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LTCC Thick Film Process Characterization

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Abstract

Low temperature cofired ceramic (LTCC) technology has proven itself in military/space electronics, wireless communication, microsystems, medical and automotive electronics, and sensors. The use of LTCC for high frequency applications is appealing due to its low losses, design flexibility and packaging and integration capability. The LTCC thick film process is summarized including some unconventional choices such as feature machining in the unfired state and thin film definition of outer layer conductors. The LTCC thick film process was characterized to improve process yields, focusing on the factors 1) Print location, 2) Print thickness, 3) Drying of tapes and panels, 4) Shrinkage upon firing, and 5) Via topography. Statistical methods were used to analyze critical process and product characteristics in the determination of the optimized LTCC thick film process. The optimized LTCC thick film process reduced the cofired panel size variation resulting in improved techniques for increasing yields.

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Key words

LTCC, cofire, shrinkage, screen print

I. Introduction

LTCC is a well-established commercial technology based on processing of unfired glass-ceramic tape layers with noble thick film materials and cofiring the conductors and dielectric, yielding a multilayer circuit stack as a monolithic structure. Processing steps are covered in detail in a comprehensive review [1]. The glass-ceramic tape shrinks with a defined tolerance upon cofiring. Due to dense circuitry and a design that is scaled up for production capacity, shrinkage tolerances compete with product tolerances. Thick film cover pads and filled vias must align with unique thin film features as shown in Figure 1 everywhere across a 5 inch panel. The cover pads provide topographical protection over vias and the thin film pads define the circuit and provide protection to the thick film layers during soldering and subsequent use. The shrinkage tolerance for the commercial tapes is ±0.3%. On a 4.60 inch characteristic diagonal dimension, this amounts to maximum positional variation of 0.0158" (401 microns). Compared to a via size of 0.010", this could cause fixed tooling (glass masters and post-processing print screens) to

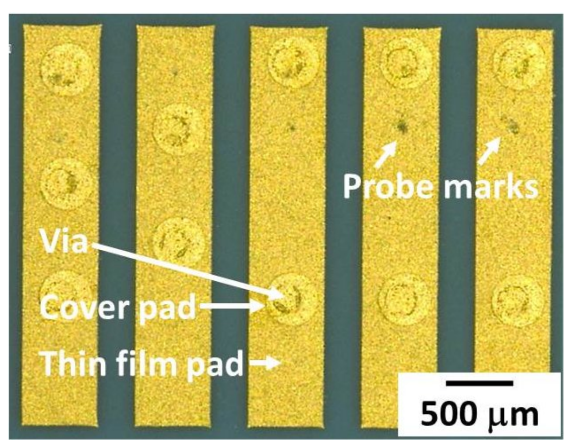

Figure 1. Acceptable thin film-to-cover pad-to via alignment is shown in this feature array.

miss critical features. Shape changes during the thick film processing stage can account for additional tolerance errors. Drying of filled vias on tapes can be responsible for shape changes that affect placement of cover pads atop vias. The process by which this shrinkage tolerance can be reduced has been examined.

II. Background

LTCC remains a technology of choice for high frequency circuits for its excellent material properties, nearly unlimited stacking capability, form and fit versatility, and environmental performance. The process flow is described below and shown in Table 1. The first step in the fabrication is to predict the shrinkage and set an appropriate expansion factor for the artwork so that the unfired tape shrinks to the correct size within tolerance. This is done by considering a vendor property certification with an in-house certification, and selecting a tape lot with appropriate properties. The lamination pressure and conductor loading, by area and thickness, are the other main factors [2, 3]

Table 1. Process Flow

Predict shrinkage/select expansion factor
Thermal condition and settle
Punch tape
Automated optical inspection
Via fill
Compress vias
Dry via filled tape
Print conductors side 1
Dry conductors
Remove backing
Print conductors side 2
Dry conductors
Remove backing on other layers
Collate
Laminate
Green machine
Cofire
Thin film circuit definition includes
PVD
Photolithography
Ion milling

Tape is conditioned by subjecting it to a thermal profile and a hold time consisting of 1 hour at 100°C. LTCC rape conditioning renders the LTCC tape dimensionally and thermally stable during downstream thick film processing. Dimensional stability is required for cover pad to via alignment and ground plane to via alignment. The tape remains on its stabilization backing for this treatment and a subsequent settling time of 72 hours (while vacuum-bagged). The design calls for alternating the tape casting direction between alternate layers of the circuit to further normalize differential shrinkage.

