EFFECTS OF SURFACE FINISH ON HIGH FREQUENCY SIGNAL LOSS USING VARIOUS SUBSTRATE MATERIALS

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ABSTRACT

The amount of information transferred on wireless networks has increased dramatically with the tremendous growth of mobile phones, Internet access, and hand held devices. In order to build the infrastructure needed to handle ever-increasing data transfer, manufacturers of electronic devices turn to high speed, high frequency electronic signals. The need to render these electronic devices portable is another technology driver. The merge of high-frequency signals with small geometry conductive traces means that the topic of signal loss has reached a critical point in existing device production.

The integrity of a high-frequency signal can be affected by several factors during Printed Circuit Board (PCB) construction. The geometry of the conductor, the type of metallization used in/on the conductor, the signal frequency, the temperature of the substrate, and the type of dielectric material insulating the conductor all play an important role.

Representatives of material supply, board fabrication, and chemical process supply commenced a project to study some of the influential factors in more detail. A primary variable was the type of metallization used on the circuit board surface. Organic solderability preservative (OSP), hot air solder leveling (HASL), electroless nickel immersion gold (ENIG), and immersion silver were studied as PCB surface finish alternatives. Substrates under investigation included woven glass PTFE, ceramic-filled woven glass PTFE, and FR4 epoxy as a control. Specifically designed microstrip circuits were tested within a frequency range of 60 MHz to 26.0 GHz for signal loss across a range of PCB operating temperatures. At this stage, data was used to 10.0 GHz. Continuing studies will inspect data to 40 GHz.

The results from the investigation allow prediction of signal loss characteristics across a broad frequency range when parts are re-designed to use alternative Pb-free surface finishes on PTFE substrates. The experimenters' intent was to allow for a simple test usable by PCB fabricators to qualify their internal processes.

INTRODUCTION

Materials and Signal Loss

The type of materials used in constructing electronic circuits becomes more critical with the use of high frequency signals. The properties that most influence the signals are related to the conductivity, permittivity (ε_r) and dissipation factor (tan δ) of the materials. Ideally, the conductors should have low resistivity. In addition, the shape, width, and thickness of the conductor trace should be consistent throughout the circuit path. Conversely, the substrate materials should be well insulating. The dielectric constant of the material should remain stable with increasing signal frequency. Through the selection of proper materials, the dissipation factor may be minimized. For productivity considerations, however, these material properties should be considered along with other characteristics such as material availability, processability, and cost.

In the current state of circuit board fabrication, FR-4 substrates are most common. Copper conductors of communications PCB's are most commonly finished with ENIG. In this case, a high frequency signal may have significant loss due to 1) the dissipation factor of FR-4 material, and 2) the resistivity of electroless nickel.

Circuit Board Surface Finishes

The selection of a board finish should be the result of carefully balancing several demands[1]. It is important to consider the cost of the plating process. Thick electrolytic gold can have a large impact on the cost of the final electronic device. The chemical process needs to be widely available in order to satisfy the worldwide procurement demands of large OEM's in the communication industry. Each shop must have competence in the chosen chemical plating process. Solderability, contact functionality and shelf-life of the board are among other functional considerations of a surface finish. As the signal speed increases, the electrical properties of the coating may become the highest priority when selecting a board finish.

Across the broad range of PCB manufacture, Hot Air Solder Level is the most commonly used board finish. In the HASL operation, molten solder is applied to the circuitry by dip or conveyorized application. Excess solder is blown off the circuitry with forced air. HASL use is limited by Lead (Pb) restrictions and by the highly variable topography that results from HASL application.

Organic Solderability Preservatives (OSP's) are thin organic coatings that are applied in vertical or conveyorized chemical processes. The coating in not conductive, so OSP's are not normally used for contact functional circuitry. The electrical signals conduct through the copper, so OSP's are thought to have little effect on high-speed signals.

