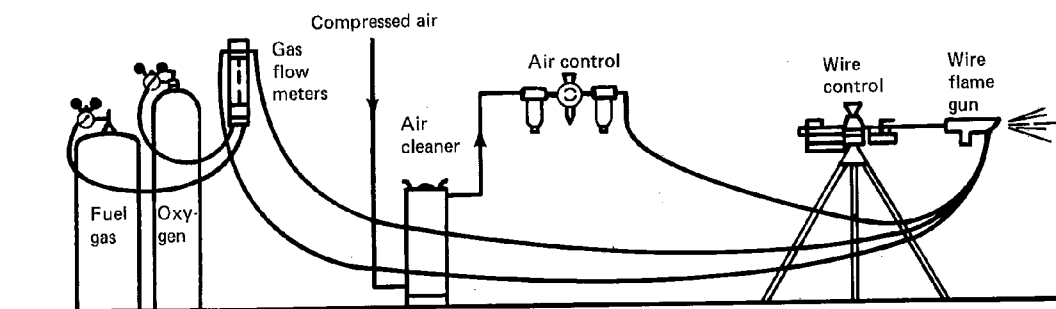


Fig. 2.2.1A — Typical wire flame spraying installation adaptable to rod and cord

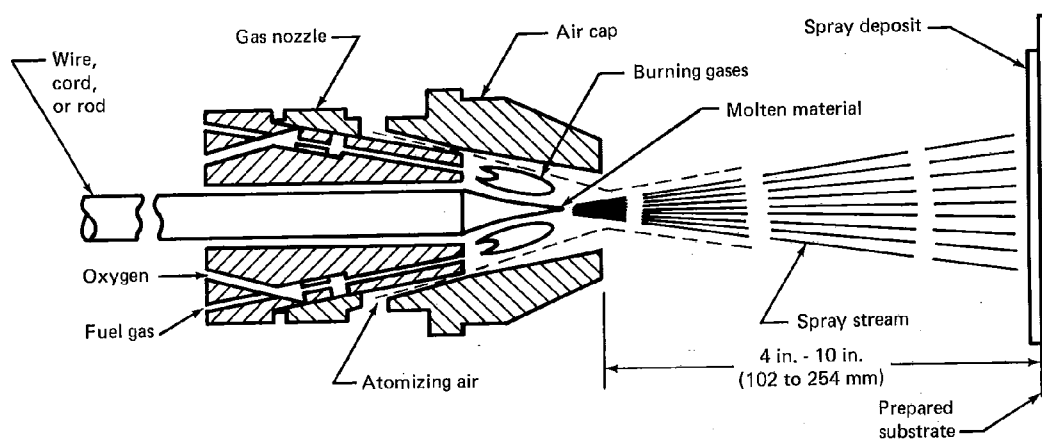


Fig. 2.2.1B — Cross section of typical wire rod or cord flame spray gun

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

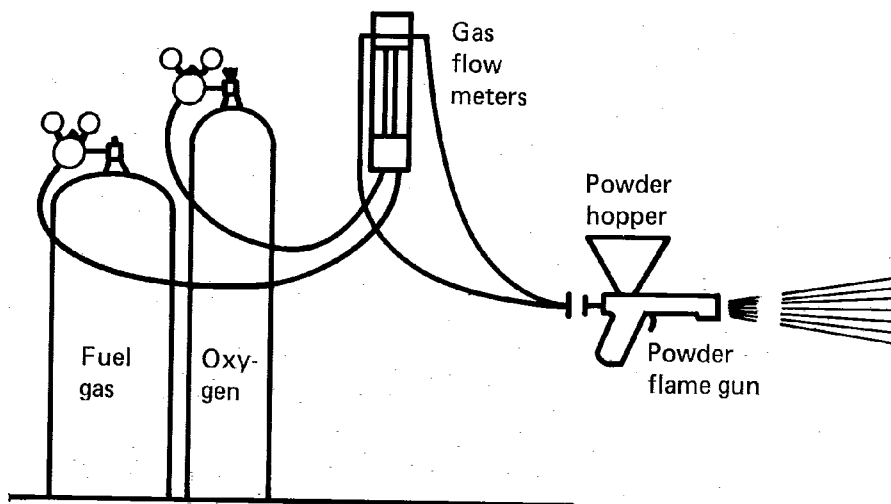


Fig. 2.2.2A — Typical installation of a powder flame spray process

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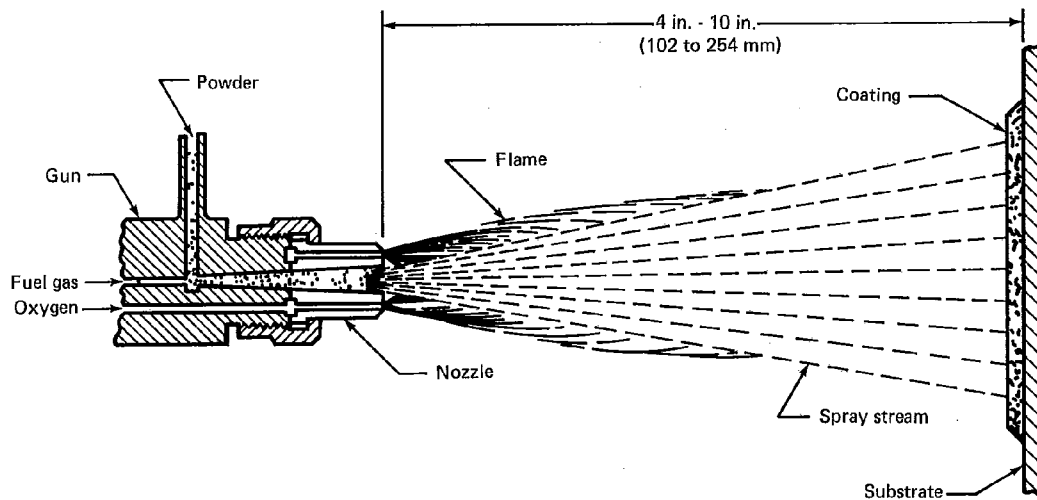


