Electron Beam Curing of Coil Coatings

By Anthony J. Berejka

A substantial number of common indoor metal items, such as the back-pieces of lighting fixtures, appliance interiors and exteriors, as well as metals used outdoors, as building siding and roofing, are first coated as flat stock provided in coils and then formed and cut into the desired articles of commerce. Many metal articles are not coated or painted as used or when assembled, but are made from factory coated flat or coiled stock. The National Coil Coating Association (NCCA) provides an extensive amount of information on this process and on market and product uses on its Web site *www.coilcoating.org.* The use of precoated metals shifts the burden of air quality compliance from the fabricator of metal products to the coil coater.

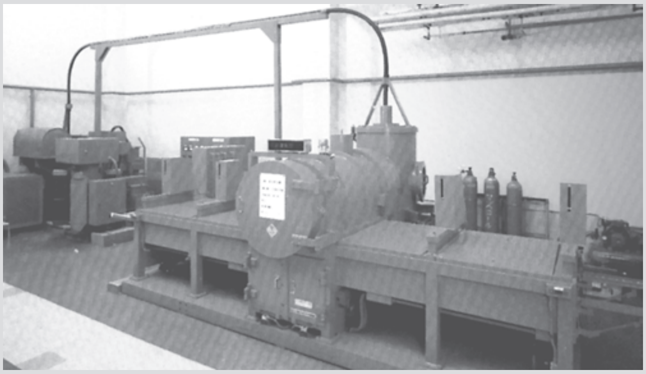
This air quality burden and the recently promulgated Environmental Protection Agency's Maximum Achievable Control Technology (MACT) standards have lead some coil coaters to consider electron beam (EB) curing.

Why EB curing? EB is known for its ability to penetrate materials and in the case of coatings penetrate down to the substrate irrespective of pigment color or loading. EB is, in a sense, color-blind in that it can deal with any color, even metallics, and achieve durable coated products. EB is also a successful process when dealing with high-volume throughput on a continuous basis. These advantages are being recognized by coil coaters. In addition, EB provides a way for coil coaters to manage the energy requirements of their coating operations while at the same time reducing potential greenhouse gas emissions.

ASTM International (*www.astm.org*) Committee D01 on Paint and Related Coatings, Materials, and Applications has a subcommittee, D01.53, on Coil Coated Metal that addresses the specific test requirements for coil coatings. In particular, ASTM D3794-00 Standard Guide for Testing Coil Coatings, developed in cooperation with the NCCA, catalogs the numerous tests that are applicable to precoated metals.

FIGURE 1

EB pilot line at the Japan Atomic Energy Research Institute (JAERI) in Takasaki used for curing coatings on metals



EB Curing of Metal Coatings

The use of EB curing of coatings and laminates on metals has been well established.[1] This commercial implementation of EB curing relied upon the curing of discrete pieces of coated steel using a low-voltage EB unit with an extended flat-bed conveyor and shielding zone (Figure 1). In the low-voltage EB-curing community, all pilot

FIGURE 2

Laboratory unit showing a diversity of EB-cured coating colors on metal test panels

lines are set-up for use with very flexible, thin gauged materials, such as papers and films. None can accommodate the stiffness of coiled metals, even a more ductile metal as aluminum. None have the large diameter coating rolls used in coil coating operations (see for example, *www.gen-world.com*) that are needed to accommodate metal stiffness and inflexibility. As a result, judgments as to the suitability of EB-curable coatings on metal coil are based on test panels (Figure 2) and not yet on coil coated under actual factory conditions. The development of lower cost, lower voltage EB units[2] and of modular EB systems[3,4] indicate that existing coil coating lines may be retrofitted with these more compact units in order for coil coaters to avail themselves of the advantages of EB curing.

