POWDER COATINGS: A TECHNOLOGY REVIEW

Preventing pollution with a tested—and improving—technology

In recent years, powder coatings have been steadily gaining popularity as an alternative to solvent-borne coatings because powder coatings do not produce significant emissions of volatile organic compounds (VOCs) or hazardous air pollutants (HAPs).

This article reviews powder coatings and their applications, and notes significant areas for their further research and development. First, we discuss historical developments, current markets, and methods for manufacture. Next, we describe methods for applying powder coatings and some health and safety issues associated with use of powders. We then give an overview of the primary types of powder-coating chemistries and their applications. In conclusion, we discuss some research areas that may help broaden the applications for powder coatings in the future.

Introduction

Organic surface coating operations are a substantial source of VOC emissions and hazardous air pollutants. EPA estimates that, in 1995, surface coatings accounted for nearly 2.55 million Mg of VOC emissions nationally, which is more than 12 percent of VOC emissions from all sources.[1] In addition, several surface coating categories—including miscellaneous metal parts, plastic parts, metal cans, metal coil, automotive and light duty trucks, and appliances—are currently scheduled for maximum achievable control technology (MACT) standards.

Environmental restrictions on emissions of VOCs and, more recently, HAPs, have led manufacturers to seek alternatives to low-solids, solvent-borne formulations. One alternative that has received increasing attention is powder coating. Since powder coatings contain no solvent, their environmental emissions are generally very low compared with conventional solvent-borne coatings. Over the past 50 years, powder coatings have grown from being specialty coatings used for limited niche applications to a major—and rapidly

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growing—mainstream segment of the international coatings market.

Background on Powder Coating

Application of organic polymers in powder form dates back to the late 1940s and early 1950s, when powders were flame-sprayed on metallic substrates. In 1955, Dr. Erwin Gemmer patented a fluidized-bed application method for thermoplastic resins on metal. This process was more efficient and faster than flame spraying. Between 1958 and 1965, most powder coatings were applied by the fluidized-bed process.

In the early 1960s, commercial use of the electrostatic powder spray process was introduced in the United States and Europe. It offered two major advantages: (1) substrates could be coated without preheating, and (2) film thickness could be reduced.

Most growth in powder markets occurred in Europe until the 1980s, when increasing demand in North America and Japan drove rapid improvement in powder technology. Today, powder coatings are available in a variety of chemistries that provide a broad range of special finishing effects such as splatter finishes and bonded metallics. **Exhibit 1** provides a historical time line showing significant occurrences in the evolution of powder coatings.[2]

While growth in powder use in North America has been partially driven by environmental restrictions on solvent-borne coatings, powders also offer other advantages.

Powder Coating Markets

Driven initially by environmental restrictions on conventional solvent-borne coatings, use of powder coatings in North America has increased rapidly over the past decade. Between 1986 and 1995, powder production in North America grew from 30,000 Mg to 117,000 Mg. From 1990 to 1995, the number of powder producers/distributors in North America more than doubled from 34 to 72.[3]

A recent slowing of the growth of powder coatings demand has led to some oversupply and a consolidation of manufacturers. However, worldwide sales of powder coatings are projected to reach $1 billion/year in 1998.[4]

While growth in powder use in North America has been partially driven by environmental restrictions on solvent-borne coatings, powders also offer other advantages. These advantages may include self-regulating thickness of the applied powder coat, absence of sagging problems, good edge covering, low overall operating costs, and near 100 percent utilization of the coating material for systems with powder recovery and recycling.[5]

In spite of their rapid growth, powder coatings still lag far behind high-solids and waterborne coatings in use. Barriers to the adoption of powder coatings include paint users' lack of familiarity with powder technology; the high capital cost of converting to powder; the need for high-bake temperatures to fuse, flow, and cure the powder; the difficulty in changing colors on a coating line; problems making on-line corrections and additions; and the inability of powder coatings to meet performance and appearance requirements in certain applications.

Nonetheless, powder coatings are now well-established in a number of markets: appliances, metal furniture, auto and motorcycle components, lawn and garden equipment, steel pipe, and reinforcement bars. Powder coatings are penetrating the automotive primer-surfacer/anti-chip market and are poised to move into auto clearcoats, where they give outstanding gloss and appearance.[6]

Manufacture of Powder Coatings

The process of manufacturing powder coatings is more like the process of making plastics than liquid paints. Powder coatings manufacturing techniques are based on equipment widely used in both the plastic and fine powder industries.[5]

In general, powder coatings manufacture involves three primary steps—premixing, melt

Exhibit 1. Selected Historical and Developmental Occurrences in the Evolution of Powder Coatings

Period	Developments
Late 1940s	Flame spraying thermoplastic powder.
1953	Dr. Erwin Gemmer developed fluidized-bed application for thermoplastic powder coatings. Patent was filed.
1955	Patent issued. Fluidized-bed application for thermoplastic powder coatings introduced into the U.S. market.
1950–1970	Various thermoset powder manufacturing methods evaluated and used. The extrusion process becomes the method of choice.
1962–1964	Electrostatic powder spray process introduced.
1966–1970	"Los Angeles Rule 66" and Clean Air Act introduced. Powder coating market objectives diverge in Europe and North America. Europe concentrates increasingly on thermoset decorative applications, while North America concentrates on high-film-build functional markets.
1966–1973	Four thermoset chemistries—epoxy, hybrid, polyurethane, and triglycidylisocyanurate (TGIC)—are introduced and become commercially available. Some melamine and acrylic chemistries remain unsuccessful.
1970s	Powder coating manufacture and use spread worldwide. Slurry application process is introduced, but remains unsuccessful. Rapid growth in powder coating production and use begins in Europe.
1980s	Initial development of pigments and additives specifically for powder coatings. Rapid growth phase in powder coating production and usage begins in North America and Japan. Rapid growth phase in powder production and usage begins in the Far East (Pacific Rim area).
1985–1993	New powder coating chemistries introduced. Various types of acrylics and cross-linkers become commercially available.
1990s	New specialty effects such as wrinkles, alligator, splatter finishes, and bonded metallics. Continued development of new raw materials and additives. Further improvements in flow, smoothness, particle size control, and spray characteristics.