Fig. 2.2.2B — Cross section of a powder flame spray gun

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

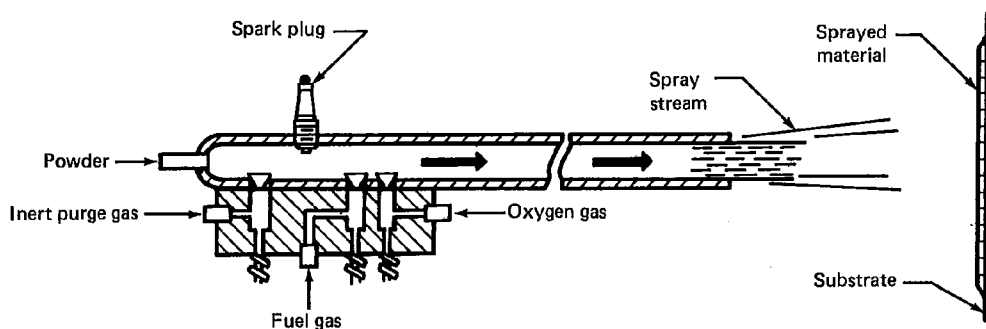


Fig. 2.2.3 — Schematic arrangement of an oxygen-fuel gas detonation gun

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

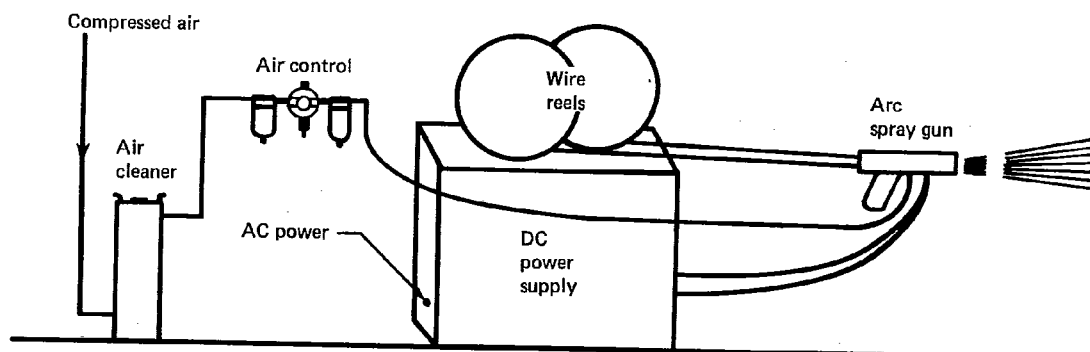


Fig. 2.3.1A — Arc spray components combined into a single unit

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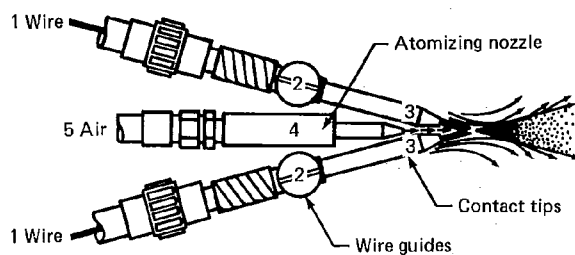


Fig. 2.3.1B — Cross section schematic of an arc spray gun

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.