Technical Challenges

Coil coatings must have excellent adhesion to metals (ASTM D-3359) and are required to maintain that adhesion while meeting the stringent demands of retaining and enhancing corrosion resistance, as determined in salt spray (ASTM B-117, Figure 3) and other exposure tests. Coil coatings must also meet the oft-conflicting requirements for surface hardness (ASTM D-3363) and for flexibility as demonstrated by having impact resistance (ASTM D-2794) and the ability to be bent or deformed as a cured coating (ASTM D-522 and ASTM D-4145, Figures 4, 5 and 6). To attain these properties, while formulating at the near-zero VOC (volatile organic compounds) levels of EB coatings, presents a formidable challenge.[5] One is often constrained by the trade-offs between lowering molecular weight and achieving a desired lower coating viscosity with the need for a substantive molecular weight between crosslinks (Mc) in order to attain the required cured coating flexibility and impact resistance.[6] Coating systems based on bimodal molecular weight distributions of oligomers and monomers that result in interpenetrating polymer networks may offer a formulating route for overcoming these dichotomies. It is known that the presence of an elastic component in a polymer matrix will thwart crack propagation and thus enhance impact resistance. Likewise, the adroit use of modified fillers, such as silane coupled fine particle silicas[7] or acrylate modified inorganic fillers,[8] have long been known to impart toughness and enhance surface hardness in polymeric systems. The reemergence of this technology is gaining fashion as "nano-particulate technology."

FIGURE 3

1,000 hours salt spray, ASTM B-117

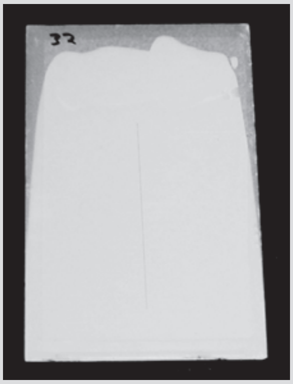


Figure 4

T-Bend, ASTM D-4145

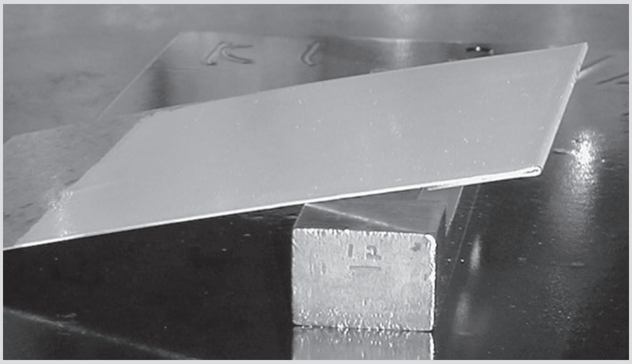
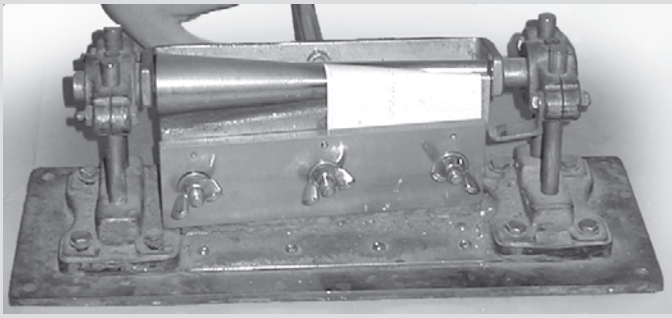


Figure 5

Mandrel Bend, ASTM D-522



Both free-radical and cationic EB-curable coating systems are being explored. Under an inert atmosphere, free-radical coatings have been shown to cure onto previously primed thin (0.2 mm) aluminum foil (flexible enough to make it through a conventional EB pilot line) at as low as 15 kGy at speeds up to 305 meters per minute. This is well beyond the current process speeds of coil coating lines. Test panels, that were EB cured with pigmented, free-radical systems deposited at the desired gauge of 20-microns thickness, have been found to meet a number of the requirements for coil coatings (Figures 3, 4, 5 and 6).