Electroless Nickel Immersion Gold (ENIG) is a two-layer metallic coating over catalyzed copper. The top layer of gold provides low contact resistance, excellent shelf-life, and good wetting. The nickel provides a barrier layer to prevent copper and gold interdiffusion. ENIG is deposited using a relatively complicated and costly vertical chemical process. Depending on electrical design of the PCB, signals may need to travel through the nickel layer. Electroless nickel/phosphorous can have undesirable magnetic properties and is less conductive than copper, gold or silver. The integrity of a high speed signal may depend on the thickness of the nickel layer and the portion of the conductor through which the signal travels.

Table 1 - Resistivity of PCB Metals[2,3,4]

Copper	1.7 μΩ.cm
Gold	2.4 μΩ.cm
Nickel	7.4 μΩ.cm
Electroless Nickel Phos.	55-90 μΩ.cm
Silver	1.6 μΩ.cm
Tin	10.9 μΩ.cm
Sn60Pb40 Solder	17.0 μΩ.cm

Immersion Silver consists of a very thin (0.15-0.50 micrometer) coating of nearly pure silver. Organic materials are typically codepoited within the silver for prevention of tarnish and electromigration. The metal coating is deposited via a relatively simple and inexpensive conveyorized or vertical chemical process. Silver is the most conductive element and consists of only the outermost coating on the conductor. The belief is that silver will not have a significant effect on high-speed signals because of its negligible thickness relative to skin thickness. The benefit of silver relative to other PCB coatings lies in its flat topography for high density circuit designs and its functionality as a contact surface.

The thickness of the board finish coatings is increasingly important with higher frequency signals due to the "skin depth" of the current flowing through the PCB trace "transmission line." The skin depth varies with the frequency of the signal and the material of the conductor, and is defined as the distance in the conductor at which the electric field has decreased to 30% of the value at the surface.[5]

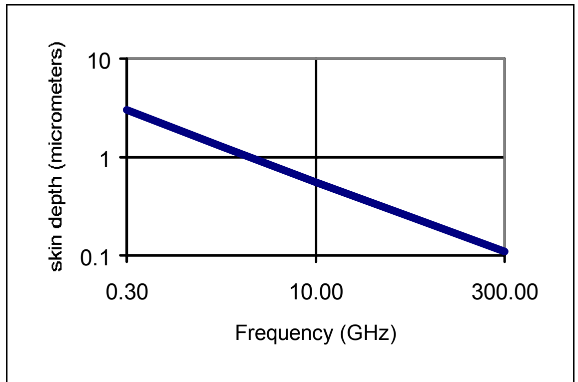

Figure 1: Skin Depth with Increasing GHz[5]

High Speed Laminate Materials

The need for circuits capable of operating at frequencies over 2GHz has motivated designers to consider materials other then traditional FR-4. Alternative materials have been integrated into either pure or multi-layer mixed dielectric packages capable of providing highspeed digital, RF/microwave, or combined circuit functionality.

To characterize the surface finish's loss performance with alternative dielectric materials, three substrate types were investigated, covering a range of dielectric and loss performance. Table 2 details the primary characteristics of the substrate materials. The materials chosen consist of an epoxy/ woven glass (FR-4), a ceramic filled PTFE/ woven glass (RF-35), and a PTFE/ woven glass (TLY-5). To insure consistent results, each material type investigated utilized a base thickness of 0.020", clad both sides with one-ounce ED copper foil.

Table 2:Laminate Material Properties

Property	**FR-4**	**RF-35**	**TLY-5**
Permittivity*	4.8+/-0.2	3.5+/-0.1	2.2+/- 0.02
Dissipation Factor *	0.02	0.0027	0.0009
Moisture Absorption	0.20%	0.02%	0.02%
Peel Strength lbs/inch	> 8.0	>10.0	>12.0
Flammability	94V-0	94V-0	94V-0

*Permittivity and Dissipation at 1.5 - 2.0 GHz.

EXPERIMENTAL

To characterize losses due to surface finish, a 50-ohm copper microstrip was fabricated on the three types of substrate materials and measured across a range of frequencies for insertion loss in decibels. The same 50-ohm test circuit was used for all test coupons of the selected material. The conductor design was altered for each substrate material according to each material's dielectric properties. Loss characteristics from the five surface finishes (OSP, HASL, low ENIG, high ENIG, and immersion silver) were compared.

