Essential Elements of Parylene Coating Thickness and Related Issues

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Conformal Coating Thickness: Comparing Parylene with Liquid Coatings

Of the five most commonly used conformal coatings, four – acrylic (AR), epoxy (ER), silicone (SR) and urethane (UR) – are classified as wet materials, meaning they are applied to substrates by three basic types of liquid-based technology:

- Brush application is recommended for smaller-batch acrylic/urethane coating projects; manual brush application is slow and subject to operator error. Extreme masking is generally necessary for epoxy and silicone brush application, and focuses on touchup of imperfect film surfaces.
- Dip methods immerse components in a bath of liquid coating material, either manually or with automated equipment suitable for larger scale production; for instance, large product-batches using epoxy coating respond very well to

machine dipping, but all liquid coatings can efficiently employ dip-immersion processes.

- Compared to brush/dip methods, very cost-effective automated spray procedures generate superior coating surface-quality for high-volume coating assignments; all liquid materials are adaptable for spray application. Typically, coating material is diluted with solvents to achieve a predetermined viscosity.

The fifth conformal coating material, parylene (XY), is not applied as a wet substance. Rather, a unique chemical vapor deposition (CVD) method transforms solid, powdered parylene dimer to a gas which permeates substrate surfaces, providing an under-, as well as an over-layer, of conformal protection. The process allows uniform conformal film application to virtually any surface topography and material, including ceramics, ferrite, glass, metal, paper, plastics, resin, and silicone. These capabilities far exceed those of liquid coatings.

Coating application methods substantially impact the thickness of film deposited on substrates.

After pertinent research, you've determined parylene is the best conformal film for your coating assignment. Especially relevant to your decision were XY's uniform protective/insulative properties, which are useful for numerous applications, ranging from printed-circuit boards (PCBs) to medical implants to military-grade systems. Among the other advantages of parylene's ultra-thin coatings are:

- adherence to an exceptional quantity of substrate geometries/materials,
- biological/chemical inertness,
- bubble- and pinhole-free conformability/flexibility at film thicknesses greater than 0.5 microns,
- excellent dielectric/moisture barrier properties,
- high optical clarity,
- penetration of extremely small crevices/spaces, and
- tin whisker mitigation.

Coating Materials and Film Thickness

Each conformal coating material displays a specialized collection of performance attributes governing use. A major problem for conformal films is applying the film at thicknesses unsuitable for the assembly and its operational purpose; this failure mechanism disrupts coating function and assembly performance. The coating-thickness required to provide optimal performance varies with film material used; each material has a specified coating-layer depth measured outward from the substrate surface that best supports assembly operation. Appropriate film-thickness for one coating may be either too wide or narrow for effective use with another, although there can be some overlap for product purposes.

Chemically inert parylene is effective at far-thinner application thickness than liquid-applied materials for coating PCBs and related electronic assemblies:

- Acrylic, urethane, epoxy — 0.025 – 0.127 millimeter (mm. -- 0.001 to 0.005 inches).
- Silicone — 0.051 – 0.203 mm. (0.002 to 0.008 in).
- Parylene — 0.013 – 0.051 mm. (0.0005 to 0.002 in.).

These general standards of conformal coating thickness are supported by IPC-610 and MIL-I-46058C guidelines. The IPC created the J-STD-001 benchmark to regulate and standardize appropriate film thickness levels for conformal coatings, providing the most reliable measure for each film material. According to these standards, and practical application, CVD parylene coats are considerably thinner (half or more in depth) than liquid materials.

Parylene's thinner coating layers offer a clear advantage for use with microelectromechanical systems (MEMS) and nanotechnology (NT) devices/structures. Often integrating their functions onto a single micro/nano-chip, MEMS/NT operating components are in the micrometer (0.001 mm)/nanometer (a billionth [10^{-9}] of a meter) functional range. Monolayer, wet coating materials are simply unable to accommodate MEMS/nano coating requirements; each operates in a range significantly thicker and more physically dense than is acceptable for MEMS/NT. Parylene films can be successful at 0.1-micron operating thicknesses, enhancing their use for MEMS/NT components.

