Alternatives To HASL: Users Guide For Surface Finishes

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INTRODUCTION

A great deal of controversy continues to surround the use of Hot Air Solder Leveling (HASL) in the production of printed circuit boards (PCBs). The financial burden, technological limitations and environmental issues surrounding the HASL process continue to grow. This requires an in-depth review by the printed circuit board manufacturing plant, as well as the assembly operation and instrument designers (OEMs), to determine what alternative surface finishes are appropriate.

The benefits of HASL replacement are many. Let's examine them by category of "user":

Circuit Board Producer

- ?? Eliminates lead and hazardous waste expense
- ?? Eliminates safety issues: toxic fumes and fire hazards
- ?? Reduces maintenance: 20 percent down time is common
- ?? Reduces utility costs for heating of hot air and solder
- ?? Fine pitch technology improvement by eliminating bridging
- ?? Improves yield
- ?? Reduces rework

Circuit Board Assembler

- ?? Improves pad coplanarity for superior solder paste print accuracy and component placement
- ?? Improves bare board cleanliness, or Surface Insulation Resistance (SIR)
- ?? Less warp due to reduced thermal stress at producer
- ?? Solder contrast aids solder joint inspection
- ?? Reduces opens and shorts (bridging) with fine pitch devices

Original Equipment Manufacturer

- ?? Improves reliability from minimal copper-tin intermetallic formation
- ?? Improves circuit density by the elimination of hole compensation
- ?? Permits device attachment solder volume control
- ?? Improves fine pitch design ability (removes board level HASL issues)

A variety of surface finish alternatives to Hot Air Solder Leveling (HASL) exist that present the circuit designer, board fabricator, and component assembler with some interesting and challenging options. Electrolytic tin, electroless nickel/immersion gold, and organic solderability preservatives (OSPs) are just a few that are available on the market.

Of these possibilities, organic solderability preservatives, also known as anti-tarnish, are gaining popularity in the industry as low cost alternative to HASL. The OSP surface finish satisfies assembly requirements for fine pitch, through hole, and mixed technology product. These coatings may be defined as a water-based organic compound that selectively bonds with copper to provide an organometallic layer that protects the copper.

Electroless nickel/immersion gold satisfies application-specific requirements for ultra-fine pitch technology, wire bond ability, and superior contact resistance. This process is two-layer, gold over nickel metallic surface finish plated onto the copper base by means of a chemical deposition process.

Pure tin offers a distinct environmental advantage over the traditional lead bearing alloys used as temporary metal etch resists and final plated surface finishes. Matte tin circuitry is a two-layer, tin over nickel metallic surface finish plated onto the copper base by means of an electrolytic process.

BACKGROUND

Printed circuit boards requiring component attachment, whether leaded or surface mount technology (SMT), must have the exposed copper land areas coated with a protective finish. This protective coating must be solderable and, at the same time, act as a barrier for preventing the copper from oxidizing which causes assembly problems for the end user. In the United States, the predominant surface finish in the PCB industry is HASL. Driven by the push for Solder Mask Over Bare Copper (SMOBC), HASL was born as a reliable method to apply solder to the copper surfaces after solder mask. A thin layer of eutectic solder is deposited onto the exposed copper by passing the boards through a hot, molten wave (or pot) of solder and subsequently blasting the excess solder from the boards using high velocity hot air. This process is currently under scrutiny due to environmental and safety issues (hazardous waste/lead exposure), technological limitations (fine-pitch device assembly), and equipment maintenance expenses to name a few.

In contrast, the alternative processes are environmentally friendly, some provide a surface planarity equivalent to the plated copper finish, and most require very low equipment maintenance.

Organic Solderability Preservatives (OSP, Anti-tarnish)

Of the OSP compounds, the two that are predominant in the industry are benzotriazole and substituted benzimidazole. The former of these has been utilized both in the metal finishing industry as a true anti-tarnish for hardware plating, and to a lesser degree, in the electronics industry for limited heat cycle solder applications on bare copper. The more recently developed

substituted benzimidazole compounds have the advantage of withstanding multiple heat cycles typically found in mixed technology PCB assembly operations (surface mount and through hole soldering). This advantage is primarily due to the coating thickness that is achieved with the substituted compounds, ranging from 5 to 20 microinches[1] (0.1 - 0.5 microns), as compared to only a monomolecular layer formed with the benzotriazole materials.

