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Review

Overview on fabrication of three-dimensional structures in multi-layer ceramic substrate

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Abstract

Three-dimensional structures in a multi-layer ceramic substrate are important in realizing ceramic-based meso- and micro-systems. During lamination and/or co-firing, three-dimensional structures, especially those with suspended structures, tend to deform and sag due to the intrinsic nature of the green (un-fired) ceramic material. Fabrication of three-dimensional structures with well-controlled dimensional stability and mechanical integrity remains a challenge. This paper discusses the challenges in fabricating structures in a multi-layer ceramic substrate. An overview is provided of the current state of the art in patterning and lamination techniques for the fabrication of these three-dimensional structures.

Keywords: A. Sintering; E. Substrate; Lamination; Patterning; LTCC

Contents

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1. Introduction

Three-dimensional structures in a multi-layer low temperature co-fired ceramic (LTCC) substrate are either surface structures (exposed to the surroundings) or embedded structures (mainly enclosed by the ceramic material). In a system, these structures serve as functional elements for mounting, fluidic handling, sensing, actuating and chemical or biological analyses. The applications of three-dimensional structures in a multi-layer substrate for meso- and micro-systems have previously been reviewed.[1–4] In addition, these three-dimensional structures are being explored to improve the performance of RF devices for high-frequency applications. Since embedded air is an ideal dielectric medium, 60-GHz patch antennae[5] and micro-strip antennae[6] have been realized in multi-layer LTCC substrates containing embedded cavities.

To fabricate three-dimensional structures in a multi-layer ceramic substrate, individual green tape is first patterned to form holes, cavities, channels or various other pre-determined shapes. These individual green tapes are stacked and bonded by uniaxial and/or isostatic lamination to form a multi-layer laminate.[7] During uniaxial lamination, the stacked green tapes are pressed only in the z-direction (the direction perpendicular to the plane of the stacked tapes) and heated. Thus, deformation of the tapes is constrained to occur mainly along the z-direction. In contrast, for isostatic lamination, the stacked green ceramic tapes are packed in a plastic bag and pressed uniformly in a heated fluidic medium with significant shrinkage occurring in all three directions. Subsequently, this laminate is co-fired in a furnace. Co-firing comprises two stages. Firstly, solvent and organic binders are removed from the laminate at the debinding stage. Then the laminate is densified at the sintering stage. After densification of the green ceramic material, a monolithic multi-layer ceramic substrate containing three-dimensional structures is formed.

During lamination and/or co-firing, these three-dimensional structures, especially suspended structures, tend to deform and sag.[1–4] Due to the intrinsic nature of the green ceramic material, suspended multi-layer green material tends to deform when lamination pressures are high (in the approximate range 10.3–20.7 MPa). This suspended ceramic material could also deform due to the softening of the glass component in the composite ceramic material during co-firing. To date, the fabrication of three-dimensional structures with well-controlled dimensional stability and mechanical integrity remains a challenge.

In this paper, the challenges and issues involved in the fabrication of these three-dimensional structures in multi-layer ceramic substrates are discussed. Subsequently, an overview is provided of techniques for patterning the structures on the green and sintered ceramic materials. Finally, techniques for the lamination of multi-layer ceramic structures are surveyed.

2. Challenges and issues

Deformation of the structures in a multi-layer ceramic substrate always occurs during processing. During isostatic lamination, shrinkage of green tape occurs in three directions, rendering dimensional control more difficult than in the uniaxial case. Surface structures in multi-layer ceramic substrates can deform under the high lamination pressures conventionally used.[8–10] The edges of the surface structures can become rounded after being packed in a vacuum packaging bag for lamination.[9,10] For surface structures with relatively small widths (typically less than 3 mm) or with relatively high aspect ratios (depth-to-width ratio greater than one), the plastic material of a vacuum packaging bag might not be in contact with all structures during vacuum packaging and lamination. This situation can cause deformation of the surface structures due to an uneven stress distribution over the structures.[9,10]

For multi-layer ceramic substrates containing embedded structures, the suspended portions of these structures might deform due to the high pressure, especially during isostatic lamination. Deformation of the embedded structures may be reduced using uniaxial lamination. However, embedded structures cannot then be fabricated in a single lamination step because the suspended portion might not be pressed uniformly. As such, multi-step lamination has to be used; the green tapes are separately laminated to fabricate at least two laminates (one as cover and one containing structures). Subsequently, these two laminates are laminated again to result in a multi-layer substrate containing embedded structures.

In addition to the lamination process, during the sintering stage, any suspended structures within the multi-layer ceramic substrate might also distort under their own weight when the glass component of the material softens.[1] A multi-layer ceramic substrate suspended over a large cavity (cavity width larger than 400 μm) tends to sag during sintering.[11] A suspended structure over a wide cavity of 10–25 mm could sag as much as 100–400 μm due to the softening of the glass component during sintering.[8] Suspended structures made of self-constrained composite ceramic material sag approximately a third as much as those made from unconstrained composite ceramic material.[8] The magnitude of deformation during sintering increases with the width of the cavity and decreases with the thickness of the suspended structures.

Integration of metallization, such as silver, gold, platinum and palladium pastes, inside embedded structures remains a challenging task. For example, the filling of fugitive or sacrificial materials (to be discussed in Sections 4.1.2 and 4.1.3) inside the embedded structures could deteriorate the printed metallization inside the structures. The integration of interconnection (via filling with silver, gold or platinum pastes) surrounding the embedded structures could also be difficult with low lamination pressure techniques (to be discussed in Section 4.2).

3. Patterning of green and sintered ceramic material

3.1. Mechanical punching and milling

Mechanical punching techniques can be used to define structures on green ceramic materials.[12–16] Punching has been used to form micro-vias with diameters of 30 and 55 μm,[14] and with 50 μm diameter and straight walls on 50–254 μm thick

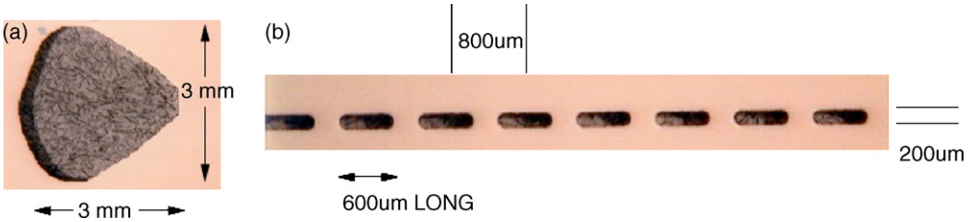

Fig. 1. Complex patterns, which are (a) a cavity with arbitrary shape and (b) channels, fabricated using the overlapped punching technique.[13]

tapes, with a via spacing of 1–10 times the via diameter.[15] One difficulty is burr formation during the punching of micro-vias (with diameters of 100 and 150 μm).[16] More burrs are formed with increasing ceramic tape thickness and punch tool clearance. More intricately shaped micro-channels with feature size of 50–100 μm have been fabricated for microfluidic applications using an overlapped punching technique (see Fig. 1).[13] Arbitrary geometries can be formed by punching multiple, overlapping circular holes into the green ceramic tape. Mechanical milling is another technique used to machine structures in a green ceramic material. The milling of channels with 0.5 mm in width on a green ceramic laminate to realize a LTCC-based polymerase chain reaction device has been demonstrated.[17] By using a small milling tool (with a diameter of 100–125 μm), structures with about 100–125 μm in width can be achieved.[1,11] However, small-diameter tools have a tendency to break easily, especially when cutting sintered ceramic substrates. Moreover, an additional step of removing the chips formed on the milled structures (especially for green ceramic material) is usually required.

