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Response Predicting LTCC Firing Shrinkage: A Response Surface Analysis Study

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Abstract—**Low temperature cofired ceramic (LTCC) technology is used in a variety of applications including military/space electronics, wireless communication, MEMS, and medical and automotive electronics. The use of LTCC is growing due to the low cost of investment, short development time, good electrical and mechanical properties, high reliability, and flexibility in design integration (i.e., three dimensional microstructures with cavities are possible). The dimensional accuracy of the resulting *x*/*y* shrinkage of LTCC substrates is responsible for component assembly problems with a tolerance effect that increases in relation to the substrate size. Response surface analysis was used to predict product shrinkage based on specific process inputs (metal loading, layer count, lamination pressure, and tape thickness) with the ultimate goal to optimize manufacturing outputs (NC files, stencils, and screens) in achieving the final product design the first time. Three regression models were developed for the DuPont 951 tape system with DuPont 5734 gold metallization based on green tape thickness.**

Keywords—**Design of experiment, LTCC, shrinkage modeling**

Introduction

Low temperature cofired ceramic (LTCC) technology incorporates high density ceramic packaging and low temperature processing. Many passive components can be buried into a multilayer, monolithic structure and fired simultaneously [1].

LTCC processing begins with a ceramic tape. The tape consists of a glass and filler dielectric material suspended in organic binders and plasticizers. To create the tape, a wet mixture called a slurry is cast onto a backing material using a continuous tape caster. The tape is cast at uniform thickness, typically between 2-10 mil, and then immediately dried. After the tape is created, it is rolled up and stored. Commercial LTCC tape can be purchased either in these rolls or precut to a specific size.

The following explains the LTCC process flow in this work.

After the tape was blanked to the correct size, it was placed in an oven for 1 h at 100°C. This conditioning process replaced the previous practice of normalization, that is, removing the backing material and allowing the tape to settle for 24 h. The benefit of conditioning rather than normalization is that the backing material did not have to be removed from the tape. This kept the tape rigid during the single-layer processing steps. The benefit of tape rigidity was to restrict tape movement (stretching can cause misalignments and compromise shrinkage measurements at the surface).

The conditioned tape was then punched. Via holes and registration holes were punched at the same time to maximize alignment between layers.

The punched tape was then screen printed. The vias were filled first, using a very dense material that does not fall out during firing. After all vias were filled and dried, conductor traces were printed on the exposed tape surface, or front side. On layers requiring backside printing, the backing material was removed to allow printing.

After the conductor prints were dried, the backing material was removed, and the layers were stacked using a mechanical fixture with pins alternately rotated 90° to the cast direction. Each stack was then wrapped in latex, vacuum sealed in bags, and laminated. The laminated panels were then baked out and fired in a box furnace.

Standard, unconstrained LTCC firing shrinkage ranges from 10-15+% in the x and y directions to 20% in the z direction [2], depending on the tape. LTCC metallizations are designed to perform similarly to the LTCC tapes during firing. LTCC panels should not show excessive warping in the areas that are printed. However, as LTCC designs become more complex and require increased amounts of metallization, the overall x-y shrinkage of the panel decreases because of high metallization density. This has created many difficulties, not only in postfired printing, but also in assembly operations. In wire bonding and die placement, where most commercial operations are done automatically, a significant variation in sizing from the original design can have a catastrophic effect on yield.

Determining optimal lamination and firing parameters for each design can cause many delays. Designers historically used a specific expansion factor for every build based on an average of past data, and artwork for all cofired metallization screens and stencils were created using this factor. Screens for postfire printing were made assuming 1:1 correlation with the cofired artwork expansion factor once the panels were fired. After firing, if the actual shrinkage amount did not match the predicted value, a lamination study was completed to determine the optimal lamination pressure to achieve the desired shrinkage. This would take anywhere from two days to a week to complete, and used up product as well as labor. At times, the shrinkage was so low that the designer would have to modify the artwork using the actual expansion factor for the particular build, and in turn new screens would be made for postfired printing, increasing costs and delaying production.