The punching operation follows for functional features such as electrical vias, alignment and registration holes, and any other structural elements such as component holes or cavities. The registration holes are used for layer-to-layer alignment. Automatic optical inspection (AOI) verifies proper punching.

Via-filling is performed by screen printing techniques using a stencil. The vias are filled from the side with the punchable stabilization backing. Once vias have been properly dried, a compression step is performed with a roller and a surface planarization step is performed through the use of a sharp edge on surfaces that will be external in the finished product. Associated traces, cover pads, ground planes, and other circuit features are screen printed on the available side of the tape to connect with these vias as called for by the design. All wet prints are also dried in a prescribed manner. If the design calls for features on a second side of the tape, the backing is removed and those features are printed and dried. Proper filling and printing is verified at each stage.

Collation is then performed in automated equipment that stacks the tapes and tacks them in place for subsequent processing. The collated and tacked panels are then laminated at high pressure and moderate temperature (typically 3000 psi for 10 minutes at 70°C). This is performed in an isostatic laminator, but additional fixturing is involved, including base plates and top plates.

Additional unique features are introduced by milling the unfired tape in a step we call 'green machining.' This defines through holes, blind and stepped cavities, and unique structures such as a valley in the laminated panel. The valley accommodates a seal frame which is subsequently mounted. The cavities and valleys involve 'sense-mode-milling,' where the milling depth is found by electrically sensing the dried ground plane through an electrically conductive milling tool. Insertion of an additional drying step prior to any machining was found to make the results more uniform.

Laminated panels are then cofired using a prescribed thermal profile that accomplishes burnout of organic binders (450°C) and sintering (850°C) of the structure into a multilayer glass ceramic MCM network.

The outer layers of the MCMs are coated with a PVD thin film stack which is photolithographically defined using ion milling as has been described elsewhere. [4, 5] It is important to note that the proper shrinkage control is key at any stage when fixed artwork (thin film photolithographic glass master or thick film solder mask screen) is used in the process for defining the 'near side' and 'far side' features. The thin film has provided superior capabilities, but comes with additional challenges. The thin film is required to completely cover all thick film structures. Neither alignment defects nor blemishes that would expose thick film to solder are permitted. The yield and reliability of thin film metallized LTCC consisting of panels with multiple circuits requires a tight tolerance in LTCC panel sizing. Targeting the panel size, controlling variation and minimizing the x/y directional shrinkage variation is has been shown to be necessary to achieve higher production yields and resulting in high reliability LTCC MCMs. This paper investigates the critical upstream thick film processes that affect the resulting final panel size variation.

1) Cofired panel size variation

Our process has some unique structural requirements with respect to alignment. Thick film cover pads on external vias mitigate via topography so that thin film layers provide the designed protection and reliability with respect to soldering. These cover pads must be properly located on their associated vias. Factors which complicate this include shape changes that occur in handling, heating, and, ultimately, cofiring. These cover pads, in turn, must be carefully located with respect to the post-fired thin film definition. Because the miniaturized design has been scaled-up for production capacity, shrinkage tolerances compete with product tolerances. If the alignment isn't satisfactory, problems ensue. The design intent is shown in Figure 1a, where there are no abrupt steps which hamper the thin film coverage. Figure 1b shows problems that occur with certain misalignments. If the cover pad does not properly cover the via, the topographical buffer at the edge of the via is lost, and the thin film may be breached by solder. If the cover pad is not safely beneath and within the thin film, the cover pad may be attacked by solder. The degradation of the cover pad material when directly exposed to solder is well known.

