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# IPC-HDBK-840

## Solder Mask Handbook

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# **Solder Mask Handbook**

Developed by the Solder Mask Handbook Task Group (5-33d) of the  
Cleaning and Coating Committee (5-30) of IPC

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# Solder Mask Handbook

## 1 INTRODUCTION

**1.1 Background** Solder masks are permanent protective coatings that perform a number of functions during the fabrication, assembly and end use of printed circuits. One of the main purposes of solder mask is to protect the circuitry from interacting with solder during the assembly process. A solder mask's job isn't solely restricted to the solder operation however, as it also helps to protect the laminate, holes and traces from collecting contaminants and from degrading during the service life of the circuit. It also acts as an insulator of known dielectric property between components and traces.

The main requirements of the solder mask (as a material qualification) are tested within the IPC-SM-840. However, increasing technical diversification created further testing needs. Not every technical requirement is relevant for every application and thus these requirements will not be part of a general material qualification. These properties are usually required for specific original equipment manufacturer's (OEM) approvals. This solder mask handbook provides the reader with the background knowledge to make an educated decision if specific properties are required and how to test them. It also provides significant educational information about process influences.

**1.2 Purpose** The purpose of this handbook is to provide additional supporting information for IPC-SM-840 regarding solder mask types, processes, characteristics and properties in order to assist with the correct selection and use of the most appropriate material for the intended application. It should be read in conjunction with the solder mask manufacturer's technical information and other solder mask specification documents, which may be relevant, such as those listed in Section 2.

**1.3 Target Audience** The target audience for this document are solder mask manufacturers, solder mask processing equipment manufacturers, printed circuit board (PCB) designers, manufacturers, assemblers and repair technicians, assembly equipment and ancillary chemical suppliers, and OEMs.

## 2 APPLICABLE DOCUMENTS

### 2.1 IPC<sup>1</sup>

**IPC-T-50** Terms and Definitions for Interconnecting and Packaging Electronic Circuits

**IPC-SC-60** Post Solder Solvent Cleaning Handbook

**IPC-SA-61** Post Solder Semi-Aqueous Cleaning Handbook

**IPC-AC-62** Aqueous Post Solder Cleaning Handbook

**IPC-CH-65** Guidelines for Cleaning of Printed Boards and Assemblies

**IPC-HDBK-001** Handbook and Guide to Supplement J-STD-001

**IPC-PE-740** Troubleshooting for Printed Board Manufacture and Assembly

**IPC-CC-830** Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies

**IPC-HDBK-830** Guidelines for Design, Selection and Application of Conformal Coatings

**IPC-SM-840** Qualification and Performance of Permanent Solder Mask for Printed Boards

**IPC-1751** Generic Requirements for Declaration Process Management

**IPC-1752** Materials Declaration Management

**IPC-2221** Generic Standard on Printed Board Design

**IPC-4761** Design Guide for Protection of Printed Board Via Structures

**IPC-6011** Generic Performance Specification for Printed Boards

**IPC 6012** Qualification and Performance Specification for Rigid Printed Boards

**IPC 6013** Qualification and Performance Specification for Flexible Printed Boards

**IPC-9691** Users Guide for the IPC-TM-650, Method 2.6.25, Conductive Anodic Filament (CAF) Resistance Test (Electrochemical Migration Testing)

**IPC-TM-650** Test Methods Manual<sup>2</sup>

2.3.23 Cure (Permanency) Thermally Cured Solder Mask

1. [www.ipc.org](http://www.ipc.org)

2. Current and revised IPC Test Methods are available on the IPC website ([www.ipc.org/html/testmethods.htm](http://www.ipc.org/html/testmethods.htm)).

- 2.3.23.1 Cure (Permanency) UV Initiated Dry Film Solder Mask
- 2.3.25 Detection and Measurement of Ionizable Surface Contaminants by Resistivity of Solvent Extract
- 2.3.28 Ionic Analysis of Circuit Boards, Ion Chromatography Method
- 2.3.39 Surface Organic Contaminant Identification Test (Infrared Analytical Method)
- 2.3.31 Relative Degree of Cure of UV Curable Material
- 2.4.27.2 Solder Mask Abrasion (Pencil Method)
- 2.4.28.1 Adhesion, Solder Resist (Mask), Tape Test Method
- 2.5.6.1 Dielectric Strength, Polymer Solder Mask and/or Conformal Coatings
- 2.6.1 Fungus Resistance - Printed Wiring Materials
- 2.6.3.1 Moisture and Insulation Resistance - Solder Mask
- 2.6.3.2 Electric Strength of Printed Wiring Material
- 2.6.3.3 Surface Insulation Resistance - Fluxes
- 2.6.3.5 Bare Board Cleanliness by Surface Insulation Resistance
- 2.6.7.3 Thermal Shock - Solder Mask
- 2.6.11 Hydrolytic Stability Solder Mask and/or Conformal Coating
- 2.6.14.1 Electrochemical Migration Resistance Test
- 2.6.25 Conductive Anodic Filament (CAF) Resistance Test: X-Y Axis

## 2.2 Joint Industry Standards<sup>3</sup>

**J-STD-004** Requirements for Soldering Fluxes

**J-STD-005** Requirements for Soldering Pastes

## 2.3 Telcordia<sup>4</sup>

**BellCore GR-78-CORE** Generic Requirements for the Physical Design and Manufacture of Telecommunications Products and Equipment

## 2.4 ISO<sup>5</sup>

**2409** Paints and Varnishes - Cross Cut Test

## 2.5 American Society for Testing and Materials<sup>6</sup>

**ASTM D-149** Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies

**ASTM D-150** Standard Test Method for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation

**ASTM D-257** Test Methods for DC Resistance or Conductance of Insulating Materials

**ASTM D-523** Standard Test Method for Specular Gloss

**ASTM D-2520** Standard Test Methods for Complex Permittivity (Dielectric Constant) of Solid Electrical Insulating Materials at Microwave Frequencies and Temperatures to 1650°C

**ASTM D-3359** Standard Test Methods for Measuring Adhesion by Tape Test

**ASTM D-3638** Test Method for Comparative Tracking Index of Electrical Insulating Materials

**ASTM E-595** Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment

## 2.6 Underwriters Laboratories<sup>7</sup>

**UL 94** Tests for Flammability of Plastic Materials for Parts in Devices and Appliances

**UL 746C** Standard for Polymeric Materials - Use in Electrical Equipment Evaluations

## 2.7 International Electrotechnical Commission<sup>8</sup>

**IEC-60112** Method for the Determination of the Proof and the Comparative Tracking Indices of Solid Insulating Materials

## 3 TYPES OF SOLDER MASK

**3.1 Direct Imaging Solder Mask** These materials are characterized by processes by which solder mask is directly placed onto the PCB only in those areas where it is needed or desired. In this case, the solder mask coatings usually are not imageable, but are applied to the PCB in the exact pattern needed, and restricted from those areas where the substrate must be exposed. This method is typically not capable of imaging very small features such as solder dams between surface mount pads.

**3.1.1 Screen Imaged (Screen Print)** One of the earliest techniques for applying solder mask to PCBs was to use a patterned screen to define the areas to be coated vs. the

3. [www.ipc.org](http://www.ipc.org)

4. [www.telcordia.com](http://www.telcordia.com) (This document is no longer available as a stand-alone document and exists as an enterprise license purchase through Telcordia)

5. [www.iso.org](http://www.iso.org)

6. [www.astm.org](http://www.astm.org)

7. [www.ul.com](http://www.ul.com)

8. [www.iec.ch](http://www.iec.ch)

areas to be left open. This technique is the same as has been used to make any particular pattern on a substrate such as pattern screening circuitry, or other applications such as signs, T-shirts, etc. Typical resolution capabilities are about 175  $\mu\text{m}$  [0.007 in] or greater.

For special applications structured screens can also be used in combination with photoimageable solder masks.

**3.1.1.1 Thermal Curable** These are typically one-part or two-part solder masks that are applied by patterned screen printing. As indicated, the curing mechanism is by exposing the solder mask to a thermal bake. This thermal bake is typically done in a batch oven, but could be in a conveyorized forced convection tunnel oven or in an infrared (IR) oven or combinations.

**3.1.1.2 UV Curable** This (typically one component) solder mask type is applied with a patterned screen process and is cured by exposing the solder mask to high intensity ultraviolet light. No thermal process is necessary but may be used in some cases to ensure full cure. UV curable solder masks are typically solvent free systems with a given rheological profile and cannot be thinned.

**3.1.2 Ink Jet** The solder mask is applied to the PCB panel by use of an ink jet printing mechanism. No imaging is necessary since the solder mask is applied only to those areas where it is needed. Its location is determined by the digital circuitry data fed into the computer that controls the ink jet mechanism. The smallest feature size possible is determined by the ink jet mechanism and the rheology of the ink (how much it flows between the time of application and curing). The resolution is expected to be better than the screen imaged technique described in 3.1.1.