Test Vehicle Fabrication

Process panels were grouped by material type and were drilled and plated in the same set up. Omni Circuits Inc. manufactured the test vehicle. Omni panel plates using an automated Uniplate horizontal line and Atotech electrolytic copper chemistry. Material was 0.020 1/1 oz. copper clad laminate. Another 1.2 mils (approximately 1.0 mils inside the via holes) was plated on to the surface. Reference cross-sectional photos Figures Appendix A1a-A5c.

Panel preparation consisted of a micro-etch pre-clean followed by pumice scrub and dry-film application. Panels were exposed using the same top film for all panels of the same material. A coupon identification legend was added in the copper of the ground plane. Panels were then developed and etched with cupric chloride. A horizontal Schmidd etcher was used for its capability to maintain line width integrity of the 50-ohm microstrip. The surface finishes were applied as follows:

OSP: Two panels of each material were processed through a horizontal line using Shipley Ronal's Ronacoat™ chemistry. Preparation consisted of pre-clean and microetch.

HASL: Two panels of each were processed in a Gyrex vertical Hot Air Solder Leveling machine. Preparation consisted of micro-etch/ pre-clean followed by a surface activator. Panels were post-baked after solder coat.

Low ENIG: Two panels each were process through a vertical dip immersion Shipley Ronal nickel/gold line with agitation. Nickel thickness was targeted at 50 µinches. XRF equipment was used to verify the mean nickel thickness of 57.7 µinches. The mean gold was measured at 6.2 µinches.

High ENIG: Same as above except nickel thickness was targeted at 200 microinches. XRF equipment was used to verify the mean nickel thickness 197.5 µinches. On this sample set, mean gold thickness was determined to be 4.9 µinches.

Immersion Silver: Two panels were processed through a vertical dip MacDermid Sterling™ immersion silver process with agitation. Immersion silver thickness was determined by XRF to be 8 –12 µinches.

Panels were CNC routed to depanelize test coupons. No solder mask or other types of surface protection were added.

Electrical Measurement

Electrical measurements were conducted at Rockwell Collins, Inc. For this set of experiments, the test specimen was a 50-ohm microstrip transmission line. Each coupon was mounted in a test apparatus that consisted of an aluminum carrier plate and stainless-steel SMA connectors. The connectors (rated to 18 GHz with 20-mil flat tabs) were soldered to the test specimen. An HP8510 vector network analyzer with TDR (time-domain reflectometry) was used to collect full, two-port S-parameters and account for the contribution of the test apparatus. HP test apparatus is shown in Figure 2.

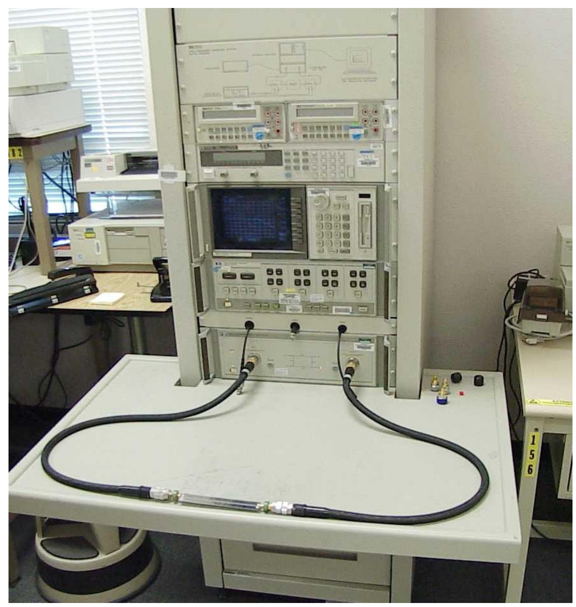

Figure 2: Measurement Apparatus

The test method consisted of visual inspection, physical measurements, system calibration, test apparatus/ circuit validation, and electrical data collection. Each specimen was visually inspected with the naked eye as well as under a microscope to ensure there was no damage. In addition, physical measurements (line widths) were taken to ensure the microstrip lines were etched to within an acceptable tolerance to yield a good 50-ohm line. Some anomalies found at this stage appeared to be dependent on imaging and plating quality.