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In order to save labor, material costs, and time in the fabrication process, it was decided to perform a DOE and regression analysis to predict a shrinkage value for each design using a formula rather than trial and error. With the changing layer count, metal loading, and tape layer requirements of various designs, it was determined that a shrinkage model was needed to better center the lamination process (3000 psi target).

Experimental Design

Following screening experiments used to select main factors and test levels, a central composite 20 run, three factor, with eight cube points, four center points on cube, six axial points, and two center points in axial DOE was completed on DuPont 951 LTCC tape. The shrinkage behavior was modeled separately on three LTCC green tape thicknesses as follows: 4.5, 6.5, and 10 mil thicknesses. The input factors and levels are shown in Table I.

The constants for the DOE were as follows: the same tape lot was used for a given thickness, the samples were fired at 850°C in the same box oven, 8 μm fired thickness using DuPont 5734 cofire Au was targeted, cavities were not present, and lamination of the green tape occurred in an isostatic laminator at a temperature of 70°C for 10 min after 5 min of preheat. The metal loading was determined by layer from gerber files generated by CAM360 V9.5 using the copper analysis tool.

The response factor for the DOE was the average shrinkage based on a sample size of one 5 sq. in panel (due to cost constraints). Green and fired punched holes in the LTCC tape were measured diagonally on each sample using an optical measurement system. A gage R and R study was completed on the optical measurement system resulting in a 12.3% gage R and R, which was determined to be acceptable for this study.

A. DuPont 10 Mil Thick 951 PX Green Tape

The DOE run combinations and results for the 10 mil thick green tape following randomization can be broken down as shown in Table II.

The analysis of variance (ANOVA), calculated by Minitab v15 can be summarized in Table III.

The LTCC firing shrinkage can be summarized as follows.

$$\begin{aligned}\%\,\text{firing shrinkage} = {} & 13.6269 \\ & - (0.00502500 \times \%\,\text{metal loading}) \\ & - (0.000344595 \times \text{pressure})\end{aligned}$$

The contour plot of the shrinkage versus lamination pressure and metal loading is shown in Fig. 1.

Based on the ANOVA, the factors of metal loading and lamination pressure were identified as significant in terms of LTCC firing shrinkage. The contour plot shown in fig 1 defines the percent firing shrinkage for given inputs of metal loading and lamination pressure for the PX tape.

B. DuPont 6.5 Mil Thick 951 P2 Green Tape

The experimental setup was replicated on the 6.5 mil thick green tape (P2). The DOE run combinations and results following randomization are shown in Table IV.

Table I
Input Factors and Levels

	Low	High
Metal loading	20%	80%
Lamination pressure	2750 psi	3100 psi
Layer count	7	17

Table II
DOE Run Combinations and Results for the 10 mil Thick 951 PX Green Tape

Run order	Metal loading	Pressure	Layer count	Shrinkage
1	25	3200	17	12.51
2	50	3000	12	12.33
3	50	3000	12	12.34
4	50	3000	12	12.29
5	25	2800	17	12.65
6	75	3200	7	12.30
7	50	3000	12	12.32
8	25	2800	7	12.56
9	75	3200	17	12.24
10	25	3200	7	12.44
11	75	2800	17	12.41
12	75	2800	7	12.38
13	50	2673	12	12.41
14	0	3000	12	12.73
15	50	3000	12	12.33
16	50	3000	12	12.30
17	50	3327	12	12.18
18	50	3000	4	12.31
19	100	3000	12	12.29
20	50	3000	20	12.34

Table III
The Summarized Analysis of Variance (ANOVA) 10 mil Thick 951 PX Green Tape

Response surface regression: shrinkage versus block, metal loading, pressure

Estimated regression coefficients for shrinkage PX

Term	Coefficient	SE coefficient	*T*	*P*
Constant	12.3794	0.01930	641.279	0.000
Block	0.0181	0.01930	0.939	0.363
Metal loading	−0.1325	0.02622	−5.054	0.000
Pressure	−0.0664	0.02316	−2.867	0.012
Metal × pressure	0.0016	0.03708	0.042	0.967

*S = 0.08459, R-Sq = 69.8%, R-Sq(adj) = 61.7%.