3.2. Laser machining

Laser machining can be adopted for the structuring of ceramic materials[12,14,18–20] and co-fired thick film.[21] The fabrication of structures with arbitrary shapes and fine features (20–120 μm) using a laser machining technique has been demonstrated[19,22] (see Figs. 2 and 3). Vias with diameters of 50–75 μm have been fabricated on green and/or sintered ceramic materials using a neodymium-doped yttrium aluminium garnet (Nd:YAG) laser,[18] an ultraviolet (UV) laser,[14] and a neodymium-doped yttrium orthvanadate (Nd:YVO$_4$) pulse laser.[15] One of the drawbacks of laser machining is that the laser-drilled vias normally have a tapered shape (i.e. 15–25 μm smaller in diameter at the back side of the vias).[15] In addition, the laser beam might induce thermal damage on green ceramic material. To minimize the thermal damage, a CO$_2$ laser can be used to structure green LTCC without inducing significant thermal effects in the material.[19] The generation of decomposed gases during material removal also provides a self-cleaning effect that could minimize debris on the structures. Ultrasonic cleaning is used to clean the part before co-firing and assist-gas jets need not be used.[19] A study of diode-pumped Nd:YAG laser for the fabrication of fine structures recommends that multiple low-power laser pulses should be used instead of single high-power pulse, in order to fabricate less tapered channels.[22] Of the three types of laser that can be used to machine green ceramic material – namely excimer (KrF, 248 nm), ultraviolet (Nd:YAG, 355 nm) and infrared (1090 nm) – the infrared laser has been reported to be the most suitable source for fabricating structures on a green ceramic material.[20] Cooling gas may be employed to remove the debris after machining.[20]

3.3. Hot embossing

Surface structures can, alternatively, be transferred to green laminates by hot embossing.[23] Hot embossing dies with intricate patterns can be manufactured using materials such as PMMA, rubber, or nickel, with lithography, electroplating, and

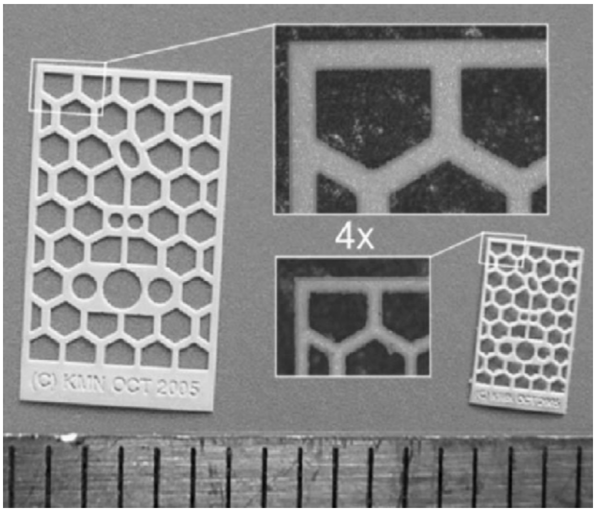

Fig. 2. Intricate structures fabricated on green tape using a CO$_2$ laser beam.[19]

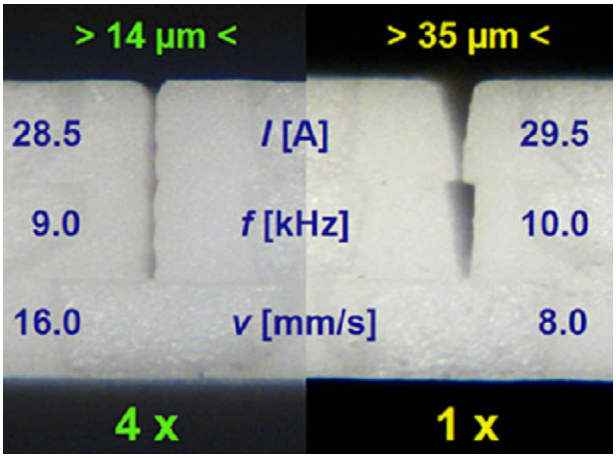

Fig. 3. Cross-section of a laser-machined structure on multi-layer ceramic material using a diode-pumped Nd–YAG laser.[22]

molding (LIGA) technology,[23] ultra-precision milling[23] or laser ablation techniques.[24] By embossing these dies into a green laminate (after lamination of few layers of green tape) using a pressure of 9.4 MPa at a temperature of 130 °C, surface structures with a height of 100–225 μm and an aspect ratio of 1 have been demonstrated.[23] Using a nickel mould, embossed micro-channels with widths of 25–200 μm on green ceramic substrates have been realized.[25] Roller embossing has been demonstrated by wrapping an electroplated nickel film mould on to a steel roller to emboss the structures on a green ceramic material.[26]

The critical parameters of an embossing process include embossing temperature, pressure and time, and areal density of the mould pattern.[23–26] The depth of the embossed pattern can be increased by increasing the embossing temperature and/or pressure.[25,26] However, a relatively high embossing temperature can cause sticking of the green material to the die, while a relatively low embossing temperature could cause cracking.[23] An overly high embossing pressure might induce cracks and fractures on a substrate. Therefore, a reduction of embossing pressure but with sufficient embossing time has been suggested to avoid cracks on the embossed substrate.[24] The areal density of the mould patterns is another factor to be considered. Increased density of the mould patterns has been found to further deform the green ceramic material due to the low fluidity and plastic deformation of the material (see Fig. 4).[25] For roller embossing, an overly high feeding speed (>10 mm/s) has been reported to deteriorate the quality of the embossed structures.[26] The high feeding speed results in a short contact time between the mould and the green ceramic. This in turn limits the flow of the material into the patterns of the mould.[26]

To minimize deformation of the edges and surface cracks after embossing of a LTCC laminate, a reduced lamination pressure in preparing laminate with higher porosity has been suggested for the subsequent embossing process.[23] Higher porosity laminate provides more room for the flow of material and thus reduces the tendency of green ceramic material to crack. Another way of minimizing the occurrence of cracks is by fabricating small slots near the locations of the embossed structures. During embossing, the pressed green ceramic material tends to creep towards these slots so as to avoid cracks or fractures on the bottom of the structures (see Fig. 5).[24]

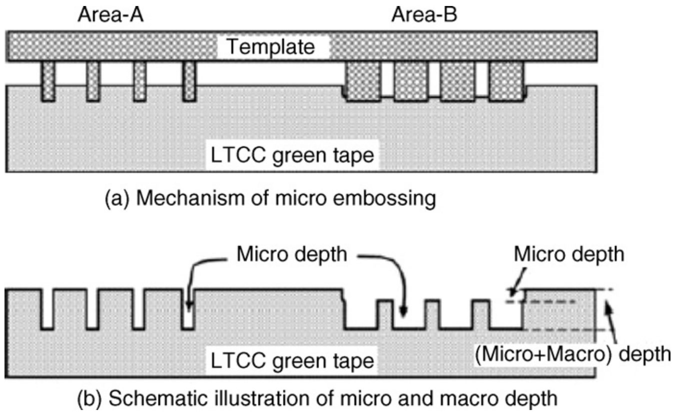

Fig. 4. Induced deformation (i.e. macro-depth in (b)) due to an increase in the areal density of microstructures.[25]

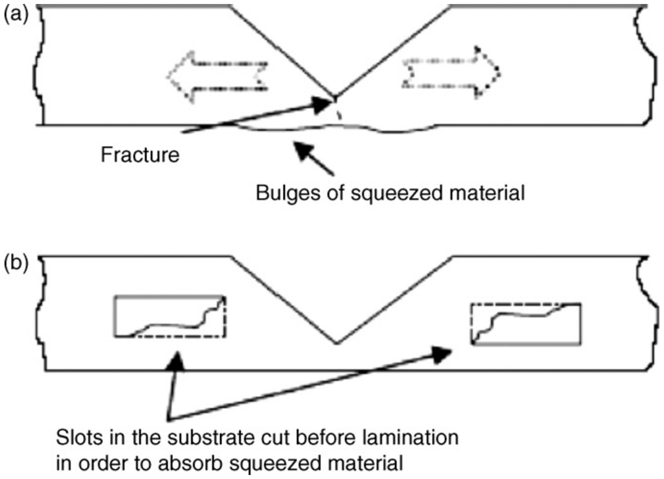

Fig. 5. (a) A crack that occurred during embossing due to squeezing of material and (b) slots fabricated for absorption of material during embossing.[24]