The measurement system was calibrated using a 3.5mm calibration kit. Each test specimen was mounted in a test apparatus and connected to the measurement system. TDR measurements were used to validate the performance of the coax-to-microstrip transitions. The loss contribution due to the connectors was verified to be so small enough that it wasn't necessary to gate its response out of the measurement. Likewise, the return loss (S11 and S22) of each specimen revealed that the mismatch losses were negligible. The final step was to collect the total insertion loss data (S21) and mathematically manipulate it by the length of the line to yield loss per unit length data as a function of frequency.

$$\textbf{Insertion Loss (dB/inch)} = 20 \times \text{LOG}\left(\left[\text{SQRT}\left(S21^2_{real} + S21^2_{imag}\right)\right] / 5.02\right)$$

The figure-of-merit collected was the total insertion loss of a 5-inch line, with final data presented as dB/inch vs. GHz. Figure 3 demonstrates the test specimen connection.

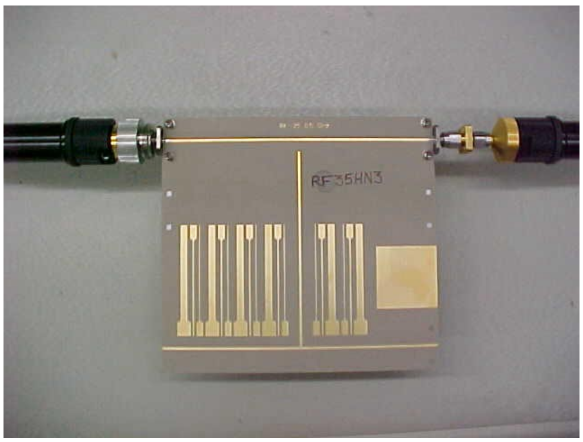

Figure 3: Test Board Measurement

In future experiments, the test specimen, apparatus, and methodology will be refined to collect more comprehensive data. The test specimen will include resonator structures that will allow differentiation among conductor and dielectric losses. Also, a more sophisticated test apparatus with custom calibration standards will yield greater accuracy, repeatability, and efficiency. Additional refinements to the test methodology/ procedure will enable the efficient collection of electrical performance parameters in to the millimeter wave frequency range.

RESULTS AND DISCUSSION

Data were gathered and evaluated to ensure statistical significance. For each test board, 400 datapoints were collected. Further, 3 boards were measured of each finish to form an average. Overall, 36,000 datapoints were recorded and analyzed. The series of data from TLY-5 material plated with High ENIG had to be discarded due to improper sample handling. The summary data set is presented as Table 3.

Table 3: Substrate and Finish Loss (dB/inch)

	loss at 10GHz	Δ due to PCB finish	
FR-4	0.80 – 0.89	0.086	(10.2 %)
RF-35	0.31 – 0.33	0.020	(6.2 %)
TLY-5	0.20 – 0.24	0.037	(16.7 %)

The averages for each variable set were collected into the summary chart Figures 4-6.

