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Fabrication of embedded microfluidic channels in low temperature co-fired ceramic technology using laser machining and progressive lamination

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Abstract

This paper describes the application of laser micromachining techniques for the fabrication of microfluidic channels in low temperature co-fired ceramic, LTCC, technology. It is shown that embedded cavities can be successfully realised by employing a recently proposed progressive lamination process with no additional fugitive material. Various microfluidic structures have been fabricated and X-ray imaging has been used to assess the quality of the embedded channels after firing. The problem of achieving accurate alignment between LTCC layers is addressed such that deeper channels, spanning more than one layer, can be fabricated using a pre-lamination technique. A number of possible applications for the presented microfluidic structures are discussed and an H-filter particle separator in LTCC is demonstrated.

Keywords: Hot isostatic pressing; Shaping; Functional applications; Biomedical applications; Laser processing

1. Introduction

Low temperature co-fired ceramics, LTCC, is well recognized as a distinct material platform for implementing multiple material technologies for a variety of cross-disciplinary applications. It offers a promising solution for realising miniaturised ‘system in package’ components, sensors and actuators and micro electro-mechanical system, MEMS, packaging by offering a range of versatile characteristics.[1–7] From the analysis of hazardous chemicals through to a variety of biological applications, LTCC offers many desirable features. In the realisation of three dimensional microfluidic structures LTCC is superior to glass, silicon, polymethylmethacrylate, PMMA, or polydimethysiloxane, PDMS, technology in terms of its quick production throughput and cost effectiveness. It allows embedded metal electrodes for the heating of liquid along with various microwave and optical components for accurate on-chip characterization of liquids. Microchannels, micromixers, hot plates, micro-heaters and micropumps, are just a few of the structures that have successfully been demonstrated using LTCC technology.[8–11] The average surface roughness of sintered LTCC substrates was found to be between 61 and 86 nm[12] and the average surface roughness of printed silver for embedded electrodes and other microwave components was measured to be between 42 and 48 nm which is suitable for microfluidic applications.[12]

Sheets of LTCC can be processed into complex three dimensional structures when it is in its soft, unfired state (also known as green tape). Laser machining has been shown to be the most popular method for the patterning of these sheets, owing to the high repetition accuracy and ability to realise small sized shapes in the material (on the order of 20–50 μm). This processing method can be used to directly fabricate micro-channels which can hold liquid samples for microfluidic applications. The effects of various lasers on LTCC have previously been reported.[13–18]

The major limitation in realising a microfluidic module is the sagging and deformation around embedded cavities that occur during the lamination of the LTCC sheets. Cold lamination techniques are adopted to avoid this cavity deformation. Cold lamination involves the use of double sided adhesive tape made from a polymer (polyethylene terephthalate)[19,20] or coating between each LTCC layer with either solvents or thinners such as butyl-benzyl-phthalate,[21,22] followed by low pressure lamination to maintain the cavity shape. Alternatively, a fugi-

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tive material, referred to as a sacrificial volume material, SVM, may be used by filling the cavities prior to lamination to provide mechanical support during the process. The SVM evaporates during firing of the LTCC stack at a controlled rate as the ceramic hardens. Carbon black-paste, cetyl-alchol or graphite based sacrificial paste are commonly used SVMs.[23–25]

Although the above mentioned techniques are useful in realising embedded cavities, they require additional material along with a longer firing profile to ensure complete removal of the introduced carbon from the microfluidic structure, increasing the processing lead time and material cost. In this study, the modified lamination process is assessed using both optical micrography and transmission X-ray photography to measure the processing effects on the embedded microfluidic structures. It is demonstrated that for the case of microfluidic structures fabricated through laser ablation, similar results can be achieved by only altering the lamination phase and dividing it into low pressure multiple lamination steps – referred to as progressive lamination.[9] The assessed technique reduces the fabrication cost in terms of additional material and firing time, along with a guarantee of leaving no residual carbon particles in cavities as a result of a non-optimised firing profile – which may require further cleaning processes if contamination is to be avoided.