**3.1.3 Laser Ablated** This solder mask material is typically applied over most or the entire panel surface. It can be applied by screen printing (with a patterned or open screen), spray, or other method. A patterned screen may be necessary to keep the material out of the holes since it is not imageable in a conventional sense. The unwanted solder mask, in areas to be opened up down to the base material or circuitry, is ablated (vaporized or burned away) by a laser. Very fine features may be obtained with this method, but the industrial use of this method is currently limited.

**3.1.4 Coverlay/Punched Film** This technique is used mainly for flexible circuits where the final structure is desired to have equivalent properties in the coverlay as in the base material. It typically utilizes an adhesive coated film that has openings punched in it where circuitry is to be exposed. This film is subsequently laminated to the circuit in a laminating press. Feature size and clearance around circuit features and registration is limited by the dimen-

sional stability of the coverlay film and circuits and the accuracy of the punch/punching process. Coverlay allows for fully tented vias.

**3.2 Photoimageable Solder Mask** These materials are characterized by their ability to be defined accurately with a photoimaging process. The image of the solder mask to remain on the panel is transferred to the panel by using a phototool or digital data, and the unwanted solder mask is washed away in a developing process. Most photoimageable solder masks are negative working, meaning that areas exposed to the correct wavelength distribution of light are hardened (partially cross linked or partially cured) and rendered insoluble in a developing chemistry that washes away the unexposed solder mask. Close tolerances (typically  $>75 \mu\text{m}$  [0.003 in]) and fine features (typically  $75 \mu\text{m}$  to  $100 \mu\text{m}$  [0.003 in to 0.004 in], sometimes down to  $50 \mu\text{m}$  [0.002 in]) are possible with these products in typical processes. These products still require a final cure step to fully cross link. The curing is typically a thermal process but can be a combination of UV and thermal cure as well.

**3.2.1 Dry Film (Photoimageable)** These solder masks are films of material coated and dried onto a carrier film, and usually vacuum laminated onto circuitized panels. They are usually available in various thicknesses in ranges of  $25 \mu\text{m}$  [0.001 in] to  $100 \mu\text{m}$  [0.004 in]. Feature sizes are limited by the solder mask thickness, but the placement accuracy and tolerances around circuitry features are good. The finished solder mask surface is typically more planar since these films typically do not conform to circuitry as well as liquid-applied solder masks. As mentioned above, the film is laminated over the entire PCB surface. It is exposed to UV light through a phototool, developed and cured to provide the finished solder mask. Due to limited chemical resistance and limitations related to design, the dry film usage has decreased over the years. However, dry film allows fully tented vias based upon its structural stability.

**3.2.2 Liquid Photoimageable (LPI)** LPI solder masks are often multiple-part liquid systems that are mixed and applied to the entire surface of the PCB panels. Screen-printing, spraying, or curtain coating may be used to apply the solder mask (a less common method is roller coating). Because these products contain solvent at application they must be dried ("tack drying") to allow them to be handled through the exposure process. The panels are then exposed to UV light through a phototool, developed and cured. The final solder mask typically conforms well to the finished circuitry. Very fine features and close tolerances to circuitry features are typically achievable with LPI solder masks.

**3.2.3 Laser Direct Imageable (LDI)** These products differ from typical LPI solder masks in that they are exposed directly by a UV laser without a phototool.

(CAD/CAM) data is fed into a laser exposure device that directly images the solder mask pattern. This allows the finest features and closest tolerances, but is currently limited in its availability due to very high cost of the laser exposure equipment and relatively slow processing time. At this time it is best suited to very small lot sizes of the highest technology products.

**3.2.4 Photoimageable Coverlay** These products are photoimageable versions of coverlay as described above. They may be applied as a liquid or dry film, and are capable of finer features and closer tolerances than the punched film described above. Some of these products do not have the same characteristics as the punched film products, particularly in terms of flammability; circuit coverage and dynamic flex testing.

**3.3 Temporary Solder Mask** In many manufacturing processes, it is necessary to protect certain through-holes or vias from being filled with solder in wave soldering operations, yet have those holes open for subsequent process steps. For these applications, a temporary solder mask is used.

**3.3.1 Peelable** Peelable solder masks are often latex based, modified to withstand reflow temperatures. Such solder masks are applied in liquid form and harden at room temperature. Following reflow operations; the latex solder mask is peeled from the substrate for subsequent operations. Latex solder masks may exude cure byproducts, such as ammonia or acetic acid. Temporary solder masks may also affect the cleanliness or solderability of the surface they cover, so care should be taken in the selection, processing, and postreflow cleaning, of a peelable solder mask.

**3.3.1.1 Tape** In some assembly operations, tapes may be used to mask or protect through-holes or vias from liquid solder. Tapes used in this way must be capable of withstanding the temperatures of solder reflow, without degradation. The most common forms of tapes used in assembly have polyimide chemistry and appear yellow/brown in color. Another common tape utilizes silicone chemistry in both the tape and adhesive system. Following reflow, the tape is removed and discarded. Tapes use an adhesive which may or may not carry ionic materials such as chloride or sulfate. Care should be taken in the selection and processing of tapes such that subsequent assembly operations, such as adhesive or conformal coating operations, are not affected. Ionic residues from tape adhesives can lead to corrosion and metal migration. Organic residues, such as silicones, can lead to loss of adhesion for electronic adhesives or conformal coatings.

**3.3.2 Soluble** Soluble solder masks refer to polymeric materials that protect through-holes and vias from mass solder operations, and which dissolve in a solvent of some sort. The solvent may be water, an aromatic solvent, or a cleaning chemical, such as a saponifier. When selecting a soluble temporary solder mask, be aware that the solubilized solder mask may deposit on other surfaces of the assembly, or on the walls of the cleaning equipment. Soluble solder masks require less labor for masking and demasking than the peelable solder masks or tapes, but increased maintenance is often needed to make sure that the machine filters are adequate and will remove the dissolved solder mask.

**3.3.2.1 Liquid** Many of the soluble solder masks are liquid when first applied to a printed wiring assembly. Dispensing can be done manually or with automated equipment. These liquids are often lower in viscosity than the peelable solder masks and are used more often in high speed or high volume production settings.

## 4 CHEMICAL COMPOSITION

**4.1 Resin Systems** Solder mask polymeric blends are often delivered to the PCB fabricator in a variety of solvent carriers. This may be due to materials compatibility issues or the necessity of compliance with local environmental regulations. The carrier systems can be categorized into three broad groups: solvent-borne, water-borne, or 100% solids.

**4.1.1 Solvent Borne** Solvent borne coatings contain one or more volatile organic compound (VOC) solvents. These solvents evolve out of the liquid solder mask during application and the drying process. In practice, the solvent carrier system may contain more than one solvent (cosolvents). These solvents, as VOCs, may contribute to the total VOC output of the solder mask application process and thus may come under regulatory scrutiny.

**4.1.2 Waterborne** As an alternative to VOC-based solvents, some formulations have used water as a carrier, usually with the addition of small amounts of cosolvents to aid in flow and wetting characteristics. Water takes longer than VOC solvents to evaporate, and so processing times may be longer.

**4.1.3 100% Solids** A 100% solids coating has no solvent carrier. These materials are applied in liquid form and then turn to solids under some driving force. These drivers may be the application of directed energy (e.g., ultraviolet light), or the application of heat to drive a chemical cure reaction. As a 100% solids coating, there is no or little outgassing during the cure process, with a lower environmental impact.



**4.1.4 Solvent Free Systems** Dry film solder masks have no solvent carrier systems and are supplied in semicured form. The dry film solder masks are directly laminated to the surface of PCBs.

**4.2 Pigments and Fillers** Solder masks are seldom pure polymeric structures. Solder mask manufacturers incorporate various organic and inorganic components into the polymeric structures to give the solder mask specific final film characteristics or processing improvements.

**4.2.1 Matting Agents** The degree of gloss and/or the degree of surface roughness in the surface of a solder mask is of concern to many assemblers. Gloss may affect automated optical inspection methods and has been shown to affect the degree of solder balling with low solids fluxes. Surface roughness can affect the degree of adhesion of the solder mask to the substrate, or the degree of adhesion of conformal coating to the solder mask. Matting agents are added specifically to affect these two properties.

**4.2.2 Fillers** A pure polymeric structure may not have the necessary final film properties desired, and may be very expensive when applied in the necessary thicknesses on PCBs. As with matting agents, filler compounds are added to give bulk to the polymeric structure. These fillers often can control the shrinkage or Coefficient of Thermal Expansion (CTE) characteristics of the solder mask. Filler agents can affect the physical properties such as hardness and abrasion properties of the cured solder mask, abrasion properties, etc.

