

A Case Study of the Impact of Fabrication Processes on PCB Broadband Electrical Characteristics

Jason Lin*, Albert Huang, Ohio Huang, Steven Chen
Compeq Manufacturing Co., Ltd., 91, Lane 814, Ta-Hsin Rd.,
Shin Chuang Village, Lu Chu Hsiang, Taoyuan Hsien, 33843 Taiwan, R.O.C.
Phone: +886 3 3231111 ext. 2711, Fax: +886 3 3138150, *E-Mail: chihchienlin@compeq.com.tw

Abstract

It is well-known that copper foil roughness, dielectric constant, and loss tangent of materials are critical factors to high frequency electrical characteristics. These parameters may not be fixed values; they can vary with the frequency as well as PCB fabrication processes. In this paper, the electrical impacts of prepreg moisture absorption and copper foil roughness imparted by adhesion promotion treatments were studied. The broadband electrical characteristics of the PCBs were evaluated by Short Pulse Propagation (SPP) test method [1] [2].

Key words: short pulse propagation, adhesion promotion treatment, oxide alternative, moisture absorption

Introduction

Nowadays PCBs encounter more and more challenges in both reliability and electrical performance as electronics industry transits to lead-free assembly and 5-10GHz or above high-speed data rates.

At elevated reflow temperatures, PCBs may suffer higher mechanical stresses. Delamination can occur if resin does not reliably stick to the inner layer copper surfaces. The idea of “just simply roughen the copper surface to improve the adhesion”, may not be applicable to those increasingly demands in loss sensitive PCBs. It has been studied that the conductive losses imparted by the roughening of metallization in PCBs can be quite significant. The increase of total loss can be as high as 49.5%, even at 5GHz, which cancel the benefit of low dielectric loss characteristics [3].

Several oxide alternatives (OA) are developed by chemistry suppliers. Each of them results in distinct macro and micro textures on the copper surface, forming various complex morphologies for reliable adhesion to the laminate prepreg. The effects of two OAs on electrical signal attenuation have been studied and a difference of 15% ~ 25% in attenuation at 1 – 10GHz range was observed [4].

New laminate materials are also developed to be compatible with lead-free reflow profile and

high frequency electrical performance. Loss tangent is one of the most important factors affecting high frequency electrical characteristics. However, they are frequency dependent and vary with PCB fabrication processes. It was reported that moisture absorbed in the laminate material degrades electrical properties. Loss tangent and dielectric constant increase with water absorption time until saturation sets in [5].

Fabrication of multi-layer PCBs includes the transition of laminate material from B-stage (prepreg, PP) to C-stage (after lamination). We learned that moisture absorbed in the PCBs (in C-stage) can be removed by baking and degradation in loss tangent and dielectric constant may be reversible. However, whether electrical degradation imparted by moisture absorption in prepreg is also reversible is not well studied yet.

In the first part of this paper, we study the electrical impacts of adhesion promotion treatments on inner layer copper surfaces with a standardized test vehicle. Four types of adhesion promotion treatments—one traditional black oxide and three OAs—were examined. The electrical influences were then characterized by the SPP test method.

In the second part of this paper, we studied the electrical impacts of prepreg moisture absorption with standardized test vehicles. Five groups of prepreg were pre-conditioned in a

humid environment with different duration to simulate various amount of water absorbed in B-staged prepreg. The electrical impacts were also evaluated by the SPP test method.

Study I: Adhesion Promotion Treatment

A. Test Vehicle Description

The test vehicle used in this study is an 8-layer PCB developed by IBM to enable the SPP test method. Its specific design features allow for the extraction of broadband PCB electrical characteristics that affects signal propagation using Time Domain Reflectometry / Time Domain Transmission (TDR/TDT) equipment.

The stripline signal layers in the two distinct core/prepreg building blocks—one resin rich with 1oz Cu foil and the other resin lean with 1/2oz Cu foil—are representative of two extreme configurations that may appear in a real product. Fig. 1 showed the specific stack-up of the test vehicle used in Study #1. Notice that the copper used in S3 and S6 is reverse treated low profile Cu foil. Adhesion promotion treatments were applied just before the lamination process.

