HeraLock™ 2000 Self-constrained LTCC Tape

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Abstract

A limitation of low-temperature co-fired ceramic (LTCC) technology involves the x-y shrinkage of LTCC structures upon firing and the control or tolerance of that shrinkage. This problem affects component design, materials utilization, lot-to-lot tolerance of fired components and surface circuit feature location. This paper discusses a novel method to prevent the x-y shrinkage of LTCC structures with the implementation of a new LTCC tape formulation.

The HeraLock™ 2000 tape is in most ways indistinguishable from a standard LTCC tape formulation. A modified form of CT2000 tape, HeraLock™ 2000 is a lead-free and cadmium-free formulation with properties appropriate for general-purpose packaging, automotive modules and RF applications requiring low-loss at frequencies up to at least 6 GHz. The main advantage of HeraLock™ 2000 tape is its unique shrinkage properties during firing. Most free-sintered tapes have shrinkage in the x and y directions similar to the shrinkage in the z-axis. In contrast, free-sintered HeraLock™ 2000 densifies by shrinking primarily in the z-axis, leaving near-zero shrinkage in the x and y directions. In an example significant for large-format manufacturing, the x-y shrinkage on six-inch square parts (152 mm x 152 mm) fired with the standard profile was 0.114% +/- 0.014%.

In its green state, HeraLock™ 2000 is handled similarly to conventional tapes. The only change in processing relative to CT2000 is a somewhat longer firing profile. The HeraLock™ tape is compatible with standard design guidelines with respect to conductors or via holes. The HeraLock™ formulation resists camber or show-through from co-fired conductors and is compatible with 100% coverage ground-planes on surface or buried metal layers.

The paper concludes by discussing the advantages of HeraLock™ HL2000 for the manufacturing LTCC modules. For example, cavity structures cut into the green HeraLock™ tape show no x-y shrinkage or distortion after firing. Large area boards can be fabricated with minimal solder pad alignment problems – a common disadvantage of LTCC. These large area boards permit the fabrication of circuits in high volume at low cost. A further benefit compared to sacrificial layer constrained sintered processes is the ability to use co-fired solderable top conductors.

Key words: LTCC, constrained sintering, RF materials, cavity structures, microwave, opto-electronic

Introduction

Low-temperature cofired ceramic (LTCC) materials can reduce the cost of building complex multi-layer circuits. Perhaps the greatest benefit of LTCC is encountered in the process of building one challenging part. Because each layer of the circuit can be processed separately before being laminated into the final structure, a flaw in one step of the process may require scrapping out only the affected print layer and not the whole module. In other words, LTCC improves manufacturing yield by replacing many of the sequential process steps of printed thick film technology with parallel processes.

In a normal course of product evolution, the manufacturer who has successfully built one part would now like to build ten or a hundred parts in the same number of process steps by expanding the LTCC panel size. Until now this normal course of evolution eventually ran into the painful tradeoff between process simplicity versus tight control of fired dimensions. This is because the shrinkage of free-sintered LTCC in the x-y direction is subject to a variation of about +/- 0.2%. Over the distance of an otherwise practical format size, say, 8” x 8” (203mm x 203 mm), this variation results in a positional uncertainty of +/- 16 mils (41 μ) in both the x and y directions. This is problematic for post-firing processes such component placement and particularly solder pad printing, and has forced large-format manufacturers to resort to adding and removing sacrificial constraining layers to reduce shrinkage and shrinkage variation. Because co-fired solderable top conductors may be incompatible with the sacrificial tape, the surface conductor prints are sequential process steps performed after removing the sacrificial layers from the fired parts. The use of sequential printing steps negates some of the primary manufacturing advantage of LTCC.

Relative to thick-film, LTCC provides some additional benefits for circuit designs that require a cavity structures or open vias through the module structure. When working with alumina, there is a critical trade-off between the cost of forming the vias and the precision of the geometry after the alumina substrate is fired: green-punching is much cheaper than laser drilling, but subject to a 0.25% shrinkage variation. In contrast, the conductor patterning and the cavity structures of LTCC modules can be formed on green tape, reducing the tolerance stack-up. However, the LTCC is still subject to shrinkage variation as well as deformation of the structure near the edges.