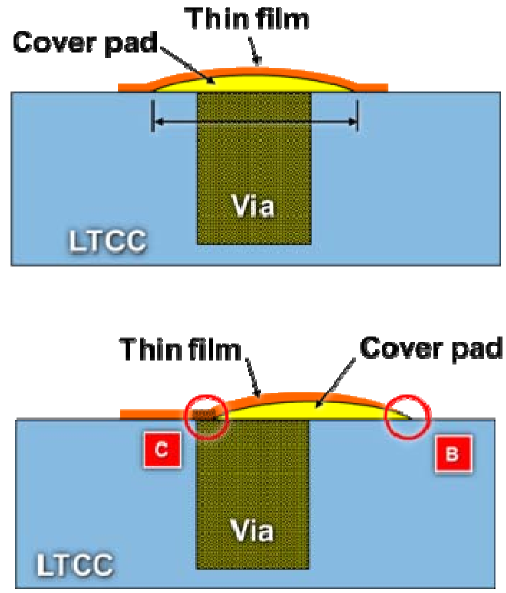

Figure 2. Role of thick film cover pads in thin film circuits.

A mild form of attach of a thick film cover pad is shown in Figure 3. The soldering process wets well to the pad, but a reaction layer results from interaction of the solder with the nearly pure gold thick film material. Additional studies are underway.

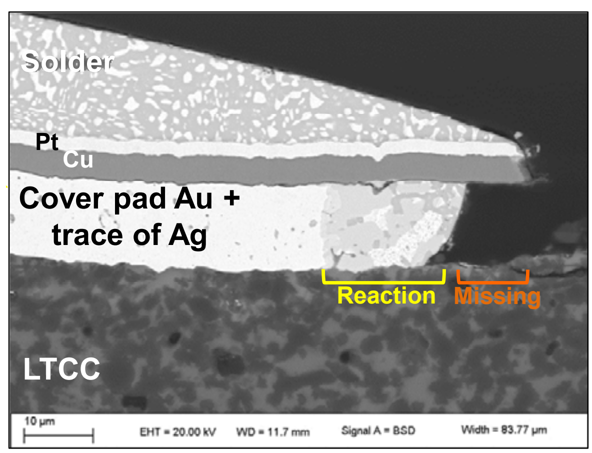

Figure 3. Attack of an exposed thick film gold cover pad edge by Sn-Pb solder.

Similarly, There was concern that via topography or the lack of a cover pad at a via boundary could lead to a breach of the thin film by solder similarly to that shown in Figure 4.

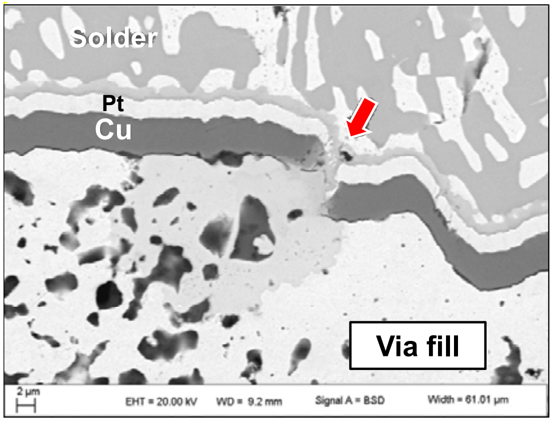

Figure 4. Breach of thin film with limited attack of the gold via fill by Sn-Pb solder.

I. Discussion of Results

The thick film process was characterized with the goals; 1) define the print location tolerance, 2) reduce the cofired panel size variations, and 3) improve the cover pad-to-via alignment. The characterization plan addresses the following processes that feed into the cofired panel size tolerance, green machining process yield, and thick film to thin film alignment: a) LTCC tape conditioning, b) Drying of via filled LTCC tape, c) Screen printing ground plane conductors. d) Drying ground plane conductors, e) Printing cover pad conductors, f) Drying cover pads conductors, g) Pre-collate drying for green machining, h) Lamination, and i) Cofiring.

