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What Are Coatings?

Look around you; coatings are everywhere. If you are indoors, there are coatings on the walls, refrigerator, cabinets, and furniture; less obviously, coatings are on the wires of electrical motors, printed circuits, inside television sets, and compact disks. If you are outdoors, coatings are on your house and car, as well as inside your car, under the hood, and on components of the automotive stereo and computer systems. Whether you drink beer or soft drinks, there are coatings on the inside and outside of the cans. The functional and decorative requirements of coatings span a broad spectrum. A diverse science and technology support the development, production, and use of coatings.

People entering coatings science should realize that although it is an old field, it is not a mature one; it offers exciting challenges and career opportunities. They will have opportunities to improve scientific understanding and to contribute to the major thrusts of coatings development: reducing emissions that cause air pollution, reducing energy requirements, and protecting metals against corrosion.

1.1. DEFINITIONS AND SCOPE

Coatings may be described by their appearance (e.g., clear, pigmented, metallic, or glossy) and by their function (e.g., corrosion protective, abrasion protective, skid resistant, decorative, or photosensitive). Coatings may be distinguished as organic or inorganic, although there is overlap. For example, many coatings consist of inorganic pigment particles dispersed in an organic matrix (the binder).

A confusing situation results from multiple meanings of the term *coating*. It is used to describe the material (usually, a liquid) that is applied to a substrate, the resulting “dry”

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film, and the process of application. Usually, the intended meaning of the word *coating* can be inferred from the context.

We limit our discussion to coatings with organic binders that are applied purposefully to a substrate. Many types of coatings are not included. Porcelain enamels on kitchen ranges are coatings, but they do not have organic chemical binders. Electroplated copper, nickel, and zinc coatings are excluded for the same reason. We further restrict our discussion of organic coatings to those materials that can be traced historically back to *paints*. What is the difference between a coating and a paint? Not much—the terms are often used interchangeably. However, it is fairly common practice to use *coatings* as the broader term and to restrict *paints* to the familiar architectural and household coatings and sometimes to maintenance coatings for bridges and tanks. We follow this practice. Some prefer to call sophisticated materials that are used to coat automobiles and computer components *coatings*, perhaps sensing that *paint* sounds too low brow. Still another common term that is essentially a synonym for *coating* and *paint* is *finish*.

In limiting the scope of this book to organic coatings that can be related to historic paints, we exclude many materials that could be called coatings. Printing inks, polymers applied during production of paper and fabrics, coatings on photographic films, decals and other laminates, and cosmetics are but a few examples. However, many of the basic principles that are covered in this book are applicable to such materials. Restrictions of scope are necessary if the book is to be kept to a reasonable length, but our restrictions are not entirely arbitrary. The way in which we are defining coatings is based on common usage of the term in worldwide business. It is close to the definition of organic coatings for statistical analyses of industrial output used by Bureau of Census of the U.S. Department of Commerce. The Census Bureau defines four broad categories: (1) architectural coatings, (2) product coatings used by original equipment manufacturers (OEM coatings), (3) special purpose coatings, and (4) miscellaneous. 2002 U.S. Census data reported that there were 1139 companies that manufactured paints and coatings [1].

The worldwide coatings market in 2003 was estimated at about $70 billion [2]. The markets in North America, Europe, and Asia are roughly equal in size, with Asia growing fastest. The value of coating shipments in the United States in 2002 according to the *Current Industrial Reports—Paint and Coating Manufacturing* are shown in Table 1.1.

Architectural coatings include paints and *varnishes* (transparent paints) used to decorate and protect buildings, outside and inside. They also include other paints and varnishes sold for use in the home and by small businesses for application to such things as cabinets and household furniture (not those sold to furniture factories). They are often called *trade sales paints*. They are sold directly to painting contractors and do-it-yourself users through paint stores and other retail outlets. In 2003 in the United States, architectural

TABLE 1.1. U.S. Coatings Shipments, 2002

Coatings	Dollars $\times 10^9$
Architectural	7.211
Product (OEM)	5.556
Special purpose	3.153
Miscellaneous	1.181
	17.101

Source: Ref. [1].

coatings accounted for about 58% of the total volume of coatings; however, the unit value of these coatings was lower than for the other categories, so they made up about 47% of the total value. This market is the least cyclical of the three categories. Although the annual amount of new construction drops during recessions, the resulting decrease in paint requirements tends to be offset by increased repainting of older housing, furniture, and so on, during at least mild recessions. Latex-based coatings make up about 77% of architectural coatings [2].