extrusion, and pulverization.[2,5,7] The powder production process can be discontinuous, which is often the case with small plants, or integrated into a continuous form of production, usually for plants with high capacity.[5]

Although some liquid additives are used, all major ingredients must be solids. The liquid additives must first be mixed with one of the solid components (that is, mixed with the melted solid). This master batch of additives and solids is then granulated for use in the mixture.[7]

Regardless of chemistry or end-use, virtually all powder coatings contain five basic ingredients:

- resins,
- cross-linkers (often called hardeners, not used in thermoplastic powders),
- additives,
- pigments, and
- extenders.[2,8]

These basic granulated ingredients are weighed and mixed. A variety of premixers can be used, but they must provide a uniform, thorough mixture with the solid ingredients.[7] The premix is fed through an extruder.

The extrudate is pelletized and forwarded to a grinding operation, where it is pulverized to the final particle size and packaged for shipment.

Pulverization is a critical step in the manufacture of powder coatings. Improper particle size distribution and the production of excessive numbers of "superfine" particles (<10 μ in diameter) can lead to poor performance and appearance. A schematic of a typical powder coating production procedure is presented in **Exhibit 2**.

Powder Coating Applications and Equipment

Cleaning and Pretreatment

Because powder coatings contain no solvent that might dissolve surface impurities, good cleaning and surface pretreatment is a key to providing maximum powder coating performance. Cleaning removes surface contaminants, such as oxides, oil, and grease. Surface pretreatments, such as iron phosphatizing, promote surface adhesion of the coating and add corrosion protection. Further information on methods of cleaning and surface pretreatment can be found in *Powder Coating: The Complete Finisher's Handbook*.[2]

In flame spraying, the powder is propelled through a flame to melt it as it travels toward the object being coated.

Application Methods: In General

Powder coatings are generally applied by fluidized bed or electrostatic spraying. Other application methods include flame spraying systems, flocking, and in-mold powder coating.[5,9] Selection of an application method depends on the coating material, part design, and production goals. The powder itself must be of a grade appropriate to the application equipment.[10]

Fluidized-Bed Application

Fluidized-bed application systems typically are used where the desired coating thickness is above 0.13 mm, such as wire products and electrical bus bars. In these systems, a fluidized bed of powder coating is generated by forcing air up through a hopper of powder. The fluidized bed of powder material has properties similar to those of a liquid.

The fluidized-bed method can be either electrostatic or non-electrostatic. In non-electrostatic applications, the part is coated by being passed through the fluidized bed of powder. The part must be preheated so that the powder will melt and adhere to it as the part passes through the bed. In electrostatic systems, the part is transported above the bed and the powder is attracted to it. Electrostatic systems allow somewhat greater control over coating thickness.[10]

Flame Spraying

In flame spraying, the powder is propelled through a flame to melt it as it travels toward the object being coated. Flame spraying permits application of powder coatings "in the field" for coating items such as lamp poles, bridge rails, and drums. Successful flame spraying requires control of the powder particle size distribution to eliminate fine particles, as well as a careful balancing of coating properties, flame temperature, and powder residence time in the flame.[7]

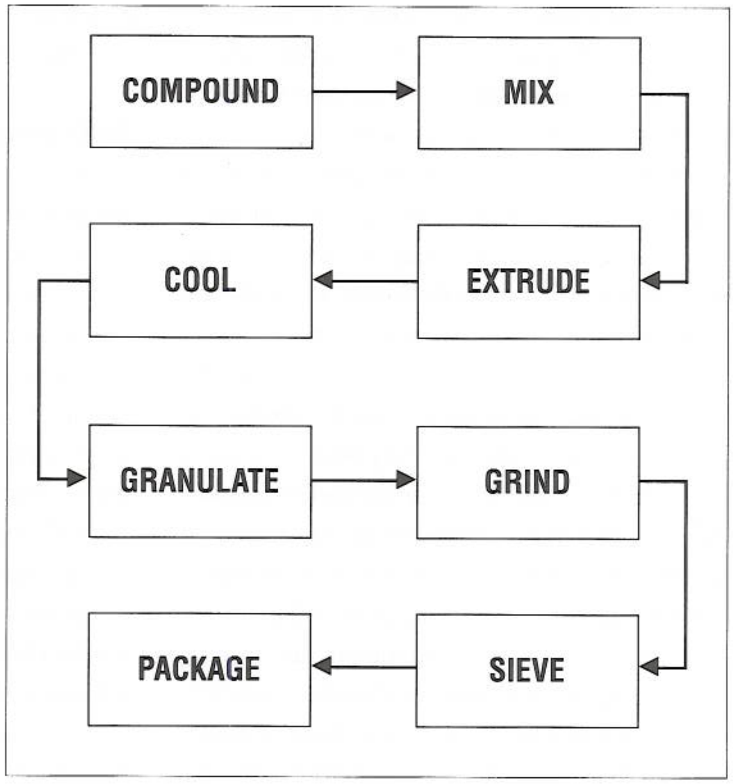
Electrostatic Spray Application

Currently, spray application of powder (other than flame spraying) can only be done electrostatically. Electrostatic spraying systems fall into two categories: corona-charging and tribo-charging.