In general, OSPs are considered the low cost, high volume alternative, particularly when applied to surface mount technology due to the excellent surface coplanarity of pads. The cost advantage of the process becomes quite apparent to the board fabricator. For example, facilities and maintenance expenses are only a fraction of the operating cost for the anti-tarnish process as compared to HASL. The process does not involve heating and delivering the high volume air or maintaining a molten pot of solder. Losses due to rework and rejected product from the HASL process are substantial and prevent a decrease in the cost of manufacturing. An OSP application system eliminates this waste and allows for flexibility to pass the savings on to the customer.

The cost advantage to the assembler lies primarily in the yield improvements of the component attachment process. Surface mount pad planarity is a technical hurdle that HASL will never overcome, especially for fine pitch devices due to the extreme variation in coating thickness. This non-uniform solder thickness can range from 30-1500 microinches (0.75 - 37.5 microns) depending upon pad geometry and orientation within the panel. In contrast, an OSP coated board provides a surface finish topography equivalent to the plated copper. This allows for improved component placement; furthermore, it will help move the assembler towards finer pitch devices and denser circuits as the limiting factor for fine pitch assembly now becomes the ability to deposit the solder paste.

It must be emphasized that implementing an OSP process may require a re-characterization of the assembly operation; a number of issues must be addressed. For example, the number of thermal cycles a product may see in the assembly process can reduce the operating window for soldering. If excessive, it may be determined that soldering in an inert atmosphere is required in the reflow process, wave solder, or both. Typically, OSP suppliers advertise up to five thermal cycles can be achieved in open air without detrimental effects to solderability. Developing a partnership with the board shop and supplier is an important consideration during the implementation phase.

A second assembly process consideration when using OSP technology surrounds the type and activity of the flux used in each of the assembly operations. Table 1 illustrates the results of an engineering evaluation used to benchmark OSPs in comparison to HASL coated PCBs at one customer site. It was apparent in the evaluation that the OSPs performed differently depending upon the type of flux used. A wide range of responses were found spanning from excellent surface mount solderability with OA or RMA type solder pastes, to relatively poor filling of holes with a low solids (2%) no clean wave solder flux that was not designed for soldering to OSP coated pads.

Assembly Operation	SMT Paste Flux Type	Wave Solder Flux Type	Results with OSP
Customer 'A'	Organic Acid (OA)	Organic Acid (OA)	Compatible with all processes
Customer 'B'	Active Rosin (RMA)	No Clean (2% solids	Compatible with SMT process, Alternative No Clean wave flux required
Customer 'C'	Active Rosin (RMA)	Organic Acid (OA)	Compatible with all processes
Customer 'D'	N/A	No Clean (2% solids)	Alternate No Clean wave flux required

Table 1

At the OEM level, the three key attributes that OSP technology provides the designer are solder joint reliability, circuit density latitude, and the ability to engineer solder joints.

A standard HASL design rule, which is used in the tooling of PCBs, is to oversize drilled holes by 0.002" - 0.003" (50 - 150 microns) to compensate for the reduction in hole diameter caused by the non-uniform HASL solder deposit. With the use of an OSP, this compensation is not necessary; it allows for a reduction of pad size and an overall increase in circuit density. Additionally, since good solder wetting occurs only where the flux comes into contact with the OSP coated copper pad, the flow characteristics of the solder are more controlled. This reduces the risk of bridging and provides the possibility for predicting final solder volume.

Electroless Nickel/Immersion Gold

Electroless nickel is well known in the metal finishing industry for its wide range of physical properties[2]. Hardness, wear resistance, corrosion resistance and minimal magnetic properties in addition to the high degree of deposit uniformity have made it a premier metal finish satisfying a wide variety of applications. Geometry's with almost any degree of complexity may be plated with electroless nickel, which is an attractive feature allowing for its entry into circuit board applications. Nickel is also a fairly active metal and quickly passivates (oxidizes) soon after plating, thus soldering to the surface becomes increasingly difficult with time. However, it has been found that if the nickel is coated with a thin deposit of immersion gold directly after plating, the solderability will be retained.