MP 1		1/2oz + plating
V 2	Voltage	Pre-preg
S 3 Resin richer building block	Signal	1oz Cu
V 4	Voltage	Core, 106x2 (89%)
V 5	Voltage	1oz Cu (reverse, low profile)
S 6 Resin poorer building block	Signal	Prepreg, 106x3 (67%)
V 7	Voltage	1oz Cu
MP 8		Core
		Prepreg, 2116x1 (54%)
		1/2oz Cu (reverse, low profile)
		Core, 1501x1 (45%)
		1oz Cu
		Pre-preg
		1/2oz + plating

Figure 1. Stack-up of Test Vehicle in Study I

B. PCB Fabrication

All test vehicles were fabricated with the cores came out of the same lot to minimize any uncertain noise on material variation. Inner-layers were imaged and develop/etch/stripped at the same time to minimize any process variation. After the inner-layers patterns were completed and checked, they were divided into four groups for different adhesion promotion treatments. A brief description of the four treatments is listed in Table 1.

Table 1. Feature of Adhesion Promotion Treatment

Oxides	Type	Color	Note
OA-1	oxide alternative	bare copper	non-organo-metallic layer
OA-2	oxide alternative	dark reddish-brown	organo-metallic layer
OA-3	oxide alternative	dark reddish-brown	organo-metallic layer
Oxide-1	traditional oxide	black	Copper oxide film

Considering inherent roughness of copper on matte side of the foil may dominate the electrical performance; we used reverse treated low-profile copper foils on this study. Under 5000X magnification, SEM analysis of these oxide treated copper surface showed (from Fig. 2 to Fig. 5) distinct morphologies textures. OA-1 resulted in the grandest roughness while tradition oxide, Oxide-1, created the finest roughness with furry-like features.