**4.3 Photoinitiators** Photoinitiators are critical components of the UV cured or photoimageable solder mask. Photoinitiators are the active chemical compounds that initiate the polymerization process. For screen printed, UV curable solder masks, the photoinitiator allows the solder mask to quickly reach the cross-linked and final cured state. For photoimageable solder masks, the photoinitiator initiates the photoimaging process step by partially curing the solder mask or partially polymerizing the applied solder mask where it is exposed to UV light so that it will withstand the developing process.

In greater detail, photoinitiators are a photochemicals subset and in which light initiates a chemical reaction by exciting chemical compounds and/or atoms or free electrons to form a more reactive compound. In solder mask formulations these photochemical reactions often setup a chain reaction and produce either free radicals or ions. Since photochemical reaction mechanisms, such as free radical or cationic reactions are well documented in scientific literature, this handbook will not discuss the exact chemical mechanisms in great detail, but will concentrate on how photoinitiators and other similar chemical compounds impact solder mask.

The vast majority of solder mask photoinitiator systems are based on free radicals which react with the unsaturated compounds. This causes them to polymerize and the reaction is almost instantaneous. Historically, some of the very early solder masks may have used cationic photoinitiators. Since this technology is dated, cationic cured solder masks will not be discussed in this handbook.

The most important factor with screen printed UV cured solder masks and photoimageable solder masks, is the light source, since this is what initiates or starts the chemical reactions. As such, the light source wavelength distribution and intensity are critical factors. Most photoinitiators are often light wavelength specific and will have different reaction rates dependent on the exact exposure wavelength. A light wavelength deviation, either longer or shorter, will probably decrease the photoinitiator effectiveness.

In free radical chemical reactions, the free radical concentration is dependent on the amount or intensity of the light source. The designed free radical concentration is important to obtain the correct solder mask cure. For free radical cure mechanisms, usually higher numbers of free radicals produced over a shorter time often produce higher levels of cross linking than a lower concentration of free radicals produced over a longer time. Since free radical generation is critical for solder mask cure any chemical compound which would absorb cross-linking wavelength light or any chemical compound which would scavenge free radicals could affect the solder mask cross-linking.

Also of importance, is the fact that many photoinitiators do not fully chemically react into the polymerized solder mask. Often, photoinitiator fragments are “free” and mobile chemicals which may outgas and/or bloom. These fragments can cause other issues; see 4.4 for more details.

**4.4 Other Components** Solder masks are usually complex mixtures which often contain twenty or more ingredients or additives. These additives may have been introduced only to impact a single solder mask property in a very specific process step (e.g., a nonionic organic anti-foam, for air release (bubble formation) in a screen printing application process). As such, these additives contribute to the solder mask performance in a very specific solder mask process step and/or in a cured solder mask state.

To make sound decisions about additives, one needs to understand why each is present in the solder mask formulation, what impact each has on solder mask processing, and what impact the additives have on cured solder mask properties. Another important factor is whether an additive reacts into the bulk solder mask or if the additive is just mixed in. If the additive is not bonded then the additive can be free to move at some future time. If the additive migrates to the solder mask surface, this is often referred to as “blooming.” If the additive is volatile, it may leave the solder mask and condense in an undesirable location.

as an oven vent (drying, curing and assembly) which in turn may drip back onto panels or assemblies being processed in the oven.

Often with additives there are tradeoffs between desired physical properties. Table 4-1 lists a few common additives and some potential tradeoffs.

**Table 4-1 Tradeoffs with Common Additives**

| Ingredient        | Function                                                                                                                     | Known Issues                                                                                                             |
|-------------------|------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Antifoam          | Decrease air entrapment during screen printing, improve solder mask flow and wetting during solder mask application process. | Solder mask with low surface energy which impact the wetting of assembly processing chemicals; may bloom during storage. |
| Pigment           | Increases visual recognition of solder mask presence and pattern.                                                            | Can decrease photo-speed; may contain halides or metal ions.                                                             |
| Inorganic fillers | Provide thixotropic properties.                                                                                              | Increased ionic content, may increase the absorption of processing chemicals.                                            |

**4.5 Flame-Retardants** PCBs very often must meet UL flammability requirements for a particular classification (V-0, V-1, etc.). To meet these criteria the PCB materials must not support combustion for specific times as called out in the UL 94 specifications. The samples submitted consist of the substrate material, coated with the appropriate solder mask that is used by the submitter. The substrate materials must also meet the flammability requirements with no solder mask applied.

To meet the UL flammability requirements, many substrate materials must have flame-retardants incorporated into the formulation. Without flame-retardants, the typical substrate materials will support combustion.

Solder mask materials typically do not contain flame-retardants, nor are they formulated from flame-retardant materials. Consequently, when solder mask is applied to the PCB substrate, it generally degrades the flammability performance compared to the uncoated substrate. The test results achieved depend upon the flame retardancy of the substrate and the ratio of the laminate thickness (flame-retardant material) to the thickness of the solder mask (nonflame-retardant). To improve upon the flammability performance of the coated samples:

- Increase the thickness of the laminate.
- Decrease the thickness of the solder mask.
- Use laminate with better flammability performance (lower “burn time”).
- Ensure proper solder mask curing.
- Proper sample preparation (edge grinding, radiused corners).

Future requirements for laminate materials that do not contain specific flame-retardants (e.g., brominated epoxies) may have an impact upon the ability to achieve specific UL ratings if the laminate materials do not have the same flame retardancy as today’s typical FR-4 laminates.

Typically classical flame-retardants have not been used in most solder mask formulations. The solder mask usually relies on the flame-retardant of the substrate or base laminate for flammability control. Historically only a very limited number of “old” solder masks used brominated basic flame-retardants. Some others have added solid fillers, like alumina trihydrate which may reduce solder mask flammability. Both of these flame-retardant methods have problems (e.g., solid fillers like the aluminum trihydrate may increase the water solubility or extractable solder mask ionic content and the brominated flame-retardants are probably prohibited by new environmental regulations).

**4.6 Curing Systems** Solder masks may use either UV, thermal or a combination of UV and thermal curing systems to achieve optimum performance and properties (cure). These chemistries vary widely and are unique to each solder mask.

## 5 SOLDER MASK PROPERTIES

**5.1 Materials Characterization Tests vs. Performance on Products** When viewing the following sections, keep in mind that many of the tests which determine the properties of the material are not designed to determine how well they will work on the final assembly. Materials characterization tests, such as ASTM, are done by the solder mask supplier. As the method of processing greatly impacts the final material characteristics, the delivered product may not always match the properties on the data sheets.

In addition, most materials specifications, including IPC-SM-840, are based on the “level playing field” concept, so that similar materials are tested in the same manner on standardized substrates. It is often left to the end-user of the solder mask to determine if the material properties on the final assembly are adequate for the end-use environment. The same test methods can often be used, but usually in a modified form from the standardized test method. When such test methods are modified, the acceptance criteria of the standards may no longer be directly applicable and engineering judgment must be used.

**5.2 Solder Mask Test Method History** The original IPC-SM-840, published in October 1977, contained test methods for parameters identified by recent field performance issues as being important to the long term functionality of the PCB. Unfortunately the test methods which were either taken from other industries or created with a specific goal in mind, did not always accomplish the task as intended. Several examples (in no particular order) include the following:



Three such tests were those initially listed for the determination of Solder Mask Cure:

- IPC-TM-650, Method 2.3.23, Cure (Permanency) Thermally Cured Solder Masks
- IPC-TM-650, Method 2.3.31, Relative Degree of Cure in UV Curable Materials
- IPC-TM-650, Method 2.3.23.1, Cure (Permanency) UV Initiated Dry Film Solder Masks

Further experience by the industry with these methods, however, determined that they were only of value as process control tools during fabrication and not suited to act as “referees” in determining the adequacy of cure of a material in the field. They were replaced for determination of cure by the use of several “functional” tests such as solder and chemical resistance, which could better demonstrate and determine the capabilities of a finished product.

Adhesion testing has created (and continues to create) much discussion. The original test required the use of a “crosshatch cutter,” which is commonly used in the paint industry. The use of this test method for solder mask however was determined by the IPC Solder Mask Performance Task Group to be inappropriate because of the number of possible test variables (e.g., thickness of solder mask, sharpness of blade, force applied, type of circuitry being covered, etc.) and subjective interpretation of the results. As a result, the “checkerboard pattern with a tape test” was developed and continues to evolve with more changes anticipated to be consistent with current board designs.

Moisture and insulation resistance is a test that has been shown to be highly variable and sensitive to many factors within the test that are very difficult to control. In one task group meeting session, a list of possible factors that need to be controlled filled the board. At this point however, while the test remains, a number of the test conditions have changed.

Thermal shock is a test which had originally been designed to test the reliability of plated through holes, which had the potential of cracking when undergoing sudden and extreme thermal change. While this can cause the solder mask to crack, as well as due to dimensional changes in the circuit board, it was determined that, in applications where this could occur, the board was most often conformal coated and, if this conformal coating remained intact, the solder mask cracking was not to be considered an issue.