Electroless nickel is an auto catalytic process using a precious metal catalyst and internal reducing agent for continuous deposit as long as the chemistry is maintained in an active state. During the chemical reaction, a small amount of phosphorus is co-deposited into the nickel creating the desired properties as previously mentioned. Due to the nature of the electroless process, the nickel deposit may be engineered to a variety of specified thicknesses, but deposits of 100 - 200 microinches (2.5 - 5.0 microns) are typical.

In contrast, immersion gold is deposited in an exchange reaction. As the nickel plated part is introduced into the gold solution, a chemical exchange occurs replacing nickel on the surface with a thin layer of pure gold. The reaction stops when

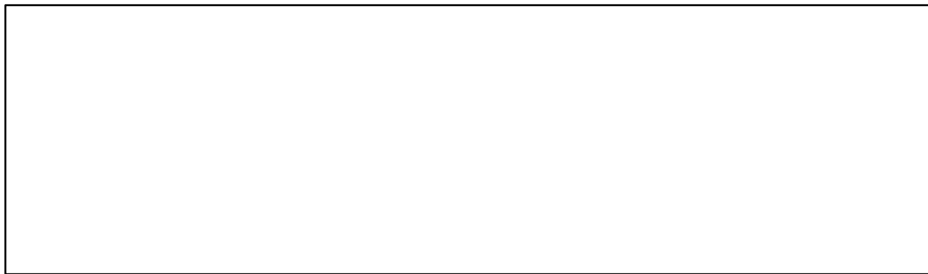
all of the exposed nickel is replaced with gold, thus an upper limit of approximately 8 microinches (0.2 microns) is found with the process.

While obviously a more complex coating method than OSP, the advantage of the electroless nickel/immersion gold process is an application specific technology on circuit boards. These include PCBs which require excellent solderability on fine pitch SMDs, corrosion resistance for on-board contact pads, and the opportunity for wire bonding of ultra fine pitch (i.e. 0.008”) chip on board (COB) designs.

There are some drawbacks which the user should be aware of when considering this finish. Of most concern, due to the nature of the fairly aggressive chemical process involved, not all solder masks are capable of withstanding the plating baths. It is desirable to plate after the solder mask application to minimize the gold area plated and provide a “solder mask over bare copper” (SMOBC) product, but those masks which are high in acrylic content should be applied after the immersion gold plating. Most liquid photoimageable solder resists with higher epoxy content should be able to withstand the chemical exposure without evidence of lifting or bath leaching, but these should be tested to verify compatibility.

Matte Tin

Tin plating has been used at Tektronix as a final solderable metal finish for many years, for both aesthetic purposes and a reliable lead free alternative. Through multiple imaging and plating steps, it allows for complex internal gold contact patterns to be made as well as surface mount and though hole circuitry. The standard thickness of the tin is 300 to 400 microinches (7.5 - 10 microns), but this may be tailored to any desired thickness or fine pitch line width as the deposit is not reflowed after the plating operation.



Nickel provides a copper migration barrier layer and a physical "shelf" for tin to prevent leaf and potential shorts. Plated tin is more familiar to the PCB industry as a temporary metal etch resist when producing bare copper product and has recently gained a certain popularity in chemical processing due to the lead free effluent, improved aspect ratio capability, and lack of stripping residues.