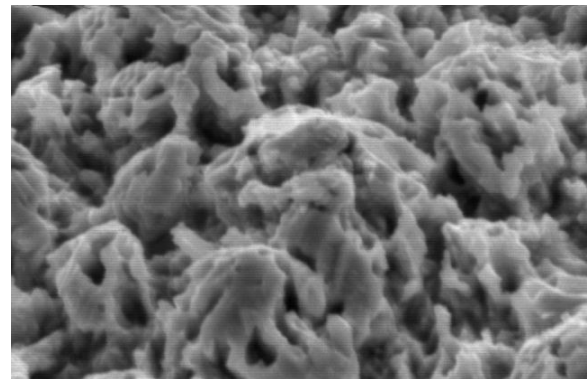


Figure 2. SEM of OA-1

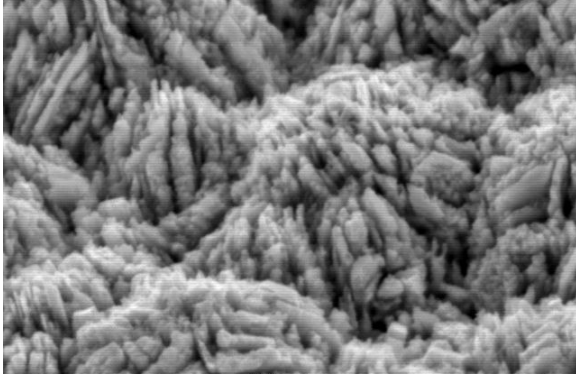


Figure 3. SEM of OA-2

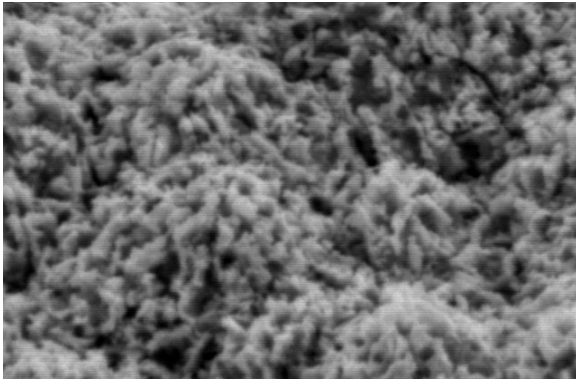


Figure 4. SEM of OA-3

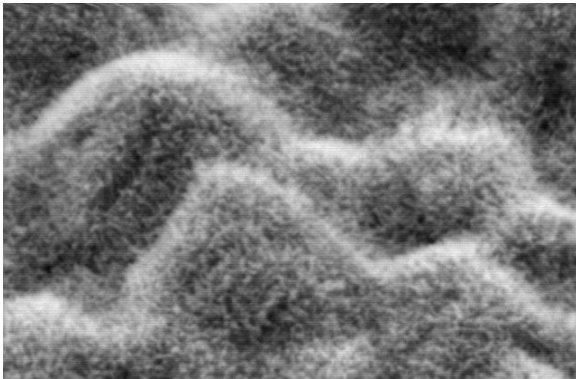


Figure 5. SEM of Oxide-1

When each of the split inner-layer groups finished treatments, they were laminated at the same time with prepreg of the same lot number to minimize any material and fabrication process variations.

C. Electrical Characteristics Assessment

The electrical impacts of different adhesion promotion treatments were examined by the frequency dependent attenuation extracted by the SPP test method.

The test was started with low frequency R & C analysis and sorting of impedance waveform matching. A 20GHz TDR was used with high performance cables and high bandwidth connectors to launch a fast rise-time pulse through an Impulse Forming Network (IFN). The generated short pulse was applied to two traces as identical as possible but in different lengths. The data measured through TDT technique were then processed by the signal processing software Gamma-Z developed by IBM (details can be found in http://www.alphaworks.ibm.com/tech/gammazan_dc2d) and a frequency dependent attenuation characterizing the electrical performance of the structure was obtained. Finally, the test vehicles were cross-sectioned to assess the average physical geometries. Through a subsequent iterative fitting process by a 2D field solver CZ2D developed by IBM, a frequency dependent attenuation curve is obtained to describe the electrical performance of the structure. Fig. 6 is an example of the attenuation curve fitting.

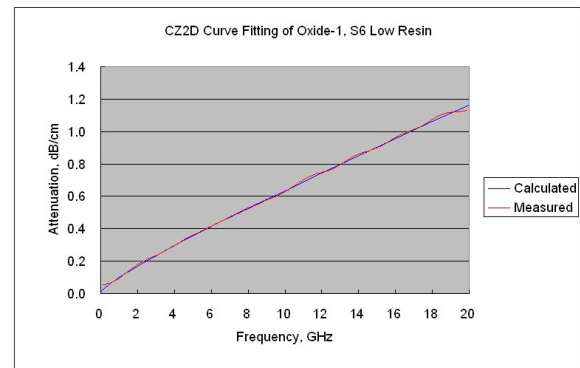


Figure 6. Attenuation Curve Fitting Sample

The resultant frequency dependent attenuations of the four adhesion promotion treatments were summarized in Figs. 7 and 8.

The attenuation of OA-1, the one with relative larger roughness, is slightly higher than the others with difference lower than 0.2% 1 - 10 GHz. One can hardly distinguish the differences of attenuation among the four adhesion promotion treatments below 10GHz.

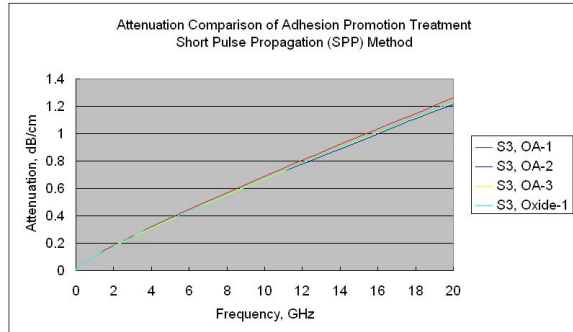


Figure 7. Attenuation Comparison, Resin Rich Building Block, S3

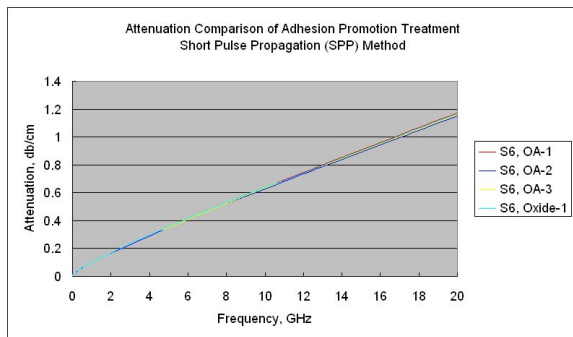


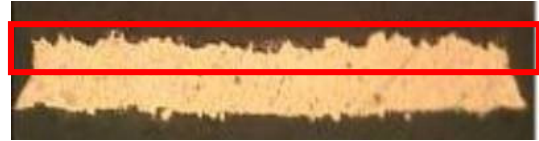
Figure 8. Attenuation Comparison, Resin Poor Building Block, S6