LTCC Tape Conditioning

An 8 run Factorial Design of Experiments was conducted with input factors shown in Table 2 to quantify the impact on dimension stability of the unfired tape.

Table 2 Input factors for conditioning experiment

1) Tape Conditioning Oven
2) Stack Count
3) Peak Temperature
4) Time at Peak

The LTCC tape was conditioned in 8 experimental groups the conditions defined in Table 3. The high flow and low flow conditions were carried out in different pieces of available equipment, adding another factor which needs to be deconvoluted. While several metric dimensions were measured, only diagonal lengths are shared here in the interest of space.

Table 3. Experimental Factors.

Air Flow	Stack Count	Temperature (°C)	Time at Temperature (minutes)
High	10	75	45
High	1	75	60
Low	1	100	60
High	1	100	45
Low	1	75	45
Low	10	100	45
Low	10	75	60
High	10	100	60

Following conditioning, all tape layers were punched with a defined registration-hole pattern. All samples within each experimental group were measured using an optical coordinal measuring system second. All samples were then processed through a belt dryer twice with the belt dryer peak temperature set at 70°C (simulating two typical drying cycles: via and ground plane conductor drying). Finally, all samples within the eight experimental groups were measured again using the same optical coordinal measuring system.

In the analysis of variance, three factors, 1) airflow, stack count, and 3) time at prescribed temperature, were shown to be statistically significant in the change in panel diagonal measurement following two 70°C drying cycles at the 95% confidence interval with an R-sq (adj) value of 89.33% (see Table 4).

Table 4. ANOVA data summary

Factorial Fit: Dia. 1 versus Oven, Stack, Time

Estimated Effects and Coefficients for Dia. 1 (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		0.000887	0.000035	25.53	0.000
Oven	-0.000332	-0.000166	0.000035	-4.78	0.017
Stack	0.000291	0.000146	0.000035	4.19	0.025
Time	-0.000200	-0.000100	0.000035	-2.88	0.063
Oven*Time	0.000259	0.000130	0.000035	3.73	0.034

S = 0.0000982705 PRESS = 2.060181E-07
R-Sq = 95.43% R-Sq(pred) = 67.49% R-Sq(adj) = 89.33%

Analysis of Variance for Dia. 1 (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00000047	0.00000047	0.00000016	16.23	0.023
Oven	1	0.00000022	0.00000022	0.00000022	22.81	0.017
Stack	1	0.00000017	0.00000017	0.00000017	17.58	0.025
Time	1	0.00000008	0.00000008	0.00000008	8.31	0.063
2-Way Interactions	1	0.00000013	0.00000013	0.00000013	13.93	0.034
Oven*Time	1	0.00000013	0.00000013	0.00000013	13.93	0.034
Residual Error	3	0.00000003	0.00000003	0.00000001		
Total	7	0.00000063				

Estimated Coefficients for Dia. 1 using data in uncoded units

Term	Coef
Constant	0.00140988
Oven	-0.00107379
Stack	3.23694E-05
Time	-1.33533E-05
Oven*Time	1.72925E-05

As a measure of how well the selected factors tested explain the results the R-sq (adj) value is good.

The lowest size change was seen when the tape is conditioned in the high air flow oven, when the tape is stacked one layer tall, and when the tape is conditioned for 60 minutes at 100°C as shown in the interaction plot in Figure 5.