Parylene's ability to provide effective, pinhole-free conformal protection with micro-level coating layers unavailable to liquid materials generates a significantly wider range of applications into the foreseeable future.

Parylene Effectiveness at Different Thicknesses

Like other coating types, parylene layer thickness is largely a function of several factors: (1) substrate material, (2) the kind of assembly being covered, and (3) its operational purpose. AR, ER and UR are effective within a film thickness range of 0.025 – 0.127 mm. (0.001 to 0.005 in.); the other liquid material – SR -- is most efficient at levels nearly twice as thick, between 0.051 – 0.203 mm. (0.002 to 0.008 in). Chemically inert parylene is effective at far-thinner application thickness than liquid-applied materials for coating electrical assemblies, 0.013 – 0.051 mm. (0.0005 to 0.002 in.).

XY's CVD process is a primary reason for its thickness advantage compared to wet substances. CVD generates consistently pinhole-free conformal films that penetrate even the smallest surface crevices on a molecule-by-molecule basis. With operating thicknesses in the 0.1 micron range, XY is exceptionally adaptable for MEMS/NT components, expanding their applications far beyond those of liquid coatings. To illustrate the scale involved,

- One nanometer (nm.) equals one-billionth of a meter (10^{-9} of a meter).

- One inch = 25,400,000 nanometers.
- By these standards. a sheet of newsprint is 100,000 nms. thick.

CVD parylene polymer film thicknesses are controllable to less than a single micron (1 µm.), or 1,000 nms., supporting XY's adaptation to functional systems operating at the molecular scale.

Parylene coatings are flexible, uniform at controllable thickness, resisting chemicals, corrosives, moisture and solvents, with minimal thermal expansion; XY can adapt to virtually any board topography, while ensuring PCB/assembly function/performance through most operating conditions. It remains adherent and intact, preserving dielectric/insulation properties, at thicknesses greater than 0.5µm., and completely penetrating spaces narrow as 0.01mm, if necessary.

However, each parylene type exhibits a collection of unique performance properties that determine appropriate applied thickness and subsequent product uses. As with other conformal materials, coating thickness is determined by assignment specifics – substrate material, assembly type, operational requirements.

- Often, these are stipulated by the client, whose end-item instructions designate in writing or through drawings precise XY coating thicknesses. Depending on PCB topography, these may vary within the assignment requirements. Parylene applicators are advised to review written/drawn specifications, and compare these to the physical assembly. The objective is accurately determining consistency between the two and identifying potential obstacles, so the applied parylene thickness reflects the assembly's physical character and functional properties.

- Considerations of the assignment's required dielectric strength also influence XY coating thickness. Higher dielectric strength necessitates a thicker coat of parylene; thinner XY films provide lesser dielectric performance.
- Additionally, clearance requirements affect coating thicknesses. This is less of an issue for enclosed PCBs, but even one mm. over-thickness can cause mechanical abrasion sufficient to damage the parylene, rendering the coating and assembly less effective.
- Balancing dielectric strength issues with those attendant to clearance requirements always factors into determining a film thickness level that supports optimal assembly performance.
- Ruggedization or other specialized assignment requirements also impact XY coating thickness.

Coating thicknesses must meet quality specifications. Parylene's exceptionally thin coatings distinguish it from liquid coating materials, but also require a similarly specific connection between the coating’s final thickness and the functional requirements of the component during operation. As with all conformal coatings, applying XY films too thin eventually renders the PCB vulnerable to a wide range of environmental/performance threats, negating the coating’s protective function. Applied too thick, XY films interfere with an assembly’s operation, particularly for those with moving parts.

