Coatings Technologies—Formulating to Meet Performance Needs

Introduction

Because of their beneficial performance properties and versatility, solvents have played an important role in the formulation of paints and coatings since the dawn of the paint industry. In recent years, regulatory programs designed to reduce air pollution have put increasing pressure on manufacturers to further reduce the volatile organic compound (VOC) and hazardous air pollutant (HAP) content of their formulations. As a result, formulators and users of (industrial) coatings now face significant challenges as they try to respond to their customers’ demands for cost-effective, high performance paints and coatings while meeting increasingly stringent regulations. In light of these regulatory pressures, manufacturers now consider alternate formulations and technologies wherever possible. Waterborne, powder and high-energy curable coatings are three leading alternative technologies.

With the increased attention devoted to alternative technologies, some may assume that solvent systems are being phased out. This is not the case. Despite advances in these newer technologies, solvent-based coatings continue to be used in most industrial coating applications. In fact, solvent-based coatings still account for approximately 40% of all coatings in the United States. Over 50% of the Original Equipment Manufacturer (OEM) and special purpose coatings consumed in the U.S. are solvent-based. The OEM and special purpose sectors comprise over half of all coatings sold. Due to the popularity of stains, sealers, and high-gloss paints, solvents also account for 20% of the architectural paints in the United States. Additionally, and less recognized, solvents continue to be an important component of waterborne coatings, and can comprise up to 10-15% of a waterborne paint formulation. This article briefly reviews the coating technologies available to formulators and users as they address the demanding performance requirements for industrial coatings. It also will address what scientific developments the solvents industry is exploring in order to continue to offer customers high performance coatings that comply with the latest regulations. The choice of a coating system depends on a variety of factors, and this article does not attempt to discuss all the options for a specific application. Rather, it discusses the major performance trade-offs associated with solvent-based, water-based, powder, and high energy cure coatings. A comparison of these technologies suggests that solvent-based coatings continue to deliver the performance attributes needed for most industrial applications.

An Introduction to Coating Technologies

Although each coating technology has unique performance characteristics, they have two things in common. First—and most importantly—coating operators must carefully manage worker exposure to ensure safety, regardless of technology type. Second are concerns about odor. Materials used in each of the different technologies have distinctive odors that may be objectionable to some workers or neighbors.

Waterborne Coatings

In waterborne and solvent-based coatings, there are four main ingredients: solvents, binders, pigments, and additives. Solvents are added to dissolve the binder and form what is known as the “vehicle.” In a traditional solvent-based coating, the solvent also helps disperse the ingredients of the coating to help them form a smooth film when applied. In a waterborne coating, water is used as a carrier in latex coatings to replace much of the traditional solvent. However, it is important to note that even though water is present in waterborne coatings, other organic solvents are still often needed to promote film formation (coalescence in latex paints).
About 80% of waterborne coatings are used in architectural coatings. However, they also are used in selected industrial applications. Because the properties of water are very different from those of organic solvents, there are important differences in the properties of waterborne coatings versus solvent-based coatings. Perhaps the most significant advantage of waterborne systems is that they emit relatively small amounts of VOCs and HAPs. With some exceptions, waterborne-coating systems also have low odor and are usually nonflammable. In addition, equipment used to apply waterborne coatings can generally be cleaned with soap and water.

On the other hand, water has a relatively slow evaporation rate, and more significantly, its evaporation rate varies dramatically with the ambient humidity and temperature. This poses an especially difficult challenge in climates with variable humidity. The heat capacity and heat of vaporization of water also are high, resulting in significant energy requirements for evaporation. In addition, the surface tension of water is much higher than that of organic solvents, requiring surfactants to wet pigments and substrates adequately. These surfactants can have an adverse effect on gloss and water resistance.

Water also tends to increase corrosion of storage tanks, paint lines, ovens, and other equipment, and thus waterborne coatings require the use of specialized, corrosion resistant equipment. Similarly, flash rusting of mild steel substrates may be a concern with waterborne coatings. In addition, waterborne coatings are more susceptible to freezing under adverse storage and application conditions.