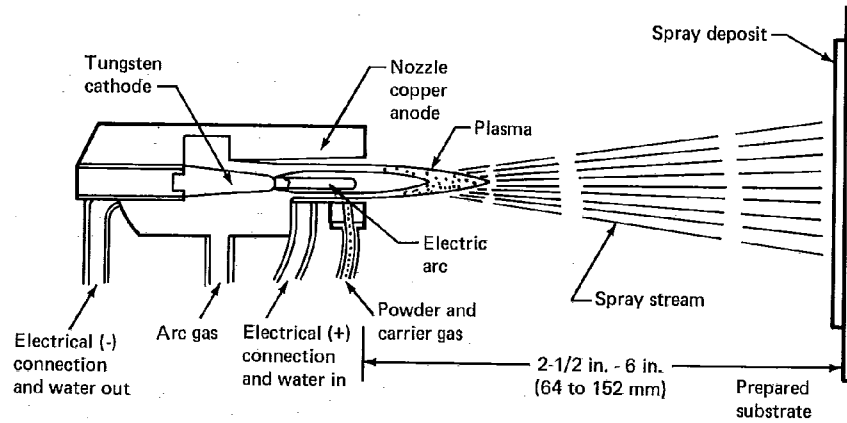


Fig. 2.3.2A — Sectional view of plasma torch

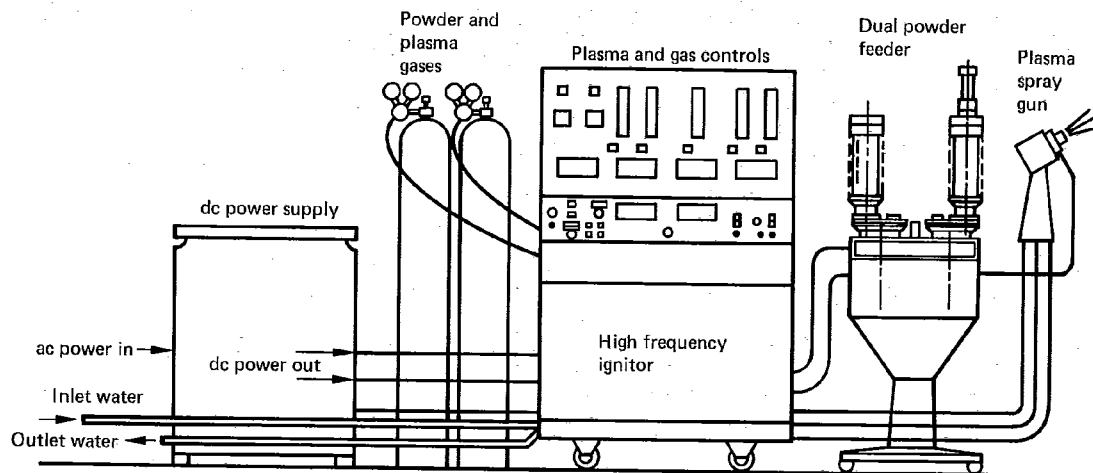


Fig. 2.3.2B — Complete installation plasma spray system

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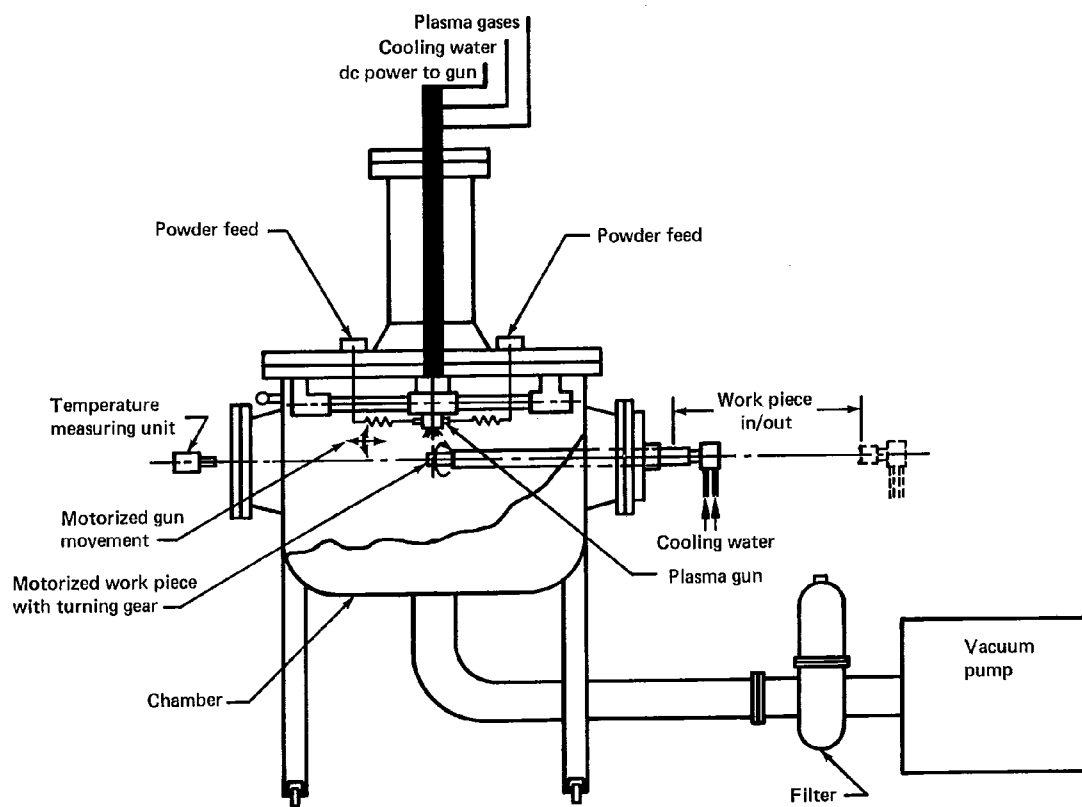


Fig. 2.4 — Controlled atmosphere thermal spray system

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.	(μ m)
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	(μ 6)
80	Aluminum oxide	60	(414)	5/16	(7.9)	Pressure	Plastic	250	(μ 6)

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)		
	1/4 (6.4)	5/16 (7.9)	3/8 (9.5)
	Blasting rate, ft ² /h (m ² /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.

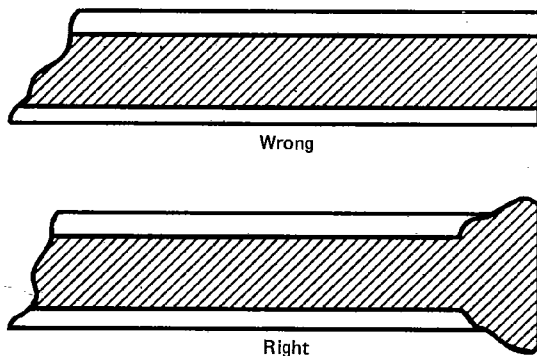


Fig. 3.5.1—Shaft with proper and improper undercut section

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.