**Chemical Resistance:** In the early days of IPC-SM-840 (circa 1970s), a test was desired that would determine the compatibility between a solder mask and the cleaning solvents used to remove flux from an electronic assembly. The most common fluxes at that time were rosin (mildly activated) based and the most common cleaning solvents were chlorinated (e.g., 1,1,1 trichloroethane) or chlorofluorocarbon (CFC) solvents. In addition, it was a common practice

in electronic assembly operations to test the cure of a solder mask by applying a drop of methylene chloride to the surface of the solder mask. If the solder mask was properly cured, the methylene chloride would show no attack in a two minute exposure.

With the advent of the Montreal Protocol (1989), and the subsequent U.S. Clean Air Act (1995), the use of chlorinated solvents and chlorofluorocarbons in electronics manufacture was banned. All test methods which incorporated these solvents had to be revised to alternative materials. In the early 1990s, most manufacturers transitioned to semiaqueous cleaners, often based on citrus/pine terpenes and/or petrochemicals. One common material used in semiaqueous cleaners was d-limonene. Consequently, the chlorofluorocarbons and chlorinated solvents were replaced by terpenes and d-limonene. Since that time, many assemblers have gone to different chemistries and different fluxes. It would be a prohibitive test to include all the primary chemical agents in use today. It is left to the user to do the compatibility studies between their chosen solder masks and their chosen material sets in assembly.

The original tests were based on two-minute exposures to the cleaning chemicals involved. Users were always able to extend the exposure time in their own engineering evaluations.

While there are other criteria and test methods that have evolved, the items listed above form the basic list of the most important characteristics measured.

**5.3 Chemical Properties of Cured Solder Mask** Sufficient understanding of the solder mask and compatibility with subsequent process materials is necessary for the production of reliable hardware. A solder mask may be exposed to several chemicals after it is applied and cured, both in the board fabrication process and the PCB assembly manufacturing process.

**5.3.1 Resistance to Solvents/Fluxes** After a solder mask is applied to the laminate surface and cured, it must be able to withstand the exposure to assembly materials and processes. This may include adhesive systems and associated solvents, fluxes raised to reflow temperatures, a wide array of cleaning chemicals, and the solvent systems of conformal coatings. Owing to the huge number of chemicals, which a solder mask may encounter, it is virtually impossible for a solder mask manufacturer to test all possible compatibilities. It is usually left to the user of the solder mask to determine if a solder mask is compatible with their selected material set(s). It is recommended that the user select some parameters critical to the end use of the assembly (e.g., adhesion, surface attach, surface insulation resistance (SIR), etc.) and determine if exposure to the assembly process degrades the selected parameters.

**5.3.1.1 History of Resistance to Solvents** Historically the number of fluxes and cleaning agents was small. The resistance to solvents tests originally developed in military standards concentrated on determining if solder masks would be degraded by exposure to the cleaning chemicals of the time. For the most part, the cleaning agents were primarily solvents, such as chlorofluorocarbons or 1,1,1-trichloroethane. When these ozone depleting chemicals (ODCs) became banned by the Montreal Protocol, the IPC committees were tasked with coming up with alternatives. At that time, semiaqueous cleaners were the popular alternative choice for removing high solids rosin flux residues. Many of these semiaqueous cleaners of that time were based on citrus and pine terpenes, which have d-limonene as a common constituent chemical. So many of the resistance to solvents test methods from that time had d-limonene or various hydrocarbons as candidate solvents. Many of the cleaning chemicals in the year 2000 time frame are based on monoethanolamine (MEA) or various alcohols, but are too numerous for a standard list of chemicals for a resistance to solvent test. The OEM must do the resistance to solvents test using their selected chemicals.

**5.3.2 Corrosion Resistance** Many PCBs are produced as solder mask over bare copper (SMOBC). It is the function of the solder mask to protect the underlying metallization against the end use environment. If the end use environment is very humid, then the solder mask has to protect the metal from humidity. If the end use environment has high levels of pollutant gasses, then the solder mask must protect against those gasses. In some cases, the solder mask may have the assistance of a conformal coating, such as with high reliability products, but such a coating cannot always be assumed. The corrosion of underlying metal may often be related to the cleanliness of the substrate prior to solder mask application.

**5.3.3 Degree of Cure** All solder masks go through a cure process in order to achieve their final film properties. Cure may be accomplished by thermal bakes, ultraviolet energy, or a combination of factors, but must be tightly controlled to avoid undercure or overcure conditions. Undercured solder mask may not have the proper adhesion, electrical strength, or chemical resistance. Overcured solder mask may be brittle and unable to withstand thermal shocks. In practice, determining the degree of cure is very difficult to determine with any degree of accuracy. In early revisions of the IPC-SM-840, a Meseran test (IPC-TM-650, Method 2.3.23.1) was used in which a radioactive isotope was applied to the surface of a cured solder mask and the degree of absorption correlated to the degree of cure. This test was finally eliminated because the correlations were often questionable and the equipment both dangerous and expensive. For dry film solder masks, an old spot test was to apply a drop of methylene chloride to the surface of the

cured dry solder mask. If the solder mask showed no evidence of attack in two minutes, then the solder mask was fully cured. Currently there are no test methods used by IPC-SM-840 which are considered to be repeatable and reproducible to determine the degree of cure. Possible techniques for future investigation include dielectric analysis and impedance spectroscopy.

**5.3.4 Permeability to Moisture** All polymeric materials or polymeric blends are permeable to moisture to some extent. In the absence of a conformal coating, the only protection against the end use environment is the solder mask. Different laminate materials vary in their hydrophilic (water absorbing) nature. For the more water loving laminate materials, a low permeability solder mask is desired. If the cleanliness of the surface of the laminate is suspect, limiting the amount of water, which can get to the contaminant, can reduce the risk of electrochemical failure mechanisms (leakage, corrosion, metal migration).

**5.3.5 Moisture Absorption** Just as solder masks are permeable to moisture, all polymeric materials absorb and retain moisture to some extent. The degree of absorbed water can affect corrosion resistance and the adhesion of subsequent materials (coatings, adhesives). Absorbed water in a solder mask can also result in blistering and delamination when the absorbed water tries to instantaneously vaporize when brought into contact with liquid solder.

**5.3.6 Permeability to Gasses** Just as solder masks are permeable to moisture, many are permeable to pollutant gasses ( $\text{SO}_x$  or  $\text{NO}_x$ ). As such, the solder mask may have to be chosen for its resistance to one or more gasses. An example would be control electronics operating near fossil fuel combustion byproducts. One standard test protocol for resistance to gasses is the Batelle Mixed Flowing Gas test.

**5.3.7 Outgassing** Most polymeric materials will lose some low molecular formulation components (e.g., plasticizing agents) when placed in a low pressure or vacuum end use environment. This process is called outgassing. For electronic assemblies exposed to the harsh vacuum of space, or the low pressure atmosphere found at 50,000 feet altitude, the potential for outgassing should be considered. Loss of plasticizer agents, or other vital constituent materials, can result in a loss of critical parameters, such as dielectric strength or adhesion. Outgas materials may also be redeposited onto other surfaces, such as relays or optics. A common test method used by NASA is ASTM E-595.

**5.3.8 Nonnutrient** The majority of military and high performance electronics must be able to function in hot and humid conditions, where biological growths, such as fungus or mold, also exist. If the solder mask has chemical constituents which biological agents consider as food, then the biological agents will grow on the solder mask, compromising the function and long term reliability.

most specifications for high performance electronics require that the solder mask contain no nutrients which may support the growth of biological agents. The IPC test method for determining the nonnutrient nature of solder masks is IPC-TM-650, Method 2.6.1.

**5.3.9 Hydrolytic Stability** In the early days of electronic assemblies (circa 1960s), many polymeric materials or two-part chemical structures, like potting compounds, would revert to liquid form or to individual constituents when exposed to long periods of high temperature and humidity. Consequently, the military began to test polymeric structures under prolonged temperature and humidity to see if the structures became liquid or soft, or reverted to the original chemical forms. In practice, modern polymeric structures no longer suffer from reversion, but the test is done to determine long term effects of temperature and humidity on polymeric structures, such as softening, blistering, or darkening. The IPC hydrolytic stability test method for solder masks is IPC-TM-650, Method 2.6.11.

**5.3.10 Pressurized Steam Resistance (Pressure Cooker Test)** A common test for high performance electronics is called Highly Accelerated Stress Testing (HAST) to determine the long-term potential for corrosion and degradation in a short period of time. HAST testing is commonly done at temperatures around 121°C [250°F], 95-100% relative humidity, and two atmospheres of pressure for 96-250 hours, in essence, a pressure cooker test. Solder masks are not tested for resistance to this test in the IPC-SM-840 document, but the solder mask may have to survive this test exposure without degradation. There is no IPC test method for pressurized steam resistance. MIL-STD-883 or MIL-STD-810 has more information on environmental stress tests.