Estimated regression coefficients for shrinkage PX using data in uncoded units

Term	Coefficient
Constant	13.6269
Block	0.0181250
Metal loading	−0.00502500
Pressure	−3.44595E-04
Metal loading × pressure	2.50000E-07

The analysis of variance for the P2 tape can be summarized as shown in Table V.

The LTCC firing shrinkage can be summarized as follows.

$$\begin{aligned}\%\,\text{shrikage} = {} & 13.6859 - (0.00597500 \times \%\,\text{metal loading}) \\ & - (0.000296982 \times \text{pressure})\end{aligned}$$

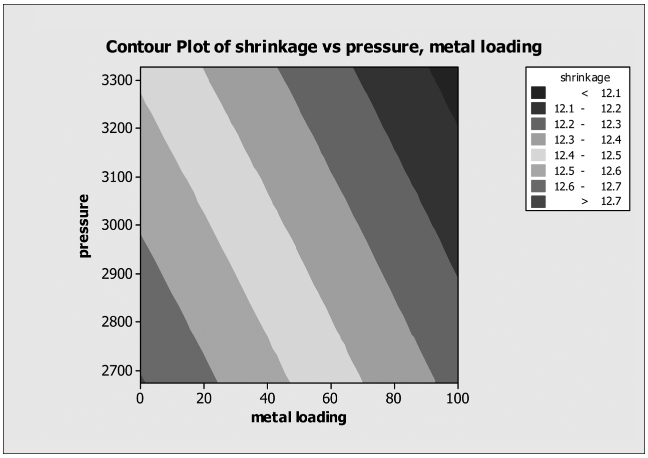

Fig. 1. The contour plot of the shrinkage versus lamination pressure and metal loading.

Table IV
DOE Run Combinations and Results for the 6.5 mil Thick 951 P2 Green Tape

Run order	Metal loading	Pressure	Layer count	Shrinkage
1	25	3200	17	12.55
2	50	3000	12	12.59
3	50	3000	12	12.51
4	50	3000	12	12.57
5	25	2800	17	12.71
6	75	3200	7	12.29
7	50	3000	12	12.64
8	25	2800	7	12.71
9	75	3200	17	12.29
10	25	3200	7	12.60
11	75	2800	17	12.40
12	75	2800	7	12.44
13	50	2673	12	12.62
14	0	3000	12	12.77
15	50	3000	12	12.54
16	50	3000	12	12.57
17	50	3327	12	12.48
18	50	3000	4	12.49
19	100	3000	12	12.30
20	50	3000	20	12.57

The contour plot of the shrinkage versus lamination pressure and metal loading is shown in Fig. 2.

C. DuPont 4.5 Mil Thick 951 PT Green Tape

The experimental setup was also replicated on the 4.5 mil thick green tape (PT). The DOE run combinations and results following randomization are shown in Table VI.

The analysis of variance for the PT tape can be summarized as shown in Table VII.

The LTCC firing shrinkage can be summarized as follows:

$$\begin{aligned}\%\,\text{firing shrinkage} = 14.4988 &- (0.0171450 \times \%\,\text{metal loading}) \\ &- (0.00045361 \times \text{pressure}) \\ &- (0.0347990 \times \text{layer count})\end{aligned}$$

The contour plots of the shrinkage versus metal loading, layer count, and lamination pressure are shown in Fig. 3.

Table V
The Summarized Analysis of Variance (ANOVA) 6.5 mil Thick 951 P2 Green Tape*

Response surface regression: shrinkage versus block, metal loading, pressure

Estimated regression coefficients for shrinkage P2

Term	Coefficient	SE coefficient	*T*	*P*
Constant	12.5338	0.01122	1116.894	0.000
Block	−0.0087	0.01122	−0.780	0.448
Metal loading	−0.1620	0.01524	−10.626	0.000
Pressure	−0.0569	0.01347	−4.225	0.001
Metal × pressure	0.0015	0.02156	0.072	0.944

*S = 0.04917, R-Sq = 89.8%, R-Sq(adj) = 87.0%.

