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Determination of LTCC Shrinkage Variations from Tape Manufacturer to Consumer

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Abstract

Low Temperature Cofired Ceramic (LTCC) technology can be applied in numerous functions due to a wide variety of benefits, particularly related to flexibility of applications. Controlling the LTCC shrinkage tolerances in the x, y, and z dimensions is critical during manufacturing and avoids an assortment of down-stream issues that will affect yields. All manufacturers of LTCC tape provide a Certificate of Analysis (COA), which contains the results of the manufacturer's shrinkage testing so production variation can be established from lot to lot. Data from this COA is generally used as a starting point in the shrinkage predictions for manufacturing purposes; however, verification of this data must be performed prior to initiating an LTCC build. This paper investigates validation of one manufacturer's COA data and explains how shrinkage differences can occur between the COA data and the data collected during the verification process. The tracking of this data is also presented as a means to ensure proper controls are in place, and the type and style of lamination and cofiring are shown to be significant contributors to these differences. Data will then be presented in association with characterization prior to and after relocation of LTCC fabrication equipment. Additionally, the COA data can be incorporated into shrinkage estimates that will be utilized to set up process parameters, tolerances, and a control plan.

Key words

LTCC, Certificate of Analysis (COA), shrinkage modeling, Design of Experiment (DOE)

I. Introduction

Low Temperature Cofired Ceramic (LTCC) technology offers the benefit of being able to integrate low temperature processing with many applications, including the embedding of passives for high density ceramic packaging. The low temperature processing also permits for the use of highly conductive metals, including gold, silver, and copper to be utilized in a multi-layer, monolithic structure that can be fired as one unit [1].

Ceramic tape is employed in LTCC processing, with the tape containing filler dielectric material and glass mixed together with plasticizers and organic binders. LTCC tape is produced via a wet process, where slurry of the above materials is cast onto a polyester backing material on a continuous tape caster. This tape can be cast in a variety of thicknesses up to 10 mils and must be dried before rolling. The purchase of commercial LTCC tape typically takes place through the purchase of these rolls, or the tape can be pre-cut to precise sizes.

The investigators' LTCC process flow is detailed in the subsequent table and section:

Table I: Overall LTCC Process Flow [2]

LTCC PROCESS FLOW
CONDITION TAPE
PUNCH/INSPECT VIAS
PRINT/DRY VIA FILL
PRINT/DRY CONDUCTORS
COLLATE & LAMINATE ALL LAYERS
GREEN MACHINE MECHANICAL FEATURES
COVER EXTERNAL VIAS
BURNOUT & COFIRE
EXTERNAL PATTERNING
SINGULATE

The tape is received in the appropriate 5" square size with 10 mil thickness, and when the tape is ready for use, thermal conditioning takes place. To condition the tape, the sheets are placed in an oven at 100^{0}C for one hour with the backing material remaining in place (unlike normalization where the backing is removed, which eliminates rigidity and can lead to inaccurate shrinkage measurements). Thermal conditioning removes unwanted solvents, while also reducing stresses that were induced during the tape casting process. Tape can be stacked in quantities up to 10 on a setter in the oven for conditioning and is allowed to cool for approximately 30 minutes on a metal surface before being bagged. Once bagged, the tape is allowed to settle for roughly 72 hours.

Punching is performed once conditioning is completed. A punch file containing the locations of all punched holes is downloaded to a mechanical punch. The punch file also comprises of fiducial holes, which will be used for alignment during printing operations as well as layer to layer alignment during stacking. Holes are punched for shrinkage measurements as well, with measurements taken in the casting direction, perpendicular to the casting direction, and diagonal across the tape. Inspection of all punched holes is performed using automated optical inspection (AOI). The AOI inspects holes for the appropriate size tolerance, as well as hole locations.

Screen printing is completed once punching and inspection are finished. Via filling is executed with stainless steel stencils initially from the side with the backing, and the paste used to fill the vias typically has a viscosity of 3,500,000 - 4,500,000 cPs so the material will not drop out during handling. Drying is also necessary once all the vias have been filled, and a compression step is performed after drying is complete to eliminate any voids in the vias. Planarization is also used on the outer layers for the purpose of minimizing post-fired via post-up and is completed through the use of a sharp edge being applied to the surface of the tape. Preventing via post-up is critical to ensure there is flat surface present for the die during chip placement, which occurs during assembly of a multi-chip module (MCM).