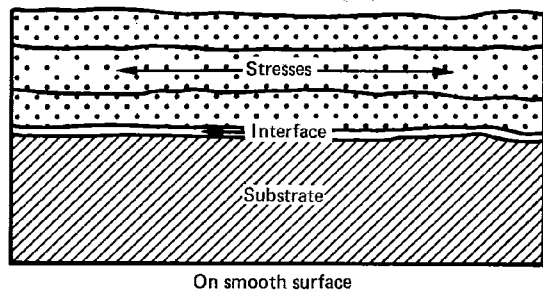
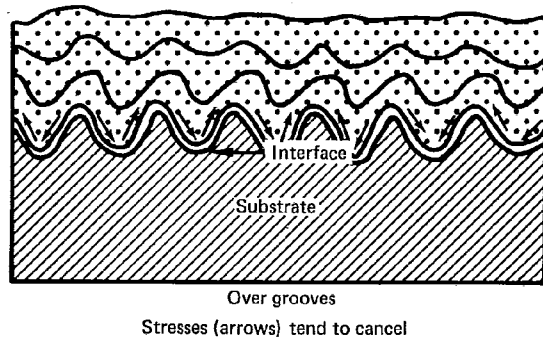


Fig. 3.5.2 — Sprayed metal

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

- | | |
|---|---|
| <p><i>4.1 Introduction</i></p> <p><i>4.2 Formation and Structure of Coatings</i></p> <p style="padding-left: 20px;">4.2.1 Form of the Spray</p> <p style="padding-left: 20px;">4.2.2 Particle Deposition</p> <p style="padding-left: 20px;">4.2.3 Substrate Surface Influence on the Molten Particle</p> <p><i>4.3 Coating Properties</i></p> <p style="padding-left: 20px;">4.3.1 Visual</p> <p style="padding-left: 20px;">4.3.2 Tensile Strength</p> | <p style="padding-left: 20px;">4.3.3 Residual Stress</p> <p style="padding-left: 20px;">4.3.4 Hardness</p> <p style="padding-left: 20px;">4.3.5 Compression</p> <p style="padding-left: 20px;">4.3.6 Wear Resistance</p> <p style="padding-left: 20px;">4.3.7 Fatigue</p> <p style="padding-left: 20px;">4.3.8 Ductility</p> <p style="padding-left: 20px;">4.3.9 Corrosion Resistance</p> <p><i>4.4 Coatings Produced Under Controlled Atmospheres</i></p> |
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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-

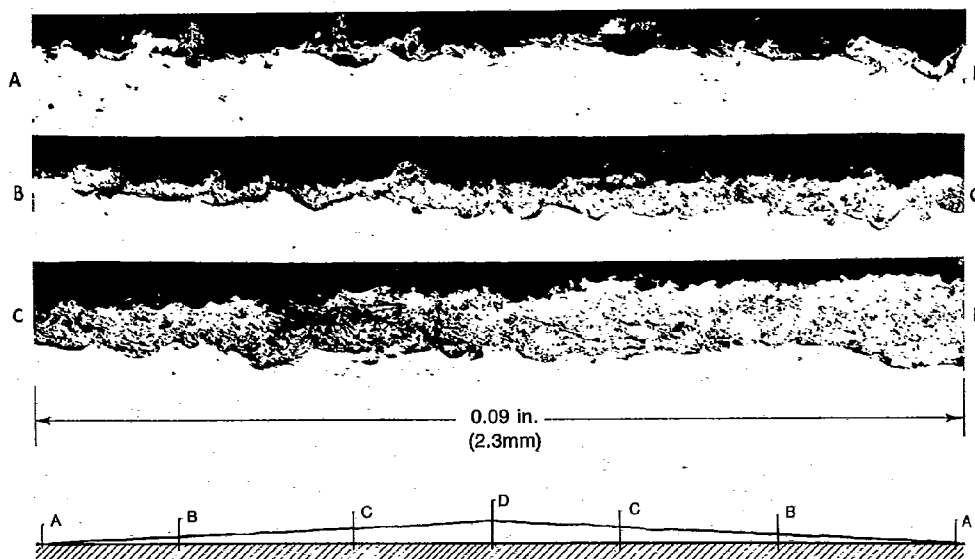
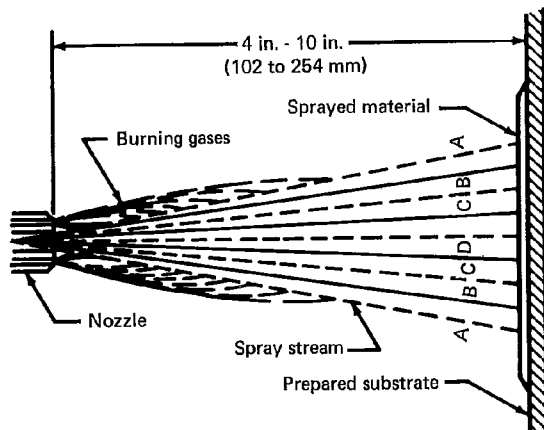