D. Cu Surface Roughness Analysis

Figs 9 and 10 showed the roughness of copper surface. Red boxes shown below are used to indicate the mating surface to the prepreg. One can observe that the shiny side of the inverse Cu foil differs in topographies as a result of the corresponding adhesion promotion chemistry. The matte side looks in the same manner for its inherent low profile properties.

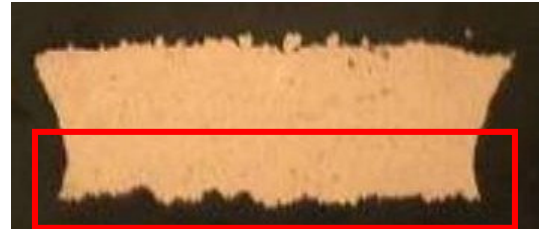


(a)



(b)

Figure 9. OA-1 Cross Section of S3 (a) and S6 (b)

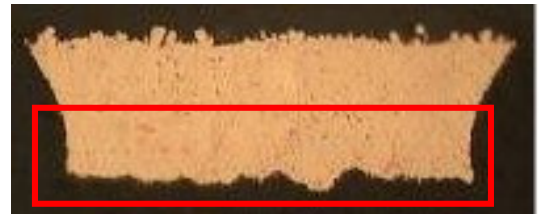


(a)



(b)

Figure 10. OA-2 Cross Section of S3 (a) and S6 (b)



(a)



(b)

Figure 11. OA-3 Cross Section of S3 (a) and S6 (b)

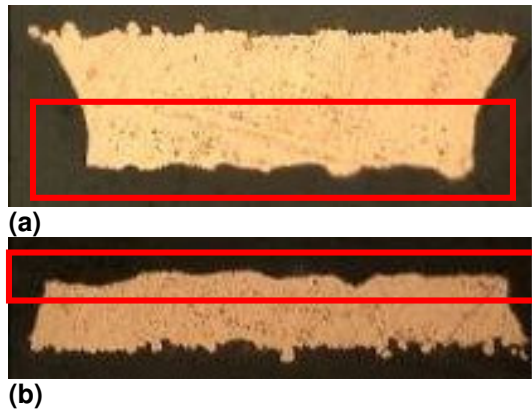


Figure 12. Oxide-1 Cross Section of S3 (a) and S6 (b)

In addition to SEM and cross-section analysis, two surface roughness parameters were also measured by the Wyko profiling system as seen in Table 2, where Ra is the arithmetic average roughness of the profile and Rz is the average distance between the highest peak and lowest valley in each sampling length. Note that oxide-1 has the finest copper surface texture while OA-1 has the grandest one. This results in ~27.7% delta in Rz.

Table 2. Roughness Measurement

	Ra, m	Rz, m
OA-1	1.98	14.67
OA-2	1.17	12.21
OA-3	1.17	11.75
Oxide-1	0.97	11.48

E. Summary

The four oxide chemistries studied here resulted in distinct Cu surface roughness and morphology. However, they did not conclude significant differences on signal attenuations. Therefore, the selection of the oxide chemistries shall be further evaluated by other characteristics such as reliability performance.

Study II: Prepreg Moisture Absorption

A. Test Vehicle Description

In this part of the study, the same standardized SPP test vehicle design was used but with different composition (compare to the Study #1). The specific stack-up is shown in Fig. 13. All cores and PP are obtained from Vender A. Copper foils used are reverse and low profile.

The prepreg between S3 and V4 and the prepreg between V5 and S6 were pre-conditioned in a 25°C/85%RH chamber with five different soak times to simulate various moisture absorption scenarios. The prepreg occupies ~ 57% volume-volume dielectric composition in resin rich building block S3 while in resin lean building block S6, the prepreg is ~ 40%.