While durability of many waterborne coatings has improved in recent years, it still lags behind that of solvent-based coatings. This can mean that a waterborne coating will not last as long and will need to be applied more frequently, which can increase the actual amount of VOCs being emitted.

Finally, although water is used in waterborne formulations, it is not the only ingredient, and therefore the use of waterborne coatings in industrial applications often generates relatively large amounts of liquid and solid waste that must be treated before disposal.

**Powder Coatings**

Powder coatings contain little or no solvents or water, and are mostly resin in a dry form. In general, the powder is given a positive charge and applied to parts that are electrically grounded so that the powder will be strongly attracted to the surfaces. Then the powdered part is put in an oven to melt the powder and form a smooth coating. Powder coatings are used in a number of industrial applications for both functional and decorative uses.

One of the major advantages of powder coatings is that they emit practically no VOCs. In addition, they can be used to achieve very thick protective coatings in one step, without the need to apply several layers of film. They can also be applied very efficiently using electrostatic spray techniques—even on parts with complex shapes—and any unused material from “overspray” can be reused. A primary limitation of powder coating systems is that they can only be used on substrates that can withstand relatively high temperatures.

Wood, rubber, some plastics, and other temperature sensitive substances generally are not coated with powder. It is also difficult to achieve high gloss finishes with powder coatings, and they are relatively difficult to touch up and repair. In addition, powder coatings are not well-suited for applications that require frequent color changes or changes of coating type. Unless there is dedicated equipment for each color, the applicator runs the risk that particles of the previously used color will contaminate the new color. Finally, because of the equipment required to apply and heat powder coatings, initial capital and operational costs can be relatively high.

**High Energy Cure Coatings**

High energy cure coatings use ultraviolet (UV) and electron beam (EB) electromagnetic radiation to polymerize specially formulated coatings directly on a substrate. In these systems, the coatings do not “dry” in the typical sense, but are cured by the electron beam or ultraviolet light source. One of the primary advantages of these systems is reduced or even zero air emissions. In addition, they cure very quickly and thus can be used in high speed production processes. Finally, because of the efficiency of the energy source, they require relatively small energy usage.

From the ease-of-use and performance perspectives, however, high-energy cure systems are somewhat limited. They typically are used only for unpigmented or low pigment finishes, because pigments tend to absorb the EB or UV rays and therefore inhibit the curing process.
They are also inhibited by oxygen in the air. UV-curable coatings also shrink considerably during cure, which can result in poor adhesion to the substrate. Additionally, complex shaped objects are not amenable to high-energy systems, as there must be a direct line of sight and constant distance between the coating and the energy source. Like powder coatings, specialized equipment is needed to cure the coating, which means that initial capital costs can be high.

**Solvent-based Coatings**

Solvent-based coatings continue to offer significant performance advantages in most industrial applications. In many ways, solvent-borne coatings have set the standard for flexibility of application and superior finish qualities. Solvent-based technology is also sometimes the only way to formulate high-quality architectural coatings where superior flow and leveling are required.

Solvent-based paints often have favorable qualities that are essential in many applications. Some qualities are: flexibility and versatility of coating application and dry time; ease of achieving high gloss for good distinctness of image (DOI) for demanding applications; and they tend to be durable, which can mean fewer applications are needed.

As noted earlier, the drawbacks of solvent-based coatings are not related to their performance attributes, but to environmental and other concerns. Since many solvents are VOCs, they are regulated by federal and state governments and special considerations go into their formulation and use in industrial facilities.

Additionally, solvents in both solvent-borne and water-based coatings must be properly selected to minimize flammability issues.

**Performance Trade-Offs**

The different coating technologies all have performance attributes that make them well suited for certain applications. Some performance characteristics relate to the type of finish that can be achieved, in other cases, the performance attributes provide flexibility to the formulator and coating applicator. These trade-offs are discussed below.