Fig. 4.2.1A — Typical transverse section of spray deposit from one pass of the thermal spray gun

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

ffects of operating conditions upon final splat configuration.

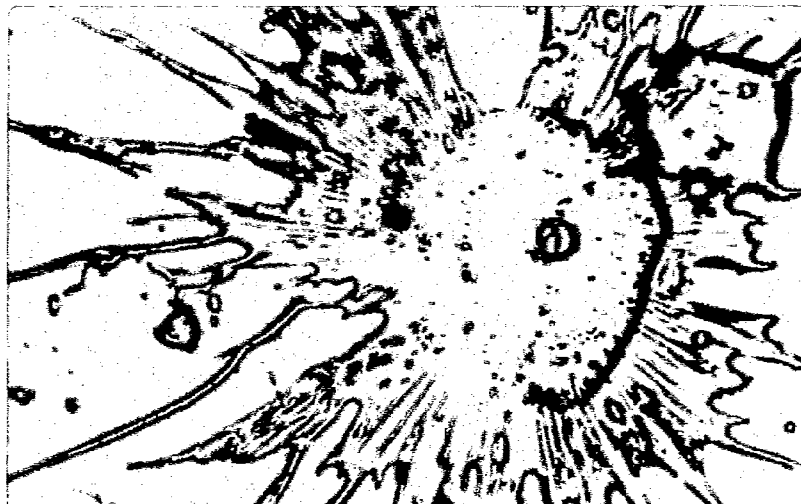
Gerdeman and Hecht considered the technique useful for rapidly determining optimum standoff distance. Figure 4.2.2A illustrates properly melted ceramic particles. The particle splash, or wetting, resulting from improper standoff distances are shown in Fig. 4.2.2B as being too close and in Fig. 4.2.2C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