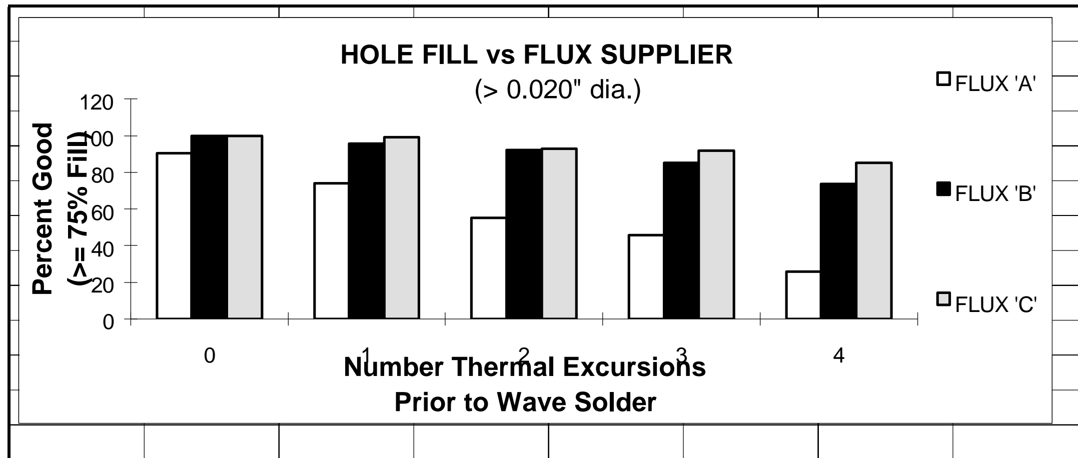
When considering this option, it is important to understand there are different tin deposits available in the industry. Two popular choices are the matte finish and the bright finish. Bright tins are typically the most aesthetic in appearance, but have a high degree of codeposited organics and can result in occasional difficulties with dewetting during the soldering operation. An additional drawback with bright tin is the plating chemistry is not as controllable as the matte tin; therefore, it has less plating capability at higher aspect ratios (ratio of board thickness-to-hole diameter) greater than 3:1. In general, the matte tin system provides an improved ability for high aspect ratio plating, fine pitch product coverage, and acceptable performance for soldering.

Assembly Considerations

Each of these alternate coatings work well with most assembly processes; although, some special considerations must be taken with the OSP surface finish. It is the mechanism of (acid) fluxing plus heat during the assembly process that dissolves the organic coating. Good solderability is achieved where flux comes into direct contact with the copper surfaces to be soldered; hence, screen print and wave solder process optimization may be required.

Another industry perception surrounding OSP technology deals with no clean, low solids flux technology. Contrary to some reports, OSP coated PCBs can be assembled in an open air environment using no clean, low solids flux technology. This includes the ability to assemble mixed technology product without the use of an inert atmosphere in the reflow or wave solder

operation. As depicted in Graph 1, some no clean wave solder fluxes perform better than others. It is recommended to evaluate several no clean fluxes for process compatibility before full production implementation. It must also be mentioned that, as seen with other finishes such as HASL, the use of nitrogen in any assembly process will provide a larger process window.



GRAPH 1: No Clean (LSF) Flux vs. Thermal Cycling

Another open air test comparing OSP against electroless nickel/immersion gold indicated very similar results. This test compared hole fill quality of 0.013 inch, O. 023 inch and 0.033 inch diameter holes using a water soluble (OA) wave solder flux. Test samples were thermally cycled one (1), two (2), and four (4) times prior to the wave solder operation. All samples passed the 75% solder rise hole fill criteria.

Board washing between assembly operations is another consideration for PCBs coated with an OSP. Aggressive surfactants or solvents such as Terpenes can actually remove the organic coating. Where cleaning between assembly operations is truly necessary, it is recommended to use water less than 140?F. If a surfactant is deemed necessary, choose one that is compatible with organic coatings. Along the same lines, reworking boards from solder paste misprints may also require cleaning. Rework capability depends upon the rework cleaning process, time delay between cleaning and re-print, and especially, the assembly process and fluxes used. More active fluxes will typically give better results. It should also be pointed out that the contrast of the OSP coated copper-to-solder paste interface is much better than HASL. This helps to reduce misprints caused by poor visual alignment of the stencil to the PCB. Additionally, OSP coated boards, unlike HASL, are easily reworkable by the PCB shop; therefore, the assembler can have a fresh coating applied to the PCB whenever the coating is damaged or if shelf life becomes an issue.