**5.3.11 Ionic Contamination** Many electronic assemblies are routinely tested for ionic contamination in the assembly process. The most common ionic cleanliness test is Resistivity of Solvent Extract (ROSE) and can be found in IPC-TM-650, Method 2.3.25. The extract solution for this test is most often 75% isopropanol/25% deionized (DI) water, for a period of 10 minutes, at a temperature of 25 to 45°C [77 to 113°F]. Solder masks should have sufficient chemical resistance to have no extractable ionic materials with these extraction parameters. If the solder mask exudes ionic materials, the conductivity of the solution will be affected and the ROSE results will show a higher level of contamination, possibly leading to rejection of the assembly. The ROSE test is also frequently used as a pass-fail test for unpopulated PCBs prior to shipment to the assembler.

**5.3.12 Flammability** Many electronic assemblies, especially airborne electronics, require that electronic assemblies be made from fire-proof or fire-resistant materials. In

the case of laminates, a brominated compound is added to make the laminate self-extinguishing. A fire on the assembly liberates the bromine from the laminate, which may extinguish the flame. The most common measure of the flammability of a polymeric material is the Underwriters Laboratory (UL) UL-94 test. A flame is held to the base of a vertically fixed sample and, after removal of the igniting flame, it is determined how long the material burns after removal of the igniting flame. A material where the flame goes out within a prescribed time limit for the sum of five burn strips receives a specific UL rating.

**5.4 Thermal Properties of Cured Solder Mask** Thermal properties of cured solder mask are important characteristics because the solder mask should be able to withstand local hot spots generated by components or from temperature exposure to environment. Some end-use applications may involve extreme temperature, or a wide range temperature fluctuation such as automotive, space, and geothermal applications. Thermal profiles, which include assembly, test, and operational temperature extremes, should be considered when selecting solder masks; otherwise, solder masks cannot protect the laminate and conductive patterns from degrading during service life of the circuit board assembly.

**5.4.1 Thermal Stress/Cycling** High temperature can cause changes in the solder mask appearance as well as the mechanical and electrical properties. Long-term effects of high temperature operation may include discoloration, embrittlement, adhesion loss, and cracking, affecting dielectric strength and insulation resistance. Low temperatures can cause cracking and delamination between the solder mask and other substrate such as laminate or underfill. IPC-SM-840 does not require the thermal stress cycling test; therefore, it is the responsibility of the end-user to perform the test for the end-use application. Some thermal cycling tests can range from -65 to 200°C [-85 to 392°F] depending on end use requirements.

**5.4.2 Thermal Shock** Thermal shock change rates greater than 30°C [86°F] per minute may also stress the solder mask due to a change in temperature rates and internal CTE mismatch within the PCB construction. This can cause cracking and delamination between the solder mask and the laminate or between the solder mask and the conformal coat or underfill. IPC-SM-840 requires solder masks to withstand 100 cycles from -65 to 125°C [-85 to 257°F] for Class H and Class T (when specified by user) without blistering, crazing or delamination. IPC-TM-650, Method 2.6.7.3, provides details of the thermal shock test.

**5.4.3 Thermal Degradation** Thermal degradation usually involves the use of a soldering iron, hot knife or hot air to locally remove the components, adhesive or conformal coat. Care needs to be taken to protect the components

solder mask or damage to the pads and substrate. The degradation can be visually observed in the solder mask appearance such as discoloration, cracking, crazing, and delamination. Thermal degradation can also lower the dielectric strength and insulation resistance. Those properties can be tested per IPC-TM-650, Method 2.5.6.1, and IPC-TM-650, Method 2.6.3.1, respectively.

**5.4.4 Thermal Conductivity** Thermal conductivity is the ability of cured solder masks to dissipate heat to the surrounding components and environment. It is an important characteristic especially in applications where components can generate too much heat. The heat needs to be dissipated for the PCB to function properly. Thermal conductivity varies depending on the solder mask formulations. Solder mask suppliers might include some proprietary material to improve thermal conductivity. Typically solder masks are not high thermally conductive materials; however, since they are usually applied fairly thin, they may not have a significant impact on a thermal structure.

**5.4.5 Maximum Operating Temperature** A solder mask will degrade if it is exposed to temperatures higher than the maximum operating temperature. This maximum operating temperature may be specified by the solder mask supplier. It is safe to operate within the supplier recommended temperature range. For cases where the temperature might exceed the maximum temperature for a short time, check with the solder mask supplier or conduct a test to verify acceptability. Most current solder mask materials are formulated for the standard tin lead solder operation. As assemblies switch to lead free solders, solder mask materials may need to be changed since they may not be able to withstand the high temperature encountered with lead free solder. IPC-SM-840 addresses resistance to lead free solder and simulation of lead free reflow to address the lead free operating temperature.

**5.4.6 CTE** CTE is the linear dimensional change with respect to an original dimension due to a change in temperature. Two measurements for CTE are usually provided, one in the X-Y plane (lateral) and one in the Z-direction (thickness). The CTE value is different whether it is above or below the glass transition temperature ( $T_g$ ). Ideally the CTE should be as close as possible to the same substrate, component, solder alloy, and coating. Some users express this as Thermal Coefficient of Expansion (TCE).

CTE is an important design consideration because, if the thermal expansion characteristics of the solder mask can be radically different than for the substrate, cracking or delamination of the solder mask may occur, negating the purpose of solder mask to prevent solder from touching the copper traces. This is particularly true for the more thick rigid solder masks. If the end-use environment has large and rapid swings in thermal conditions, a CTE mismatch can cause cracking in the solder mask.

**5.4.7 Glass Transition Temperature ( $T_g$ )** The glass transition temperature ( $T_g$ ) is the temperature at which an amorphous polymer transitions between a super-cooled liquid and its glassy solid. As a result, amorphous polymers exhibit substantially different physical properties above and below the glass temperature. The  $T_g$  is also dependent on the rate at which the temperature changes through this phase change. Exposure of any material above the  $T_g$  will affect the electrical and physical properties of the solder mask. Examples include tensile strength, increase of adhesion and decrease of bulk resistivity. The end user must determine if the operating temperature is above the  $T_g$  and how this change in physical properties affects their design and assemblies.

## 5.5 Mechanical Properties of Cured Solder Mask

**5.5.1 Thickness** The cured solder mask should cover all required surfaces. Solder masks are usually thin, especially at the copper edges as evidenced in the change in the solder mask color at the copper pattern edge. Cured solder masks range from a few microns to several hundreds of microns and is often measured by taking cross sections in different areas of the PCB. Solder mask thickness is highly dependent on several factors such as board design, application method, plating quality and solder mask type. In some cases successive coatings may be required.

**5.5.2 Adhesion** Adhesion is the ability of the solder mask to adhere to the laminate and the conductor patterns. In addition, solder mask must allow for adhesion of conformal coating, marking, etc, used in postsolder mask processes. Adhesion is an important characteristic since poor adhesion can result in blistering and delamination. IPC-SM-840 requires the solder mask to be tested for adhesion to rigid PCBs, flexible PCBs, and adhesion to final metal finishes including bare copper and a variety of metals as specified in IPC-SM-840. The adhesion can be tested with and without the conformal coat. If a surface mount adhesive is used to bond the components to the solder mask surface, the adhesion should also be tested by the user. The adhesion is tested using a tape test per IPC-TM-650, Method 2.4.28.1, and/or Method 2.4.29.

**5.5.2.1 Cross Hatch Before and After Soldering** It is a common belief in the industry that the crosshatch is an easy way to determine the adhesion of solder mask to the typical PCB substrates as well as adhesion between solder mask layers (double coating). There are several standards describing similar methods like ISO 2409, ASTM D-3359 and also the superseded Revision A of IPC-SM-840. Basically, all methods describe the use of a cutting tool (or a cutting tool and a specific ruler) to create parallel cuts crossing each other and thus resulting in (usually 25) solder mask squares. The final rating is based on the surface area where the solder mask chips off.

These standards usually allow a choice of a mechanical or an automated set up. Very important factors for repeatable results are the uniform pressure on the cutting tool, a uniform cutting rate and the resulting penetration of the cuts to the substrate surface as well as a crossing angle of 90°. All of these factors are very difficult to control with a mechanical set up and practical test have proven that these factors can change the repeatability of results by 100%. One additional very important factor is the inspection of the cutting edge of the blade. If the cutting edge is not uniform or sharp enough it needs to be sharpened or replaced. Thus, the frequently used Swiss pocketknife might not be the best tool.

Most standards request to test in at least three different places whereas the differences between the results should not vary more than one classification unit. Since all norms require a homogenous, nontopographic substrate in the crosshatch area this adhesion testing method cannot be used for many modern PCB designs. Some norms require an additional tape test over the crosshatch area. Even if the tape is specified, there are several additional factors, which may influence the results:

- The application pressure on the tape.
- The hold time prior to removal.
- The removal angle.
- The removal speed.

Since there are numerous factors which can change the results significantly, the crosshatch results should not be rated as a scientific measurement.