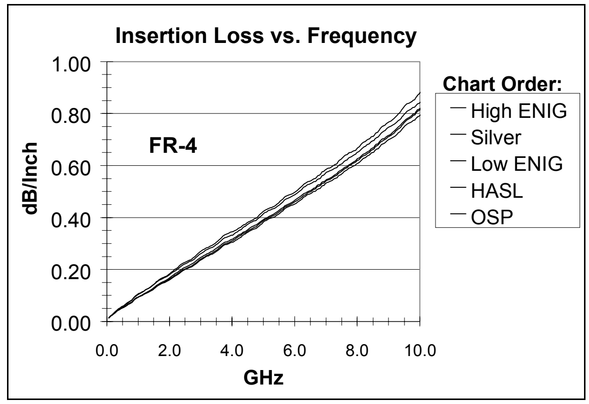

Figure 4: Loss vs. Frequency on FR-4 material

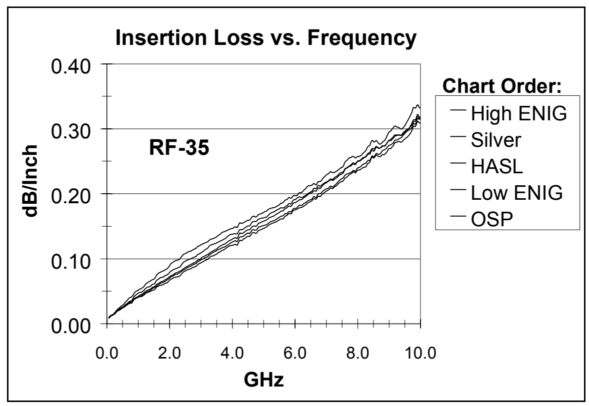

Figure 5: Loss vs. Frequency on RF-35 material

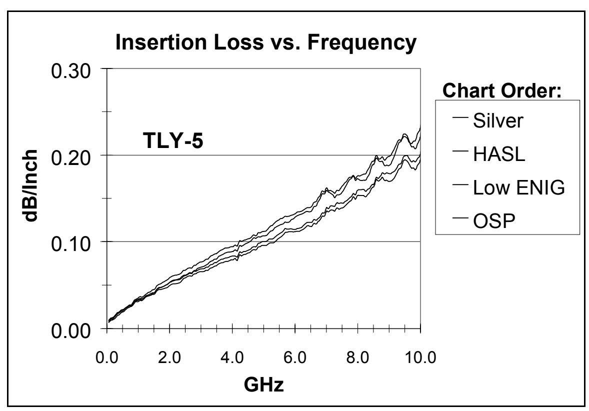

Figure 6: Loss vs. Frequency on TLY-5 material

The insertion loss from samples manufactured with FR-4 material was calculated to be about 0.84 dB/inch at 10GHz. The variation due to surface finish at high frequency was 0.0860 db/inch (10.2%).

The insertion loss from samples manufactured with RF-35 material was calculated to be about 0.32 dB/inch at 10GHz. The variation due to surface finish at high frequency was 0.0198 db/inch (6.2%).

The insertion loss from samples manufactured with TLY-5 material was calculated to be about 0.22 dB/inch at 10GHz. The variation due to surface finish at high frequency was 0.0372 db/inch (16.7%).

An increasing amount of ripple in the signal was found above 6 GHz. TDR analysis yielded insight into the location of the ripple's cause within the microstrip coupons. Surface irregularities such as the plating defect in Figure 7 were determined to affect the signal. This defect was assigned to an imaging problem and is representative of the type of defect that becomes troublesome as high frequency signals are applied.

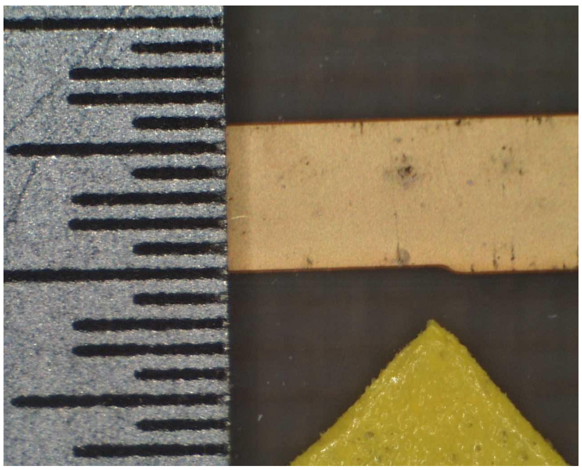

Figure 7: Line Width Irregularity affecting Signal

Statistical Analysis

Data points were extracted from the loss analysis of each material ranging from 1-10 GHz and placed in a block format. The data for each material type was analyzed using Anova to validate if frequency and surface finish supported the hypotheses. The measurements for all three material types concluded that frequency and surface finish were significant variables, producing F statistics well above the F-critical values.