As a final note, in the case where the circuitry is plated with tin, reflow under the solder mask during wave or infrared reflow is possible if the temperatures are not properly controlled. The melting point of pure tin is 232 °C as compared to 183 °C of eutectic solder, thus the window is larger than plated solder circuitry but should be nonetheless taken into consideration.

Electrical Contact Considerations

An area that is not adequately discussed in most publications deals with the performance of alternative surface finishes in electrical contact applications. Electrical testing of bare boards and effects of non-solder coated PCB mounting holes utilized for grounding purposes need to be taken into consideration in the design and selection process. For example, in the case of OSP, even though the coating is applied to a clean bare copper surface, the organic coating has an insulating property. Additionally, since the copper will oxidize, steps must be taken to accommodate for this. The following areas are affected by this phenomenon:

At the PCB Plant:

Continuity electrical test should be performed before the coating process so as not to damage the finish while probing the surface pads with a “flying lead” or a “bed of nails” test fixture. Oxides on the copper pads created by previous baking processes may interfere with proper contact, thus a chisel point pin for electrical test is recommended.

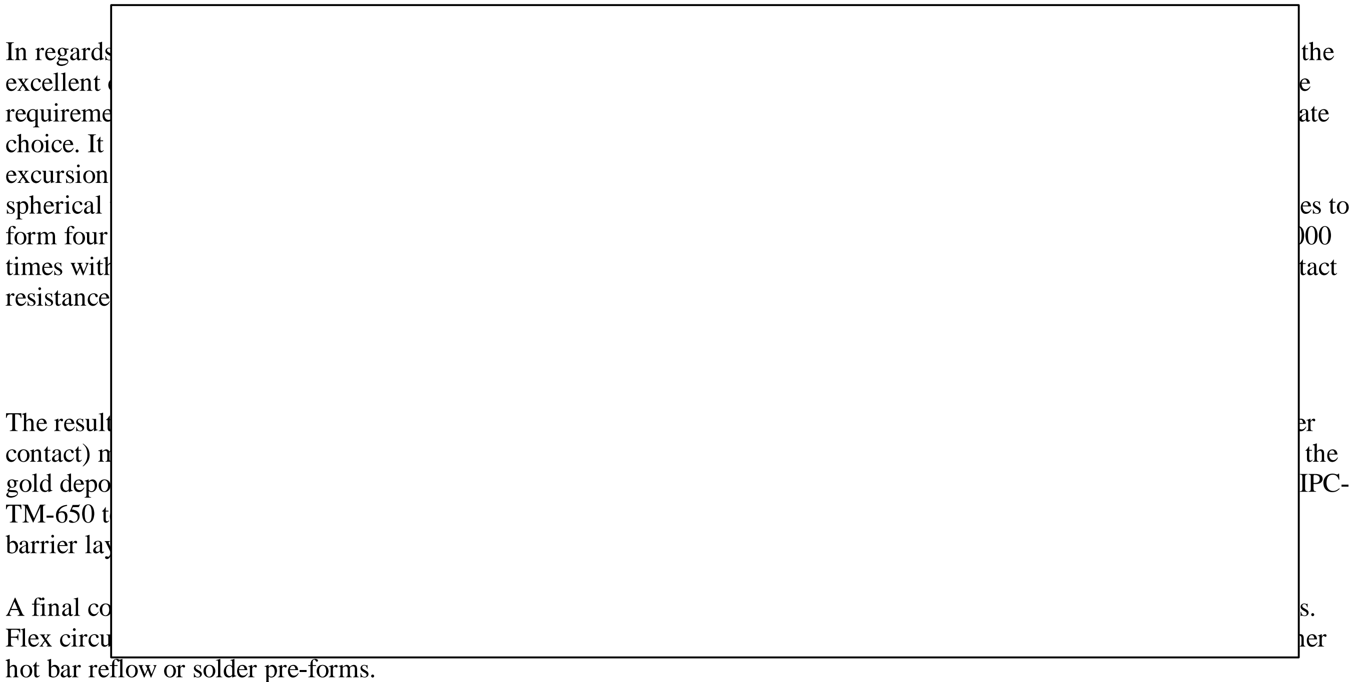
At the Assembly Plant:

Circuit grounding relying on mounting hardware is occasionally used in instrument assembly for grounding the PCB to the chassis or stand-off posts. If the grounding pads are OSP coated copper, it may require a higher torque or more contact screws to make an adequate ground. This phenomenon may be especially evident during functional testing of the assembled boards. Depending upon the board design, electrostatic discharge (ESD) pads and other electrical test pads may be effected. One solution is to screen these surface areas with solder paste, thus becoming solder coated during the reflow process.