Heralock™ HL2000 LTCC tape gives the x-y shrinkage control of sacrificial layer constraint in a free-sintered process. This eliminates the cost of adding and removing sacrificial materials and retains compatibility with cofired solderable top conductors. Each layer of tape is self-constrained, so the shrinkage control of HL2000 is consistent whether the module has two layers or twenty, and is ideal for forming cavity structures that will not deform during firing. In this paper we will give an overview of the HL2000 manufacturing process, discuss a series of experiments quantifying the shrinkage control of HL2000, and describe the benefits of using this new tape system.

HL2000 Standard Process

The HL2000 tape is handled using standard free-sintered LTCC processes (see Table 1). Relative to the sacrificial tape constraining process, HeraLock™ requires three fewer process steps. The standard isostatic lamination process involves fifteen minutes at 75^{o}C with a laminating pressure of 4500 PSI. The HL2000 firing profile (Figure 1) has a burnout zone at about 450 C and a peak firing temperature of 870 C +/- 10 C. Between about 720 C and the firing peak the firing temperature needs to be ramped at a rate of 5 to 5.5 ^{o}C/min for optimal RF performance. As will be discussed further, the shrinkage control of HL2000 is relatively insensitive to variations in the firing profile.

X-Y Shrinkage Measurements

An experiment was performed to evaluate how the peak firing temperature affects the shrinkage of HL2000. A 4.75" x 5.5" (120 mm x 140 mm) green laminate was printed with a distinctive conductor pattern and then cut into six strips. The size of the conductor pattern (nominally 4.40" or 112 mm) was measured with calipers at five points on each strip before and after firing in order to calculate the shrinkage. Three parts were fired at a peak temperature of about 850 C; the remaining parts were fired at about 875 C. The results (see Table 2) show measured values of shrinkage ranging from 0.07% to 0.10%. Given the limited resolution of the experiment (about +/- 1 mil or +/- 0.023%), the results did not reveal a statistically significant change in shrinkage with peak firing temperature.

Table 1: Comparison of sacrificial layer and self-constraint process steps.

Sacrificial Tape Constraining Process	Heralock™ HL2000 Self-constraint Process
Blank tape	Blank tape
Via Punch	Via punch
Via & inner conductor metallization	Via & conductor metallization
Lamination w/ sacrificial layers	Lamination
Fire	Fire
Remove sacrificial layers	⇩
Outer conductor metallization	
Fire	
Singulate	Singulate

A similar experiment was performed to evaluate the effect of changes in the ramp rate on the shrinkage of HL2000. The selected range for the variations involved were was 600 C and 720 C; otherwise the profile was not significantly different from the standard profile shown in Figure 1.

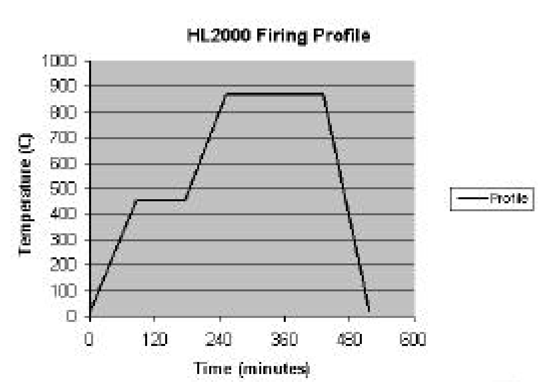

Figure 1: HL2000 firing profile.

As noted earlier, the optimal RF performance of the tape requires a controlled ramp rate in the region between about 720 C and 875 C.

The results of this experiment are listed in Table 3; a picture of the parts is shown in Figure 2. Again, these experiments did not reveal a significant change in the shrinkage for these profile variations.

Table 2: Effect of peak firing temperature on shrinkage (ΔL) of HL2000.