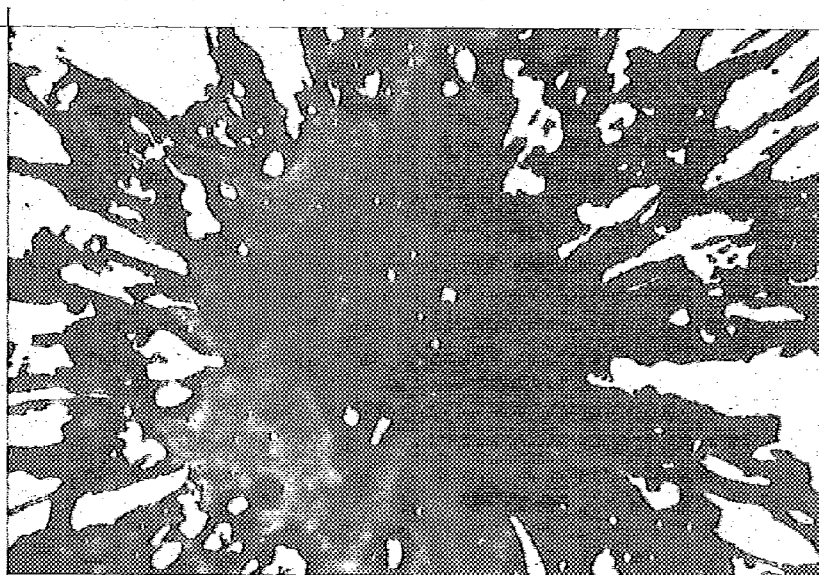
In the case of the sprayed drop, solidification may take place at any instant in the cycle of events. It is apparent, therefore, that in considering the formation of sprayed coatings, retraction of individual drops, or aggregates of drops as a result of surface tension, must be taken into account. Oxide 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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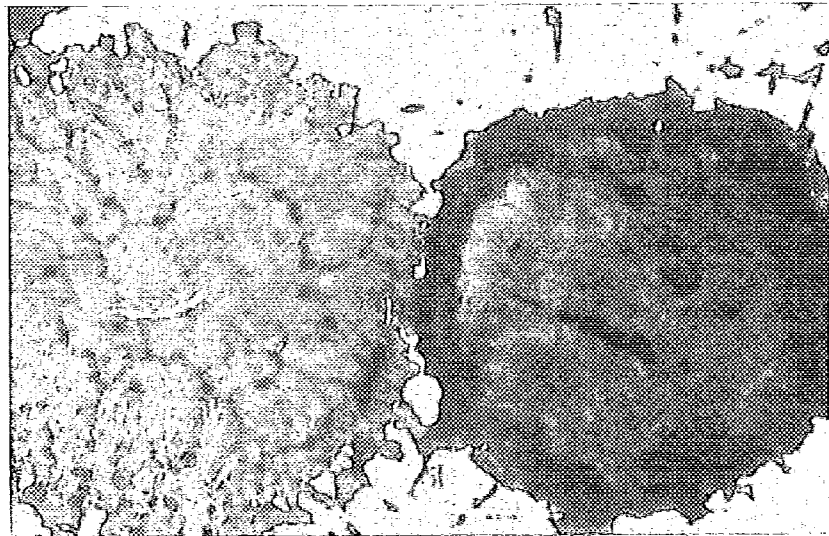


Fig. 4.2.2D — Recooled metallic particles (2000 x)

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 heterogeneous 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.

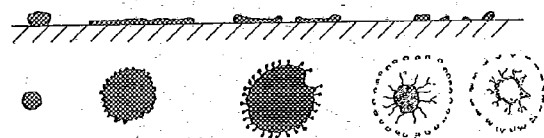


Fig. 4.2.2E—Splash forms of mercury on glass

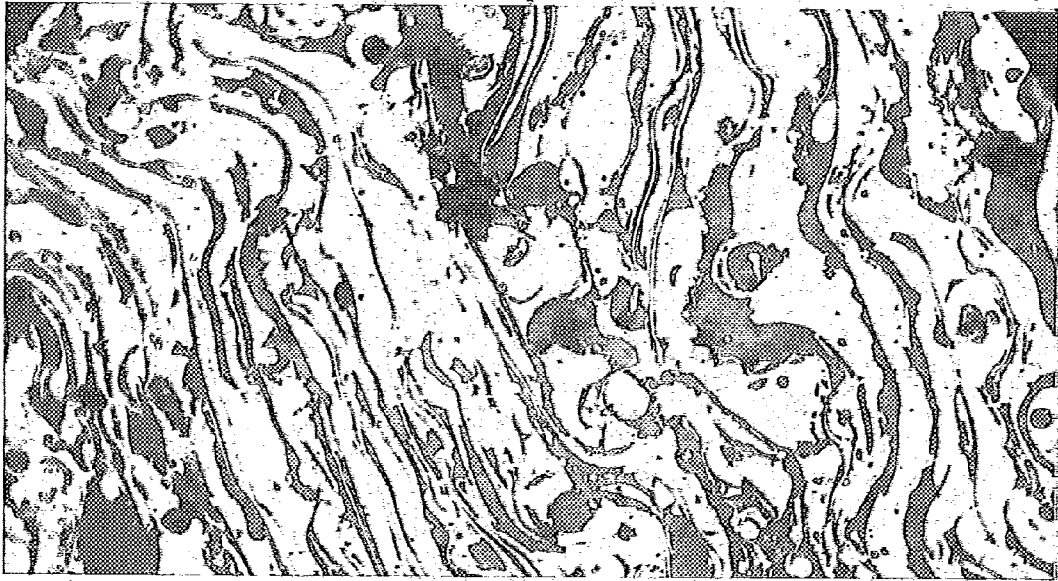


Fig. 4.2.2F — Transverse section through 0.8C (carbon) steel wire flame sprayed coating (250 x)