Assuming the crosshatch tests are performed very well, differences can be found after different process steps such as before and after hot air solder leveling (HASL). This may be based upon an increased cross-linking of the polymeric matrix. However, the crosshatch test not only shows the adhesion, it is also heavily influenced by the hardness or the brittleness of the solder mask. Thus, even though the crosshatch result might diminish after HASL, this may not necessarily be an indication that adhesion decreased. In some cases it might be an indication that the solder mask is more brittle now.

**5.5.3 Abrasion Resistance** Potential for mechanical abrasion should be considered when selecting a solder mask. This may occur due to improper handling, storage, or shipping and may result in scratches, scrapes, dents, creases, and marred surfaces which can become areas of concentrated stress or contamination ingress. Abrasion may also cause solder mask peeling and exposure of copper or metals. IPC-SM-840 utilizes pencil hardness as a measurement of abrasion resistance.

**5.5.4 Cracking and Flaking** Solder masks can also crack and flake due to temperature gradients, poor adhesion and/or CTE mismatch. The cracking and flaking are sites

for solder ball attachments, dendrite growth, electrochemical migration, etc. Users should test the selected solder mask to verify that cracking and flaking are not encountered in the end-use applications.

**5.5.5 Shrinkage** Solder mask formulations contain solvents/thinner so that the solder mask can be applied by curtain coating, spray or screen printing. These volatile materials increase the volume of the coating and, as these materials evaporate, there is a certain amount of shrinkage. In addition to shrinkage due to solvent evaporation, there can be shrinkage due to volatile generation of by-products during the cure process. Shrinkage can lead to residual stresses particularly around the conductor patterns. Wide variation in thickness can produce additional strain on the solder mask. The higher the stress or strain, the more likely the solder mask will blister or crack when subjected to temperature exposure.

**5.5.6 Hardness** Solder mask hardness varies depending on the type of the solder mask and processing conditions. The hardness is measured using a pencil per IPC-TM-650, Method 2.4.27.2. The requirement is that the solder mask should not be damaged by a pencil softer than F.

**5.5.7 Machineability** Solder masks are applied to the PCB panels and cured during the circuit board fabrication process. Individual circuit boards are then routed, scored or punched from the panel. Registration holes are punched or drilled. Those normal fabrication processes should not damage, crack or tear the solder mask. IPC-SM-840 requires that the solder mask shall not be cracked when inspected without magnification when subjected to drilling, routing, scoring or punching. Good design practice provides for the pull back of solder mask and metal features from the machined areas.

**5.5.8 Flexibility** Some degree of flexibility is needed for thermally induced stress and physical bending of the circuit board due to dynamic loading. Young's modulus, or modulus of elasticity, is temperature dependant. A material with a low modulus is flexible while a high modulus material is more rigid. For high degrees of flexibility, a specifically designed flexible solder mask should be used.

**5.5.9 Young's Modulus** Young's modulus or modulus of elasticity represents the stiffness of the material. A soft material has a low modulus while a hard material has a high modulus. In comparison to conformal coat where often a low modulus material is preferred, users should select a solder mask based on the processing and environmental exposure.

**5.5.10 Poisson Ratio** Poisson ratio is the ratio of lateral strain to axial strain. Poisson ratio is mostly used in finite element analysis and is a difficult process not often performed on solder mask.



**5.6 Visual Appearance (Gloss)** The gloss test method concept is fairly simple. An ASTM test method which describes this test method in detail is ASTM D-523. In this test method, a light beam is directed towards a surface at a specific angle and the amount of light reflected at a specific angle is measured as shown in Figure 5-1.

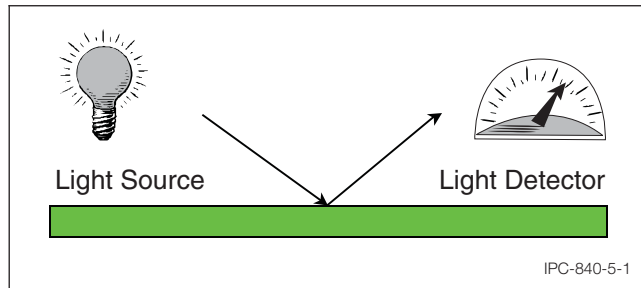


**Figure 5-1 Measurement of Light Reflection for Solder Mask**

The location and number of test areas per panel and test angle should be selected such that accurate and repeatable measurements can be taken. This will be very dependent on the physical area being measured. The angle selected will affect the amount of surface area required for a measurement. To obtain a gloss value on bare PCBs the most commonly used angle is 60°. The minimum measurement area is dependent on test equipment. For some gloss instruments, like the Gardner™ Micro-TRI-Gloss, the minimum area is 9.0 mm x 18.0 mm [0.354 in x 0.709 in] at 60°.

The actual test area should be defined since the gloss level of solder mask over copper will be different than solder mask over bare laminate. Vias, soldering pads, through holes or over areas interspersed with copper and laminate will also change the measured gloss value and may provide a higher than actual value. Thus a planar substrate area should be chosen. Some acceptable test areas may be on one of the circuit boards in the panel or any breakaway portion of the circuit board - if a large enough area of solder mask covered copper is available. In many cases it may be preferable to use a special area set aside on the panel for the gloss measurement. This area would be part of the normal scrap portion of the panel, but gloss levels measured at this point would be demonstrated, through data, to correlate to the overall gloss level of the circuit boards on that panel.

Solder mask manufacturers use specific terminology to delineate products with differing gloss. Common terms, from highest to lowest gloss are gloss (or high gloss), semi-gloss, satin, semi- or satin matte, and matte. There are no industry standard levels of gloss and each manufacturer will likely have different limits for each gloss level.

**5.6.1 Color, Opacity and Transparency** Solder masks can be purchased in many different colors, although the standard is still green. PCB fabricators and OEMs can have preferences as to solder mask opacity regardless of color.

Opacity involves the ability to see the etched circuitry through the solder mask. As with colors, opacity is a customer preference and may not affect the electrical properties.

**5.6.1.1 Effect on Through Exposure** There is however one area where the opacity of the solder mask could play more than a cosmetic role. The laminates of today usually have a UV blocking agent manufactured into the resin system. Consistency is not always guaranteed and in this case a solder mask with a higher level of opacity would usually help prevent the effect of UV light exposing the solder mask on the opposite side of the panel from the point of light source, better known as “shoot through.”

**5.7 Electrical Properties of Cured Solder Mask** The solder mask, in the vast majority of applications, is a permanent part of the printed board assembly. As a dielectric material, the electrical properties of the solder mask must be considered as part of the assembly design. If these properties become compromised, circuit function and reliability are at risk of failure.

**5.7.1 Dielectric Strength** Dielectric strength is defined as the maximum voltage that a dielectric material can withstand under specific conditions without resulting in a voltage breakdown, usually expressed in volts per unit dimension (e.g., volts/mil).

Dielectric strength is a critical parameter in power electronics, where potential gradients are high, or in electronics subject to power spikes. Dielectric strength is most often measured with AC or DC hipot testing. The applicable test methods for solder mask dielectric strength are IPC-TM-650, Method 2.5.6.1, and ASTM D-149.

**5.7.2 Dielectric Constant** IPC-T-50 defines dielectric constant as the ratio of the capacitance of a configuration of electrodes with a specific material as the dielectric between them, to the capacitance of the same electrode configuration with a vacuum or air as the dielectric. Dielectric constant and dissipation factor vary with frequency.

For the nonmaterials-scientist, this means that solder masks alter the capacitance between conductors. As applications go higher in frequency, this additional capacitance can affect waveform shapes and rise times. Therefore, the dielectric constant of the solder mask needs to be considered in the dielectric budget of the design of the assembly. If this is not taken into account, the signal can be degraded during propagation.

ASTM D-150-98 and ASTM D-2520-98 are methods for determining the dielectric constant and dissipation factor (see 13.1) of organic materials.

**5.7.3 Dissipation Factor (Loss Tangent)** IPC-T-50 defines dissipation factor as a value that represents the tendency of insulating or dielectric materials to absorb some of the energy in an alternating-current signal.

The higher the dissipation factor, the greater the loss of signal level as the signal propagates through the electronic assembly. This becomes a critical factor for high frequency applications. If a solder mask has too high a dissipation factor, it might not be a good candidate for high frequency applications.

While such data is rare, many designers need to know how dielectric constant and dissipation factor vary within the design range of the application.

**5.7.4 SIR/Resistivity** SIR represents the degree of insulation between adjacent conductors on the surface of a PCB. The higher the SIR levels, the better the ability to insulate adjacent conductors. This insulation characteristic is one of the critical measures to be monitored in compatibility testing. For more information on SIR, the reader is referred to IPC-9201. For solder mask, the applicable test methods can be found in IPC-TM-650, Methods 2.6.3, 2.6.3.1, 2.6.3.2, and 2.6.3.3, inclusive.