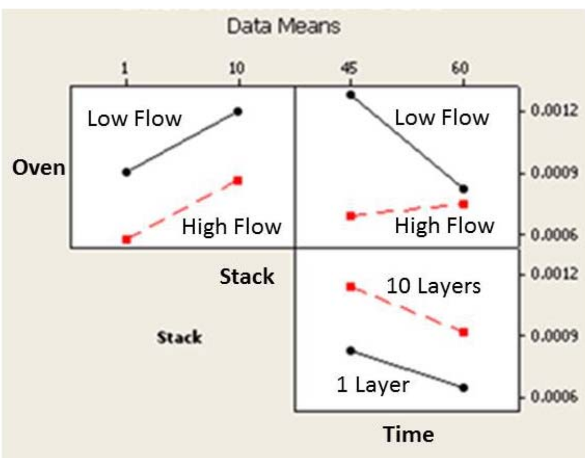

Figure 5. Interactions.

Print location

The print alignment of a given thick film printer is directly affected by the screen printer's print location repeatability (PLR). A PLR study was performed to determine the capabilities of the two different models of screen printer, a legacy screen printer and a new screen printer with tight control. Intially, print alignment on Screen Printer A was gross (several mils). By rebuilding the theta-stage, the PLR was brought into line with a new screen printer (B) as shown below, for a sample size of 30.

Screen Printer (A) PLR: +/- 0.000665
Screen Printer (B) PLR; +/- 0.000792

The F and T test statistic validate that the population mean and variance of both screen printers are not significantly different at the 95% CI as shown in Table 5.

Table 5. PLR Statistical study .

Ratio of standard deviations = 1.045
Ratio of variances = 1.092

95% Confidence Intervals

Distribution of Data	CI for StDev Ratio	CI for Variance Ratio
Normal	(0.372, 1.250)	(0.760, 1.563)
Continuous	(0.638, 1.070)	(0.407, 1.144)

Tests

Method	DF1	DF2	Test Statistic	P-Value
F Test (normal)	129	111	1.09	0.634
Levene's Test (any continuous)	1	240	1.96	0.163

Print thickness

Print thickness and resulting LTCC panel weight has been shown to correlate with panel size (shrinkage). Based on the screen mesh selected to achieve the designed print resolution, a DOE was performed to optimize the wet and dry thickness target for a given screen mesh size opening. A 360 mesh screen having 0.5 mil emulsion was used in the process capability study. Results of the capability performed study on the existing Screen Printer (1) are given in Table 6 below:

Based on the extreme conductor print thickness process variation seen on Screen Printer 1, the capability was repeated on the Screen Printer 2 under the same conditions. The results of the new process capability study are also presented in Table 6 below: The down-selected thick film printing process benefited the yield impact with respect to thin film feature alignment, mechanical dimensions, and green machining. The baseline process had been 40±4 µm wet thickness, and included qualitative assessments. Layer 1 through 6 ground plane and cover pad print thicknesses use 32–36 µm wet print thickness. Layer 7 and 8 ground planes use 36 – 40 µm wet print thickness. A requirement for green machined areas is 32 µm minimum dry thickness. The optimum wet and dry thickness target was selected based on the lowest print thickness variation which was changed from a target 40 µm to 34 µm wet thickness.

Table 6. Print thickness for printer 1

Print Thickness Target	Wet Thickness Target Range (µm)	Dry Thickness Range (µm)	Nominal Dry Thickness (µm)	Specification Limits (+/- 4µm)	Normal Distribution	Out of Control Points (I Chart)	Within cp	Within cpk	Overall cp	Overall cpk
Thin	32 - 36	15-20	16	12 - 20	yes	one	0.51	0.50	0.44	0.42
Thick	36 - 40	20.5	18	14 -22	yes	four	[illegible]	[illegible]	[illegible]	[illegible]

Drying of tapes and panels

The drying equipment and profiles are critical, and outside of this effort, drying equipment has been improved. Based on the change in tape size following one drying cycle, room-temperature drying of filled vias was chosen at the expense of schedule to ensure the best alignment of subsequently printed cover pads.

Drying has also proved critical for machining of unfired panels which occurs after lamination of a panel because 'sense mode' milling is employed, where machining depth is determined by sensing the electrical conductivity of the buried ground plane layer. Optimum wet/dry thickness requires machining yield feedback due to minimum conductor thickness requirements for electrical sensing. Machining sensing errors have been a significant "in process" yield issue in development runs. One wouldn't expect dried thick film to exhibit conductivity, necessarily,

but this conductivity is used successfully in the sense mode operation. Drying as a pre-treatment for better success in milling has been employed to improve yields.