At the Instrument Level:

Electromagnetic interference, or EMI shielding, may be effected if the grounding issue is overlooked. During Merix’ OSP introduction phase, a PCB design issue became apparent on product utilizing plated through holes for mounting and grounding purposes. The concern related to potential problems surrounding dissimilar metals between the now copper mounting holes and the plated hardware. These plated through holes are typically masked prior to the wave solder operation to prevent the holes from plugging with solder. This process leaves the mounting holes with bare copper. A new grounding hole design that provided a non-plated through hole for mounting and grounding was developed (illustration 1). This design provides minimal exposed copper without plugging the mounting hole during wave solder. A second benefit from this design is the elimination of the temporary mask operation prior to wave soldering. Another solution, depending upon the mounting hardware, would be to selectively gold plate the mounting holes. This only requires an artwork modification on product already using the selective plate process.

Illustration 1



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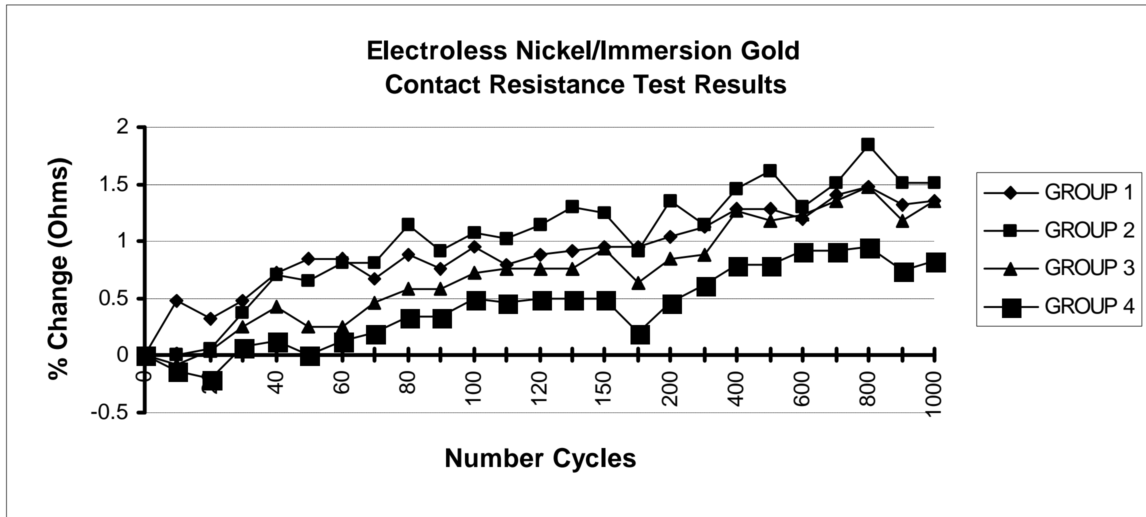
These “flying lead” designs require a certain amount of bending to allow for uniform bonding to the planar pad arrays. In this case, electroless nickel/immersion gold is a poor choice as the percent of elongation of the nickel less than 1%. This lack of

ductility will create cracks in the nickel when bent and possibly adhesion failure to the central copper conductor. A more appropriate choice for this application is the OSP coating.