**Quality of Finish**

Use of solvent-based systems is the easiest way to achieve certain high-quality finishes. For example, a solvent-based coating may be the best option for an application that requires very high gloss finishes. Such finishes are difficult to achieve with powder or water-based systems. High energy cure coatings can provide very high gloss, but can be used only with clear or low pigment coatings.

Similarly, if a coating user desires good distinctness of image (DOI), a solvent-based coating is usually the only workable option. DOI refers to the ability of a coating to reflect images without distortion, and is a highly valued quality in the automobile industry, among others.

In certain wood coating applications, the “depth” of a coating is important for consumer acceptance.

A deep-looking finish can be readily achieved with a solvent-based lacquer. Achieving such a finish is also possible with certain waterbased systems, although it is generally more difficult. Other aesthetic properties, such as a “wet” look, are also best achieved with solvent-based coating technologies.

**Flexibility for Formulators and Coating Operators**

In addition to the quality of the final finish, formulators must balance a number of other factors in order to develop high performance coatings for specific applications. When it comes to striking the proper balance, solvent-based coatings generally provide broad flexibility to both formulators and coating applicators.

**Application under Difficult Conditions**

For most coating systems, evaporation rate is a key performance factor. With solvent-based systems, practically any evaporation rate can be achieved simply by adjusting the solvent mixture. For waterborne coatings, on the other hand, the evaporation rate is a function of temperature, and in particular, relative humidity. As relative humidity increases, the evaporation rate slows. At 100 percent relative humidity, where the ambient air is fully saturated with water, there is no evaporation at all and a water-based coating will not dry. Although formulators of water-based coatings have overcome some of the initial evaporation shortcomings associated with this technology, temperature and humidity still have a much greater impact on water-based systems than they do on solvent-based systems.
In order to achieve consistent performance with a waterborne coating, an applicator must control the heat and humidity in the drying area. Controlling these factors is possible for enclosed coatings operations, but often can require significant energy usage because of the heat capacity and heat of vaporization of water. For some applications (particularly non-enclosed applications such as aerospace and ship coating operations), it is not feasible to control humidity and temperature. Because of its relatively constant temperature and low humidity, the Los Angeles area in southern California has a climate in which waterborne coatings can often be used successfully. Because it also has the most severe ozone problem in the United States, many coating operations in that area are required to use such coatings. However, a waterborne coating that performs well in a warm, dry climate like California or Arizona may simply not work in other parts of the country, especially during certain times of the year.

**Touch-up and Repair**

In some applications, it is important to be able to touch up and repair the coating quickly and easily. For example, regardless of the type of coating used, the finish on a piece of furniture can be easily damaged during shipping or after furniture is placed into use. Traditional solvent-based lacquers are easily repaired. The solvent in touch-up coating partially dissolves the existing finish coat, and allows the new resin to bind with the old. This makes it relatively simple, for example, to touch up even a very visible spot on a tabletop. In contrast, when alternative coatings are used, the entire tabletop may have to be refinished. This is not only costly, but also increases waste generation and requires the use of more coating to cover a greater area. A similar issue exists in autobody refinishing. Using a solvent-based system, a small blemish on a car body can be readily touched up. With an alternative technology, however, the whole component (such as the hood or fender) may need to be refinished.

Color-matching is also much easier with solvent-based systems. Where the color match is particularly sensitive, the use of alternative coating technology may require that the entire object be repainted. Such a result is clearly not desirable either from a cost or an environmental perspective.

**Surface Preparation**

For most coating applications, it is best to have the substrate completely free of contaminants to ensure proper adhesion of the coating. But in some cases—particularly where industrial maintenance coatings are used—this can be difficult or impossible. For solvent-based coating applications, substrate cleaning is less of an issue than for most alternate technologies. In many cases, the solvent in the coating actually dissolves the contaminants on the substrate (as well as partially dissolving any existing coating) to promote good adhesion. For waterborne and powder coatings, pretreating and cleaning of the substrate is much more of an issue. In these cases, surface cleaning is often accomplished with solvents, thereby increasing solvent use and potential VOC emissions.