Product coatings, also commonly called *industrial coatings* or *industrial finishes*, are applied in factories on products such as automobiles, appliances, magnet wire, aircraft, furniture, metal cans, chewing gum wrappers—the list is almost endless. This market is often called the *OEM market*, that is, the original equipment manufacturer market. In 2003 in the United States, product coatings were about 29% of the volume and 33% of the value of all coatings. The U.S. shipments in 2003 were $8.6 billion of the world market, estimated at $24 billion [2]. The volume of product coatings depends directly on the level of manufacturing activity. This category of the business is cyclical, varying with OEM cycles. In most cases, product coatings are custom designed for a particular customer's manufacturing conditions and performance requirements. The number of different types of products in this category is much larger than in the others; research and development requirements are also higher.

Special purpose coatings include industrial coatings applied outside a factory, along with a few miscellaneous coatings, such as coatings packed in aerosol containers. It includes *refinish coatings* for cars and trucks that are applied outside the OEM factory (usually in body repair shops), *marine coatings* for ships (they are too big to fit into a factory), and striping on highways and parking lots. It also includes *maintenance paints* for steel bridges, storage tanks, chemical factories, and so on. In 2003 in the United States, special purpose coatings constituted about 13% of the total volume and 20% of the total value of all coatings.

The Census Bureau defines *miscellaneous paint and coating products* as paint removers, thinners, pigment dispersions, glazing compounds, and so on.

Coatings are used for one or more of three reasons: (1) for decoration, (2) for protection, and/or (3) for some functional purpose. The low gloss paint on the ceiling of a room fills a decorative need, but it also has a function: It reflects and diffuses light to help provide even illumination. The coating on the outside of an automobile adds beauty to a car and also helps protect it from rusting. The coating on the inside of a beverage can has little or no decorative value, but it protects the beverage from the can. (Contact with metal affects flavor.) In some cases, the interior coating protects the can from the beverage. (Some soft drinks are so acidic that they can dissolve the metal.) Other coatings reduce the growth of algae and barnacles on ship bottoms, protect optical fibers for telecommunications against abrasion, retard corrosion of bridges, serve as the recording medium on compact disks, and so on. Although the public most commonly thinks of house paint when talking about coatings, all types of coatings are important throughout the economy, and they make essential contributions to most high-tech fields. For example, computer technology depends on microlithographic coatings to construct microprocessors.

Traditionally, coatings have changed relatively slowly in an evolutionary response to new performance requirements, new raw materials, and competitive pressures. An important reason for the relatively slow rate of change is the difficulty of predicting product performance on the basis of laboratory tests. It is less risky to make relatively small changes in composition and check actual field performance before making further changes. Starting in the 1930s, the pace of technical change increased as new synthetic polymers were introduced. Since 1965 a major driving force for change has been the need to reduce *VOC* (*volatile organic compound*) emissions because of their detrimental effect on air quality. Coatings have been second only to the gasoline–automobile complex as a source of VOC pollutants responsible for excess ozone in the air of many cities on many days of the year. This situation has resulted in increasingly stringent regulatory controls on such emissions. The drive to reduce VOC emissions has also been fueled by the rising cost of organic solvents. Other important factors have also accelerated the rate of change in coatings. Increasing concern about toxic hazards has led to the need to change many raw materials that were traditionally used in coatings. Furthermore, manufacturers often want their coatings modified so that they can be used at faster production rates, baked at lower temperatures, or changed in color. Product performance requirements have tended to increase; most notable is the need for increased effectiveness of corrosion protection by coatings.

1.2. COMPOSITION OF COATINGS

Organic coatings are complex mixtures of chemical substances that can be grouped into four broad categories: (1) *binders*, (2) *volatile components*, (3) *pigments*, and (4) *additives*. *Binders* are the materials that form the continuous film that adheres to the *substrate* (the surface being coated), that bind together the other substances in the coating to form a film, and that present an adequately hard outer surface. The binders of coatings within the scope of this book are organic polymers. In some cases, these polymers are prepared and incorporated into the coating before application; in other cases, final polymerization takes place after the coating has been applied. Binder polymers and their precursors are often called *resins*. The binder governs, to a large extent, the properties of the coating film. The major resin types used in coatings are given in Table 1.2.

Volatile components are included in a large majority of all coatings. They play a major role in the process of applying coatings; they are liquids that make the coating fluid enough for application, and they evaporate during and after application. Until about

TABLE 1.2. U.S. Resin Sales by Type, 2004

Resin Type	Pounds $\times 10^6$	Dollars $\times 10^6$	Growth Rate (%)
Acrylics	925	1350	3
Alkyds	445	356	0 to −1
Amino resins	335	94	1 to 2
Cellulosics	31	59	−1
Epoxies	380	475	2
Polyesters	275	261	4
Urethanes	249	600	3
Poly(vinyl aetates)	640	992	1 to 2
Poly(vinyl chlorides)	240	156	0
Miscellaneous	200	400	av. 2
	3495	4743	av. 2

Source: Ref. [3].