In corona-charging systems, an electrostatic generator (usually a high negative voltage applied to a pointed electrode) creates an electrostatic field between the gun and the part. Powder sprayed into the field picks up an electrostatic charge and is attracted to the part along electric field lines between the electrode and the part. The charge allows the powder to adhere to the part until it is passed through the curing oven. The amount of powder that adheres to the part (first-pass transfer efficiency) is influenced by several factors, including the size and shape of the powder particle, the field strength, and the distance from the gun to the part.[10,11,12] Corona-charging is an inefficient process. Only a small fraction of the ions generated actually impart a charge to the powder particles, and only about 60 percent of the powder particles receive a charge.[7]

One problem that affects powder coatings applied by corona-charging systems is back-ionization. When a sufficient layer of powder builds up on the part, it can cause air in the interstices of the powder to ionize and migrate out from the powder layer. As these ions move out from the coating layer, they neutralize the powder particles near them, causing the powder to fall off the surface. This can significantly reduce transfer efficiency and, if the powder does not flow well during cure, may create a "wavy" surface on the cured coating.[11]

Exhibit 2. Schematic of a Typical Powder Coating Production Procedure



Another problem associated with corona-charging systems is the difficulty of uniformly coating a part, particularly where coating of recessed areas is affected by Faraday cage effects. For a part with recessed areas, the Faraday cage effect causes the powder to build up on the edges of the recessed area rather than penetrating into it. In many cases, spray gun operators attempt to compensate for this by spraying for a longer period of time into recessed areas. This uses excess powder and creates a thicker layer of coating on the edges of the recess; it also may not prevent undercoating inside the recess.[11]

In tribo-charging systems, charge is imparted to the powder by friction between the powder and the walls of the spray gun. Polytetrafluoroethylene is typically used for the walls of the spray tube in a tribo gun. Tribo-charging does not create a large electric potential difference between the gun and the part, and the air flow from the gun plays a major role in the transfer of powder to the part. Because there are no significant magnetic field lines between the gun and the part, Faraday cage effects are minimal; tribo-charging systems are, therefore, effective at coating parts with deep recesses.[7,12]

Powder Delivery Systems

Powder delivery systems for spray application are an important component affecting the efficiency of powder use and the uniformity of the layer of powder applied to the part. Delivery systems consist of a feed hopper, a powder pump, and a feed hose.

Hoppers can be either gravity-fed or fluidized. In gravity-fed hoppers, the powder is fed to the pump from the bottom of the hopper, which is usually conical. Mechanical agitation is sometimes used to prevent powder bridging at the bottom of the hopper, which can cause powder to feed unevenly. In fluidized-bed hoppers, compressed air is introduced at the bottom of the hopper to "fluff" the powder, giving it a liquid-like consistency that makes the powder easy to pump. Since the powder is mixed with air, the powder output rate for these systems is lower than for gravity-fed hoppers.[10]

The pump that transports the powder from the hopper to the gun works by the venturi principle. A tube is inserted into the fluidized bed and compressed air is blown perpendicularly across the top of the tube. The air blowing across the tube creates a suction that draws the powder out of the hopper and into the flowing air stream, which flows through the powder hose to the gun. The powder feed rate is controlled by changing the compressed air pressure, and an additional compressed air stream can be added to the unit to control surging in the feed lines. Standard venturi pumps deliver powder at a rate that is +/- 10 percent of the desired output rate, causing operators to increase powder output to ensure that parts are not undercoated. This can lead to substantially greater powder use than would be needed in a more tightly controlled system.[13]

An alternative to this delivery system that permits closer control of the powder delivery rate is auger feed control. This method works on the principle of providing highly accurate quantities of powder to the pump to control the rate of powder delivery to the part. An auger powered by a small horsepower motor feeds the powder into the delivery system. Original versions of this technology involved delivering powder to a secondary powder chamber, from which it was augured to the gun pump. The newer generation, however, places the auger directly into the powder hopper, which makes the unit more practical for color changes. Both of these auger methods claim to provide a +/-1 percent feed rate accuracy.[13]

Although powder coatings contain no solvents, their curing reaction may emit volatile components.

Use of systems that provide better control of powder delivery rates can result in substantial reductions in powder use rates and prevent cycling of powder coverage between insufficient coverage and oversupply.

Environmental, Health, and Safety Issues

A major factor in the acceptance and growth of the powder coating industry has been its environmental advantages over conventional, solvent-borne liquid coatings. The vast majority of powder coatings currently in use cure by addition reactions and do not generate any VOCs during application or cure.[14] No solvents are involved in the mixing, application, or cleanup of powder coating operations, virtually eliminating solvent emissions and the need for venting, filtering, or solvent recovery systems that may be required to control VOCs. This can greatly simplify the permitting process needed for installation, expansion, and operation of facilities and make regulatory compliance easier. It can also allow for the inclusion of a finishing operation in a nonattainment area where other systems may not be permitted.[15]

In addition, powders used for powder coatings are solids and most are classified as nonhazardous. Their use eliminates or minimizes problems and expenses associated with the disposal of hazardous wastes from a finishing process. Powder coatings do not produce sludge, foul spray booth filters, or have solvents. Up to 99 percent of powder overspray can be recovered and reused. With automatic recycling units, overspray powder is used and returned directly to the feed hopper for reuse in the system. Waste powder is disposed as a non-water-soluble solid waste.[15]

Although powder coatings contain no solvents, their curing reaction may emit volatile components. Powder coating products cured with tetramethoxymethyl glycoluril give off small amounts (approximately 1 percent) of methanol, but these coatings account for only a small amount of powder coating use. Most powder coatings show a volatile loss of about 1 percent when tested by

ASTM D2369 (Volatile Content of Coatings),[16] but the Karl Fischer Analysis shows that this loss is essentially absorbed water.[14]

Most of the raw materials used to formulate powder coatings are solids that have no appreciable vapor pressure and low biological mobility. Most powders do not contain lead or cadmium compounds, and relatively few compounds in powders are regulated by the Occupational Safety and Health Administration (OSHA).