Estimated regression coefficients for shrinkage P2 using data in uncoded units

Term	Coefficient
Constant	13.6859
Block	−0.00875000
Metal loading	−0.00597500
Pressure	−2.96982E-04
Metal loading × pressure	2.50000E-07

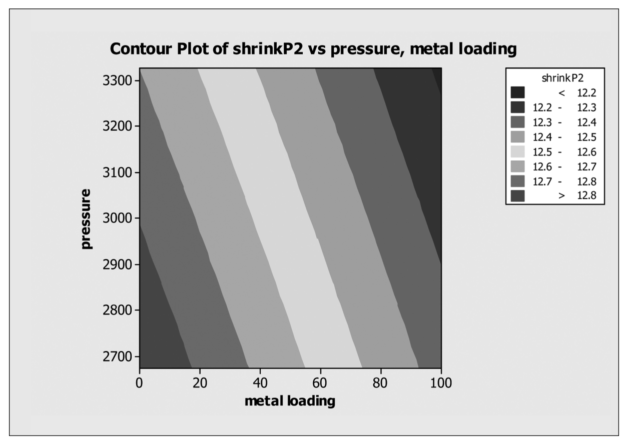

Fig. 2. The contour plot of the shrinkage versus lamination pressure, and metal loading.

Table VI
DOE Run Combinations and Results for the 4.5 mil Thick 951 PT Green Tape

Run order	Metal loading	Pressure	Layer count	Shrinkage
1	25	3200	17	12.64
2	50	3000	12	12.58
3	50	3000	12	12.46
4	50	3000	12	12.57
5	25	2800	17	12.76
6	75	3200	7	12.17
7	50	3000	12	12.42
8	25	2800	7	12.83
9	75	3200	17	12.14
10	25	3200	7	12.68
11	75	2800	17	12.21
12	75	2800	7	12.28
13	50	2673	12	12.57
14	0	3000	12	13.00
15	50	3000	12	12.74
16	50	3000	12	12.59
17	50	3327	12	12.46
18	50	3000	4	12.68
19	100	3000	12	12.00
20	50	3000	20	12.48

Table VII
The Summarized Analysis of Variance (ANOVA) 4.5 mil Thick 951 PT Green Tape

Response surface regression: shrinkage versus block, metal loading, pressure

Estimated regression coefficients for shrinkage PT

Term	Coefficient	SE coefficient	T	P
Constant	12.5217	0.01812	691.056	0.000
Block	−0.0433	0.01812	−2.392	0.034
Metal loading	−0.3185	0.02461	−12.941	0.000
Pressure	−0.0472	0.02174	−2.172	0.051
Layer count	−0.0402	0.02174	−1.851	0.089
Metal × pressure	0.0140	0.03481	0.401	0.696
Metal × layer count	0.0016	0.03481	0.045	0.965
Pressure × layer count	0.0087	0.02807	0.312	0.761

*S = 0.07940, R-Sq = 93.8%, R-Sq(adj) = 90.2%.

Estimated regression coefficients for shrinkage PT using data in uncoded units

Term	Coefficient
Constant	14.4988
Block	−0.0433333
Metal loading	−0.0171450
Pressure	−4.53610E-04
Metal loading × pressure	−0.0347990

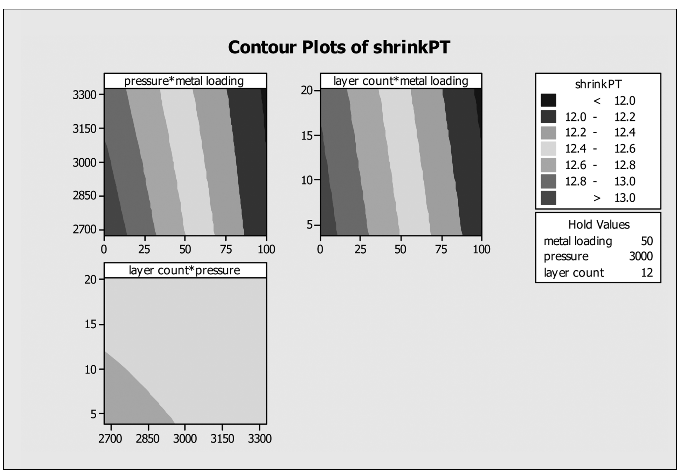

Fig. 3. The contour plots of the shrinkage versus metal loading, layer count, and lamination pressure.