Shrinkage Variation upon Firing

Shrinkage upon firing is factored into the design in LTCC. The shrinkage is not, in itself, a problem, but its tolerance needs to be tightly controlled. 5" square panels consisting of 8 laminated layers were cofired in a 'box' furnace 850°C peak temperature and 45 minutes time at peak temperature. The furnace used had a work zone of 12" x 14" x 18". All cofire trials included a single panel positioned in the center of the furnace to eliminate a temperature gradient factor of +/- 12°C.

The cofire statistics can be summarized in Table 7:

Table 7. Cofire statistics

Test Group	Diagonal Within cp	Diagonal Within cpk	Diagonal Overall cp	Diagonal Overall cpk
One	0.54	-0.27	0.59	-0.30
Two	1.02	0.85	0.70	0.58

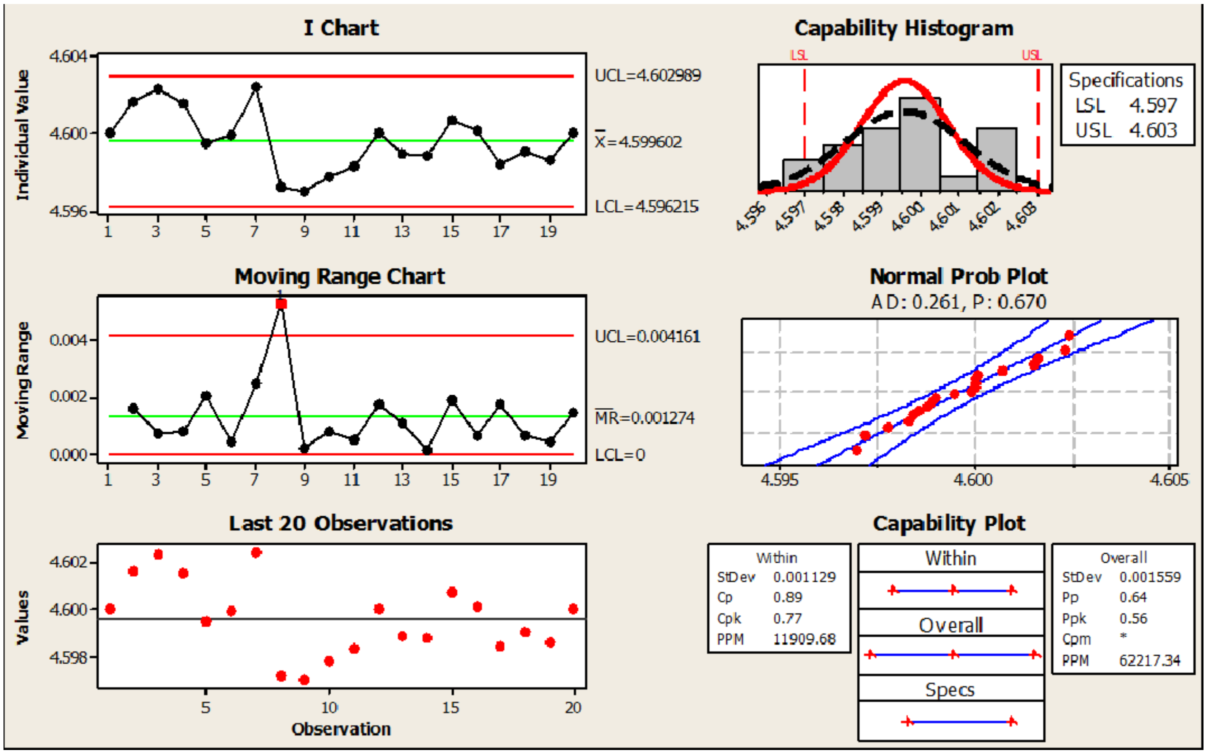

Figure 6.