#	**Peak Firing Temp**	**DL** mils (μ)	**DL /L**
1	850 C	4.4 (112)	0.10 %
2	850 C	3.9 (99)	0.09%
3	850 C	4.5 (114)	0.10%
4	875 C	4.0 (102)	0.09%
5	875 C	3.2 (81)	0.07%
6	875 C	3.2 (81)	0.07%

The variation of the five shrinkage values measured for each strip in the experiments described above was about 3 mils (76 μ). This means that the window of these measurements was almost as large as the shrinkage; too high to allow an accurate measurement of the shrinkage variability. In order to quantify the shrinkage variation, a more precisely defined feature was needed. A new technique was used that replaced the printed conductor with a series of small indents. Calipers were set at a length of 5.0000” and the tips of the calipers were used to make a series of small imprints on the surface of the green laminate as shown schematically in Figure 3. The same calipers were used to measure the imprint spacing after firing.

Table 3: Effect of firing profile ramp rate on the shrinkage of a 4.4” (112 mm) length L of HL2000.

#	**Modified Zone** (C)	**Ramp Rate** ^{O}C/min	**DL** mils (μ)	**DL/L**
1	Dried only	-	-	-
2	600 – 700	0.5	3.8 (97)	0.09 %
3	650 - 725	0.5	3.8 (97)	0.09%
4	600 – 700	1.7	4.5 (114)	0.10%
5	650 - 725	1.7	4.3 (109)	0.10%
6	none	5.5	3.7 (94)	0.08%

Two 6” x 6” (152 mm x 152 mm) parts were made with four layers of HL2000 tape; each layer of tape was oriented in the same direction to allow resolving any directional bias in the shrinkage. The two parts were fired at the nominal peak temperature of 870 C but were placed at extreme positions (front bottom versus top back) in the box furnace. As shown in Table 3 these results show a slight bias in the shrinkage results depending on whether the measurement direction is taken along the length of the tape (i.e., the direction in which the tape is cast) or along the width.

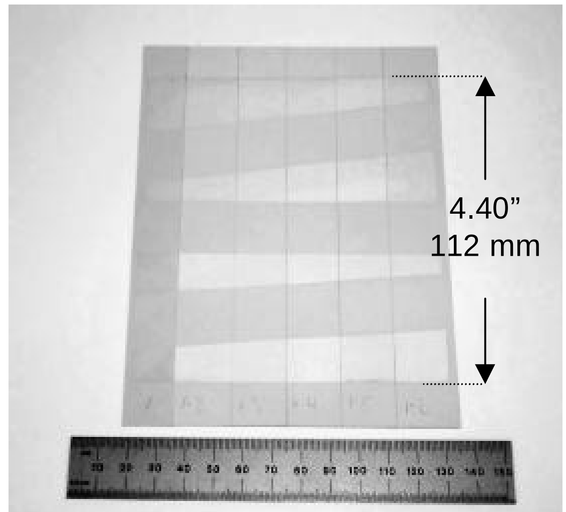

Figure 2: A green laminate of HL2000 has been cut into six strips; five of the strips have been fired with different profiles; the first part remains green.

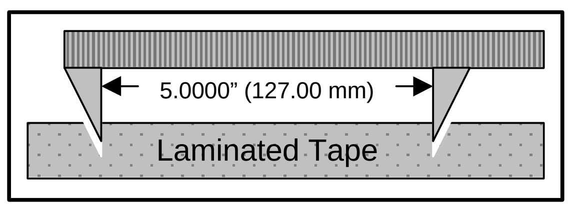

Figure 3: For the caliper imprint method, digital calipers are used to place precisely spaced indents on the surface of laminated tape; the same calipers are used to measure the spacing after firing.

Table 3: Caliper imprint shrinkage results.

Direction	**Average Shrinkage**	**Std. Dev. s**
x (Length)	0.107 %	0.0095 %
y (Width)	0.121 %	0.0139 %

Flatness

An advantage of most constrained sintering processes is that the fired part tends to be free from camber and show-through. This benefit may not be fully utilized with sacrificial layers when the sacrificial tape is incompatible with co-fired top conductors. Like LTCC processed with older constrained sintering processes, HL2000 tape is resistant to show-through and camber, but it is also compatible with co-fired surface conductors.

An experiment was performed to evaluate conductors formulated from different silver powder types and co-fired on HL2000 tape as well as an unconstrained LTCC tape, CT2000. Samples of the parts from this experiment are shown in Figure 4. No inorganic binders or oxides were used in the conductor pastes to reduce camber or show-through. The flatness and camber of the fired parts was measured with a CyberOptics surface analyzer. The measurements were made in a dual differential format; the difference between the maximum and minimum heights was recorded.