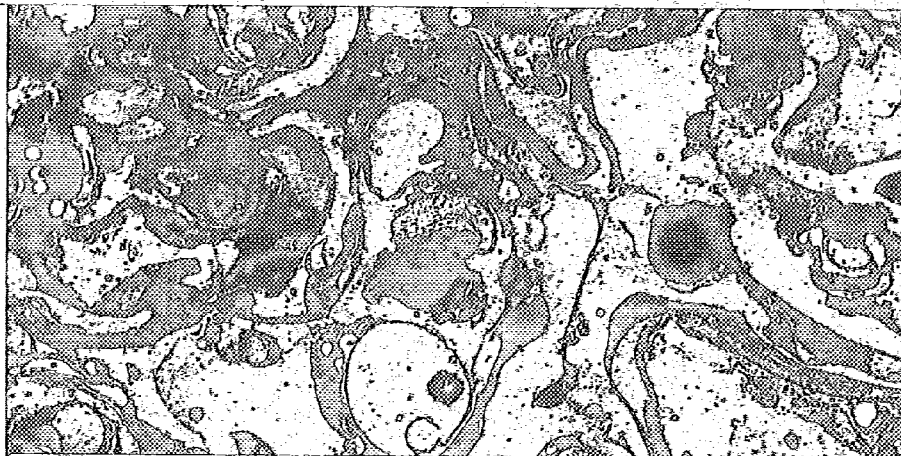


Fig. 4.2.2G Frontal section of 0.8C steel wire sprayed coating. Light areas are steel, gray areas are iron oxide, and black areas are voids (250 x)

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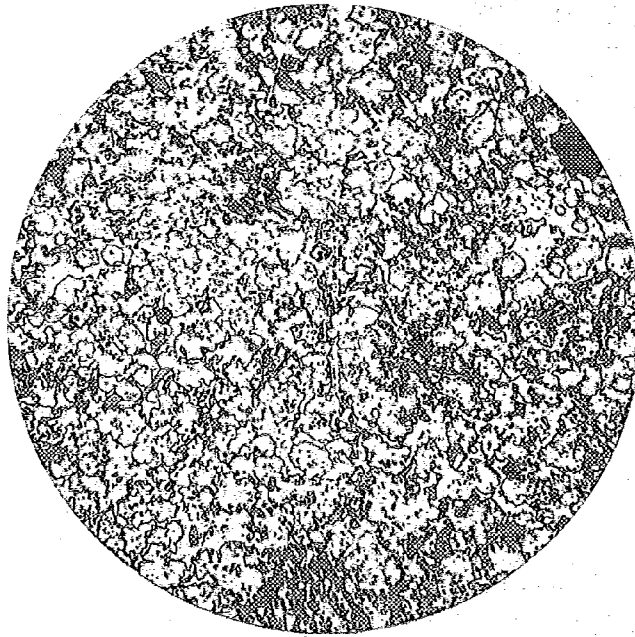


**Fig.4.2.2H — Fused NiCrBSi brazing alloy (250 x)
(Aerospace Materials Specification 4775)**



**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.

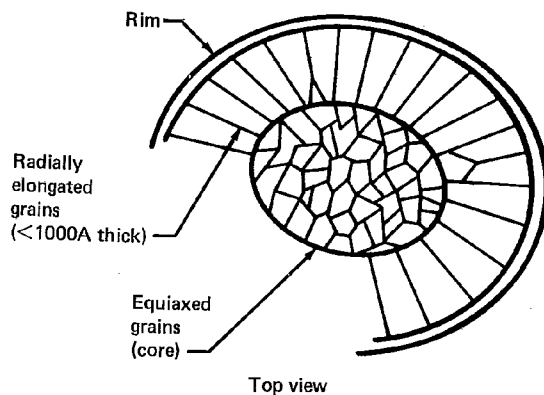


Fig. 4.2.3 — Planar morphology of a solidified particle

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	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 oxide	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)