**5.7.5 Moisture and Insulation Resistance (M&IR)** M&IR is a measurement of surface insulation resistance during exposures to elevated temperature and humidity. The values for M&IR will relate to the degree of water permeability of the solder mask. It is desired that the solder mask maintain a high level of insulation throughout any exposure to high temperature and humidity. If a solder mask is incompletely cured, or has some degree of contamination present, either under the solder mask or over the solder mask, both SIR and M&IR can be severely degraded. The applicable test method for M&IR of solder masks can be found in IPC-TM-650, Method 2.6.3.2. IPC-9201 also addresses M&IR.

Many individuals who deal with solder masks and PCB materials and processes have expressed confusion over the terms “moisture and insulation resistance (MIR or M&IR)” and “surface insulation resistance (SIR)” when reading IPC-SM-840, the specification for solder masks, and other IPC materials specifications.

In all practicality, they refer to the same thing, though term purists will argue. Both of these terms refer to the exposure of material systems (e.g., SMOBC) to elevated levels of temperature and humidity, often under electrical bias, to examine propensities for degradation of insulating properties by temperature and humidity. The two terms can usually be used interchangeably, though SIR testing has the wider usage.

Surface insulation resistance is the measurement of a characteristic property of a material set, such as solder mask

over bare copper. The measurement of SIR can take place at ambient conditions, where it is sometimes called insulation resistance (IR), or at some elevated conditions of temperature or humidity, of varying test times or conditions. Over the years, the term “SIR testing” has evolved to represent a wide variety of biased temperature humidity tests.

The term moisture and insulation resistance testing is usually found only in the IPC-SM-840 and applicable IPC-6010 sectional performance specification (i.e., IPC-6012, IPC-6013, etc.) It is a measurement of insulation resistance at ambient conditions prior to temperature-humidity testing, at elevated temperature-humidity conditions during the cyclical humidity test, and finally at ambient conditions at the end of the test. It is a temperature-humidity-bias test, and so is sometimes generically called SIR testing.

The results are dependent not only on the capability of the solder mask material, but also on the board (circuit height, spacing, uniformity, design etc.) and the process of masking the board.

**5.7.6 Volume Resistivity** Volume resistivity is a three dimensional measure of the insulating characteristics of a solder mask throughout the bulk of the solder mask material. Volume resistivity of solder mask is most commonly tested per ASTM D-257. In practice, the volume resistivity of a solder mask is only important when a solder mask is used as an insulating media between circuitry on an assembly and a laminated plate (e.g., heat sink).

**5.7.7 Comparative Tracking Index (CTI)** CTI is defined by UL as that voltage which causes tracking after 50 drops of 0.1 percent ammonium chloride solution have fallen on the material. Tracking is the process that produces a partially conducting path of localized deterioration on the surface of a solder mask as a result of the action of electric discharges on or close to an insulation surface. UL personnel have indicated that this test is basically a measure of the ability of a material to provide a specific level of insulation performance after having been processed onto a finished PCB. UL 746A references ASTM D-3638 testing for electrical properties but Europe as well as some areas in Asia refer to the European test method IEC-60112. Table 5-1 compares both methods.

Both methods are similar with ASTM D-3638 tests slightly less severe and with five test runs only. IEC-60112 needs typically 17 test runs. These are seven to find the CTI voltage, five to reproduce it with 50 droppings and another five to reproduce the 100 dropping voltage.

**5.7.8 Electrochemical Migration** Electrochemical migration, also known as electromigration, metal migration, or dendritic growth, is the dissolving of metal from one trace of a circuit assembly in the presence of an electrolyte, and migration of that metal from one trace to another.

Table 5-1 Test Method Comparison for Measuring Electrical Insulation Performance

|                        |                            | IEC-60112-2003                                                                                                                                                                               | ASTM D-3638-93 (1998)                                                                                                                                                                                                 |
|------------------------|----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Item                   |                            |                                                                                                                                                                                              |                                                                                                                                                                                                                       |
| Reference              |                            |                                                                                                                                                                                              | IEC 60112-1971                                                                                                                                                                                                        |
| Test Specimen          |                            | (>20* >20* ≥3) mm <sup>3</sup><br>Smooth, untextured                                                                                                                                         | >2.5 mm<br>thinner specimen to be layered<br>surface uniform, scratch free                                                                                                                                            |
| Conditioning           |                            | 24h, 23°C ± 5K, (50 ± 10)% RH                                                                                                                                                                | ASTM D-618 Process A                                                                                                                                                                                                  |
| Electrodes             | Dimensions                 | All with tolerances                                                                                                                                                                          | Same without tolerances                                                                                                                                                                                               |
|                        | Sharp Edge                 | Flat (0.01-0.1) mm                                                                                                                                                                           | Radius (0.05-0.1) mm                                                                                                                                                                                                  |
|                        | Pressure on Specimen       | (1 ± 0.05)N                                                                                                                                                                                  | 100g                                                                                                                                                                                                                  |
|                        | Distance                   | (4 ± 0.1) mm                                                                                                                                                                                 | (4 ± 0.2) mm                                                                                                                                                                                                          |
| Test Circuit           | Trafo                      | (100-600)V, (48-62)Hz, 0.6kVA                                                                                                                                                                | (100-1000)V, 60Hz, 1kVA                                                                                                                                                                                               |
|                        | Voltmeter                  | True rms ≤1.5%                                                                                                                                                                               | 0-600)V, ≤2.5% of full scale                                                                                                                                                                                          |
|                        | Amp. Meter                 | 1A, ≤3%                                                                                                                                                                                      | 1A, ≤10% of full scale                                                                                                                                                                                                |
|                        | Stability                  | ΔU ≤10% @ 1A                                                                                                                                                                                 | —                                                                                                                                                                                                                     |
|                        | Over Current Breaker       | 0.5A ± 10% → 2s ± 10%                                                                                                                                                                        | >0.1A → >0.5s                                                                                                                                                                                                         |
| Test Solution          | A                          | NH <sub>4</sub> Cl purer then 99.8%<br>Demin. H <sub>2</sub> O <sub>23°C</sub> <1mS/m<br>ρ <sub>23°C ± 1K</sub> = (3.95 ± 5) Ωm                                                              | —<br>Demin. H <sub>2</sub> O <sub>23°C</sub> <20mS/m<br>ρ <sub>23°C ± 1K</sub> = (3.85 ± 5) Ωm                                                                                                                        |
| Test Solution          | B                          | 0.1% NH <sub>4</sub> Cl + wetting agent                                                                                                                                                      | —                                                                                                                                                                                                                     |
| Dropping Device        | Δt                         | (30 ± 5)s                                                                                                                                                                                    | (30 ± 5)s                                                                                                                                                                                                             |
|                        | height                     | (35 ± 5) mm                                                                                                                                                                                  | <40 mm                                                                                                                                                                                                                |
|                        | t <sub>50droplets</sub>    | (24.5 ± 2)s                                                                                                                                                                                  | —                                                                                                                                                                                                                     |
|                        | mass <sub>50droplets</sub> | (0.997-1.147) g                                                                                                                                                                              | —                                                                                                                                                                                                                     |
|                        | mass <sub>20droplets</sub> | (0.380-0.480) g                                                                                                                                                                              | —                                                                                                                                                                                                                     |
|                        | volume <sub>1droplet</sub> | —                                                                                                                                                                                            | (20 +5/-0) mm <sup>3</sup>                                                                                                                                                                                            |
| Test Specimen Platform |                            | Defined                                                                                                                                                                                      | Undefined                                                                                                                                                                                                             |
| Procedure              |                            | 23°C ± 5K<br>uncontaminated specimen<br>Voltage steps 25V<br>find 50 droplets withstand voltage<br>reproduce it five times<br>find 100 droplets withstand voltage<br>reproduce it five times | 20°C ± 5K<br>clean off contaminations<br>5 tests at different voltages<br>2 results with less than 50 droplets<br>2 results with more than 50 droplets<br>graphical determination of the 50 drop<br>withstand voltage |

gradient. The dissolved metal ions drop out of solution as it crosses the space between electrodes, creating a metallic sliver between electrodes. Electrochemical migration requires three factors to occur: an ionic contaminant, a voltage gradient, and humidity levels sufficient to form an electrolyte.

**Note:** The terms “electromigration” or “dendritic growth” are also sometimes found in technical papers on solid state physics and describe metal filament growth in semiconductors under dry condition. The term “electrochemical migration” is used to refer to this metallic growth phenomena on circuit boards in the presence of humidity.

Electrochemical migration testing or electromigration testing is very similar to SIR and M&IR testing. A test sample, processed with some fluid such as flux, is placed into a humid environment for an extended period of time, under the influence of an applied bias. The insulation resistance

is monitored throughout and the test patterns examined after testing to determine if metal migration had occurred.

The most common electrochemical migration methods are found in Telcordia Technologies (Bellcore) document GR-78-CORE, or IPC-TM-650, Method 2.6.14.1. These two methods are identical.