MP 1		1/2oz + plating
		Pre-preg
V 2	Voltage	1oz Cu
		Core, 1067x2 (66%)
S 3 Resin richer building block	Signal	1oz Cu (reverse, low profile)
	b-stage	Prepreg, 106x3 (74%)
V 4	Voltage	1oz Cu
		Core
V 5	Voltage	1oz Cu
	b-stage	Prepreg, 2116x1 (54%)
S 6 Resin poorer building block	Signal	1/2oz Cu (reverse, low profile)
		Core, 1506x1 (45%)
V 7	Voltage	1oz Cu
		Pre-preg
MP 8		1/2oz + plating

Figure 13. Stack-up of Test Vehicle in Study II

B. Test Vehicle Fabrication

Prepregs used in the test were from the same lot number to minimize any unwanted variation of material itself. They're divided into five test groups as seen in Table 3, each with different moisture absorption time.

Table 3. Prepreg Moisture Absorption Condition

Test Group	Soak time in 25°C/85%RH chamber (hrs)
TH-0	0 (Fresh pre-preg)
TH-12	12
TH-24	24
TH-72	72
TH-120	120

The most fresh prepreg (TH-0), packaged from the material supplier, was kept securely vacuum-packed until the last moment for lamination. Groups TH-12 to TH-120 were prepared by unpacking the packages at the same time and then placed in a Temperature & Humidity Environmental Chamber controlled at 25°C / 85%RH. When the corresponding soak time reached, the test group was removed from the chamber followed by packaging them in sealed bags. The bags were kept securely unpacked until the last moment for lamination.

All of the test vehicles were fabricated by the cores of the same lot number to minimize any

undesired noise due to variation of material. Inner-layers were pre-cleaned, imaged and develop/etch/stripped at the same time to minimize any process variation. Once all of the inner-layers patterns were visual inspected by AOI, they were split into five groups ready for lamination with the prepreg prepared. Finally, they were laminated and fabricated at the same time to minimize any unwanted variations imparted by processes.

C. Electrical Performance Assessment

The electrical performance was examined by the frequency dependent attenuation, loss tangent, and dielectric constant extracted by the SPP test method. To minimize the influences of moisture trapped in the PCBs, all of the test vehicles were preconditioned by baking at 125°C for 6hrs and cooled to room temperature prior to electrical measurement. The SPP test procedures are the same as that described in Study #1. An example of attenuation curve fitting is shown in Fig. 14.

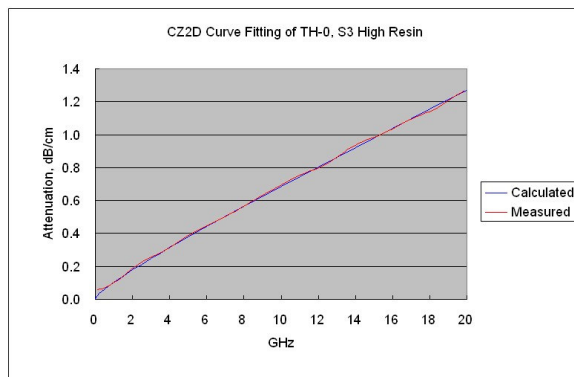


Figure 14. Attenuation Curve Fitting Sample

It should be noted that the losses extracted by this methodology are “effective”, including dielectric loss and conductive loss. Since the Cu foils used in signal layer S3 and S6 are reverse and low profile type, the differences in attenuations will be mainly caused by dielectric loss. The resultant frequency dependent attenuations are summarized in Figs 15 and 16. The data showed that the attenuation increased 1.14% at 10GHz in high resin block S3 while in low resin block S6, the attenuation increased 0.84%. It's seen that the performance impact of prepreg moisture absorption to higher resin block is larger than the lower one. The attenuations change due to moisture absorption of prepreg prior to lamination is irreversible by

baking PCBs.