3.4. Photolithographic techniques

Photolithographic techniques have been developed to fabricate structures with feature sizes ranging from 100 μm to few centimetres on a partially sintered ceramic tape or laminate (see Fig. 6).[27] The green ceramic material is sintered at a temperature lower than the peak firing temperature. As a result, the ceramic is partially densified and contains open pores into which etchant can diffuse during the subsequent etching process. A dry negative resist film is laminated on to this partially sintered ceramic tape. After developing the desired patterns on the dry resist film, HF etching solution is used to etch the glass component in the partially sintered ceramic material and realize the surface structures. The lamination of dry resist film on to a partially sintered green tape is difficult to control in such a way that air bubbles and delamination are avoided. Photoformable LTCC tapes can be used as an alternative.[1] After exposure to UV light, a sodium carbonate spray shower is used to etch the unexposed

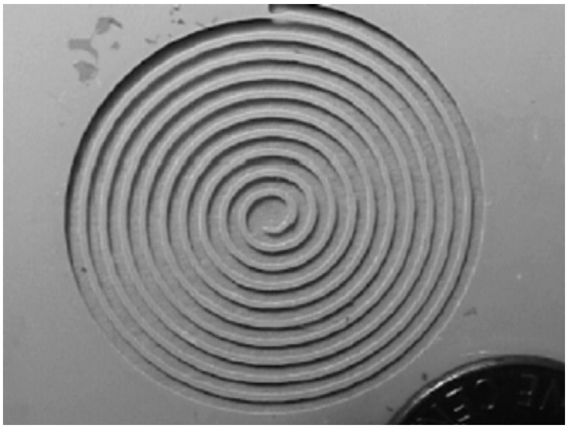

Fig. 6. Spiral structure etched on partially fired LTCC tape with coil diameter of 2 cm and coil strand of 400 mm.[27]

Table 1
Comparison of current patterning techniques in multi-layer ceramic technology.

Technique	Advantages	Disadvantages
Punching	Intricate geometries possible (with overlapped punching technique) Micro-vias with diameters of 30–100 μm Moderate via density, volume, and throughput	Burr formation Wear and tear of punches and dies Micro-punches (diameter less than 100 μm) could damage easily Limited accuracy
Mechanical milling	Complex geometries with feature sizes of 100–125 μm Relatively large structures possible (>1 mm)	Chip formation Wear and tear of tools Micro-tools (diameter less than 100 μm) could damage easily
Laser machining	Complex geometries with feature sizes of 20–120 μm Non-contact technique (no wear and tear of tools) High accuracy, high via density, and moderate volume	Thermal damage Tapered vias and channels Low-to-moderate throughput
Embossing	Intricate geometries possible, with feature sizes of 25–100 μm Roller embossing (high throughput)	Wear and tear of molds Structures depth limited by thickness of green tape Occurrence of cracks Sticking of green ceramic material on mold
Chemical etching	Structures with feature sizes of 25–30 μm	Chemical etchant required Control of etching rate is difficult

area. Structures with partially etched depth have been fabricated and structures with feature sizes smaller than 30 μm have been claimed to be achievable.[1] Using jet vapour etching, round holes with a diameter of 25 μm on a green ceramic material have been demonstrated.[28] Using a collimated jet, acetone vapour is ejected through the green ceramic material to dissolve the organic material and to remove the composite ceramic material. These wet processes employ chemical reagents or etchants. It is difficult to control the rate of material removal by these chemicals to achieve repeatable structure dimensions.

3.5. Relative merits of patterning methods

To fabricate structures with feature sizes ranging from 50 μm to few centimetres, techniques such as punching, milling, and laser machining can be used. Complex structures that might be machined using CNC milling or laser machining can also be fabricated using the overlapped punching technique described above. However, overlapped punching can damage the green tape, as well as shortening the lifetime of the punching tool and die and causing them to wear unevenly, since relatively more punching steps are required in realizing complex structures such as spiral or serpentine channels than in producing simple vias. Embossing, meanwhile, can be used to fabricate denser and more intricate structures and only a single step is required. However, the maximum achievable depth of the structures is one of the limitations of the embossing process. To our knowledge, no embossed structures deeper than the thickness of a single layer of green tape have been demonstrated.

In summary, therefore, punching is by far the most commonly used method, especially to fabricate vias for interconnections. Embossing and laser machining are techniques that deserve examination for the fabrication of more complex structures with smaller dimensions in meso- and micro-systems applications. The advantages and disadvantages of these machining techniques are summarized in Table 1.

4. Lamination of multi-layer ceramic substrate

The lamination of multi-layer ceramic substrates with embedded structures is a more difficult process to accomplish than the initial patterning of the layers. Currently available lamination techniques are summarized in Table 2, and more detailed discussions are given in the subsequent sub-sections.

4.1. High pressure lamination techniques

4.1.1. Lamination with temporary inserts

To fabricate three-dimensional structures in a multi-layer ceramic substrate, temporary inserts can be employed to support partially embedded structures during lamination.[29] The temporary inserts are mechanically removed after lamination. A more flexible insert that could be poured, shaken or flowed out after sintering can be used to support the embedded structures.[30] It is time-consuming to tailor specified inserts for each desired structure, and the removal of temporary inserts is also difficult. Instead of using solid inserts, surface structures can be filled with a liquid-based material which solidifies to form supports for the embedded structures in a multi-layer ceramic substrate.[31] However, the solidified material has to be removed from the multi-layer ceramic substrate after lamination. A major limitation of these techniques[29–31] is that they are not feasible for fabricating a completely embedded structure.

4.1.2. Lamination with fugitive materials

Fugitive materials are used here to refer to those materials that completely decompose after co-firing. Sacrificial materials, which will be discussed in Section 4.1.3, are those materials that will not decompose or decompose only partially. Post-processing is required to remove them from the structures.

Fugitive materials can be employed to support the surface and embedded structures in a multi-layer ceramic substrate during lamination and/or sintering. After serving the role of supporting

Table 2
Comparison of current lamination techniques in fabricating three-dimensional structures.

Technique	Advantages	Disadvantages
Lamination with insert	Better dimensional control for surface structures Support structures during lamination	Limited to relatively large and simple structures Tailored and removable inserts required Difficulty in insert removal as sticking of green laminate to insert may occur No support during sintering
Lamination with fugitive material	Complex 3D structures and suspended thick film (with dimensions of 100 μm to 10 mm) Could achieve fully enclosed and embedded structures Could provide support during lamination and sintering	Relatively poor dimensional stability Filling and patterning of fugitive materials are difficult
Lamination with sacrificial material	3D structures and suspended thick film Could provide support during lamination and sintering	Chemical etching required Fabrication of totally embedded structures is not feasible Filling and patterning of sacrificial materials are difficult
Lamination with adhesive material	Complex 3D structures (with dimensions of 100 μm to 10 mm)	Precise alignment between tapes or laminates is difficult Delamination could occur between laminates Required compatible adhesive and ceramics system Additional lamination steps required Interconnection between sintered substrates is not feasible for using adhesive layer No support during sintering
Gluing method (post-firing)	Relatively good dimensional control Relatively large embedded structures (more than 10 mm)	Precise alignment between sintered substrates is difficult Interconnection between sintered substrates is difficult Post-processing required to join the sintered laminates
Co-firing of thick film	Support structures during sintering	No support during lamination Location and volume of metallic loading are difficult to estimate

the structures, fugitive materials decompose during either the debinding or the sintering process. Waxes,[32,33] cetyl alcohol[34] and polymeric materials[32,35–37] have been proposed as fugitive materials. These materials are completely removed during debinding and before sintering of a multi-layer ceramic substrate. Thus, no support can be provided to the structures during sintering.