Printing of conductor patterns and traces on internal layers is executed after via filling or planarization is complete on the unprotected tape surface, or near side. Some layers will most likely require a conductor print on the backside, so the polyester film will be removed to permit printing. Conductor printing is performed with the use of silk screens, which come in a variety of mesh sizes. Lastly, the conductor prints will also be dried.

Once the layers are dry, a manual or automated stacking process is performed by removing the backing material, if not previously, and critical layer-to-layer alignment is completed. If accomplished manually, the layers will be stacked using pins in a mechanical fixture; whereas, if the layers are stacked using automation, tacking is performed after aligning the layers (alignment is performed using the punched fiducials mentioned previously) before placing the stack on to the mechanical fixture. The fixture is wrapped in latex and double vacuum bagged, with the latex used to prevent the vacuum bags from being perforated. Once the parts have been sufficiently vacuum sealed, they are laminated using an isostatic laminator at 70^{0}C for 10 minutes, plus an additional 5 minutes of pre-heat time with a target pressure of 3000 PSI.

The laminated panels then have mechanical features introduced through green machining if necessary. Also, the external vias may need protection if thin film deposition is to be completed, so a pad will be printed over the critical externally exposed vias to act as a protective barrier. Finally, the LTCC panels are fired in a box oven.

Depending on the tape vendor, typical LTCC firing shrinkages in the X and Y directions range between 10-15%, while the Z dimension is typically around 15-20% [3]. LTCC tape and the corresponding metal systems used with them are intended to process/shrink comparably during firing. Warpage should be avoided at all costs; however, LTCC designs increasingly have become more complex, which makes predicting shrinkage in all dimensions more problematic due to the need for increased amounts of metallization causing decreased shrinkage. If shrinkage is predicted inaccurately, a host of downstream operation problems are possible, including being unable to align post-fired prints, inaccurate thin film deposition alignment, inability to saw to correct dimensions, or a variety of assembly operation issues, which can all cause significant yield fallout.

Ideally, settings for lamination and firing for all designs should be kept similar. However, lamination pressures can be adjusted between different designs when the same expansion factor is used for these varying products. Once the panels are fired, the tooling needed for downstream processing will not be applicable if the predicted shrinkage was not accurate. In a worst case scenario, new tooling will be required, which can lead to crucial delays in production.

In order to more precisely calculate shrinkage, the following shrinkage model was developed [4]:

% firing shrinkage = 13.6269 - (.00502500 x % metal loading) - (.000344595 x pressure) (1)

where pressure is in PSI, and which considered the factors of metal loading, lamination pressure, and layer count (layer count was found to be not significant though). This shrinkage model was utilized on several builds with some success; however, as will be shown later, this model was not sufficient going forward. The suspected reasons for inadequacy in this model were due to the introduction of large cavities, along with other mechanical features, and the lack of a factor for incoming tape lot shrinkage. Therefore, a DOE must be completed to define the critical variables, which occurs by utilizing data from 4 different products that are fabricated in-house.

II. Experimental Design

A. *Incoming Tape Lot Shrinkage Verification*

To verify incoming tape lot shrinkage, a procedure was developed through discussions with the tape manufacturer, wherein their testing procedure was used as a point of reference, and the current process is described as follows: thermal conditioning and punching of 8 random pieces of tape from a specific lot is completed as described earlier, and then all 8 pieces have four shrinkage measurements (see Fig. 1) taken. Collation can either be done manually or using automation, and two panels of 4 layers each (with the casting direction rotated 90^0 on every other layer) are laminated at 3000 PSI for 10 minutes at 70^0C using an isostatic laminator, with the fixturing mentioned previously. The two panels are then fired in the box oven, and the panels are measured again and the shrinkage is calculated by:

$$\% \text{ Shrinkage} = \frac{\text{Unfired punch dimension} - \text{fired dimension}}{\text{Unfired punch dimension}} \times 100\% \quad (2)$$

Incoming tape lot shrinkage verification performs an important role in the development of a new shrinkage model. However, shrinkage data provided through the COA is only a starting point, and verification of the COA shrinkage data must take place prior to undertaking any LTCC build. Table II shows the testing that has taken place to verify shrinkage data from incoming tape lots.