GRAPH 2: Electroless Nickel/Immersion Gold Contact Resistance

High Frequency Considerations

In microwave structures, the signal loss of the conductor with its associated surface finish must be considered in conjunction with circuit design. The selection of a surface finish is not as critical for the electrical performance of internal microwave structures, such as striplines and embedded microstrip designs, due to the minimal interactions of the signals with the surface finish. Surface finish selections for external microwave structures can influence the electrical performance of the system. Edge coupled structures, such as couplers, coupled line filters, etc. will be influenced the greatest. Signal frequency and line width and spacing tolerances will also effect the selection of surface finishes for external structures. Higher frequencies results are smaller skin depths and a greater portion of the signal residing in the outer portions of the signal feature. Experience at Merix indicates that at frequencies greater than 2 GHz, the extra losses from the electroless nickel can be excessive in some edge coupled structures. For tight tolerance line widths and line spacing structures, the thickness of the surface finish will be critical and require size compensation of the underlying signal feature. In this case, the tight line width and spacing tolerances favor the OSP coating.

Reliability Considerations

The October Project Committee[3] has been active in evaluating OSP technology as a viable, alternative surface finish to HASL as it is the only non-metallic surface finish available. Through a series of reliability evaluations by committee members, it was concluded that organic coatings meet the technical and reliability requirements of the industry. For example, Digital Equipment Corporation and Battelle performed a study to determine the reliability of bare copper versus solder coated boards[4]**.** This investigation examined the failure mechanism of metal migration under bias using fine-line technology product. *Conclusion was that bare copper boards are more reliable than solder down to a 0.004" inch line and space.*

The presence of exposed copper after the assembly operation is another topic of discussion when dealing with OSP technology. As with most soldering operations, a 100% wetting of the base metal does not always occur, regardless of the surface finish selection. This is difficult to visually observe with HASL coated product, but contrasting base metals will show this condition, such as OSPs. The phenomenon will be mostly visible along the perimeter of SMT pads and topside (annular ring) of plated through holes after wave soldering. As many OEM users have demonstrated, this exposed copper does not pose any reliability problems. Copper forms a protective oxide layer (like aluminum) which does not continue to decompose. PCBs have been produced for many years with electrolytic gold or tin as the surface finish, and all contain a significant

amount of exposed copper. The only difference is the copper cannot be readily observed as it is located on the circuit sidewalls, and not the surface.

In the assembly operation utilizing the electroless nickel/immersion gold, the concern may arise regarding joint embrittlement which could affect the reliability of the solder connection to the device. In typical applications where solder paste stencils apply between 0.006” to 0.010” thick solder paste, the volume of immersion gold (3-8 microinches) is not significant as compared to the volume of solder being deposited. Currently, this surface finish is widely used in telecommunication applications around the world.

Electrolytic tin plating surface finish has been available for many years. Occasionally, the concern of "tin whiskers" arise which has caused some apprehension for using pure tin and has actually been rejected by some companies. This phenomenon, while not completely understood, is often associated with areas of high plating stress and occurs before soldering operations. At Merix, tin whiskers have been a rare occurrence, in fact, the last reported incident was in the early 1980's from a ten year old bare circuit board plated with bright tin that was found in the warehouse. To our knowledge, no product that has gone through the soldering process has exhibited whiskers with either the bright or matte tin plated finish.

Gold Wire Bond Considerations

Ultra-high density packaging designs occasionally have the requirement for direct die attach and chip on board (COB) assembly. This combination of fine pitch bond-out leads and need for surface co-planarity excludes the solder, organic, and tin surface finish options. Traditionally, this requirement has been satisfied by electrolytic pure gold plating in the 30 to 50 microinch range. However, this thickness requirement for wire bonding can be at odds with surface mount device attachment reliability due to an increase in tin/gold intermetallic solder joint embrittlement.

In an independent study[5] which evaluated gold wire ball bonding, wire pull tests were performed to determine the bond strength to the immersion gold plating. In the test, 0.001” (25 micron) American Fine gold wire (EL3-6%, T.S. 8 grams) was used with bond temperature set at 160 degrees C. Results are depicted in table 2. Wire bond data for electroless nickel/immersion gold shows that this surface finish is a viable option to the traditional electrolytic pure gold plating.