FR-4	F-value	F-critical
Surface Finish	18.74	2.86
Frequency	3272.55	2.71

RF-35	F-value	F-critical
Surface Finish	21.05	2.86
Frequency	2898.12	2.71

TLY-5	F-value	F-Critical
Surface Finish	9.90	3.29
Frequency	587.04	2.90

Figure 8: ANOVA Significance of Variables

CONCLUSIONS

The following observations were made as conclusions to this experiment:

- Signal frequency variation, as expected, had the primary influence on loss measurements. All substrate materials and microstrip plating finishes suffered from loss in signal integrity as signal frequency increased. The maximum loss due to signal increase was on FR-4 plated with High ENIG. Nearly 0.9 db/inch was observed at 10 GHz. More than 1.6 db/inch was measured at 18 GHz (the rated limit of the connector used) but this data was discarded until improved apparatus is installed.

- The substrate material had a profound effect on insertion loss measurements. The variation in insertion loss due to the selection of board substrate was on the order of 0.6 dB/inch. The substrate material and its loss tangent should be the basis for establishing the loss range within which the circuit is capable of functioning.

- The surface finishes had less influence on loss characteristics than expected. Anecdotally, our team expected the High ENIG surface to be substantially more lossy than all other finishes. In fact, all surface finishes were measured to within 0.1 dB/inch even at 10GHz. The expectation at higher frequencies is that the EN barrier will begin to show more profound losses compared to other finishes. Updated information will be presented for higher frequencies at the time of presentation.

- Surface finish selection became more important with higher frequency. The difference in insertion loss among board finishes was within 0.0072 db/inch at 0.06 GHz, while the delta was more than 10 times as large, 0.0860 dB/inch at 10GHz. On a 5 inch PCB trace, the loss accumulates to a total of 0.43 dB, a value as important as loss due to substrate material.

- The use of OSP and HASL is widespread in the electronics industry. There has been some question as to the effect of new finishes such as Immersion Silver with high frequency signals. The data supports the hypothesis that the Silver has little effect on signal loss due to the conductivity and thinness of the Silver coating.

- Electroless nickel has a detrimental influence on signal conservation. The effect of EN appears to increase at higher frequencies. ENIG coatings as deposited in standard practice (High ENIG in this experiment) demonstrate substantial signal loss above 5 GHz. Lower thickness EN coatings effectively extended the frequency range at which the microstrips were functional. Lower thickness EN may be appropriate for some electronic devices, but may be inadequate for other applications. At the time of this article's publication, the common EN minimum thickness specification was 120 microinch (3 micrometer).

- Selection of a PCB surface finish will depend on several factors. HASL may not meet component density limits. OSP's insulating characteristics may restrict its use in some communications devices relying on surface contact conductivity. ENIG, a clear choice for many handheld communications devices, may become restricted due to its variability in loss performance and impact on high frequency signals. Immersion silver appears to meet many of the functions required of future PCB designs.

- The conductor shape, line width consistency, and etching quality of PCB fabrication steps becomes increasingly important when studying high-frequency signals. In addition, the profile of the copper foil cladding the dielectric material (as documented in Appendix Figures A6 a-c) will affect performance. The electrical testing method described in this experiment is relatively simple and may be applied at PCB fabrication shops as a support for their OEM customers' design departments.

ACKNOWLEDGEMENTS
The authors wish to express their appreciation and admiration of the expert engineers participating in this study. Dan Ash and Lonnie Cotton of Powerwave Technologies advised us on critical measurements and sample construction. Christina Conway and Mike Davidson of Rockwell Collins were instrumental in providing mechanical and electrical measurements. Mary King and Ed Komarnicki of MacDermid provided surface analysis and cross-section photography.

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APPENDIX A: Microstrip Cross-Sections