Urethane polyester powder coatings cured with caprolactam (or other) blocked isocyanates may emit caprolactam during cure. Caprolactam initially was designated as a HAP under the Clean Air Act Amendments, but was later delisted.[17] Essentially no free caprolactam is present in the powder supplied to the applicator. Furthermore, caprolactam does not show up as a VOC when tested by ASTM D2369 since the test temperature is well below the temperature at which the unblocking reaction occurs. However, during the curing reaction, caprolactam is released in the oven in the applicator's plant and vented to the atmosphere as a vapor.[14] Not all of the caprolactam present will volatilize, but the theoretical amount of caprolactam that could be emitted ranges between 4 and 8 percent for most urethane polyester powder coatings.[14]

Triglycidylisocyanurate (TGIC) has received attention for possible health and safety issues. The American Conference of Governmental Industrial Hygienists (ACGIH) is reviewing all the toxicological data on TGIC, and a threshold limit value (TLV) is expected to be established. A TLV for powder coatings containing TGIC is also under consideration. The European Occupational Exposure Limit is 3 mg/m^3 for powder containing TGIC.[18]

Because of their particulate nature, powder coatings must be considered a nuisance particulate with a TLV of 10 mg/m^3 of total dust.[14] Although the absence of solvents in powder coatings eliminates the flammability problem, suspensions of powder in air can explode. Consequently, manufacturing and application facilities have been designed to avoid powder explosions.[7]

Coating Chemistries

Powder coatings are divided into two broad categories: thermosetting and thermoplastic. Thermoplastic powders are based on thermoplastic polymers, which flow to form a smooth continuous coating when heated to their melting point, and solidify upon cooling. Physical properties of thermoplastic powder formulations depend upon the type of resin and its initial molecular weight. Thermoplastic resins do not cross-link; the fusion process is strictly a melt-flow physical reaction. After cooling, the coating film can be remelted when sufficient heat is applied.[8,9]

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Unlike thermoplastic powders, thermosetting powders chemically react to form cross-links between polymer molecules.[19] Thermosetting resin systems are lower-molecular-weight, solid resin systems that go through a melt-fusion process when heated to form a higher-molecular-weight polymer. Their cross-linking nature makes thermosetting powder coatings more resistant to coating breakdown.[8,9,16]

Thermoplastic Powder Coatings

Thermoplastic powder coatings, the original powder coatings, are based on thermoplastic resin systems with high molecular weights.[8] The properties of the coatings depend on the basic properties of the resin. These tough, resistant resins are difficult and expensive to grind into the very fine particles necessary for the spray application and fusing of thin films. Consequently, thermoplastic coatings are used more as functional coatings of >10 mils thickness and are applied mainly by the fluidized-bed application technique.[8,20,21] They do not generally compete in the same markets as liquid paints.[18]

Typical examples of thermoplastic powder coatings are polyethylene, polypropylene, nylon (polyamide), and polyvinyl chloride (PVC).[7,8,17,22] These coating types and their applications are described below.

- *Polyethylene*

Polyethylene coatings were the first thermoplastic powder coatings offered to industry.[18] They provide excellent protection against corrosion and have a high chemical resistance. Polyethylene coatings are resistant to most acids, alkalies, salts, and alcohols at temperatures up to 93°C, and to many solvents at room temperature.[9] The surface of these coatings is easily cleaned. Laboratory equipment is a major market for polyethylene coatings.[8] These coatings are softened by several oils and greases.

Polyethylene coatings were the first thermoplastic powder coatings offered to industry.

For optimum adhesion, metal surfaces should be cleaned and roughened before coating. Blast cleaning can be an effective means of achieving good results, but adhesion to metal substrates is generally poor.

Pigmented formulations of polyethylene coatings are suitable for use in exterior applications, but the natural clear type is degraded by UV light.[9] Typical applications for polyethylene coatings include test tube racks, laboratory tools, fume exhaust ducts, glass bottles, filter plates, impellers, beaker covers, chemical tank lids, and pipe hangers.[8,9,19]

- *Polypropylene*

Polypropylene coatings are chemical modifications of natural polypropylene. Because polypropylene is so inert, it shows little tendency to adhere to metals or other substrates.[8,9] To render it useful as a protective coating, self-priming powders were developed.

Polypropylene is a nonpolar crystalline polymer that exhibits a balance of toughness and chemical and solvent resistance. Since it is not soluble in any solvent at room temperature, it can be applied readily only as a powder or as a dispersion in a diluent. Polypropylene coatings provide resistance to all solvents at room temperature, but nonpolar solvents, such as hydrocarbons and aromatics, swell or dissolve the coating at elevated temperatures.