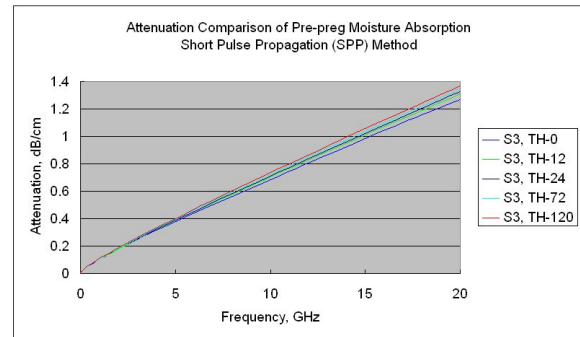


Figure 15. Attenuation Comparison, Resin Rich Building Block, S3

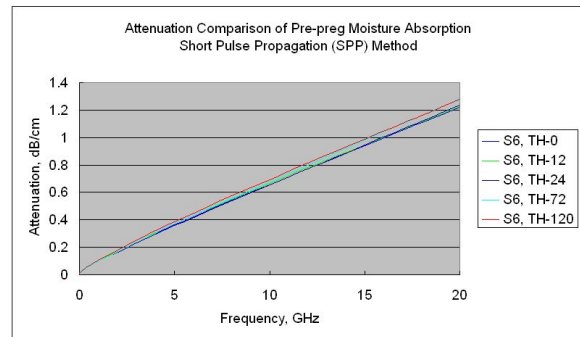


Figure 16. Attenuation Comparison, Resin Lower Building Block, S6

The resultant frequency dependent loss tangent is summarized in Figs 17 and 18. The data showed that the loss tangent increased ~ 10.0% at 10GHz in high resin block S3 while in low resin block S6, the loss tangent increased ~ 5.8%. One can observe that the electrical impact of moisture absorption on prepreg to higher resin building block is larger than the lower one. The electrical properties change in loss tangent due to moisture absorption of prepreg prior to lamination is irreversible by baking PCBs.

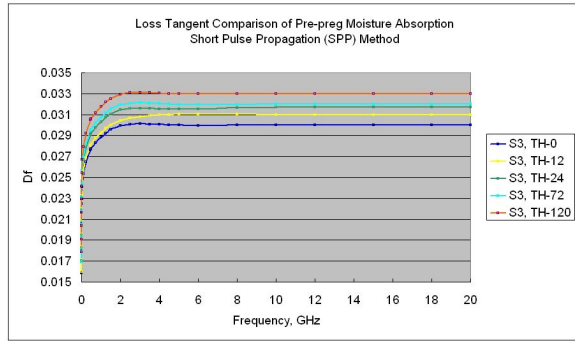


Figure 17. Loss Tangent Comparison, Resin Rich Building Block, S3

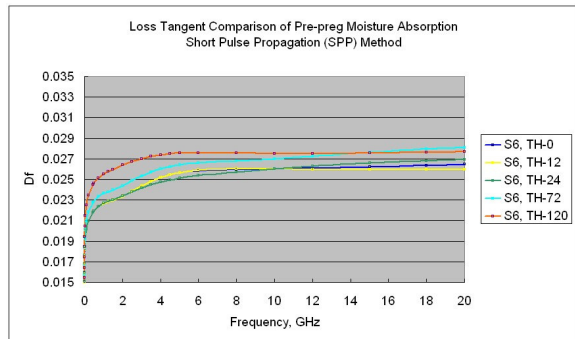


Figure 18. Loss Tangent Comparison, Resin Poor Building Block, S6

The trend of loss tangent drifts due to prepreg moisture absorption can be seen in Fig. 19. It's observed that more moisture absorbed in the prepreg, higher loss tangent in the finished PCBs will be.

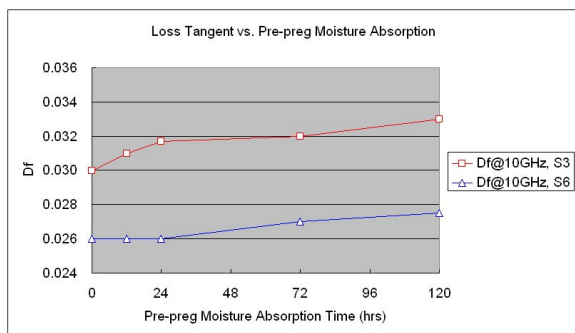


Figure 19. Loss Tangent vs. Pre-preg Moisture Absorption

The resultant frequency dependent dielectric constant is summarized in Figs 20 and 21. The trend of dielectric constant drifts versus prepreg moisture absorption time can be seen in Fig 22. One cannot observe consistent trend from these plots, which implies that moisture absorbed in

the B-staged prepreg will not eternally change the dielectric constant in the finished PCBs.