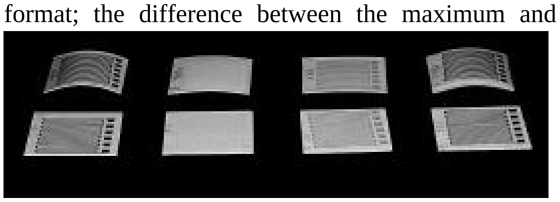

Figure 4: Test patterns printed with experimental pastes made from four different powder types on a CT2000 LTCC and HL2000 tapes. The CT2000 parts are in the back, the corresponding HL2000 parts are in the front row.

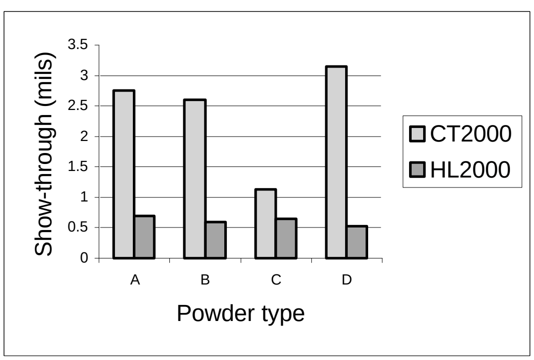

Figure 5: Show-through measurements on conventional LTCC (CT2000) and HL2000 with 80 mil (2mm) pads of experimental conductors made from different powder types. The HL2000 results are similar to those from a blank part.

The show-through was measured with a window of 160 mils (4 mm) on the back surface under the series of 80-mil (2 mm) square pads. A similar measurement on a blank gives a typical value (maximum – minimum reading) of about 0.52 mils (13 µ). As shown in Figure 5, the show-through on the CT2000 tape ranged from about 0.5 mils to about 2.5 mils (13 µ to 64 µ) more than the blank reading. In contrast, the values measured on HL2000 were not significantly different from the blank part result.

The camber was measured along a 500 mils (12.5 mm) window on the back side of the parts parallel to the runners of the snake pattern. With this size window, the typical blank result was about 0.56 mils (14 µ). As shown in Figure 6, the camber on the parts made with CT2000 tape ranged from about 6 mils to about 30 mils (150 µ to 750 µ). The camber values measured on HL2000 were not significantly different from the blank part result (the average camber was about 0.03 mils (0.8 µ) larger than the blank value).

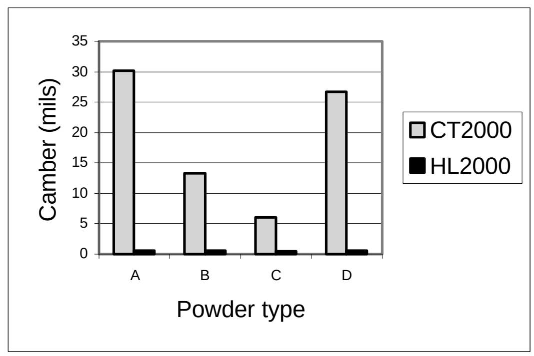

Figure 6: Camber measurements on conventional LTCC (CT2000) and HL2000 measured over a distance of 500 mils (12.5 mm.

Application Benefits

The Heralock™ HL2000 tape has several benefits for LTCC manufacturers. Because the green structure does not shrink, a larger number of parts can be manufactured with a given format size. Other advantages include the simpler manufacturing process of standard LTCC, good RF dielectric properties, resistance to camber and show-through, and tight shrinkage control for large-format manufacture. This unique set of advantages can translate to significant cost reductions for many applications.

The HL2000 tape has good properties for RF applications at frequencies up to at least 6 GHz. The relative permittivity is approximately 7.7 with a loss tangent of 2 $x10^{-3}$ as measured at 2.5 GHz. The temperature coefficient of the resonant frequency is less than 50 ppm as measured at 1.6 Ghz. The tight control of feature dimensions allows the fabrication of microwave structures with more consistent frequency response.