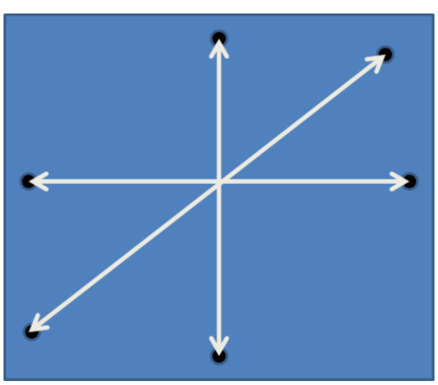

Figure 1: Example shrinkage measurements

Table II

	COA Shrinkage	Verified Shrinkage	Difference
Tape Lot 1	12.70%	12.90%	0.20%
Tape Lot 2	12.60%	12.87%	0.27%
Tape Lot 3	12.60%	12.89%	0.29%
Tape Lot 4	12.90%	13.11%	0.21%
Tape Lot 5	12.70%	12.95%	0.25%
Tape Lot 6	12.50%	12.77%	0.27%

There are differences between the reported shrinkage in the COA and verified shrinkage data obtained using the processes detailed above. So naturally, the question of what causes these differences must be investigated. In working with the tape supplier, two sources of variation were identified that causes these differences. The first source of variation is type of laminator, which is integral in being able to replicate shrinkage data from the COA. The COA data obtained in the above table is from a uniaxial laminator, and as mentioned in the previous section, the use of an isostatic laminator was employed to produce the verified shrinkage values. The tape supplier maintains there is always a uniaxial/isostatic offset in shrinkage value, which varies from lot to lot. The second source of variation comes from style of firing that occurs. The tape supplier uses a belt furnace; whereas, the data obtained above is from the use of a box oven. Table III below summarizes these differences.

Table III

	Tape Manufacturer Equipment	Honeywell Equipment
Lamination	Uniaxial	Isostatic
Cofire	Belt furnace	Box oven

Next, from a process engineering standpoint, the difference that is obtained from the COA, to the verified, should be control charted to track variation from lot to lot, and this technique is demonstrated using Minitab v16 in Fig. 2.

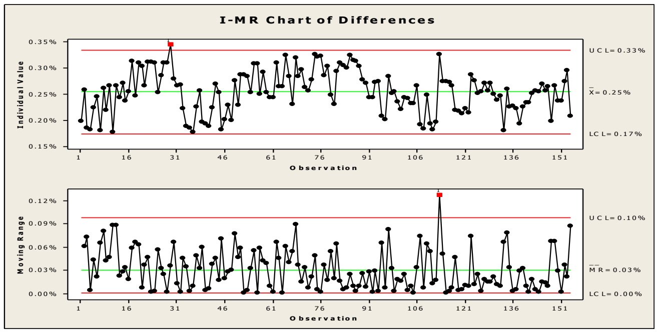

Figure 2: Control Chart of Verified Shrinkage minus COA Shrinkage

As shown in Fig. 2, the verification process is relatively stable (there is only one data point outside of the control limits), and from a data analysis perspective, there is no concern about the precision of the control limits due to the quantity of data that has been collected. However, there is some concern regarding the range of the control limits, but currently, the control limits are being designated by Minitab.

B. Shrinkage Verification Before and After Relocation

During the past year, a major relocation was undertaken of all LTCC fabrication process equipment. As part of that relocation process, data analysis was completed for process equipment related to shrinkage verification. The first piece of equipment studied was the punch, with the laminator and box oven examined as well. Prior to relocation, a statistically significant quantity of tape was punched and four shrinkage dimensions, which were described earlier, were measured on all pieces of punched tape. This procedure was repeated once the relocation of the punch was completed using the same lot of tape. The table below shows the p-values for the two data sets, and also shows the p-values for the 2-sample t-tests that were used to compare the two data sets (p-values greater than 0.05 show normality [per Anderson-Darling], along with no difference between data sets).

Table IV

	Old Facility P-Value	New Facility P-Value	2-Sample t P-Value
Shrinkage dimension 1	0.277	0.483	0.383
Shrinkage dimension 2	0.519	0.770	0.709
Shrinkage dimension 3	0.186	0.388	0.973
Shrinkage dimension 4	0.107	0.380	0.244

The above p-values for the old and new facility show all of the data to be normal, and the 2-sample t-test p-values show there is no significant difference between the two facilities. Next, all of the punched tape was stacked into four layer stacks and laminated at 3000 PSI at 70^{0}C for 10 minutes. Measurements were again taken so a comparison could be performed, and the results are shown in Table V. Lastly, all of the panels were fired in a box oven, and measurements were taken after firing so one additional comparison could be completed.

Table V

	Lamination 2 Sample t P-Value	Cofire 2 Sample t P-Value
Shrinkage dimension 1	0.350	0.737
Shrinkage dimension 2	0.464	0.158
Shrinkage dimension 3	0.978	0.354
Shrinkage dimension 4	0.240	0.834

Again, the p-values show no significant difference, compared to 0.05, between the two locations.