Carbon material has been proposed as a supporting material for fabricating embedded structures in a multi-layer ceramic substrate.[1,3,11,34,37–42] Carbon material in either solid or paste forms can be used to realize three-dimensional structures in a LTCC substrate.[3,37] Using carbon tape or screen-printed carbon paste, embedded structures are directly fabricated by laminating the carbon material in between the LTCC tapes (without machining any pre-determined structure on the LTCC substrate). Embedded channels with dimensions of 0.30 mm × 0.25 mm × 16.4 mm have been realized using this technique.[37] Other three-dimensional structures, such as suspended conductors, trenches with metallization, and embedded structures with internal electrodes, have been demonstrated (see Fig. 7).[37] Higher lamination pressures have been proposed for embedding thicker fugitive materials inside the LTCC laminate without causing delamination at the edges (see Fig. 8).[37] By printing carbon paste on to a LTCC tape and laminating it with other layers of LTCC tapes, a LTCC membrane with a diameter of 7–10 mm has been fabricated as a pressure-sensing element.[39–41]

By controlling the carbon burnout, the carbon material can be maintained as a supporting medium for the embedded structures during both the debinding and the sintering processes. To control the carbon burnout, the furnace environment is switched between inert and oxidizing gases.[11,38] Carbon burnout is slowed down by using an inert gas environment such that it can remain to provide support for the embedded structures during sintering.

Another way of controlling the carbon burnout is by modifying the sizes of the carbon particles in a carbon paste (1–15 μm).[39,40] Carbon paste containing fine carbon particles decomposes at a lower temperature than one that contains coarse particles.[40] Carbon needs to be completely burned out before the elimination of the open pores in the LTCC material, in order to avoid cracks and deformation of the embedded structures. The swelling of an embedded structure can be minimized by using carbon paste containing fine particles and lowering the heating rate from 5 to 3.5 °C/min (see Fig. 9).[40] In addition, an increase in thickness of the printed carbon paste (i.e. channels with greater depth) and also an increase in width of the inlet/outlet channels can help in reducing the swelling of an embedded structure.[41] This is because the increased channel depth and inlet/outlet channel width provide more room for the decomposed carbon to escape from the embedded structures. These findings indicate that appropriate choices of the carbon material and/or the design of an embedded structure could improve its dimensional stability.

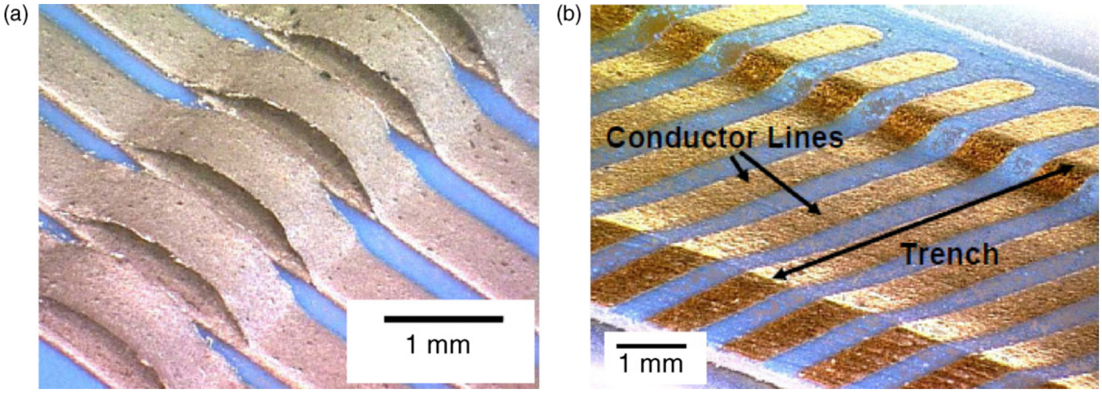

Fig. 7. (a) Suspended conductors and (b) metallized trenches fabricated using a technique of lamination with carbon material.[37]

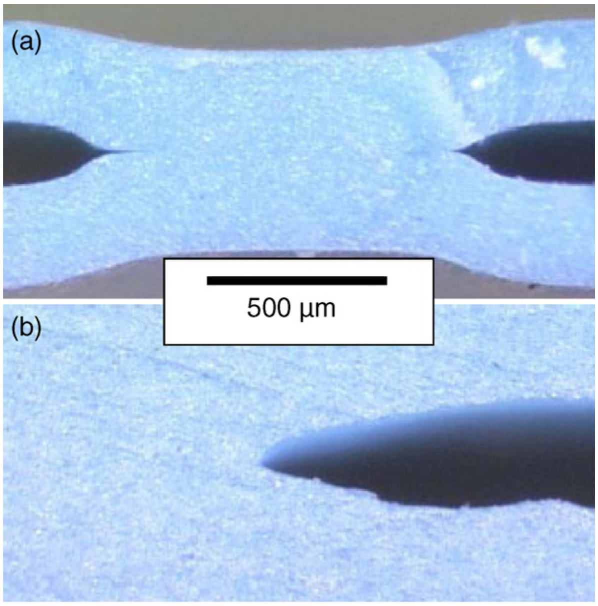

Fig. 8. (a) Delamination at the edge of an embedded cavity using a 20.7 MPa lamination pressure and 200-µm thick carbon tape; (b) complete lamination at edge, using 207 MPa lamination pressure and 400-µm thick carbon tape.[37]

Instead of switching the sintering environment between inert and oxidizing gases[11,38] and modifying the carbon paste,[40] multi-step burnout profile has been proposed for controlling the carbon burnout behaviour.[42] The onset temperature of carbon burnout can be controlled by changing the heating rate. Meanwhile, the burnout rate can be controlled by holding the temperature for a certain period. However, densification of self-constrained LTCC tends to be retarded if a slow heating rate is used or if the temperature is held after initial crystallization of the glass component in the LTCC material.[42] Thus, multiple burnout steps are essential to suppress carbon burnout, to avoid pressure build-up, and to ensure complete burnout before the elimination of the open pores in the LTCC without retarding its densification. An embedded cavity with dimensions of 10 mm × 10 mm × 0.50 mm has been fabricated using this technique (see Fig. 10).[42]

One of the main concerns when using a lamination technique with fugitive materials is that the dimensional stability of the structures is difficult to maintain. Filling a structure on a LTCC substrate with a fugitive material is difficult to control. Incomplete filling with carbon material will affect the dimensional stability of the embedded structures.[42] Indeed, non-uniformity

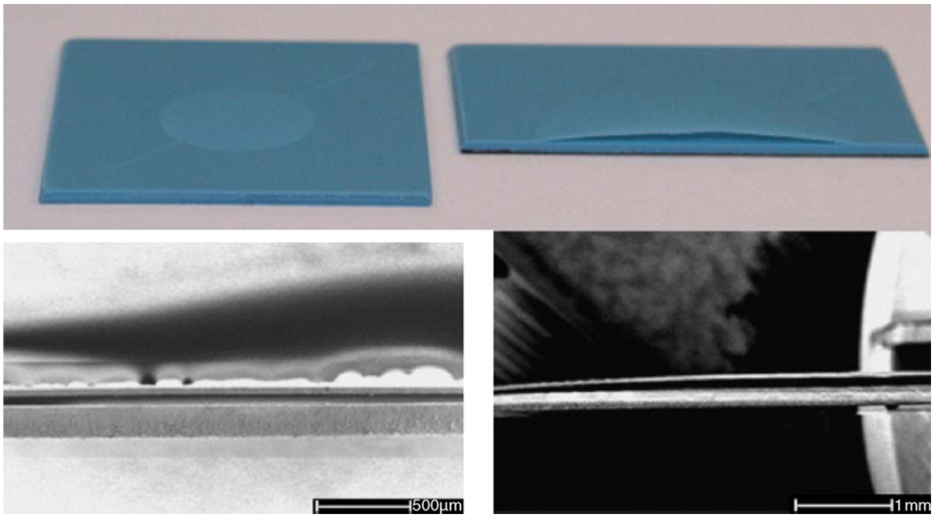

Fig. 9. Optical and SEM pictures of flat 7 mm-diameter (left top and bottom) and swollen 14 mm-diameter LTCC membranes (right top and bottom) fabricated using a lamination technique with carbon material.[40]