Accurately deposited in a single coating-run between 0.5 microns through 50+ microns (2 mm.), typical XY thickness standards are in the 15 micron range, according to IPC CC 830 and MIL-I-46058C guidelines. Here again, coating purpose largely determines its ultimate thickness:

- Typical thickness for a barrier layer ranges from 5 to 20 microns, while a
- dry lubricity layer on silicone generally requires less than one micron of parylene.

Operationally, the coating process runs until all the dimer is vaporized and deposited. Final XY coating thickness is further determined by the quantity of parylene dimer vaporized relative to the assignment’s overall load surface area. Thus, dimer quantity needs to be carefully calculated and controlled, based on the surface area of the load in the deposition chamber. Because the association between dimer quantity and surface area is so critical to the success of each coating assignment, the most consistent coating thicknesses are achieved with similar size production lots. Odd lots, or those of divergent sizes, require additional focus to project specifics to ensure appropriate coating thickness.

Does Thicker or Thinner Parylene Coating Provide Better Performance?

Parylene conformal coatings are applied in micron-thin coating layers. This property distinguishes XY from liquid coating materials -- AR, ER, SR and UR -- which require applications at least twice as thick in most cases (and frequently more), limiting their range of uses. Compared to liquid processes, gravity and surface tension generate negligible impact with parylene CVD, which eliminates film bridging, pinholes, puddling, run-off, sagging or thin-out during application. XY's coefficient of friction coefficient can be as low as 0.25 to 0.30.

However, application in exceptionally clear, thin layers, can sometimes be a disadvantage. For instance, SR's thicker coating level adds an additional layer of cushioning and shock protection to the PCB or assembly it covers. Parylene requires several layers of coating to provide even similar impact resistance. In general, thinner is better for XY but, as with all uses for all conformal coatings, much depends upon the specific coating project and its functional requirements, post-application, after operation commences.

This condition can be illustrated for parylene by two cases, concerning XY's insulation resistance (IR) and breakdown voltage (BV) performance:

- Insulation resistance is the alternating-current resistance between two electrical conductors or two systems of conductors separated by an insulating material, such as XY conformal coating. IR is generally greater with thicker, rather than thinner, parylene layers. However, parylene IR-values exceed the prescribed specification for successful IR by approximately one order magnitude, regardless of XY coating thickness.
- Breakdown voltages of most parylene types – N, C, D, F – are also a function of the polymer's applied thickness. An insulator's BV is the minimum quantity of voltage sufficient to cause the insulating material to become electrically conductive. For XY, as for other conformal films, BV defines the maximum voltage difference that can be applied across the material before it conducts. These circumstances also differ by XY type. For instance, parylene C is superior to N for films under 5 micrometers (0.0002 in). Regardless of type:
  - the voltage breakdown per-unit of parylene thickness generally increases with diminished thickness,
  - indicating more current is required to breakdown XY's insulative power

  - at thinner, rather than thicker, film layers --
  - thus, BV capacities increase as XY layers diminish in size.

This condition is opposite than that for parylene IR, where thicker layers offer greater protection.

However, despite certain operational cases where thicker parylene coatings offer better performance, thinner XY coating layers represent one of the material's greatest functional advantages. Thinner coatings respond optimally to proliferating development of MEMS/NT applications, which require the same protections from contaminants as larger components. With operating components in the micrometer (0.001 mm)/nanometer (a billionth [10^{-9}] of a meter) functional range, conventional coatings cannot service MEMS/NT requirements; only XY can provide coating functional at these minute levels. Parylene's use for biocompatible implants is also best-served by thinner coating levels, which need to operate efficiently within the body, where operating clearance can be too small for effective liquid coating.

Parylene also offers excellent dry-film lubricity for implant and surgical instruments, providing wear and abrasion resistance. XY's low surface energy and hydrophobic properties generate reliable solutions to the friction/stiction problems affecting biomedical and MEMS/NT applications. In most cases, thinner XY coats are preferable to thicker.