C. Status of Existing Shrinkage Model

During the relocation process, shrinkage data from the varying products built prior to shut down was thoroughly analyzed. The results from this analysis are shown below in Tables VI and VII.

Table VI: Process Capability of 4 Products

Within	C_p	C_{pk}
Product 1	0.72	0.05
Product 2	0.64	0.36
Product 3	0.56	0.54
Product 4	0.58	0.30

Table VII: Overall Process Capability of 4 Products

Overall	P_p	P_{pk}
Product 1	0.56	0.04
Product 2	0.44	0.25
Product 3	0.59	0.56
Product 4	0.53	0.28

As tables VI and VII clearly show (a C_{pk} of 0.33 is only 1 sigma, and a C_{pk} of 0.66 is 2 sigma), the shrinkage model used to predict shrinkage for these products was not sufficient, and a new model must be developed.

D. Updated Shrinkage Model

To build upon the existing shrinkage model [4], a DOE was constructed using existing shrinkage data from four products stated in the previous section. The constants for this DOE were that all panels were laminated in the same isostatic laminator with the exact amounts of time and temperature, and all panels were fired in an identical box oven using the same firing profile. Tape lot shrinkage values originate directly from the COA data that comes with the tape. The metal loading was established utilizing CAM360 V10.8 through the use of the copper analysis tool and the associated Gerber files; however, a new metal loading was developed wherein the average metal loading is now calculated to sum each layer's metal contribution and to take the average for each layer versus averaging all individual metal contributions for a given design (the average for a given design has increased from 16% [old method] to 36% [new method]).

Also, questions were raised regarding mechanical features (cavities, valleys, through-holes, etc.) introduced to the parts on all 4 products. These features were also considered as part of this DOE; although, mechanical features were found not to be significant to the new shrinkage model and thus are not shown in Table VIII and IX.

To also demonstrate the validity of this new equation, the two shrinkage models were used to back-calculate the shrinkage for all of the runs shown in Table VIII. When the new shrinkage equation is used, the calculated fired dimension is 0.004 inches greater than nominal; whereas, with the old equation, the calculated fired dimension is now almost 0.009 inches from the nominal, meaning the new equation gets twice as close to nominal as the old equation.

Table VIII

Run Order	Product	Tape Lot Shrinkage (%)	New Average Metal Loading (%)	Lamination Pressure (PSI)	Average Shrinkage (%)
1-7	Product 1	12.5	34.3	3450	12.47
8-22	Product 2	12.9	32.4	3050	12.94
23-31	Product 3	12.6	31.1	2400	12.60
32-44	Product 4	12.7	38.8	3250	12.69

Table IX

Predictor	Coef	SE Coef	T	P
Constant	-6.579	1.127	-5.84	0.000
tape lot shrinkage	1.54320	0.08938	17.27	0.000
New Average Metal Loading	0.011960	0.003765	3.18	0.003
Lamination Pressure	-0.00024656	0.00004339	-5.68	0.000

S = 0.0456633 R-Sq = 93.3% R-Sq(adj) = 92.6%

The LTCC firing shrinkage can now be re-summarized here:

% shrinkage = - 6.58 + (1.54 x tape lot shrinkage) + (0.0120 x metal loading) – (0.000247 x lamination pressure) (3)

where the lamination pressure is in PSI.

As can be seen, a new factor for tape lot shrinkage must be added due to the significance shown in Table IX. Also, the R-Sq. (adj.) improved from 61.7% [4] to 92.6% with the development of this new equation. Lastly, verification of this equation has taken place as part of a requalification build, along with our first product built at the new facility in the past few months. As Table X shows, the new equation has significantly improved our process capability.

Table X

	C_p	C_{pk}	P_p	P_{pk}
Requalification	1.28	0.84	1.20	0.79
Product 5	1.20	1.17	1.25	1.22

III. Conclusion

A method for verifying incoming LTCC tape lot shrinkage is developed, and this process is utilized to confirm no changes have taken place during LTCC fabrication equipment relocation. Also, a new LTCC shrinkage equation was developed due to past inadequate process capabilities, based on four products' incoming tape lot shrinkage, lamination pressure, metal loading, mechanical features (not significant), and firing shrinkage. Regression analysis was utilized to develop this new equation, and validation took place during a requalification build. This new equation was used to determine the expansion factor for the first real build at the new facility and will continue to be used on all LTCC builds going forward.

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