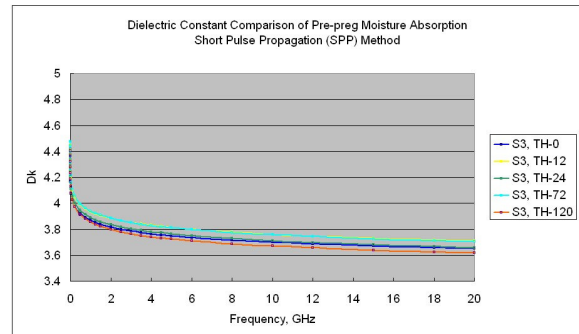


Figure 20. Dielectric Constant Comparison, Resin Rich Building Block, S3

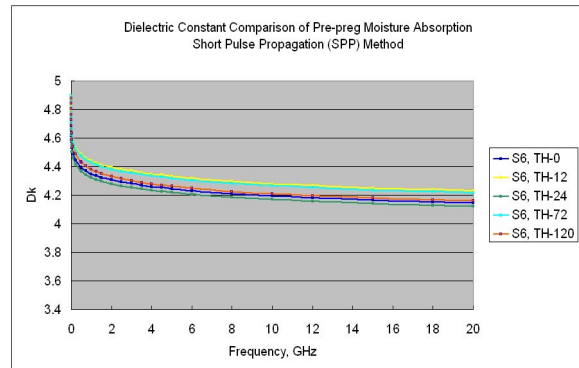


Figure 21. Dielectric Constant Comparison, Resin Poor Building Block, S6

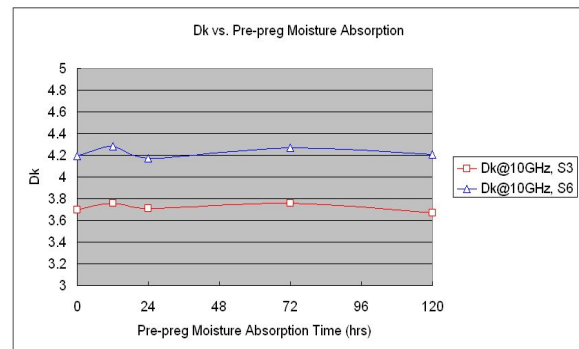


Figure 22. Dielectric Constant vs. Pre-preg Moisture Absorption

D. Summary

We concluded that moisture trapped in the prepreg (obtained from Vender A) results in eternal electrical degradation of PCBs. The phenomena of elevation in attenuation and loss tangent are irreversible even by baking at 125°C for 6hrs. The impact to the high resin building block is more severe than that of the low resin.

It's also seen that dielectric constant is not influenced by prepreg moisture absorption prior to PCB lamination process.

Conclusion

The impacts of copper surface roughness and moisture in PP during PCB fabrication processes on broadband electrical characteristics were presented in this paper.

Adhesion promotion treatment that roughens copper surfaces and forms complex morphologies for improved reliability is a contributor to conductive loss.

When evaluating adhesion promotion treatments, a balance between "good enough" electrical characteristics and reliable mechanical bonds to laminate prepreg should be realized. "Excessive" rough copper surface will no doubt degrades conductive loss and cancel the benefit of low dielectric loss characteristics.

Of the raw material chosen in this study, PP moisture absorption prior to lamination resulted in eternal degradation of dielectric loss. We also learned in the follow up studies, that the degree of degradation does vary with the type of raw material used.

Moisture absorption on PP may irreversibly elevate the effective loss tangent by 10% for high resin PP on certain material and it may cancel the benefit of using reverse treated low-profile Cu foils and/or the use of low loss materials. Fortunately, the impact can be minimized by optimization of PCB manufacturing process flow and by carefully regulate PP storage conditions.

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