Polypropylene coatings are resistant to water, salt, detergent, and most acids and bases. Strong oxidizing agents, such as nitric acid, will attack the material even at room temperature.[9] Typical applications for polypropylene powders include conveyor chutes, freezer shelving, chemical processing pipe coating, drum and tank linings, and plating racks.[8,9,19]

- *Nylon (Polyamide)*

Nylon powder coatings are manufactured from either polyamide 11 or polyamide 12 monomers.[9,17] The coatings produced from these resins are tough; have excellent abrasion, wear, and impact resistance; have a low coefficient of friction when applied over a suitable primer;[8,18] have unusually good solvent resistance and good chemical resistance; and exhibit excellent machinability.[9] They provide hard, smooth coatings of uniform thickness, which bond securely to most metallic surfaces and to many nonmetallic surfaces, such as glass, when applied over a primer.

Nylon coatings withstand higher temperatures than most other thermoplastic finishes. They are recommended for continuous operation up to 82°C in air and can be used up to 138°C in the absence of air, such as under oil.[9]

Typical applications for nylon powders include truck drive splines, meat carcass hooks, meat smoking baskets and racks, vapor degreaser baskets, printing press rolls, hospital equipment, furniture shipping carts, appliance door hinges, lighting fixtures, poles, and aircraft and boat steering wheels.[8,9,17,19]

- *Polyvinyl Chloride (PVC)*

PVC coatings are used with a primer to achieve adhesion to both cold and preheated substrates and low-solvent, sliding-wear resistance.[8,9] Self-adhering, primeless PVC powders are in development and can be considered for less demanding applications.[17] They are smooth, glossy, and resilient coatings with good chemical, electrical, and room temperature impact resistance.[9,18] PVC coatings are extremely weatherable coatings that are most often medium-soft and provide good scuff resistance and toughness.[8,9] These powders are also formulated with plasticizers to provide coating flexibility and various degrees of hardness.[17,19]

However, plasticizers are a source of volatile materials. Although the percentage of volatiles typically does not exceed 1 percent by weight for most compounds, treatment of PVC exhaust may be necessary.[17] Vinyl chloride monomer is a suspected carcinogen.

Typical applications for PVC powder coatings include dishwasher baskets, refrigerator racks, battery boxes, playground equipment, conduits, fan guards, air-conditioner grills, bus bars, lawn furniture, cable trays, fence posts, shelving, and chain-link fencing.[8,9,17,19]

- *Other Thermoplastic Coatings*

Other thermoplastic powders include ethylene acrylic acid (EAA) copolymers and fluoropolymers. EAA powders have good adhesion to most metal substrates and a low melt temperature (93°C), which makes them preferred for flame spraying in the field. They also have good chemical, impact, and abrasion resistance, as well as good low-temperature flexibility and outdoor durability. However, they are moderately expensive coatings and have low mar resistance. Typical uses include coatings for bridge railings, chemical process tanks, snowplow blades, and concrete truck chutes.[19]

Architectural polyvinylidene fluoride (PVDF) coatings have excellent outdoor durability and weathering resistance when used with a suitable primer. They also have excellent flexibility, and abrasion and corrosion resistance, but are expensive. They are typically used on aluminum extrusions, exterior wall panels, and roofing panels, as well as pumps, valves, and piping used in the chemical process industries.[19]

Thermoset Powder Coatings

Thermoset powder coatings can be applied as thinner films (0.025–0.10 mm) for decorative coatings or as thicker films (0.25–0.76 mm) for functional coatings where the protective properties of the coating are critical. Thermoset powder coatings are characterized by their excellent adhesion to metal. This property eliminates the need for a primer; they are generally one-coat systems.[9]

The binders for thermosetting powder coatings consist of a mixture of a primary resin and a cross-linker, or hardener. The four major classes of thermoset powder coatings are epoxy, hybrids, polyester, and acrylic. Epoxy coatings are based on bisphenol A (BPA) or novalac resins cross-linked with polyamine or phenolic hardeners. Hybrid coatings also contain BPA epoxy resins, but are cross-linked with carboxy-functional polyester resins. Polyester coatings contain polyester with various cross-linkers that include TGIC, hydroxy alkyl bisamides, and blocked isocyanate, or amino resin. Acrylic coatings contain acrylic resins with the cross-linkers dibasic acid and blocked isocyanate, or amino resin. In addition to the individual classes, various blends, sometimes called alloys, of these classes are used.[7] Following are brief descriptions of these coating classes and their applications.

Architectural polyvinylidene fluoride (PVDF) coatings have excellent outdoor durability and weathering resistance when used with a suitable primer.

- *Epoxy*

Epoxy powder coatings were the first commercially available binder system.[8] They are the oldest, and one of the largest, classes of thermoset powder coatings.[7] Epoxy powder coatings have good mechanical properties, adhesion, and chemical and corrosion protection.[7,8,9] They also have a fast cure time. However, their low resistance to UV rays precludes their use on objects exposed for long periods to direct sunlight.[9,23] Although they can be cured at temperatures as low as 135°C, once cured, most epoxy coatings can perform satisfactorily at continuous exposure temperatures up to 149°C.

Hybrid powder coatings, or epoxy-polyesters, are best noted for their excellent first-pass transfer efficiency, which translates into ease of application.