Via topography

With thin film exterior metallization, the via cover pad to via alignment is critical because it buffers the topography of the via. This is primarily for the reliability of the soldered pads with vias so the thin film completes an impervious layer and the largely pure gold cover pad and via fill materials are not attacked by solder breaching the thin film. Two types of possible attack were shown in Figure 2. It was noticed that if we reduced the topography of the via, we reduced the sole dependence of the via reliability upon the via cover pad. Some typical vias are shown in Figure 7.

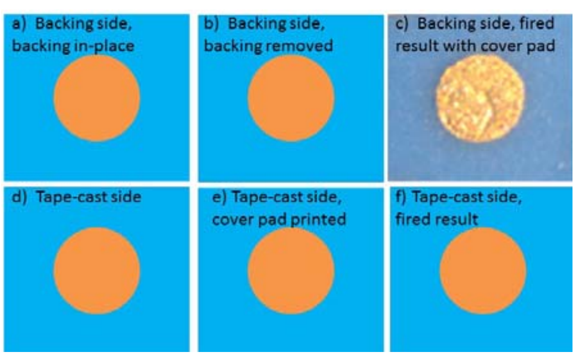

Figure 7. Origins of via topography

Because the vias are filled from the backing side and dried with the backing in place, the subsequent removal of the backing results in a via topography that results from a fracture as shown in Figure 7b. The resulting topography is shown in Figure 7c following printing of a cover pad and firing as part of an MCM stack. The opposite side is in contact with a separation layer during via fill, and removal of this separation layer leaves a smoother surface. As shown in Figure 7d. The unfired appearance of such a via covered with a cover pad is shown in Figure 7e, and the fired result in Figure 7f. By planning to use the smoother via surface on the external surfaces of the circuit, the safety factor for the thin film coverage is increased.

Optimized thick film process

The optimized thick film process includes the following provisions. Two-layer LTCC tape stacks, on perforated trays, are conditioned in optimized belt ovens at100°C for 60 minutes. Vias are filled using a new (linear encoded print head) printer using multiple passes, through electroformed stencils. Vias are compressed 10 to 15 minutes after via fill prior to room-temperature drying on perforated trays. Layer 1 through 6 use ground plane, trace, and cover pad prints with 32 µm to 36 µm wet print thickness. Layer 7 and 8 reference ground planes use

36 µm to 40 µm wet thickness. This achieves a required 32 µm minimum dry thickness in areas using 'sense-mode' green machining. Cover pads are printed prior to ground plane conductors and all printed conductors are dried at 80°C for 5 minutes. In addition, the layer one punch file is inverted so that the side defined by the stabilization backing is internally located and the coarse surface topography is eliminated. Layer 8 already benefits from this approach.

III.- Conclusion

The thick film process affecting LTCC panel shrinkage variation has been characterized and improved to enable improved thin film alignment as a result of implementing a more uniform tape conditioning process, reducing the target thick film print thickness to match the capability of the required thick film screen, and defining a required print thickness tolerance. Variation due to firing shrinkage was improved from Cpk of 0.39 to_Cpk of 1.05 with a specification tolerance ±3 mils across a 4.6 inch diagonal.

Independent of these process improvements, design factors were also negotiated including layout changes to increase the physical spacing between the thick film cover pad edges and the thin film features, reduction of cover pad size, and consideration for solder-free areas that are intact, but not threatened by solder interactions..

Process centering has improved through elimination of varying lamination pressures as demonstrated on a lot size of 20 panels wherein fired size variation tolerance was reduced by 50%. Associated photolithography yields have increased significantly.

Improvements in the green machining manufacturability and process yields included redesign of a cavity, implementation of additional thick film drying of all individual tape layers prior to collation to ensure uniform drying of the printed circuit pattern, improving the uniformity of the drying process, definition of the required thick film wet/dry circuit ground plane and reference ground plane print thicknesses.

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