Nickel Thickness (?m)	Gold Thickness (?m)	Average Bond Strength (grams)	Minimum Bond (grams)	Standard Deviation	Percent Standard Deviation
4	0.10	6.56	6.3	0.24	4%
7	0.10	5.46	5.0	0.30	5%
4	0.15	7.59	6.9	0.40	5%
7	0.15	7.29	6.6	0.40	6%

Table 2

Cost Considerations

An economic consideration in the selection of alternative surface finishes is the manufacturing cost of the bare printed circuit board. An operational cost analysis was recently completed at Merix Corporation detailing the annual expenses associated with the HASL process[6]. Many factors were incorporated in this comprehensive study that may not have been included with a traditional operational cost analysis. During the course of the investigation, a number of "hidden" items and tasks were found to be necessary in order to support the HASL process; but not all were included in the normal operating cost.

These hidden items accounted for an additional 42% in costs which normally would not have been captured in the traditional cost analysis. For example, the cost of materials and labor associated with masking and cleaning selectively gold-plated contacts was found to be a major expense. Exposed gold circuitry must be masked prior to processing through the HASL line in order to prevent the gold from dissolving into the molten solder bath. The method for subsequently removing this mask is equally, if not more, labor intensive. Another example not included is the additional cleaning that is often required by PCBs coated with a dry film solder mask. These masks typically absorb ionic contaminates introduced by the HASL process (flux & oils), thus requiring an added cleaning operation to satisfy surface insulation resistance (SIR) specifications.

A relative cost comparison of the alternative finishes is summarized in the following "Design Selection" chart.

DESIGN SELECTION CHART

Comparison	**HASL**	**OSP**	**IMMERSION GOLD**	**MATTE TIN**
Surface Co-planarity	Poor	Best	Best	Good
Hole Compensation	Required 0.002"-0.003"	Not Required	Not Required	Required 0.002"-0.003"
Fine Pitch Quality 0.020" or less	Poor	Best	Best	Good
Surface Contrast (Assembly)	Poor solder/solder	Best solder/copper	Best solder/gold	Good solder/tin
Solder Volume (Assembly)	Not Predictable	Predictable	Predictable	Predictable
Environmental Hazard	High (Pb)	Low (Water based)	Medium (Ni)	Medium (Ni)
Thermally Stressed	Yes	No	No	No
Electrical Contact Use	Fair	Poor	Good	Fair
PCB ShopGold Contact Masking	Yes (Difficult)	Not Required	Not Possible	Selective Plate Possible
Grounding Insulator	No	Yes	No	No
SMOBC	Yes	Yes	Limited	No
Reflow under Solder Mask	No	No	No	Possible
Microwave	Fair	Best	Less than 2GHz	Less than 2GHz
Wire Bond	No	No	Yes	No

DESIGN SELECTION CHART				
Comparison	**HASL**	**OSP**	**IMMERSION GOLD**	**MATTE TIN**
Shelf Life (Typical)	12 Months	12 Months (Process Dependent)	Testing Required	12 Months
Availability	Yes	Yes	Yes	Limited
Cost of Surface Finish	Standard (1x)	Lowest (0.2-0.3x)	Highest (1.5-2x)	Standard (0.9-1x)

Chart 1 Process Benefits Comparison

Conclusions

Viable, dependable, and environmentally friendly surface finish alternatives to HASL coated PCBs currently exist on the market. These surface finishes can provide improved assembly performance at a lower total cost. Of the three discussed, the OSP surface finish is reliable and considered by many to be the high volume, low-cost replacement for HASL. While obviously a more complex coating method than OSP, the advantage which the electroless nickel/immersion gold process provides is an application specific technology on circuit boards. These include PCBs which require excellent solderability on fine pitch SMDs, corrosion resistance for on-board contact pads, and the opportunity for wire bonding of ultra fine pitch chip on board (COB) designs. Matte tin offers a distinct environmental advantage over the traditional lead bearing alloys used as temporary metal etch resists and final plated surface finishes. It has the additional advantage to allow for complex circuits with internal gold plated switch contacts without the requirement of masking and subsequent cleaning processes. Other surface finish options continue to appear, such as electroless or immersion palladium, and are a clear indication that the industry is moving away from HASL towards a more proficient and environmentally friendly alternative.

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