Depending on the base resin, epoxy coatings can be used in functional applications with a thick film (0.25–0.61 mm) or for decorative applications with a thin film (0.038–0.076 mm).[8] Typical decorative applications include institutional furniture, shelving, and tools. Protective applications include pipe, rebar, electrical equipment, primers, and underbody automotive parts.[7,8,9]

- *Hybrids*

Hybrid powder coatings, or epoxy-polyesters, are best noted for their excellent first-pass transfer efficiency, which translates into ease of application. These coatings are excellent for applications to configurations that have recessed areas and sharp corners.[8]

Hybrid powder coatings have slightly better overbake properties and resist yellowing better than epoxy powder coatings.[8,9,20] Hybrids also have better color retention and UV resistance than epoxy powder coatings, but they still do not have good exterior durability.[7] The polyester component accounts for slightly softer surface hardness, but promotes excellent flexibility.[8,9]

Because of their physical properties and application ease, hybrid powder coatings are used in thin-film decorative applications where weathering is not a requirement.[8] Typical applications for hybrid powder coatings are metal indoor furniture, drawer slides, shelving, water heaters, fire extinguishers, radiators, household and hardware goods, and toys.[7,8,9,20]

- *Polyester*

Polyester powder coatings are divided into two main groups: urethane polyester and TGIC-polyester powder coatings. These polyester groups exhibit excellent flexibility and durability with very good outdoor UV resistance. Polyester-urethane powders are formulated in a variety of gloss levels and employ hydroxyl polyester resins and a blocked cross-linker or hardener. They combine outstanding thin-film appearance and toughness with excellent weathering properties.

During the curing process for aliphatic polyester-urethane powder coatings, as the temperature of the substrate increases to 174 to 184°C, the blocking agent emits volatiles through the film surface. For this reason, aliphatic polyester-urethane powder coatings are recommended for thin films, 0.025 to 0.076 mm. Thicker films may result in a hazy surface or possible offgassing if the volatiles are not emitted before complete cross-linking occurs.

Aromatic polyester-urethanes exhibit the same physical and application properties as aliphatic polyester-urethanes without blocking agents. Typical applications for urethane polyester powder coatings include fluorescent light fixtures, steel and aluminum wheels, patio furniture, chrome wheels and tires, air-conditioner cabinets, ornamental iron, electrical housing, range hoods, lawn and garden equipment, and automotive exterior trim.[7,8,9,15]

Polyester-TGIC powder coatings are based on technology developed in Europe. They have good exterior durability and mechanical properties. They are typically baked for 20 minutes at 177 to 191°C.

However, more recent formulations have cure temperatures as low as 149°C.

Other advantageous properties of TGIC powder coatings are high film thickness and good edge coverage. Thicknesses over 0.076 to 0.13 mm offer excellent flow, gloss, and toughness. Compared to the polyester urethane powder coatings in the 0.025 to 0.051 mm range, polyester-TGIC powder coatings show a definite "orange peel" surface. Research is currently under way to improve the thin film flow of TGIC systems. Their adhesion and corrosion-resistance properties are comparable to polyester urethanes, but their resistance to solvents and chemicals is lower.

TGIC has been identified as a potential mutagen.[9] Partly as a result of concern about toxic hazards, use of tetra (2-hydroxy alkyl) bisamides as cross-linking agents for carboxylic acid-functional polyester in exterior durable coatings is being investigated.[7]

Examples of applications for TGIC-polyester powder coatings include outdoor furniture, farm equipment, fence poles, air-conditioning units, aluminum extrusions, automotive trim and accessories, transformers, and any post-forming application requiring weatherability.

In addition to these two primary types of polyester powders, polyester amide powders are now being formulated. These powders are useful in applications where outdoor durability is needed, such as for garden and patio furniture. These powders cure by a condensation process that produces water, so films must be relatively thin to prevent problems caused by outgassing of water.[20]

- *Acrylic*

Acrylic powder coatings provide the best exterior durability of any thermoset powder coating. They are characterized by their hardness and high resistance to stains, detergents, and moisture. Acrylic powder coatings tend to have poorer impact resistance than polyester coatings and poor adhesion to untreated substrates.

These coatings consist of three basic acrylic chemistries: acrylic urethanes, glycidyl methacrylate (epoxy functional) acrylics (GMA), and acrylic hybrids.[8] Urethane-cured and GMA acrylic powder coatings are the major types sold in the United States.

Acrylics show good resistance to alkali. They also demonstrate good electrostatic spray properties. This makes application of thin films possible and controllable.

The search for thinner films, improved appearance characteristics, lower temperature curing, and more rapid curing presents substantial challenges for future powder development.

Typical applications for acrylic powder coatings are kitchen appliances (range side panels, refrigerator cabinets and doors, dishwasher exteriors, microwave ovens), automotive trim coating, washing machine parts, bathroom fixtures, brass beds, aluminum extrusions and wheels, office furniture, and garden tractors.[8,15,18]

Current and Future Developments

The continuing spread of powder coatings into new applications will help further reduce VOC and HAP emissions from surface coating operations. Currently, the primary driver for powder coating technology development is to provide powder coatings at least equal in performance to liquid coatings without sacrificing ease of application and environmental advantages.[24]

The search for thinner films, improved appearance characteristics, lower temperature curing, and more rapid curing presents substantial challenges for future powder development. Improvements in powder technology need to provide better flow, coalescing, and leveling characteristics at lower baking temperatures, as well as faster cross-link times at lower temperatures while maintaining processability and storage stability of the powder.[7] To a significant extent, these factors compete, so that improvements in one area come at the expense of declining performance in others.

Further developments in powder resins and cross-linkers are expected. Specific areas in which powder coating technology advances are evolving include: UV-curable powder coatings, thinner films, and specialty finishes.[14,21]

UV-Curable Powders

The high-temperature cure required for powder coatings has limited their application primarily to metal substrates. To broaden the possible applications of powder, developers have been researching materials that cure at lower temperatures.

The curing range for most powder coatings is typically 150 to 200°C. At these temperatures, some substrates thermally distort, and others emit volatile compounds. For example, plastics may emit low-molecular-weight fractions (e.g., monomers, moisture), and wood products may emit terpenes and water. In either case, the final coat may be damaged if temperatures are high enough to cause the evolution of volatile compounds.