1945, almost all of the volatile components were low molecular weight organic solvents that dissolved the binder components. However, the term *solvent* has become potentially misleading because since 1945, many coatings have been developed for which the binder components are not fully soluble in the volatile components. Because of the need to reduce VOC emissions, a major continuing drive in the coatings field is to reduce the use of solvents by making the coatings more highly concentrated (higher-solids coatings), by using water as a major part of the volatile components (waterborne coatings), and by eliminating solvents altogether. *Vehicle* is a commonly encountered term. It usually means a combination of the binder and the volatile components of a coating. Today, most coatings, including waterborne coatings, contain at least some volatile organic solvents. Exceptions are powder coatings, certain solventless liquid coatings, radiation-curable coatings, and a small but growing segment of architectural coatings.

Pigments are finely divided insoluble solid particles that are dispersed in the vehicle and remain suspended in the binder after film formation. Generally, the primary purpose of pigments is to provide color and opacity to the coating film. However, they also have substantial effects on application characteristics and on film properties. Although most coatings contain pigments, there are important types of coatings that contain little or no pigment, commonly called *clear coats*, or just *clears*. Clear coats for automobiles and transparent varnishes are examples.

Additives are materials that are included in small quantities to modify some property of a coating. Examples are catalysts for polymerization reactions, stabilizers, and flow modifiers.

Most coatings are complex mixtures. Many contain several substances from each of the four categories, and each substance is usually a chemical mixture. The number of possible combinations is limitless. The number of different applications is also limitless.

Formulation of paints started millennia ago as an empirical art or craft. Successive generations of formulators built on the experience of their predecessors and formulated coatings with increasingly better performance characteristics. Gradually, formulators began trying to understand the underlying scientific principles that control the performance of coatings. Most coating systems are so complex that our understanding of them today is still limited. Real progress has been made, but the formulator's art is still a critical element in developing high performance coatings. Because demands on suppliers of coatings to develop new and better coatings are increasing at an accelerating pace, time is now too limited to permit traditional trial and error formulation. Understanding the basic scientific principles can help a formulator design better coatings more quickly. In the chapters ahead, we present, to as great an extent possible, the current understanding of the scientific principles involved in coating science. Important considerations when working on a formulating problem, including experimental design and combinatorial or high throughput methods, are provided in Chapter 34.

We also identify areas in which our basic understanding remains inadequate and discuss approaches to more efficient and effective formulation despite inadequate understanding. In some cases, in which no hypotheses have been published to explain certain phenomena, we offer speculations. Such speculations are based on our understanding of related phenomena and on our cumulative experience acquired over decades in the field, but they are dangerous because they may be wrong. We recognize the risk that, with time, speculation tends to become accepted as fact and may even be cited as evidence or adopted as an experimentally supported hypothesis. It is our intent, rather, that such speculations promote the advancement of coatings science and technology by stimulating discussion that leads to experimentation designed to disprove or support the speculative proposal. We believe that the latter purpose outweighs the former risk, and we endeavor to identify the speculative proposals as such.

Cost is an essential consideration in formulation. Novice formulators are inclined to think that the best coating is the one that will last the longest time without any change in properties, but such a coating may be very expensive and unable to compete with a less expensive coating whose performance is adequate for the particular application. Furthermore, it is seldom possible to maximize all of the performance characteristics of a coating in one formulation. Some of the desirable properties are antagonistic with others; formulators must balance many performance variables while keeping costs as low as possible.

The formulator's product is a formula. A coatings company's formulas are among its most important assets. They are followed by the manufacturing department to produce the ultimate products. A formula includes a list of ingredients and amounts by weight and by volume, with the amounts often totaling 100 or 1000 gallons to facilitate scaling to different-sized equipment. It also includes specific manufacturing directions, warnings of safety hazards, information about individual ingredients, quality control tests, specifications, and cautions against potential manufacturing pitfalls, (e.g., "Do not heat above 50°C"). In addition, there should be a unique code number, a date, the name of the formulator, approval by a supervisor, a statement of why the formula was developed (if it is new) or changed (if it is a modification of an older formula). Typically, responsibility for a new formula is turned over to the manufacturing department after one to three successful production batches. The manufacturing department should not change formulas but should request changes from the technical department if changes are desired. It is important for companies to manage their formulas well, protecting their confidentiality while keeping them in good order. It should be anticipated that the formulas will play a central role in expansions, licensing, acquisitions, and certain legal actions, such as product liability suits.

REFERENCES

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