Confirmation Run on RF MCMs (Metal Loading and Expansion Factor Calculations)

From the shrinkage prediction equations, a green tape expansion factor can be determined which is used for NC file generation as well as stencil and cofired print screen fabrication. The green design expansion factor was determined as follows.

$$\text{green design expansion factor} = 1/(1 - \text{predicted shrinkage}/100)$$

In an effort to validate the equations, four subsequent products were fabricated using manufacturing outputs generated with these equations as shown in Tables VIII, IX, X, and XI.

A typical RF MCM similar to the products validated in the confirmation run is shown in Fig. 4

Table VIII
Product 1*

Gerber	Tape layer	Area (sq. in)	Metal loading (%)
	1	0	0
	2	0	0
	3	0	0
	4	0	0
Metal 01	5	0.0575	1.989619377
Metal 02	6	0.1147	3.968858131
Metal 03	7	0.7164	24.78892734
Metal 04	8	0.2441	8.446366782
Metal 05	9	0.2538	8.78200692
Metal 06	10	0.7201	24.91695502
Metal NS	11	0.2252	7.792387543
Average		0.211981818	7.33501101

Note: Metal loading based on LTCC network area of 1.70 in × 1.70 in (2.89 sq. in)

Predicted shrinkage based on average metal loading
12.5562566

Calculated expansion factor for LTCC 1 based on Average Metal Loading
1.1435924

Calculated shrinkage verification dimension (green state)
5.71796198

*The fired shrinkage verification dimension averaged 4.9997 in compared with a nominal of 5.000 in with a standard deviation of 0.0024 in. The average shrinkage calculated for the lot of LTCC networks was 12.54% compared with the predicted shrinkage of 12.55%. Product fabrication utilized progressive lamination with an initial pressure of 1200 psi and a final lamination pressure of 2750 psi.

Table IX
Product 2*

Gerber	Tape layer	Area (sq. in)	Metal loading (%)
M00	1	0.9027	56.59561129
N00	2	0.0492	3.084639498
P00	3	0.0435	2.727272727
R00	4	0.9048	56.72727273
Metal 05	5	0	0
S00	6	0.7587	47.56739812
T00	7	0.2075	13.00940439
U00	8	1.0026	62.85893417
V00	9	0.3492	21.89341693
W00	10	0.3221	20.19435737
Y00	11	1.0037	62.92789969
Z00	12	0.24	15.04702194
Average		0.482	30.21943574

Note: Metal loading based on LTCC network area of 1.1 in × 1.45 in (1.595 sq. in)

Predicted shrinkage based on average metal loading
12.4412623

Calculated expansion factor for LTCC 2 based on average metal loading
1.14209047

Calculated shrinkage verification dimension (green state)
5.71045236

*The fired shrinkage verification dimension averaged 4.999 in compared with a nominal of 5.000 in with a standard deviation of 0.0036 in. The average shrinkage calculated for the lot of LTCC networks was 12.43% compared with the predicted shrinkage of 12.44%. Product fabrication utilized progressive lamination with an initial pressure of 1200 psi and a final lamination pressure of 3000 psi.

Table X
Product 3*

Gerber	Tape layer	Area (sq. in)	Metal loading (%)
M00	1	1.2529	78.55172414
AB00	1 (B)	0.1	6.269592476
N00	2	0.1885	11.81818182
P00	3	0.1873	11.74294671
R00	4	0.9975	62.53918495
S00	5	0.1732	10.85893417
T00	6	0.291	18.24451411
U00	7	1.0887	68.25705329
V00	8	0.3423	21.46081505
W00	9	0.3468	21.74294671
Y00	10	1.2737	79.85579937
Z00	11	0.2593	16.25705329
Average		0.541766667	33.96656217

Note: Metal loading based on LTCC network area of 1.1 in × 1.45 in (1.595 sq. in).