Optical Clarity of Parylene at Increased Film Thickness

Generally applied at micron-thin coating layers, XY offers numerous barrier, dielectric, insulative and similar protective benefits to PCBs and related electronic assemblies. One property of parylene applied in its normal range of 0.013 – 0.051 mm. (0.0005 to 0.002 in.) is exceptional optical clarity, which makes it suitable for coating lenses and other devices requiring visual transparency, like photosensitive components.

Exhibiting minimal absorption in the visible spectrum, XY is transparent and colorless, providing optically-advantageous characteristics, whose benefits can be enhanced when appropriately strategized during film application. Parylene CVD penetrates targeted surfaces, adding an operational underlayer to its overall external conformal protection. The resultant optical clarity is sufficient to maintain the visual integrity of museum/gallery level artwork and culturally important archival items. XY coatings also enhance visual clarity and performance of light-emitting diode (LED) systems.

Properly managed, CVD can also add to the film's normal visual clarity. Reduction of peak chamber pressure during polymer deposition can improve many aspects of film quality, including adhesion, coating uniformity, and transparency. With respect to adapting current CVD methodologies for physiological and biological systems' applications,

- fabrication of multidimensional polymeric platforms can create highly-reproducible microtextured membranes,
- with added optical clarity at the micron/sub-micron level,
- to further study fundamental cell-environment interactions
- useful to improved healthcare.

Transformed to a clear, colorless coating during CVD, XY films provide excellent-to-superior optical clarity, with an accurate, well-defined view, especially in thin film form (<1 um.). Thinnest parylene films maintain true optical clarity, a quality that can diminish slightly as coating thickness increases; this change is generally almost imperceptible, since XY layer application rarely exceeds .50 mm., sufficiently minute to retain dependable visual perception through the film.

However, the same property also means XY-coated devices are visible to anyone investigating beneath the film, including those interested in reverse engineering the item. In these cases -- because thicker parylene layers will do little to interfere with visual clarity – additions to the coating may be required. To prevent potential incidents of fraudulently replicating proprietary or similarly exclusive design, additional pigmented liquid coatings – generally epoxy or polyurethane -- can be added to completely cover the unit, concealing its components. These wet films possess surface resilience similar to XY, making their removal difficult, while obscuring the covered assembly.

Differences in the relation between optical clarity and coating thickness are evident to a minor degree, depending on parylene material type. For instance, parylene C is optically clear while parylene N exhibits a slight haze at thicknesses > 5 µm. These differentials remain visually insignificant, as thickness increases across XY types, but should be noted.

In addition, parylene types N, C, and D degrade after prolonged exposure to ultraviolet (UV) light, a condition that also affects parylene F at a much slower rate. Parylene AF-4 is far superior to the others in resisting film degradation but, along with F, is substantially more expensive to use than N, C, and D (4 times more for F, 15/20 times for AF-4).

Whatever the XY-type, evidence indicates the products of degradation absorb UV light, regardless of thickness. Yellowing results, increasing incrementally with length of exposure, and according to the UV-resistance level of the particular XY-type being used. Film yellowing will significantly diminish the coating's optical clarity, regardless of its thickness.

Optical clarity is not the only parylene property negatively impacted by extended UV exposure. XY films ultimately oxidize under these conditions, causing main-chain scission, the source of molecular level breaks, and the development of larger-scale rupture throughout the coating surface. Thicker films will sustain surface integrity longer, but yellowing will eventually commence, and coatings will crack.

In most cases, however, colorless parylene generates advantageous optical properties for a wide range of uses -- including artwork/museum artifacts, cameras/sensors, computer touchscreens, healthcare/medical devices, LEDs, and opto-electronic components supporting reliable aerospace, scientific, and telecommunication functions.

XY is recommended when protective conformal film is needed to safeguard products' visual clarity and color. Unless subjected to UV or other elemental over-exposure, parylene coatings seldom are so thickly applied that their optical clarity declines to the extent covered surfaces are visually obscured.