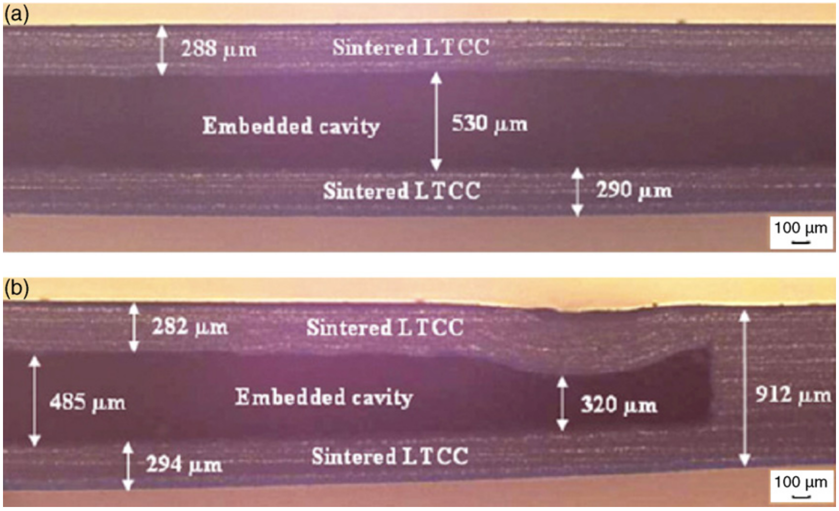

Fig. 10. Cross-section of (a) centre portion and (b) corner portion of an embedded cavity fabricated using a lamination technique with carbon material and a multi-step carbon burnout profile.[42]

of the carbon black and graphite layers is one of the key drawbacks in fabricating suspended structures with a uniform gap.[43] Besides affecting the LTCC material, the melted fugitive material might also dissolve the thick film layers and in turn affect the dimensional stability of the metallic traces and the functionality of a LTCC-based device.[37]

The technique of directly sandwiching screen-printed carbon paste or patterned carbon tape between LTCC tapes and subsequently laminating them appears unable to produce embedded structures with vertical or sharp walls[3,37,40] (see Figs. 8 and 9). One of the limitations of this technique is that the fabrication of embedded structures with widths of 650 µm and below is diffi-

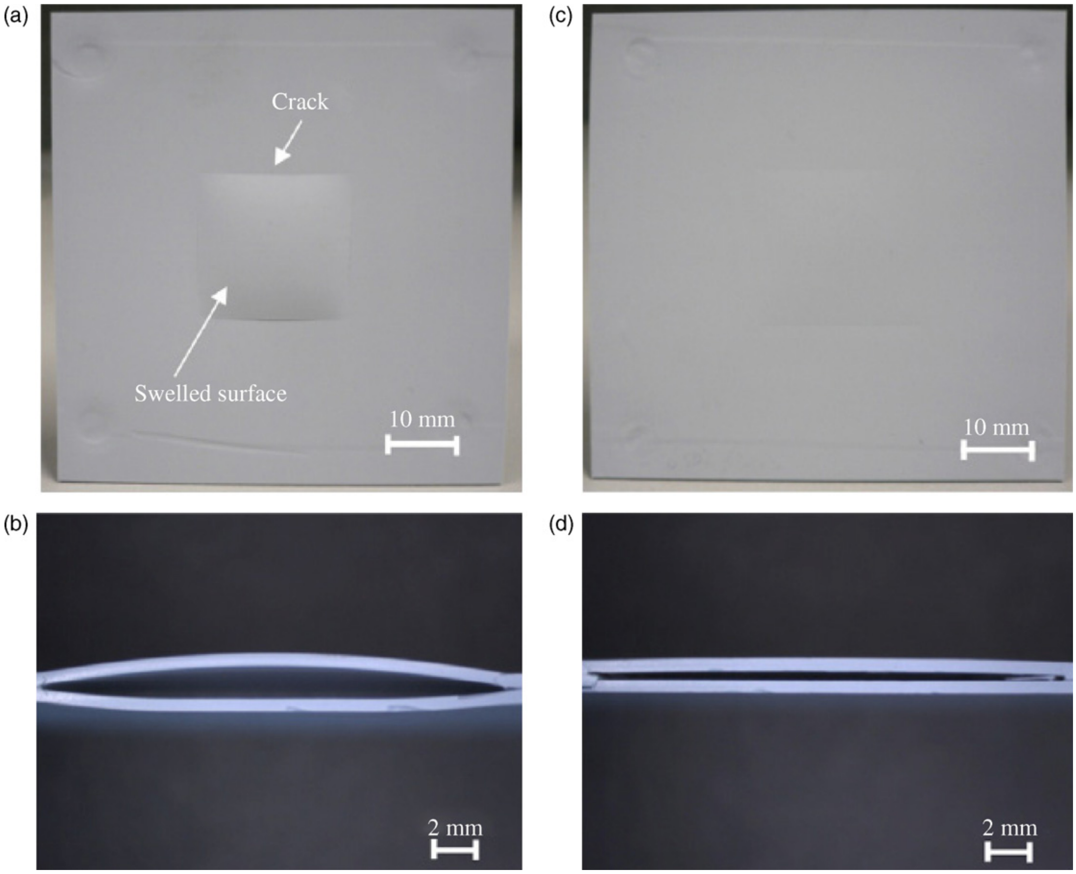

Fig. 11. Top and cross-sectional views of an embedded cavity fabricated using (a and b) a standard co-firing profile and (c and d) a co-firing profile with additional isothermal heating for carbon burnout.[8]

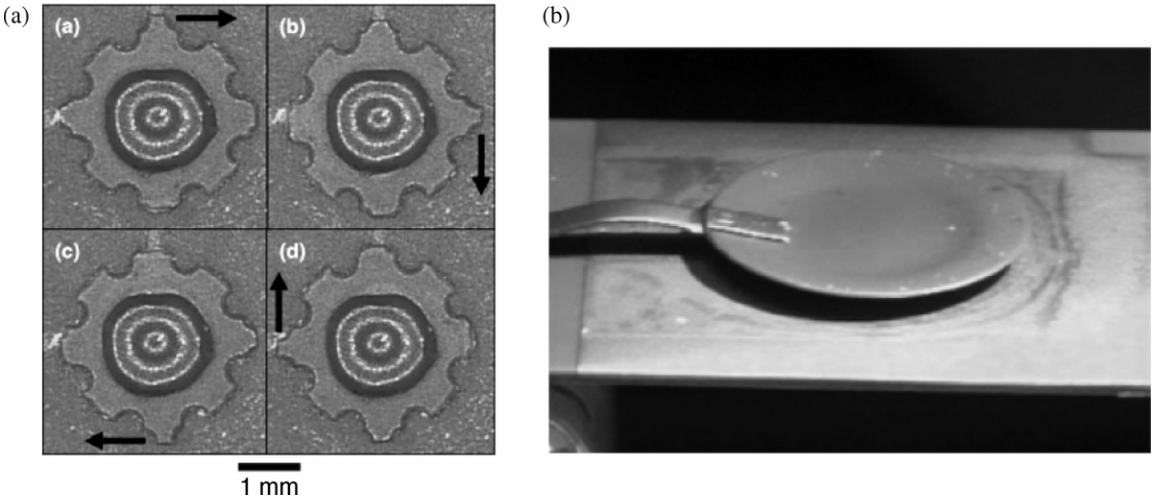

Fig. 12. (a) A 3-mm freely rotating wheel (parked at four positions around one revolution) and (b) a 12 mm-diameter cantilevered capacitor plate fabricated using setter tape.[3]

cult if thick carbon material (with 200 μm thickness) is used.[37] Cracks are prone to occurring in the LTCC material because it experiences bending moments during the lamination process.

Complete burnout of fugitive material is important and control of the burnout is essential to avoid the deformation of embedded structure and the pressure build-up that could induce cracks.[8,39–41] Swelling of the LTCC membrane after carbon burnout,[39–41] the occurrence of cracks without proper control of carbon burnout (see Fig. 11)[8] and the contamination of LTCC-based open channels by carbon paste due to incomplete burnout[10] have all been reported.

In summary, the lamination of multiple layers of ceramic tape using fugitive materials is one of the most promising techniques for fabricating three-dimensional structures. However, more studies are required in order to optimize the process. Especially needed is an understanding of the physico-chemical interaction of a fugitive material and the composite ceramic material during sintering.