A sample circuit pattern printed on HL2000 is shown in Figure 7. The top surface has been printed with CL47-8013, a solderable AgPt conductor. The bottom surface is printed with a 100% coverage ground-plane of TC2303 silver conductor. On a part with a fired laminate thickness of about 15 mils (0.38 mm), the maximum camber was less than 3 mils (75 μ) over a 2” (51 mm) window.

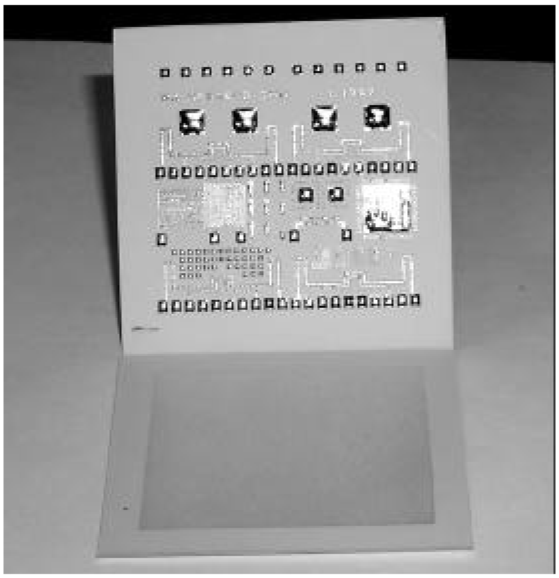

Figure 7: Samples of HL2000. The top of part has been co-fired with CL47-8013 AgPt conductor and dipped in 62-36-2 SnPbAg solder. The bottom part is a ground plane printed and fired with TC2303 Ag.

The positional tolerance (i.e., the maximum deviation from nominal position) of a patterned feature due to shrinkage variation can be calculated as size multiplied by variation. Figure 8 shows a graph of the expected tolerance of position for three processes: standard free-sintered LTCC, DP951 with sacrificial constraint layers, and free-sintered Heralock™ HL2000. To calculate this tolerance, the total shrinkage variation for standard LTCC was taken to be +/- 0.2% regardless of format size. For both HL2000 and constrained sintered DP951, the total shrinkage variation was calculated as +/- 3σ, where the standard deviation of the shrinkage is measured over a length of five inches (127 mm) [0.04% for DP951 with sacrificial layers[1], and 0.014% for HL2000]. Figure 8 shows that for a given format size a much smaller variation of feature position will be observed for HL2000 than for the other two processes. Alternatively, for a given tolerance requirement, HL2000 allows a much larger part format.

Z Shrinkage tolerance

Shrinkage and densification of HL2000 occurs in the Z direction only. Accurate knowledge of the Z shrinkage tolerance is crucial for the design of high frequency electronics[2]. Circuit designers need to be able to accurately predict the tolerance of final fired thickness in the substrate.

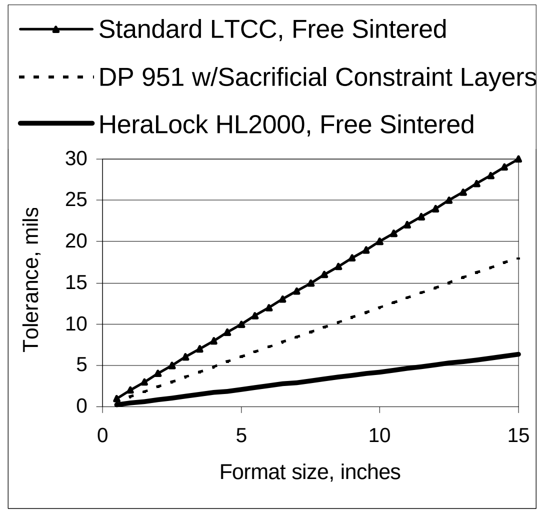

Figure 8: Positional tolerance plotted versus LTCC format size for three different processes.

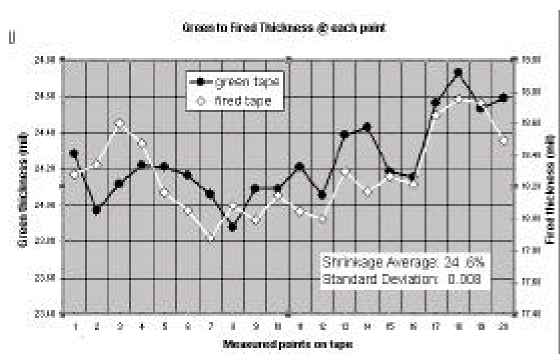

Figure 9: Z shrinkage measurements (green and fired) at specific points on tape.