Work is progressing on both free-radical and cationic-cure systems, the latter not requiring inerting and showing the possibility of overcoming the historic extended propagation step of cationic curing that would pose problems in coil coating operations (potential blocking). This issue of whether to EB cure a primer coating or the colored top coating or both is being discussed as the coatings in development for this application demonstrate enhanced adhesion to metals, as aluminum, galvanized steel and Galvalume™, on their own right. The industry, however, is rightfully con-

Figure 6

Mandrel Bent EB coating

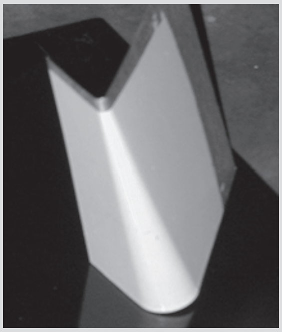


Figure 7

EB-curable coating wetting Galvalume

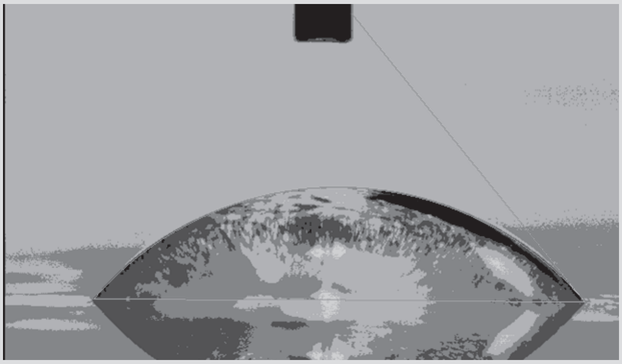
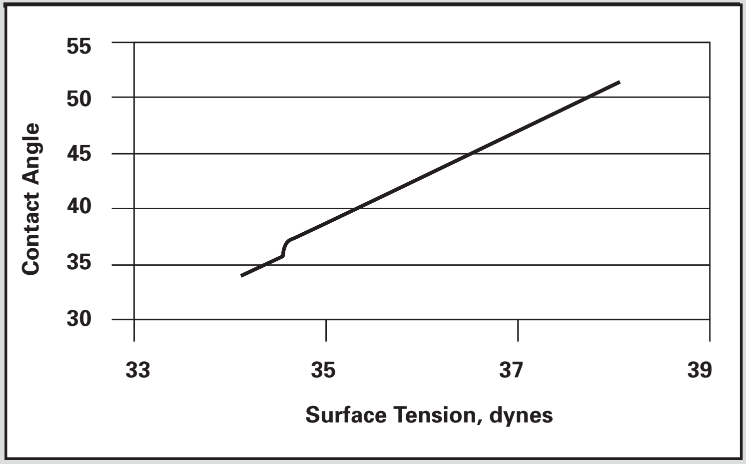


FIGURE 8

Surface tension vs. contact angle relationship for EB-curable coatings



cerned about the long-term corrosion resistance of any single coat system and will likely stay with its current multiple coat operations, including a metal pretreatment. Assurances of the viability of single coat systems will grow as more basic understanding is gained as to the requirements for a given coating to adhere and remain bonded to a specific metal. For example, using a contact angle goniometer, it was found that within an ordered series of EB-curable coatings, a surface tension of 35 dynes or less was required in order for this particular type of EB coating to wet and then adhere to Galvalume on curing (Figures 7 and 8).[9]

Environmental Conservation

Beyond the ability to comply with Clean Air Act requirements, that is to meet the demands for a MACT, EB curing offers the coil coating industry added benefits in terms of energy conservation. If one looks at some basic information on the evaporation and drying of solvents and diluents, like water, and compares it to EB curing, one finds a remarkable savings in the energy merely required to dry or cure a coating (Table 1).[10] This fundamental data does not take into consideration the heat needed to bring a metal up to temperature nor the overall efficiencies of a drying system.