4.1.3. Lamination with sacrificial materials

The use of various sacrificial materials has been reported. Lead bi-silicate glass can be used as a sacrificial material, but it needs to be chemically etched after sintering.[38] Buffered hydrofluoric acid is usually used for the etching step; residues of the sacrificial glass frequently remain after etching.

Setter tape, which is made of ceramic powders such as zirconium oxide, alumina and magnesium oxide, is another type of sacrificial material that can be employed to realize a movable functional component in a LTCC platform, such as a wheel and a cantilevered capacitor plate (see Fig. 12).[3] Any portions of LTCC tape sandwiched between setter tapes remain unbonded during lamination, and this allows the creation of the movable features. After co-firing, the setter particles are removed from the LTCC structure by blowing with compressed gas or another working fluid.

Silk husk paper can be used as a sacrificial material to support structures during lamination and sintering. A leaf-spring vertical actuator has been realized using this technique.[43] The paper is burnt during co-firing, and leaves a layer of ash that must be removed afterwards. This layer of ash is used to maintain the gap around the suspended structure during sintering (see Fig. 13).[43]

The fabrication of a capacitive anemometer has been demonstrated by using mineral sacrificial paste containing carbon and calcium carbonate.[44] This paste can be used to support the suspended structure during lamination and sintering. During the co-firing process, the carbon material decomposes and the calcium carbonate ($CaCO_3$) transforms to calcium oxide (CaO) that acts as a supporting medium for the suspended structure (see Fig. 14).[44] This residual material can then subsequently be removed using dilute phosphoric acid (H_3PO_4).

Sacrificial materials generally have to be removed by a chemical reagent[38,44] and this removal process is not straightforward. For example, particles from a setter tape could be trapped in the LTCC structure after co-firing.[3] Thus, the complete removal of setter particles could be difficult and the particles might also roughen the LTCC surface. The shrinkage mismatch between the setter tape (1%) and LTCC tape (12–15%) could induce cracking

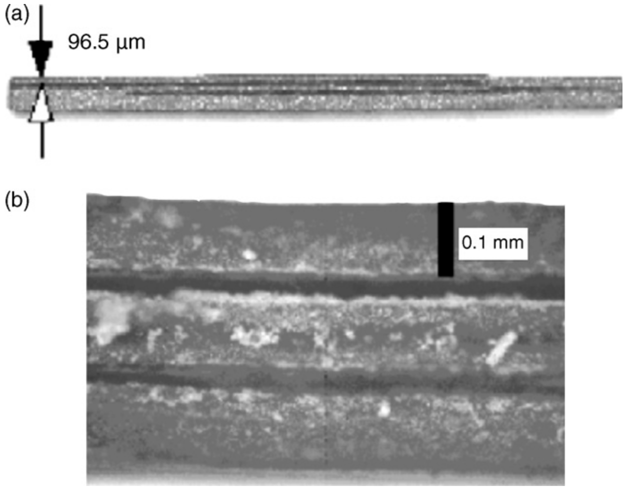

Fig. 13. (a) Ceramic leaf-spring actuator fabricated using a lamination technique with sacrificial material and (b) ash observed inside the suspended structure.[43]

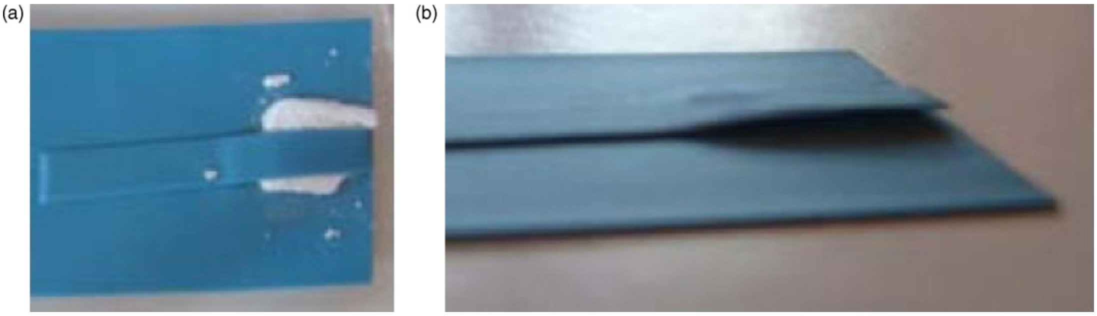

Fig. 14. LTCC sandwich-cantilever (a) before co-firing and (b) after co-firing fabricated using lamination technique with mineral paste (28% $CaCO_3$ and 72% C).[44]

or deformation on the structure.[3,44] Certain mineral materials, such as borax, could react with the metallization.[44]

An access path is also required through which the chemical reagent or etchant can reach the sacrificial material.[38,44] This technique is therefore not applicable to the fabrication of totally enclosed structures in a multi-layer ceramic substrate.

4.2. Low lamination pressure techniques

4.2.1. Lamination using adhesive materials

By employing inter-layer adhesives, embedded structures can be fabricated with lower lamination pressures than are required for the techniques of Section 4.1. The use of lower lamination pressures helps to minimize unwanted deformation of suspended green LTCC structures. One of these low lamination pressure techniques employs double-sided adhesive tape, consisting of an acrylate adhesive and a poly-ethylene terephthalate (PET) film, to bond the green LTCC tapes at room temperature and under a pressure of 2.5–5 MPa.[45–47] The bonded multi-layer LTCC tapes are then co-fired. During the co-firing, the organic binder of the LTCC material is first burnt out. The adhesive tapes melt and diffuse into the pores of the LTCC material. The capillary forces exerted by the molten polymeric material tend to pull the LTCC tapes together. The fabrication of a complex three-dimensional structure – for example a gear wheel with an inner cavity – has been demonstrated using this technique (see Fig. 15).[48] Poly(2-ethyloxazoline) (PEOX) and pressure-sensitive-adhesive (PSA) materials can also be used as adhesive layers to bond the LTCC tapes with a pressure ranging from near 0 to 7 MPa.[35] Using these adhesive materials, the fabrication of vertical vias, embedded conductors and surface cavities has been demonstrated

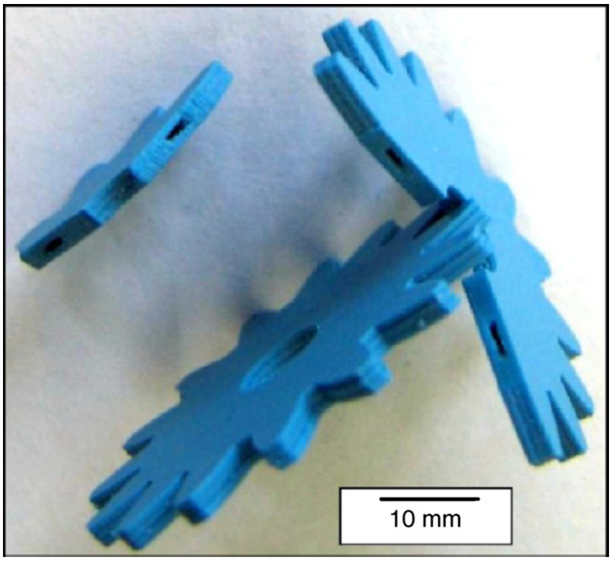

Fig. 15. LTCC-based gear wheel with a partially embedded cavity fabricated using a low lamination pressure technique.[48]

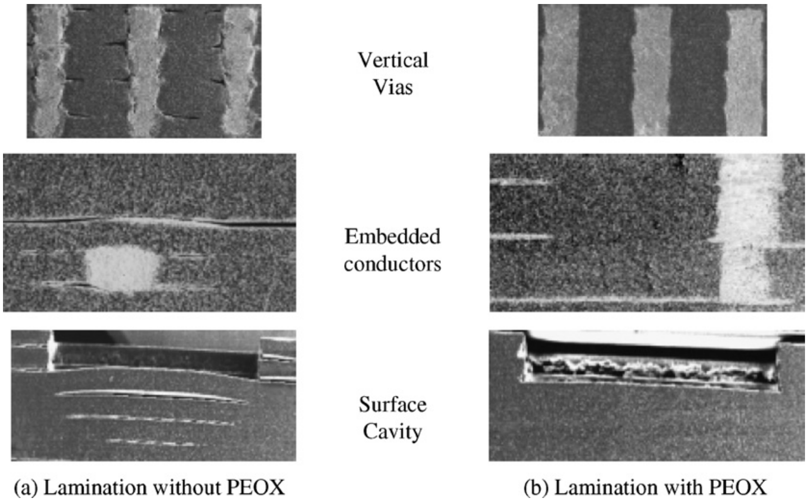

Fig. 16. Vertical vias, embedded conductors and surface cavity fabricated using low lamination pressure with PEOX.[35]