Electrochemical migration is subtly different than conductive anodic filament (CAF) growth. In general, electrochemical migration (or dendritic growth) occurs on the surface of a PCB or assembly under the influence of temperature, humidity, and electrical bias. CAF is typically a similarly induced failure, but which occurs internal to the circuit board, along the boundary between the resin and laminate reinforcement.

More information on CAF can be found in IPC-9691 “Users Guide for the IPC-TM-650, Method 2.6.25, Conductive Anodic Filament (CAF) Resistance Test (Electrochemical Migration Testing).”



**Documents**

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The mechanism for CAF is the transfer of copper (Cu) ions and the deposition of Cu salts in the presence of moisture and voltage bias influenced by concentration and pH gradients. The conductive path is the growth from the anode by a salt, as compared to dendrite formation on the surface of the board where metal ions deposit on the cathode. CAF is associated primarily with mechanically drilled holes where the mechanical drilling disrupts the glass reinforcement fibers in glass bundles, permitting the absorption of subsequent processing chemistry between the fibers and epoxy.

**5.7.9 Impedance Concerns** The characteristics of the solder mask that are important include how it is physically implemented relative to other materials such as permittivity and loss tangent. If it's a very lossy material at high frequencies, that alone would strongly discourage its use in high and/or controlled impedance applications.

The most formidable potential problems are in microstrip implementations, where the solder mask performs a significant role in the impedance determination. The most significant variables are likely to be variations in the dielectric constant, and (even more important) the thickness variations of the solder mask.

If the solder mask dielectric constant is about the same as that of PCB material (e.g., FR4 or polyimide), then the influence can be related to the thickness of the coating as a function dielectric constant.

In stripline configurations, the solder mask effect is not a factor, since there is generally a ground plane between the solder mask and the sensitive conductor patterns.

**5.8 Shelf Life and Storage** Solder mask suppliers define the shelf life as well as the storage conditions for their specific products. This information is usually provided in the technical data sheets and/or on the packaging. Usage of product, which was stored under different conditions than recommended and/or longer than recommended, may result in insufficient process compatibility and/or different end properties. It is possible that product changes are not very obvious at first but can cause costly damage during the solder mask process or assembly processes and/or unacceptable end-properties. For example: The viscosity of a product may not change to an alarming extent, however the developability of the product decreased over time resulting in solder mask residues in plated-through holes (PTHs) of an expired material.

Photoimageable solder masks are light sensitive, usually in the UV wave length range. Solder mask suppliers select packaging for these products to avoid light transmission during storage and transport. As soon as these original packages are opened UV light exposure should be avoided.

The solder mask supplier should be contacted for recommendations in case the storage time is exceeded or the storage conditions were not appropriate.

**5.9 Pot Life** Most liquid solder masks are shipped to the PCB fabricator in two or more parts, typically referred to as “ink” and “hardener” or similar terms. “Pot life” can be defined as the time between mixing of the two or multiple parts and application to the PCB, or the completion of the photoimaging steps (development in particular).

Typically the single parts are not mixed together until shortly before use because there is a chemical reaction that begins to take place, albeit very slowly, as soon as the components are mixed. Manufacturers typically provide information on the maximum recommended time between mixing and completion of the application and/or imaging steps. Pot life is affected by the temperature of the mixed solder mask. All chemical reactions speed up with elevated temperature so it is advisable to keep mixed solder mask from seeing any elevated temperature - cooler is usually better.

Effects of excessive time after mixing can include slower or nondevelopment (lock-in), slower exposure and/or application difficulties. In some cases the adhesion of the solder mask to the PCB can degrade if pot life is excessive.

One-component materials usually do not have a pot life (unless there is an oxidative or evaporative process). The pot life is usually equal to the shelf life (unless otherwise specified by the manufacturer).

## 6 DESIGN ASPECTS

**6.1 Choosing a Solder Mask for the Application** Every application is certainly different and thus solder mask requirements vary between the different OEMs and often even for specific jobs. However, there are general trends seen within specific industries and specific applications, often based upon a specific environment that the PCBs are used in. The following sections discuss some of these general trends.

**6.1.1 Automotive** Since the birth of automotive electronics, the purpose of solder mask has changed. Originally, solder mask was used only as a processing aid to prevent solder defects during wave soldering. Since those early days, electronic assembly technology has progressed from through hole designs, to surface mount, to chip on board technology. The assembly process and chemicals have also changed from 100% cleaning and conformal, to no-clean and no-coat. Today, it is the foundation of complex electronic structures.

Likewise, application of automotive electronics into the vehicle has increased and has diversified. It started with noncritical vehicle functions, and has expanded into critical vehicle control and safety systems, such as air bag controllers, engine control, ignition systems, steering by wire, brake by wire, and throttle control by wire.

is to bring most consumer electronic devices into the vehicle, such as mobile media and communication.

Some of the major facts that distinguish automotive electronics from some other typical electronic applications are the following:

- Automotive electronics must have very high reliability with expected and negotiated lifetimes often in the 15 to 20 years range.
- Very low expected and negotiated failure life.
- Mandated maximum failure rates for emission control systems.
- Often a very harsh operating environment (wet and corrosive, high temperature).

Automotive applications have widely varying requirements which range from typical consumer requirements for assemblies such as remotely operated keys to very stringent harsh environment and very high reliability, like under hood on engine applications where the temperatures may reach 175°C [347°F]. Such requirements vary widely with each individual OEM. Table 6-1 contains some general ranges and typical environmental requirements for temperature, humidity and corrosion resistance.

**6.1.2 Aerospace** The use of solder mask for aerospace applications has specific requirements. The material should protect circuitry from foreign object debris (FOD) such as solder balls, solder splines, wire clippings, etc., as well as solder process chemistries. Solder mask is also used to inhibit moisture absorption at a minimum and keep liquids from interacting with the circuitry.

Material characteristics may include but are not limited to:

- **Outgassing** – No material in a vehicle may outgas above certain limits. This keeps residue from leaving a solder mask and depositing onto a sensitive surface, such as, optics. A common test method used by NASA is ASTM E-595.
- **Material Resistivity** – Solder mask should be able to withstand all of the chemical environments that the hardware will encounter.

- **Thermal** – Often applications require solder mask to maintain structural integrity at all times through temperature excursions of -65 to 125°C [-85 to 257°F] during product qualification with temperature change rates of 8 to 10°C/minute [14 to 18°F/minute]. Some test methods require dramatically higher rates of temperature change.
- **Vibration and Shock** – Solder mask should not flake off at 20 Gs or greater in some cases.
- **Vacuum** – Solder mask for aerospace can generally expect to see 0 Torr (0 bar).

**6.1.2.1 Avionics** Aviation electronics (avionics) are high reliability, often life critical, devices, which have to operate in hostile environments (humidity, salt air, heat, cold, pollutant gasses) reliably for 20-30 years or longer. Designs are often very complex, requiring multiple manufacturing processes. With these long life times and critical reliability parameters, avionics are often field repaired numerous times throughout the life cycle of the hardware. Therefore, when designing avionic assemblies, the designer must select a solder mask which can do the following:

- Survive the heat of reflow in the intended manufacturing process. This usually involves single or double pass reflow surface mount technology (SMT) only, a wave solder exposure (through hole or mixed technology), and at least one component removal and replace operation (e.g., replacing a ball grid array (BGA)).
- Be compatible with all adhesive and adhesive cure processes.
- Be compatible with all fluxes used and cleaning chemistries used.
- Be compatible with hand soldering fluxes and topical cleaning solutions.
- Be compatible with the conformal coating to be used.
- Be able to survive the heat generated by hot components.
- Maintain consistent dielectric properties throughout the assembly process, and which do not change with age.

**6.1.3 Telecommunication** In addition to the general solder mask requirements which are covered by IPC-SM-840,

**Table 6-1 Typical Environmental Requirements for Automotive Applications**

| Application           | Temperature Range              |                                | Humidity                    | Corrosion                            |
|-----------------------|--------------------------------|--------------------------------|-----------------------------|--------------------------------------|
|                       | Minimum                        | Maximum                        |                             |                                      |
| Under hood on engine  | -60 to -40°C<br>[-76 to -40°F] | 140 to 175°C<br>[284 to 347°F] | 85°C/85%RH to<br>65°C/95%RH | 20 to 60 days salt spray             |
| Under hood            | -60 to -40°C<br>[-76 to -40°F] | 105 to 125°C<br>[221 to 257°F] | 85°C/85%RH to<br>65°C/95%RH | 20 to 60 days salt spray             |
| Passenger compartment | -40°C [-40°F]                  | 85 to 125°C<br>[185 to 257°F]  | 40°C/90%RH to<br>85°C/85%RH | 1 day salt fog to 14 days salt spray |
| Trunk                 | -40°C [-40°F]                  | 85 to 125°C<br>[185 to 257°F]  | 40°C/90%RH to<br>85°C/85%RH | 1 day salt fog to 14 days salt spray |