To quantify Z shrinkage, measurements were performed on 4 layers of HL2000 green tape, nominally 5.75 ± 0.1 mil thick. The tape was cut into 6”x5” (150mm x 125mm) pieces and stacked without applying heat or pressure. An array of 4 x 6 marked points were made on a sheet of clear Mylar; the positions of the proving points were marked on the Mylar. The thickness was measured at the marked points through the protective Mylar with a Fisherscope MMS using an eddy current probe ETA 3.3 H. This was done initially on the green-stacked sheets and again after the parts were isostatically laminated and fired. The results, summarized on Figure 9, show an average shrinkage of 24.6% and a standard deviation of 0.8%.

Cavities and Embedded Passive Components

Because the tape maintains its x-y geometry through firing, cavities cut into the tape show minimal distortion. As an example, Figure 10 shows a circular cavity that has been cut in half before one of the sides has been fired. After firing, only the change in color distinguishes the two halves.

Constraining the shrinkage to the Z-direction opens the door to a variety of applications for LTCC. Among these are thermal management structures for high power modules [2] (utilizing mezzo-scale MEMS) and biomedical applications. Devices like micro heat exchangers, micro fluidic channels, heat pipes, etc., will be realized with minimal distortion upon firing. [3][4]

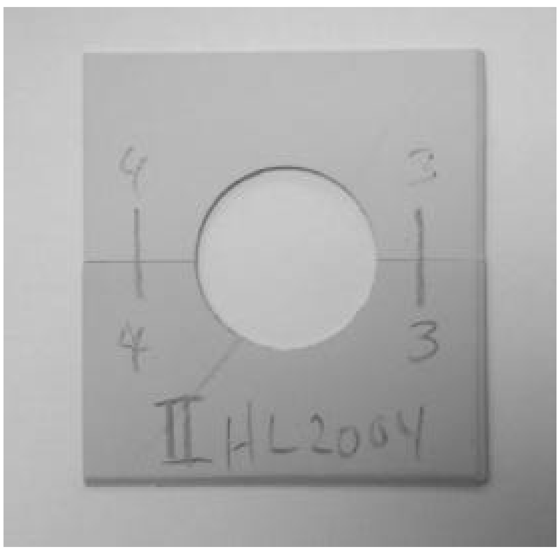

Figure 10: A 0.50” (12.5 mm) circular cavity has been cut into a green laminate of HL2000. The structure has been cut in half; the top has been fired and the bottom left in the green state.

Compared to surface constraint methods, the advantage of HL2000 tape for cavities only increases with the module thickness. This is because each layer of tape is self-constrained, while a surface-constrained part allows significant deformation between the top and bottom layers. This effect is shown in Figure 11. Low x-y shrinkage along with minimization of the necking effect along cavity walls enables the co-firing of passive components into the tape [3][4]. Transformers, IC’s, capacitors, resistors, etc. may be separately sintered and then placed into green pre-cut cavities in the tape.