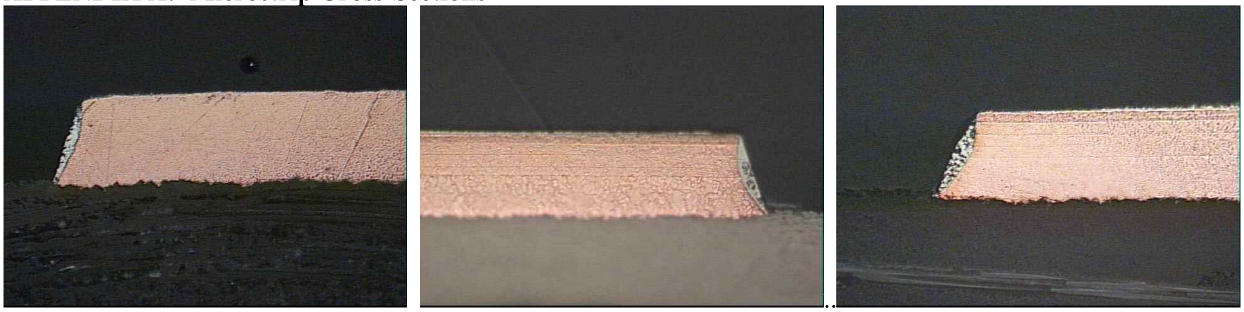

Figure A1 a-c: HASL on FR-4, RF-35, and TLY-5 (500X)

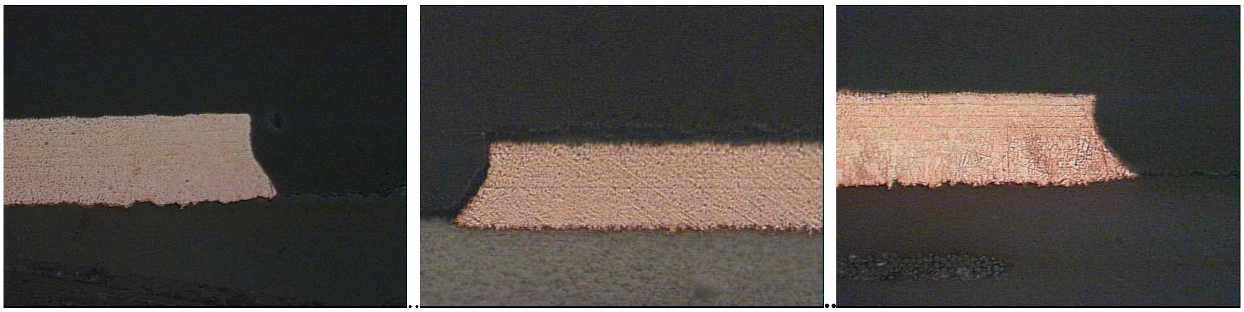

Figure A2 a-c: OSP on FR-4, RF-35, and TLY-5 (500X)

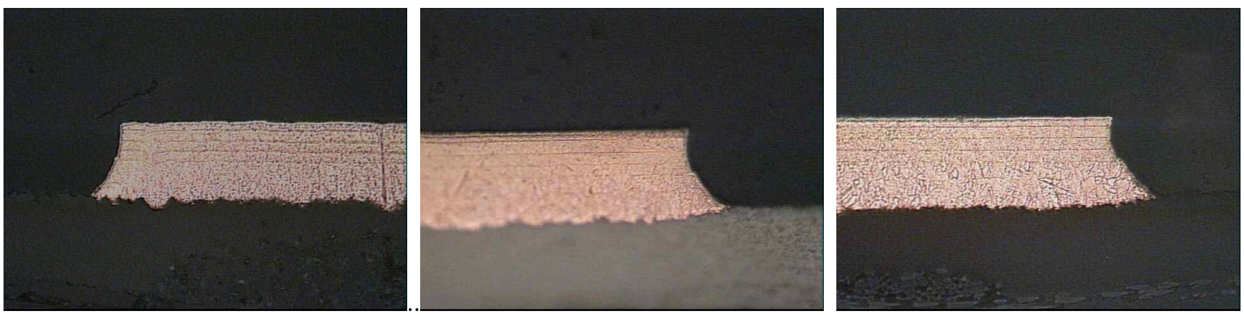

Figure A3 a-c: "Low" Nickel Gold on FR-4, RF-35, and TLY-5 (500X)