One emerging area of development for low-temperature curing powders incorporates both powder coating and UV technologies.[25] In this technology, the melt/flow process for the powder is decoupled from the curing process.[26] The coating is applied as a powder, and then heated to melt the powder and form a continuous film. The film is then cured by UV radiation. Temperatures experienced by the substrate are lower because the temperature required to melt the powder is 120°C or less, which is lower than would be required for a typical powder coating cure.

The promise of low-temperature curing has made UV-curable powders of interest for potential application to wood composites, hardwoods, and plastics.

In addition to lowering the temperature experienced by the substrate during the coating process, UV-curable powder coatings offer other potential advantages. Since the melting, flow, and leveling of the coating are separate from the coating cure, smooth films can be formed that do not have the orange-peel appearance associated with many conventional powders.[27] Because they are not heat-cured, radiation-curable powders have better package stability than other powders formulated to cure at low temperatures.

The promise of low-tempe2rature curing has made UV-curable powders of interest for potential application to wood composites, hardwoods, and plastics. A number of hurdles must be overcome here, including dealing with the evolution of volatiles from wood substrates at low temperatures and getting powder coating to adhere to non-conductive plastic substrates.[28]

In addition to wood and plastic substrates, UV-curable powders are of interest for use on metal substrates for assemblies with temperature-sensitive components, for rapid cure applications, and for heavy metallic substrates. The first commercial UV-curable powder line is being used to paint assembled electric motors containing heat-sensitive components such as lubricants and wires.

The fast curing of UV coatings has made this technology of interest for precoated metal stock and coil coating, where rapid line speeds are critical. For heavy components that are a substantial heat-sink, the lower temperatures needed for UV-curable powders mean that less time and energy are needed for heating the component, and less time is needed to cool the component after cure.[23]

Examples of UV-curable powders currently under development include clearcoats for wood and metal, and smooth and textured colored topcoats. Future applications for this technology are anticipated for automotive, farm equipment, general industrial, and wood and plastic substrate applications.[29]

Thin Films

Film thickness is a significant factor in the appearance of a coating. In high-volume coating applications, such as cans, coil, blanks, and automotive applications, thinner films reduce material use rates, which can significantly reduce manufacturing costs. Recent applications in the appliance, shelving, and blank coating industries report achieving consistent film thickness from powder coatings in the 0.02 to 0.03 mm range. This film thickness range can be obtained with epoxy, hybrid, polyester, and acrylic powder coatings.[21]

The ability to create thin films successfully with powder coatings involves several interrelated areas for development. Further developments are needed with resins and cross-linkers to achieve melt-flow properties that permit the creation of smoother thin films without compromising the package stability of the powder. High-quality appearance in thin-film powder coatings depends on powder melt flow and leveling, which in turn depends on the powder melt viscosity and the time window between the melting of the powder and its cure. The viscosity of the powder melt is relatively low prior to cross-linking. As the resin cross-links and forms a network, the viscosity increases rapidly. The flow window—i.e., the length of time between melting the powder particles and the rapid increase in viscosity caused by significant cross-linking—is critical for achieving a smooth finish.[7,14]

The glass transition temperature (T_g) of the resin is a key property that affects these characteristics. T_g is the temperature below which the segments of the polymer molecules do not have sufficient energy to move past each other, and stresses on the polymer are relieved through changes in bond angles and lengths.[30] T_g is determined by the chemical composition and the molecular weight of the resin. Melt flow and leveling are improved by lowering T_g. However, powder processing and storage stability are improved by increasing T_g.

Flexible, high-molecular-weight resins tend to have good package stability while having lower melt viscosity than rigid resins.[7] Further research is needed to develop coating systems with both optimal processing and flow characteristics needed to create high-quality thin films.

Efforts are ongoing to refine powder manufacturing processes to produce smaller-particle-sized powders that do not contain excessive quantities of superfine particles that can impact-fuse in the powder delivery system. Smaller particles can more evenly cover the substrate surface at low application rates, making it easier to achieve smooth thin films.

Powder delivery system improvements are needed to ensure smoother and more consistent delivery of the powder to the substrate to maintain a consistent powder coating thickness over a large area. The development of powder application equipment using low delivery and fluidizing air pressures has been and will continue to be critical to achieving thinner films.[21]

The creation of new special effects in powder coatings can open new applications and markets not previously available to powder coatings.

Specialty Finishes

Powder coatings are available today in a wide range of finishes: gloss, metallic effects, hammertones, textures, multicolor, and others. The techniques used to achieve these special effects for powder coatings are much different from those used for conventional coating solutions. For example, in the case of gloss control, certain fillers, such as silicas and calcium carbonate, can be used to reduce gloss (to a range of about 50 to 90 measured on a 60°E gloss meter). However, matte finishes cannot be produced.

One of the most effective methods used to produce low-gloss finishes in powder coatings involves the combination of more reactive and less reactive components. Special effects in powder coatings are created by blending powders of varying particle sizes, reactivities, and compatibilities.

The creation of new special effects in powder coatings can open new applications and markets not previously available to powder coatings. New and unique types of specialty finishes are expected to be forthcoming.[14]

Other Developments

Improvements in powder coating application equipment are also needed to expand powder applications. Improvements to powder delivery rate control and first-pass transfer efficiency of powder systems are needed for powder clearcoat systems for the automotive industry. Improvements in the efficiency of powder particle charging will help improve transfer efficiency of powder systems.[14]

Manufacturers are becoming increasingly interested in the ability to form completed pieces from coated metal coil and coated blanks. In this approach, rather than coating a formed item, such as the housing for a large appliance, which might have several faces and difficult-to-reach corners, the item is constructed from a precoated piece of metal.