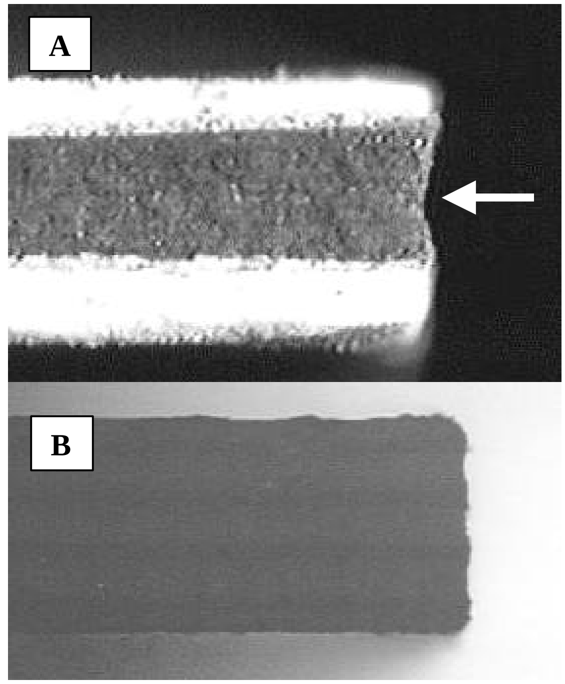

Figure 11: A. LTCC with sacrificial constraint.
B. HL2000 stacked tape

Figure 12 shows the side view schematic of an embedded passive device. To demonstrate the feasibility of this approach, a prototype was built with a co-fired ferrite transformer placed in a cavity green-punched in HL2000. The ferrite was placed in the green cavity before firing; the fired part is shown in Figure 13.

Figure 12: Embedded passive schematic (side)

Figure 13: Co-fired ferrite transformer (top view)

HL2000 for the Next Generation High-speed Optical Packages

Fiber optic packages are expected to thrive in the high-speed communication industry in the near future. HeraLock™ is ready to take the challenges of the new opto-electronic packages [5]. The realization of buried fibers in MCM-C modules is possible thanks a distortion free substrate. Complete packages that include circuit metallization, cavities for IC's, and embedded components are no longer in the future. Figure 14A (top), shows a buried co-fired optical fiber in CT700, a conventional LTCC tape. The distortion of the tape is due to the shrinking of the tape around the solid fiber inside. In contrast , figure 14B (top) shows an undistorted HL2000 substrate cofired with a buried 1 mil (25 μ) diameter sapphire optical fiber. The bottom of the figure shows light transmitted through the fiber in the fired structure.

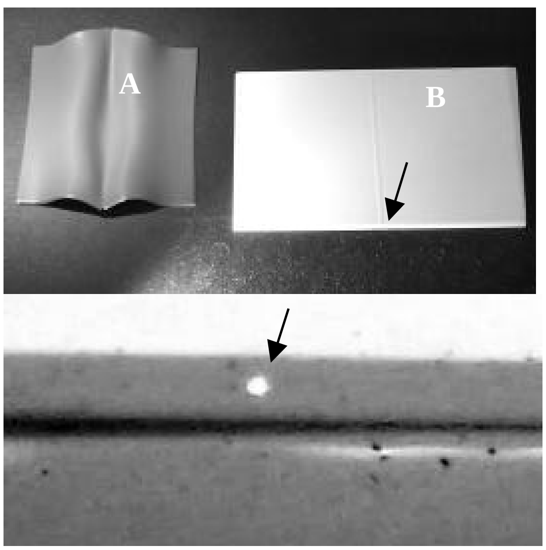

Figure 14: *Top*: Sapphire optical fiber cofired in CT700, a conventional LTCC (A) and in HL2000 (B). The arrow indicates the end of the optical fiber shown below. *Bottom*: Illuminated 1 mil (25 μ) diameter optical fiber co-fired in HL2000 ceramic laminate.

Conclusion

Free-sintered, the Heralock™ HL2000 LTCC tape exceeds the x-y shrinkage control of older sacrificial layer constrained sintered technology. In particular, the shrinkage variability of HL2000 is less than one half that of a conventional LTCC tape processed with sacrificial layers. This reduction in variability translates to a significant benefit for large-format LTCC processes.

The uniform self-constraint of HL2000 gives the tape excellent compatibility with materials that have a significantly different densification profiles and prevents the deformation of cavity structures even on thick modules. Modules made from HL2000 are nearly free from camber and show-through even when co-fired with high-coverage ground planes and thick solderable conductor prints.

The use of HL2000 eliminates the need for placing sacrificial layers before firing and removing them after firing. Eliminating these sacrificial layers has also eliminated the need for most post-fired conductors. A highly solderable co-fired AgPt conductor has been developed to take advantage of these tape properties.

HL2000 tape gives several opportunities for significant cost savings compared to modules made with older technologies by giving all the benefits of shrinkage control with none of the added cost of adding and then removing sacrificial layers. In addition, its unique properties allow the building of structures incompatible with sacrificial tape processing or free-sintered conventional tape.

Acknowledgements

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