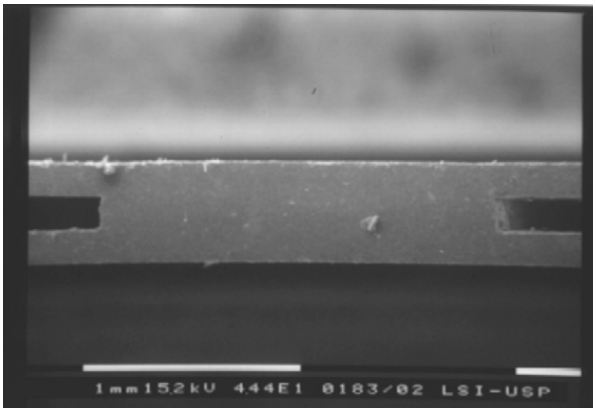

Fig. 17. Embedded structures fabricated using a low lamination pressure technique.[51]

(see Fig. 16). The technique of using adhesive materials has been employed in fabricating embedded channels with a cross-sectional area of 0.5 mm × 0.5 mm in LTCC-based polymerase chain reaction (PCR) and DNA-detection devices.[49] This technique has also been used to create embedded air cavities, which serve as an ideal dielectric in an LTCC stacked patch antenna (with dimensions of 11 mm × 6 mm × 0.392 mm).[50] Instead of using adhesive tapes, organic liquids, such as natural honey, glucose, and polyester resins, can be used as gluing agents to bond the LTCC tapes at room temperature and under a pressure of 2.5 or 5 MPa.[51] The gluing agents are removed during the debinding stage. A multi-layer ceramic substrate with integrated metallization and embedded structures has been fabricated using this technique (see Fig. 17). Solvents, such as DuPont thinners and plasticizer butyl benzyl phthalte, can also be employed to bond LTCC tapes at atmospheric pressure.[34,52] The fabrication of square embedded cavities with widths of 2, 5, and 10 mm has been explored using this technique. An embedded cavity with an area of 6 mm × 1.8 mm has been fabricated by bonding an embossed LTCC laminate to another, unpatterned, LTCC laminate at low lamination pressure using a mixture of polypropylene-glycol (PPG) and ethanol (see Fig. 18).[23]

By solely lowering the lamination pressure (without an adhesive medium), the fabrication of cooling channels with widths of 2–5 mm in a multi-layer substrate has been attempted.[18] To further improve the lamination process, multi-step lamination (at least two lamination steps) can also be used to form a multi-layer substrate containing embedded structures.[53] Multi-layer laminates containing embedded structures are fabricated separately. Subsequently, these two laminates are laminated again to form a multi-layer substrate containing multiple embedded structures. To avoid deformation of the internal structures, the lamination pressures are reduced in the later lamination steps. This multi-step lamination technique has been proposed to form surface structures at the top and bottom surfaces of a multi-layer substrate.[54] The fabrication of cooling channels (with widths of 2 mm) in a LTCC-based laser diode assembly has been demonstrated (see Fig. 19).[55] The lamination was performed at 70 °C and 6.9 MPa.

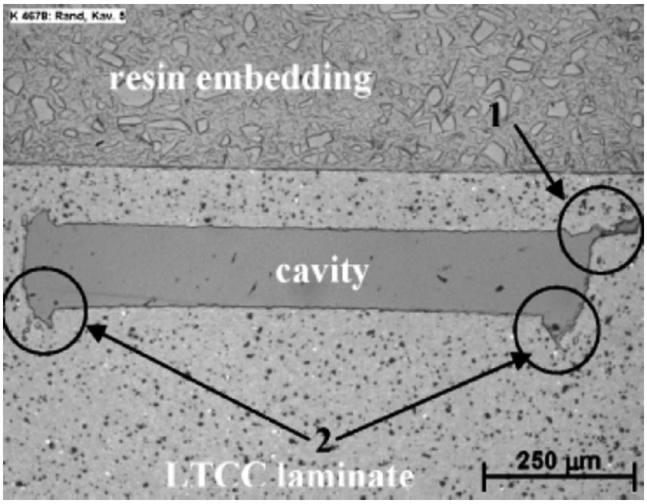

Fig. 18. Cross-section of an embedded structure fabricated using embossing and a low lamination pressure technique.[23]

Overall, the deformation of structures in a multi-layer ceramic substrate is minimized by employing a relatively low lamination pressure. However, this technique does not provide support for the embedded structures in a multi-layer LTCC substrate during sintering. To fabricate embedded structures with a relatively large dimension (more than 10 mm), a supporting medium is certainly needed to prevent distortion of the suspended LTCC structures.[8] Several technical challenges have to be resolved to further improve the mechanical integrity and the dimensional stability of embedded structures fabricated using low-pressure lamination techniques.

The quality of embedded structures is dependent on the lamination process parameters. Insufficient lamination pressure can result in weak bonding between the LTCC tapes and induce delamination (see Fig. 20(a)).[52] The use of overly low lamination pressures (i.e. below 10 MPa) has also been reported to cause delamination.[18] To ensure good bonding quality, higher lamination pressures (as high as 15–20 MPa for DuPont 943X green tape) have been recommended. However, a relatively high

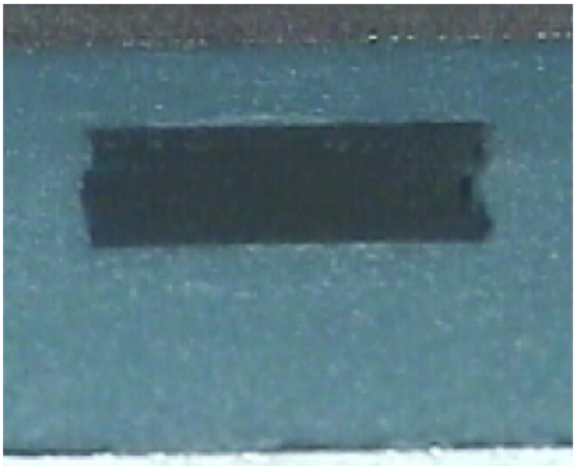

Fig. 19. Cross-section of a 2-mm wide embedded cavity fabricated using a multi-step lamination technique.[55]

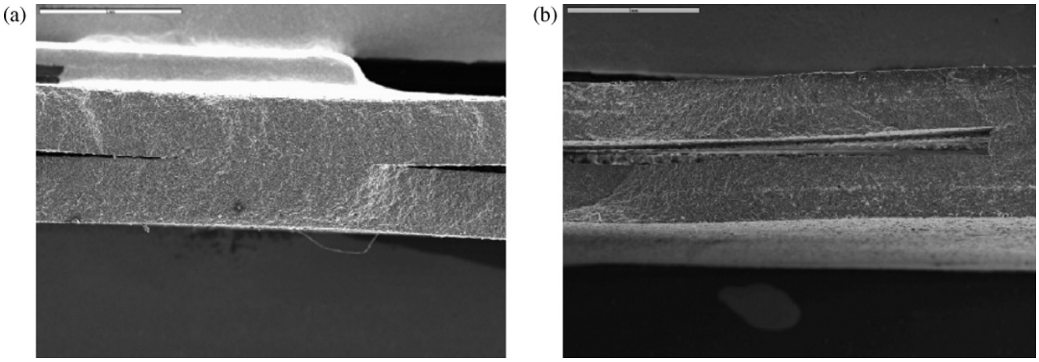

Fig. 20. (a) Delamination due to insufficient lamination pressure (cross-section of 10-mm wide embedded cavity) and (b) sagging of embedded structure caused by relatively high lamination pressure (cross-section of a 5-mm side embedded cavity).[52]

lamination pressure will in turn deform the embedded structures (see Fig. 20(b)).[52] Deformation of a suspended LTCC structure over a 1-mm wide channel has been observed after lamination at only 1 MPa.[8] Thus, lamination pressure has to be optimized to minimize the deformation of the embedded structures without inducing delamination.