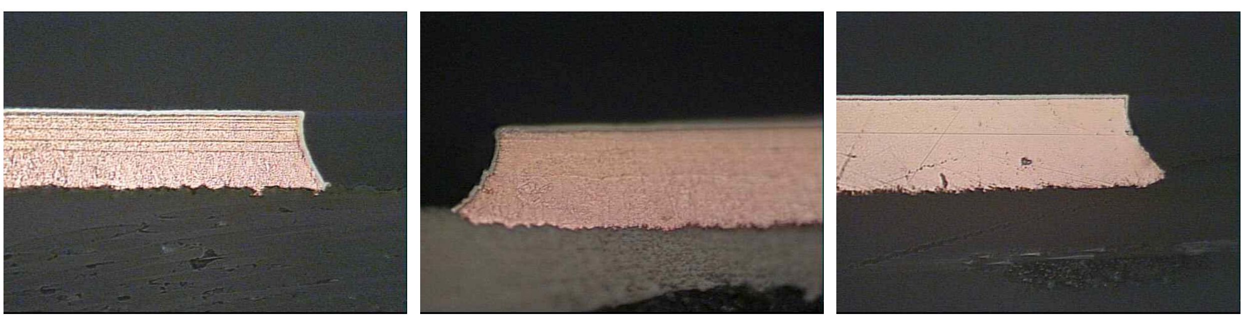

Figure A4 a-c: "High" Nickel Gold on FR-4, RF-35, and TLY-5 (500X)

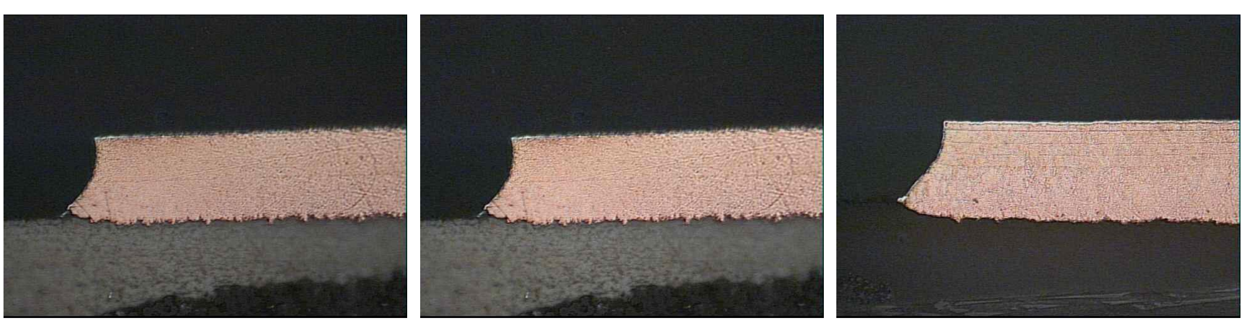

Figure A5 a-c: Immersion Silver on FR-4, RF-35, and TLY-5 (500X)

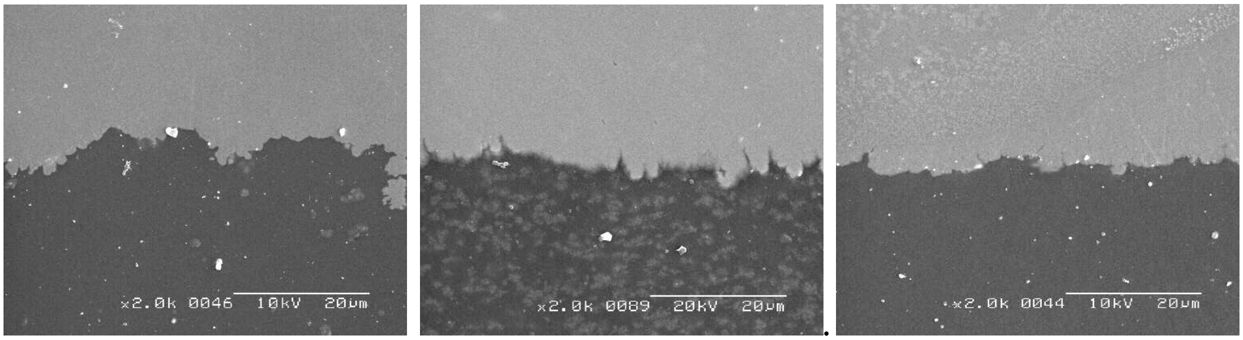

Figure A6 a-c: Copper Foil Profile of the Substrates: FR-4, RF-35, and TLY-5 (2000X)