In some coating operations it is desirable or necessary to frequently change the color of the coating being applied. This can pose a challenge with powder coatings because the applicator may actually need to have dedicated equipment for each color. Otherwise, small specks of the previous color are likely to appear in the new coating, unless the applicator performs a time-consuming cleaning of the coating equipment between each color change.

**Clean Up**

With both water and solvent based coatings, the application equipment and piping must be drained and flushed between colors. With solvent-based coatings, this is a relatively simple process. The solvent used to clean the piping and equipment is typically reused several times before it is recycled through distillation, used as a supplemental boiler or heating fuel, or disposed of through incineration. Using standard collection procedures, solvent losses are minimal and waste disposal costs can be relatively low, especially for still residues from recycling equipment.

For water-based systems, liquid waste from the cleaning of spray lines and piping cannot be reused and disposal can be relatively costly. Aqueous wastes consist mostly of water and suspended pigment and resin particles and soluble organics, with only small amounts of volatile solvents. Because of the low energy content, liquid waste from a water-based system cannot be incinerated or used as supplemental boiler or heating fuel;
and because of the high water content, distillation is usually not a practical alternative. Instead it must be disposed of as wastewater. In most cases this requires pretreatment, which can increase costs and also trigger permit requirements.

**Versatility with Electrostatic Spray**

Metal coating operations often use electrocoating or electrostatic spray techniques that minimize overspray and therefore increase transfer efficiency. It is significantly easier to manage the electrical conductivity for solvent-based and powder coatings than for waterborne systems. This not only affects performance, but also has environmental implications as well. High transfer efficiency means lower air emissions and also less overspray that must eventually be disposed of as liquid or solid waste.

**Substrate Issues**

Solvent-based and high energy cure coatings can be used on essentially all substrates, but there are substrate limitations for water-based and powder coatings. As noted above, powder coatings must be heated to high temperatures and therefore cannot be used on wood, rubber, some plastics, and other temperature sensitive substrates. Although waterborne coatings can be used on most substrates, they generally are not suitable for the initial coat (the base coat or wash coat) that is applied to wood. Because wood absorbs water, the application of a waterborne base coat actually raises small wood particles on the surface of the wood. This problem—known as “grain rising”—can be avoided with solvent-based coatings.

**Flexibility of Use in Resin Systems**

Resins have special properties that make them especially well suited for certain applications. Urethanes, for example, provide a high gloss finish that is necessary in industries such as aerospace, where the coating must provide exceptional weather and chemical resistance without causing drag on the plane. Cellulosics are used primarily in the wood furniture industry because of their aesthetic properties and their ability to adhere to wood. These are just two examples of the dozens of resin systems used today in industrial applications.

In many cases, the choice of a coating technology is largely dependent on the type of resin system needed for a particular application. Virtually all resin types can be used in solvent systems, while the choice of resins that can be used efficiently in other systems is more limited. For example, both powder and high energy cure coatings are limited primarily to acrylic, epoxy, polyester, and urethane resins. Most resin systems are now available in water-based systems, although many of them are not widely used. Solvent-based systems continue to provide formulators with the most flexibility in choosing different types of resins for their coatings needs.

**Solvents for a New Millennium**

Meeting the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standard for ozone will present a major challenge in the coming years for all parts of industry and society. With certain exceptions noted below, the solvents used in coatings are generally classified as VOCs.