Deposition of adhesive material or solvent is another challenge that needs to be resolved. The deposited solvent film (on the LTCC tape) should be uniform and should not be too thin in order to evenly dissolve the binder system in the LTCC material for improved bonding quality between the LTCC tapes.[52] Using an adhesive layer, such as double-sided adhesive tape,[45–47] uniform lamination is difficult to achieve and air bubbles might be trapped between the layers during the lamination process. Deposition of an excessive amount of solvent could weaken the mechanical integrity and stability of green LTCC material.[22] A reliable method for depositing adhesive material and solvent on to the LTCC is desirable, to improve the dimensional stability of the embedded structures.

When adhesive material and solvent are used in bonding the LTCC tapes, the co-firing profile during the debinding stage has to be optimized to burn out the additional organic binder or solvent from these bonding materials. Optimization of the debinding process is even more critical in fabricating thick or large-area LTCC substrates, to avoid excessive pressure build-up (from the decomposition of the additional binder or solvent) that could induce cracks in the substrate. A relatively slow heating rate, such as 0.5 °C/min, is generally used during binder burnout.[45]

It is essential to ensure compatibility between the adhesive material and the binder system of the LTCC. The adhesive material should have a higher decomposition temperature than the LTCC binder.[46] The binder system in the LTCC will therefore decompose earlier and create pores at the interface of the LTCC layers into which molten adhesive can diffuse. This inter-diffusion of material is necessary to pull the LTCC layers together and to establish bonding between the layers. In addition, the LTCC powder particles must be large enough to facilitate particle interpenetration. If pores in the LTCC are too small, the capillary flow of molten PET can be hindered.[45] In general, an adhesive material that works for one particular LTCC material might not be suitable for another LTCC material.[34]

The integration of metallization (such as gold or silver paste) with embedded structures using low lamination pressure techniques remains a challenge. As the number of layers of LTCC increases, the difference in thickness increases between the LTCC layers with and without metallization. It is recommended that metallization cover not more than 50% of the area of the LTCC green tapes in order to achieve good bonding.[56] If a larger proportion of the LTCC area is covered by metallization, delamination tends to occur when the LTCC laminate has more than 10 layers.[7] As a result, a relatively high pressure is required to improve the inter-layer bonding between the LTCC layers with metallization. This high pressure is particularly important when laminating LTCC layers with a relatively high density and fine metallization lines. An excessively high loading of metallization on green tapes could also constrain the shrinkage of the tapes, increasing the amount of deformation of ceramic material during sintering and potentially causing delamination at this stage of processing.[56] Delamination of LTCC layers with metallization has also been observed (see Fig. 21).[51] This delamination

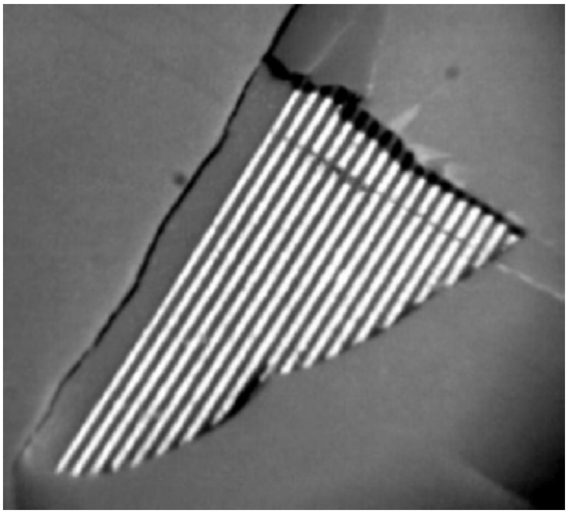

Fig. 21. Delamination of LTCC with metallization due to low lamination pressure.[51]

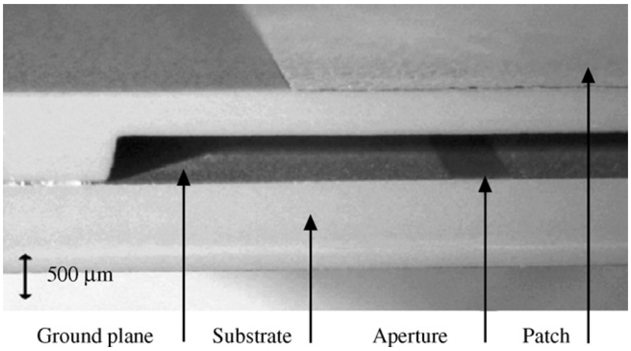

Fig. 22. Cross-sectional picture of an antenna-containing embedded cavity fabricated using a gluing technique.[6]

is attributed to the presence of excessive organic adhesive material. The solvent (used as an adhesive material) can melt the LTCC tape surface.[52] Thus, the printed metallization on the tape might be damaged since the solvent might dissolve the organic binder in it. There would certainly be value in formulating an adhesive material or solvent to provide good bonding at low lamination pressure without deteriorating printed metallic pastes.

For a multi-step lamination technique, fabrication of embedded structures with a relatively large width could be difficult without using supporting materials.[53,55] One possible approach to improve dimensional tolerances is to combine a multi-step lamination technique with supporting materials to fabricate surface and embedded structures.

4.2.2. *Gluing of post-fired laminates*

Gluing techniques have been used to fabricate embedded structures. For example, a sintered, unpatterned multi-layer ceramic substrate can be glued to another sintered substrate containing a cavity, encapsulating that cavity.[5,6] Relatively large embedded cavities (e.g. with areas of 18.6 mm × 18.6 mm[5] and 14 mm × 11 mm[6]) have been fabricated using this technique for high-frequency antennae (see Fig. 22). Gluing is a post-firing process. Thus, the interconnection between two sintered substrates is difficult to establish. This is because the glass component in the sintered metallic paste (on both side of the sintered substrates) needs to be remelted to induce inter-diffusion in establishing an interconnection between the substrates. An alternative solution is to use low temperature transfer tape (LTTT) to bond the two sintered substrates and to establish the interconnection between them.[57,58] Alignment between sintered substrates during gluing or post-firing with LTTT is a key practical concern in industry.

4.2.3. *Co-firing with thick film*

Integration of metallization over the suspended structures can be used to reduce the sagging of embedded structures during the sintering process.[38] Due to the shrinkage mismatch between the metallization and the ceramic material, the metallization tends to exert a tensile stress, preventing the suspended ceramic material from sagging. The volume and the location of the metallic loading over the suspended structure are the critical parameters that have to be optimized. This technique, however, cannot provide support for a suspended structure during the lamination process.

5. Conclusions

Patterning and lamination techniques for fabricating three-dimensional ceramic structures are reviewed. The capabilities, limitations, and drawbacks of these techniques are discussed. The selection of a technique to form structures on individual tapes or laminates depends on the structural requirements. Punching, milling and laser machining could be used to fabricate structures with dimensions larger than 100 μm. To fabricate more complex or relatively small structures (with dimensions less than 100 μm), techniques such as embossing and laser machining could be explored. A comparison of these machining techniques is summarized in Table 1.

Compared to machining, lamination is a more critical process because of the possibility of unwanted dimensional distortion. Currently available lamination techniques are summarized in Table 2. Overall, lamination techniques relying on a fugitive material and low-pressure lamination with adhesive materials are the most promising approaches. There is, however, room for the development of a more reliable lamination technique to fabricate three-dimensional structures, especially embedded structures, with well-controlled dimensions. More research is required, either to optimize the existing techniques or to explore alternative techniques to realize three-dimensional structures in multi-layer ceramic substrates.

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