Environmental regulations will continue to drive new developments in coatings technology.

Items constructed from coated coil are cut from the coil, thereby leaving uncoated cut edges that are vulnerable to corrosion and leaving some amount of waste-coated metal. Coated blanks avoid these problems while still offering the advantage of flat-line coating. Coatings used on blanks and coil must be very flexible to withstand forming and also must offer rapid cure to provide for quick processing rates.[9]

Another new area for powder coatings is aqueous powder slurries. These are currently used in Europe but not in the United States. Since they are waterborne coatings, powder slurries offer greater flexibility in formulation and application, particularly in terms of application equipment and additives. However, slurries are not practical for all powder chemistries, and settling and film quality problems may be difficult to overcome.[6]

Summary

Environmental regulations will continue to drive new developments in coatings technology. For pollution prevention professionals, the rapid development of powder coatings technologies means that many of the rules of thumb that applied to powder coatings a few years ago may no longer be valid today or in the near future.

However, since many powder developments are being driven by the needs of large coatings users, appropriate diffusion of this technology into medium and small businesses is an ongoing need. We hope that this article will help pollution prevention assistance providers to understand better the current state of powder coatings technologies and emerging developments to look for in the near future.

Notes

1. Nizich, S.V., Misenheimer, D., Pierce, T., Pope, A., & Carlson, P. (1996). National Air Pollutant Emission Trends, 1900–1995. EPA, EPA-454/R-96-007 (NTIS PB97-155329), Research Triangle Park, NC.

2. Powder Coating Institute (1994). Why powder coating? In Powder coating: The complete finisher's handbook (Chapter 1, pp. 1–7), Cincinnati, OH: C.J. Krehbiel Company.

3. Gill, D. & Matheney, M. (1996). Powder coatings: An overview. In Proceedings of the Advanced Powder Symposium, St. Louis, MO.

4. Fattah, H. (1996). Paints and coatings: Powder coatings lose their sheen. Chemicalweek 158(32), 49.

5. Misev, T.A. (1991). Powder coatings: chemistry and technology. New York: John Wiley & Sons, Inc.

6. Schoff, C.K. (1995). New trends in coatings technology. ASTM Standardization News, 23, 24–27.

7. Wicks, Z.W., Jones, F.N., & Pappas, S.P. (1994). Powder coatings. In Organic coatings: Science and technology (Volume II: Applications, properties, and performance), New York: John Wiley & Sons, Inc.

8. Gill, D. (1996). Back to basics: A fundamental look at powder coatings. In Proceedings of Powder Coating '96 Conference, Indianapolis, IN.

9. Farrell, R. (1996). Powder coatings. Metal Finishing 94(5A), 138–143.

10. Liberto, N. (1996). Powder coating equipment. Metal Finishing 94(5A), 213–224.

11. Guskov, S. (1996). Application of powder coatings: Old problems, new findings, new development. In Proceedings of Powder Coating '96 Conference, Indianapolis, IN.

12. Knobbe, A.J. (1996). Powder spray guns. Metal Finishing 94(5A), 225–228.

13. Hale, J.W. (1996). Methods of powder delivery. In Proceedings of Powder Coating '96 Conference, Indianapolis, IN.

14. Richart, D. (1995). Powder coating: current developments, future trends. In Proceedings of the Waterborne & High-Solids, and Powder Coatings Symposium, New Orleans, LA.

15. Dawson, S. & Reddy, V. (1990). Powder coating applications, Dearborn, Michigan: Society of Manufacturing Engineers.

16. American Society for Testing and Materials (1997). ASTM D2369: Volatile content of coatings, West Conshohocken, PA: ASTM.

17. Federal Register, Volume 61, Number 118, 30816–30823, June 18, 1996.

18. From website: http://www.oxyplast.com/pr/pr_2.html.

19. Powder Coating Institute (1994). Powder coating materials. In Powder coating: The complete finisher's handbook (Chapter 3, pp. 12–19), Cincinnati, OH: C.J. Krehbiel Company.

20. Robison, T. (1994). Thermoplastic powder coatings. Products Finishing 59(2A), 48–55.

21. Ulrich, D.L. (1993). User's guide to powder coating, Dearborn, Michigan: Society of Manufacturing Engineers.

22. Siminski, M.C. (1996). Thermoplastic coating powders review. In Proceedings of Powder Coating '96 Conference, Indianapolis, IN.

23. Moore, D. (1994). Thermosetting powder coatings. Products Finishing 59(2A), 56–61.

24. Kiefer, S. (1995). An overview of powder coating technology trends. Metal Finishing 93, 88–89.

25. Witte, F.M., DeJong, E.S., & Misev, T.A. (1996). UV curable powder coating systems: A promising future. RadTech Report, 10(5), 13–17.

26. Mills, P. (1997). UV powder coatings for metal: Opening new doors and solving old problems. RadTech Report, 11(6), 16–19.

27. Thames, S.F. & Rawlins, J.W. (1996). A review of ultraviolet-curable powder coatings. Powder Coating (November) 19–27.

28. McFadden, B. (1997). UV curable powder coatings: New market possibilities. RadTech Report, 11(1), 16–17.

29. Biller, K. & McFadden, B. (1996). The ultimate low temperature cure in powder coatings. In Proceedings of Powder Coating '96 Conference, Indianapolis, IN.

30. Rodriguez, F. (1982). Physical states and transitions. In Principles of polymer systems (Chapter 3), New York: McGraw-Hill.

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