Although energy considerations are not often included in cost analyses, this fundamental data complements the industry's traditional use of low-cost solvent-borne polyester systems. From an energy use perspective, this illustrates why traditional coatings have been more often solvent-based, rather than water-borne. Industry uses the more energy consumptive water-borne acrylic coatings for enhanced

TABLE 1

Energy demands to dry/cure coatings

System	Solvent	Solvent	Water	EB Curable
Solids	30%	40%	40%	100%
Diluent	heptane	toluene	water	none
Boiling point, °C	98	111	100	NA
Vapor pressure, 20°C	35 mm Hg	22 mm Hg	17 mm Hg	NA
Heat of vaporization (calories/gram solvent)	76	88	540	NA
Energy to dry/cure 1g dried coating (calories/gram solvent)	177	132	810	7 (30 kGy)
Energy to dry/cure 1g dried coating, J/g	740	555	3390	30

exterior performance. When comparing the energy demand needed to dry a water-borne coating, EB curing would require two orders of magnitude less energy to attain comparable properties. This does not take into account the thermal inefficiencies of forced air drying systems. Unlike thermal convection systems, EB curing is a direct means of energy transfer. Energy emitted from an EB unit is directly absorbed in the coating and causes the chemical changes that convert a liquid coating into a dried and cured material and does so irrespective of pigment and pigment loading.

By way of illustration, a coil coating operation using a 150 cm (60 inches) wide aluminum stock and running at a line speed of 125 meters/minute (410 feet/minute) will produce 11,250 square-meters of coated product per hour (13,455 square-yards/hour). With a high-solids coating (60% solids) deposited at a desired 20-microns (0.8 mils) dried film thickness, ~375 liters of wet coating per hour (100 gallons per hour) of coating would be consumed, of which ~150 liters would be VOCs (40 gallons). Assuming a solvent density of 0.9, this means that 135 kilos (~300 pounds) of VOCs will have to be dealt with per hour.

Studies of forced air drying and solvent recovery systems have shown that it takes ~27.3 kilo-Joules (kJ) of energy for such forced air systems to evaporate a gram of solvent.[11] For the 135 kilos (135,000 grams) of solvent, ~3,700,000 kJ of energy per hour (1,030 kilowatt-hours/kWh) would be needed. If the VOCs are recovered and then used to fuel the forced air ovens, there would still be considerable greenhouse gas emissions. Assuming a simple solvent having only seven carbon atoms was used, such as heptane, the resulting equivalent in greenhouse gas emissions of just carbon dioxide (not including nitrous oxides) from the 135 kilos (300 pounds) of burnt solvent would be 415.8 kilos (917 pounds) per hour of operation or ~2,500 metric tonnes on an annualized 6,000 hour production schedule. (One gram-molecular-weight or mole of heptane at 100 upon combustion yields seven moles of carbon dioxide at 44 grams per mole for a total of 308 grams of CO_2.) Table 2 presents a summary and compares these factors with the use of an energy-efficient EB system that converts 70% of incoming line power to usable EB.

Additional energy is required to heat the metal substrate and varies with the gauge and type of metal and also depends upon the specific heat of a given alloy. In coil coating, further energy demands are made to remove the heat from metals. Sometimes cold water provided through electrically powered chillers is needed, further

TABLE 2

Comparison of solvent-based drying with EB curing

System	Solvent	EB Curable
Coating solids concentration	60%	100%
Dried coat weight, g/m^2	20 g	20 g
VOCs/m^2, grams (0.9 density solvent)	12 g	0 g
Total force air system energy demand, kJ/m^2 (calculated 27.3 kJ/g to dry)	328 kJ	NA
Total EB energy demand, kJ/m^2 (30 kGy or 0.030 kJ/g at 70% electrical input to effective EB)	NA	0.86 kJ
Total energy demand/hour (11,200 m^2/hour production)	~3,700,000 kJ	~9,600 kJ
Total energy demand/hour	1,030 kWh	2.67 kWh
Greenhouse gas emission potential		
CO_2 from solvent combustion	37 g/m^2	none
Facility CO_2 emission potential	415.8 kg/hour	none

adding to the overall energy demand. Obviously, with water-borne systems, the water vehicle itself cannot be used as fuel, as in the case of recovered solvent. This adds additional energy demands and exacerbates the differences between water-borne systems and radiation-curable ones and even between water-borne systems and the traditional solvent-borne coil coatings.