Unless they are controlled by an incinerator on a painting operation, for example, these solvents are emitted to the air after they perform their function. Thus, solvent emissions from coatings and industrial operations are among several significant sources of VOC emissions. Emissions of VOCs in and of themselves do not necessarily give rise to health or environmental concerns. In many areas of the country, however, they react with oxides of nitrogen (NOx) in the presence of heat and sunlight to form ground-level ozone—the primary component of “smog.” For that reason they are regulated as “ozone precursors” under the federal Clean Air Act and similar state laws. Another federal regulator pressure on formulators concerns chemicals and chemical categories that are classified as Hazardous Air Pollutants or HAPs, including a handful of common solvents. Under the Clean Air Act, EPA is required to develop regulations that apply to “major sources” of HAP emissions. A major source is any facility that has the potential to emit, on an annual basis, 10 or more tons of any single HAP or 25 tons of all HAPs combined. These regulations are often referred to as MACT standards because they are based on the maximum achievable control technology. As discussed above, these regulatory concerns have spawned a multitude of options for coatings formulators, including converting to alternate technologies. The solvents industry constantly develops new technologies to meet its customers’ demands for high performance, quality coatings that satisfy applicable regulatory requirements.
Formulation of Low-VOC and Low-HAP Coatings

In order to address the challenge of formulating low VOC and low HAP coatings, today’s formulators have become more sophisticated in selecting the optimum solvent or solvent blend for their application. One simple approach is to use non-HAP and VOC-exempt solvents in the formulation, when possible. For many years, VOCs have been regulated using a mass based approach. VOCs are either considered reactive and subject to VOC regulation or negligibly reactive and exempt from VOC regulation. Since 1995, several coating solvents have been added to the list of VOC-exempt compounds. Since the use of a VOC exempt solvent in a formulation does not count against the overall VOC content, formulators can make effective use of these exempt solvents to help reduce the VOC content of a solvent-based paint. EPA also has the authority to add or remove chemicals from the HAPs list, and any person may petition EPA to remove a substance from the list. From a coating formulation standpoint, the use of non-HAP solvents can be another reformulation option that employs proven solvent technology, while taking into account regulatory requirements.

Relative Reactivity

A key development in VOC control policy is California Air Resources Board’s (CARB’s) recent use of relative reactivity instead of a mass-based VOC content limit in aerosol coatings. This new policy recognizes that individual VOCs are not equal in their potential to form ozone.

The potential contribution that each VOC makes to ozone formation depends on its photochemical reactivity: the higher the reactivity, the greater the potential contribution to ozone formation. Recognizing this difference, the CARB has developed a compliance rule for aerosol coating products that allows the product to contain more total VOCs than would otherwise be allowable if the overall photochemical reactivity of the product does not exceed a specified relative reactivity. The regulations became effective June 1, 2002 for general aerosol coatings and June 1, 2003 for makers of specialty aerosol coatings, such as marine parts, automotive body products and shellac sealers. EPA recently has proposed acceptance of this rule as part of California’s State Implementation Plan for ozone attainment and is actively studying relative reactivity for possible implementation in its own VOC policy.

In terms of solvent formulation, the photochemical reactivity approach has shown that it is much better at quantifying the ability of a solvent to generate ground level ozone than the simple mass-based VOC approach. Industry-sponsored research has shown that the substitution of high reactivity products with those that have lower photochemical reactivity may reduce ground level ozone in urban environments. By using lower reactivity solvents in formulations, solvents can continue to provide the performance benefits and contribute to improved air quality - a win/win situation for both the environment and consumers.

Conclusion

While the past few decades have put increasing pressure on formulators and users of paints and coatings to reduce VOCs and HAPs, much attention has been focused on waterborne, powder, and high energy cure coatings. Notwithstanding advances in these technologies, solvent-based coatings continue to be an important choice for coatings formulators. With advances in solvent science and research into scientifically-based reactivity strategies, modern oxygenated and hydrocarbon solvents can bring essential performance benefits to the coatings industry while economically addressing environmental concerns. Solvent producers and coatings formulators continue to provide compliance solutions while meeting customer demands for product performance and durability.
End Notes

1. For a more detailed discussion about managing solvent flammability, the Solvents Industry Group has written a bulletin, *Working with Modern Hydrocarbon and Oxygenated Solvents: A Guide to Flammability and Static Electricity* which can be downloaded at no cost from www.americanchemistrycouncil/solvents

2. When using VOC-exempt solvents in a formulation can reduce the VOC content of a solvent based paint, solvent substitution using VOC-exempt solvents is not a one-for-one process, and is sometimes not feasible.

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