Predicted shrinkage based on average metal loading
12.422433

Calculated expansion factor based on average metal loading
1.14184492

Calculated shrinkage verification dimension (green state)
5.7092246

*The fired shrinkage verification dimension averaged 4.9998 in compared with a nominal of 5.000 in with a standard deviation of 0.0036 in. The average shrinkage calculated for the lot of LTCC networks was 12.43% compared with the predicted shrinkage of 12.42%. Product fabrication utilized progressive lamination with an initial pressure of 1200 psi and a final lamination pressure of 2500 psi.

Table XI
Product 4*

Gerber	Tape layer	Area (sq. in)	Metal loading (%)	Tape
W00/Y00/Z00	1	0.242	8.37370	PX
AB00	2	0.2116	4.61002	PX
AB00	3	0.2576	5.61220	PX
AC00	4	0.4632	10.09150	PX
AD00	5	2.6826	58.44444	P2
AE00	6	1.2628	27.51198	P2
AF00	7	1.1471	24.99128	P2
AH00	8	4.0196	87.57298	PX
AJ00/AK00	9	3.9827	86.76906	PX
AL00/AM00	10	1.5104	32.90631	PX
Average (weighted)		1.57796	34.68835	
Average PX		1.52672	30.06822	
Average P2		1.69750	36.98257	

Note: Metal loading based on LTCC network area of 1.1 in × 1.45 in (1.595 sq. in)

Predicted shrinkage based on average metal loading
12.6215

Calculated expansion factor based on average metal loading (weighted average)
1.1442

Calculated shrinkage verification dimension (green state)
5.7092246

*The fired shrinkage verification dimension averaged 4.998 inches compared with a nominal of 5.000 inches with a standard deviation of 0.0021 inch. The average shrinkage calculated for the lot of LTCC networks was 12.62% compared with the predicted shrinkage of 12.61%. Product fabrication utilized progressive lamination with an initial pressure of 1200 psi and a final lamination pressure of 2600 psi.

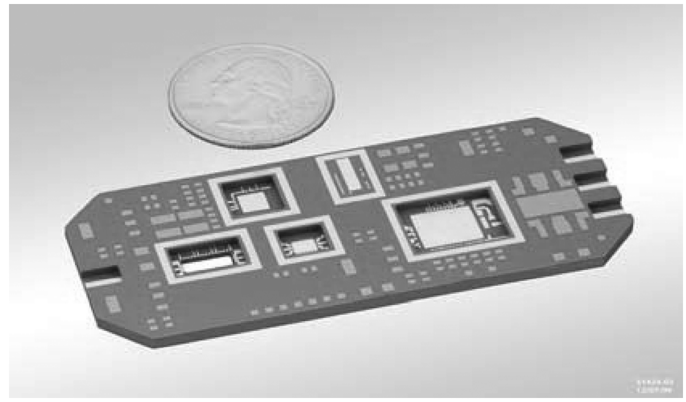

Fig. 4. A typical RF MCM similar to the products validated in the confirmation run.

Conclusions

The goal of the study was to analyze and model the shrinkage behavior of DuPont 951 tape. Response surface analysis yielded a methodology to more accurately predict shrinkage of LTCC products based on design factors such as metal loading, layer count, and tape thickness. This allowed for the adjustment of manufacturing outputs (punch files and cofired print tooling) to provide a final adjustment of shrinkage using lamination pressure. As the green tape thickness decreases, the DOE factors and levels tested more closely model the shrinkage behavior as determined by the ANOVA. It was determined that when two different tape thicknesses are used on a given design, a weighted average can be used to model the tape thickness. The accuracy of the shrinkage models was validated in the confirmation run builds of the functional product.

The shrinkage models developed here apply to our specific process and equipment and it is highly recommended that these experiments be repeated when applied to a different set of conditions.

Future Work

The future work planned can be summarized as follows:

1) Study the effect of progressive lamination.
2) Characterize the shrinkage variation versus position in the firing oven.
3) Develop shrinkage models for cofired silver metallizations.
4) Study the effects of varying lamination parameters.

Acknowledgment

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