Market Barriers to Change

A good deal of leading-edge development work targeted at coil coatings is being conducted by modest-sized companies (for example, Polyset and Strathmore Products of New York and R&D Coatings of Pennsylvania). Major coil coaters, however, express a desire to complement these outstanding efforts with continued reliance upon their more traditional suppliers. Most of these suppliers have some capability in the area of radiation-curable coatings. Nonetheless, they seem reluctant to displace their existing business in solvent-borne technology with radiation-curable systems. Often, there is even a disjuncture within a company between its coil coating division and those engaged in radiation curables, something the coil coater finds difficult to understand.

A major barrier to industry change is that most coil lines, whether captive or those of toll service providers, have been amortized and, within the United States, sufficient industry capacity is now in place. Solvent recovery and/or incineration systems are also in place, enabling most producers to meet MACT requirements. Since total energy costs, including the costs of operating solvent recovery/incineration systems, and certainly environmental costs, such as greenhouse gas emissions, are not part of conventional product cost analyses, there seems to be little incentive for the coil industry to change technologies. Emission control costs in themselves do not take into account total energy costs, including operating costs for thermal drying systems. Entrepreneurial risk will have to be assumed if a coil coater is to embrace what appears in the long term to be a more profitable route, all cost factors considered including energy and the environment, to efficient coil coating, that is the use of EB curing.[12,13]

Another barrier to change is that in many instances the coating is specified by the coil coater's own customer, particularly by those who use toll coating facilities. Thus, any given coater maintains hundreds of different coatings on hand as qualified materials. Unlike the graphic arts area, wherein color matching is relied upon and it is up to the printer to choose his vendor of choice, in coil coating, the vendor of the coating is often specified by the coil coater's own customer. Nowhere is this more evident than in the specification of coatings based upon polyvinylidene fluoride (PVdF) in which even the trademarked brand of the base resin is specified. PVdF is known for its outstanding outdoor weathering properties. Co-polymers of PVdF, which are presently used in the solvent-based coatings, can also be formulated into EB-curable systems. These EB materials ought to maintain the same outstanding weathering properties of PVdF systems, but yet enable the coil coater to take advantage of the environmental and energy benefits of EB curing. PVdF itself has long been known as a radiation-curable polymer.[14] However, it will take a considerable effort on the part of the manufacturers of EB-curable coil coatings to demonstrate the long term outdoor exposure performance and weatherability comparable to systems that have been in use for several decades.

EB curing of coil coatings clearly represents not only a way to meet the most stringent MACT standards, but also a way in which to achieve both energy efficiency and to reduce, if not eliminate, greenhouse gas emissions. At an assumed cost of electricity of $0.08 per kWh, the annualized (6,000 hour year) savings in energy costs alone (~$490,000) would enable a coil coater to expense or depreciate a suitable EB system within a few years. For the coil coating industry to adopt this environmentally benign process will require present suppliers of coil coatings to work with the more innovative smaller companies that have addressed this market's needs, to pull together their own internal resources on radiation-curable materials, and commit to obsolescing their present solvent-based product lines.

Aside from captive coil coating lines operated by major metals companies, the coil coater is most often a toll service provider. The purchaser not only specifies the metal, but also the metal pretreatment, the type and color of the coating and even the coating brand. As the NCCA points out, a common challenge to overcome within the coil coating industry includes maintaining multiple colors in small volumes. For an innovative technology as electron beam processing to succeed, a change will be needed in the coil coating marketing paradigm wherein the coil coater, and not necessarily the purchaser of coated coil, becomes the one who primarily specifies the coatings. This requires a highly cooperative effort between the ultimate customer and purchaser of the coated coil or metal, the coil coater and the supplier(s) of coil coatings. This shift in market structure would also enable coil coaters to greatly reduce their inventories and lists of "qualified" coatings down to a more manageable number. This will provide a clear benefit to the coil coater's customer while providing significant environmental benefits. By centralizing coating operations in highly efficient facilities, coil coaters have already shifted the burdens of environmental compliance from the users of coated metals, the metal fabricators, to themselves. Implementation of EB curing would enhance the environmental compliance of coil coating operations while providing energy savings and even reductions in greenhouse gas emissions.

Author's Note

More detailed information on greenhouse gases is provided on the U.S. Department of Energy's Energy Information Agency Web site at *www.eia.doe.gov.* ◗

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