Since pre and post lamination steps are the same for all components fabricated in LTCC, parallel processing of microfluidic and electrical components is feasible. The technique used in this work eliminates the need to use a screen printer to deposit adhesives or filling SVMs, resulting in a further reduction in the required processing equipment.

2. Experimental procedure

2.1. Fabrication of channels in LTCC

Channels and cavities can be machined in the green state of LTCC substrate using either laser ablation or mechanical drilling techniques. The presence of organic ‘vehicles’, used to maintain the materials flexibility and malleable properties, in green tapes makes it easy to cut and mould them to the desired shapes. After firing, laser absorption into the material reduces significantly and thus become ineffective in cutting sintered ceramic and glass particles. It has been demonstrated that a 1064 nm, infra-red laser is suitable for the ablation of LTCC green tapes, resulting in a clean cut with minimal induced damage to the pattern edges.[26] A 1064 nm infra-red laser from LPKF (Protolaser™ 200) was used in this study.

When the glass particles, which are a major constituent of green tape, melt during the firing stage, shrinkage occurs. This shrinkage has to be characterized accurately and its effects on the final LTCC structure have to be considered during the design phase. Constrained sintering techniques and self-constraining tapes are also available in which the tape shrinks primarily in a single direction, which can be beneficial for electronic packaging applications.

There are a variety of LTCC substrates available to use, each with their own pre and post-firing mechanical properties along with their individual optimised processing and shrinkage profiles. The requirements of the final product along with the processing stages should be considered and matched to the appropriate green-tape material prior to its design. In this work, the green tape ‘943 PX’ made by DuPont was used. These sheets have a thickness of 254 μm, density of 3.2 g/cm^2 and camber of less than 0.001 in./in. As this technique relies on a thick platform, thicker LTCC sheets are preferred. The shrinkage of the used green tape is approximately 9.5% in the X and Y directions, and 10.3% in the Z direction – where the X and Y directions are the length and width of the 2D design, respectively, with the Z direction representing the material thickness. Therefore, the desired length and width of the design features were kept 9.5% larger than the intended resultant size. The post-fired thickness of 230 μm for each sheet was expected for the Z dimensions of the features.

After designing the desired features in a standard CAD format, the green tape was loaded into the laser ablation machine. The edges of the design features are read by the machine and the laser is pulsed along those edges. The laser used in this study has a spot diameter of 25 μm and can define features as narrow as 30 μm for this particular material thickness. This cutting width was accounted for when the laser machining paths were created.

The laser marking along the edges of a rectangular shape enables the mid-section of green tape to be removed, which results in the machining of a channel. The substrate is ablated completely and is removed via a vacuum pump for widths smaller than 100 μm. Channels as narrow as 30 μm have been machined prior to this work by using a single ablation path along the an LTCC sheet, using a low laser power profile.[12]

As the Protolaser 200 uses an optical scanning system, the features which are not directly under the laser source were machined with a slight tilt; varying the laser beam angle with reference to the static material position causes this effect. However, features which are wider than the thickness of the substrate show no significant tilting effect.

Excessive laser power can damage the substrate, resulting in ragged or burnt edges along the channel and therefore careful optimisation of the laser parameters is necessary prior to machining. For optimum cutting, the pulse repetition rate, along with the etching speed, defines the resolution of edges and laser power controls the depth of penetration. It is recommended that the laser power is maintained at the material’s critical ablation point, and to repeat the process if it is necessary to drill further into the material in order to leave clean-cut features. Various channels of different widths were fabricated by using a laser fluence of 3.31 J/cm^2 with seven cycles on the surface of the substrate followed by nine more runs with a Z-offset equal to half of the thickness of substrate in the laser focusing position. The Z-offset allows the laser to focus into the material, increasing its effective cutting depth.

2.2. Pre-lamination of LTCC sheets

Deep channels with small dimensions that are composed of more than one LTCC layer are difficult to align using manual alignment methods; there is also a greater chance of the cavity walls deforming during the lamination process. Fig. 1

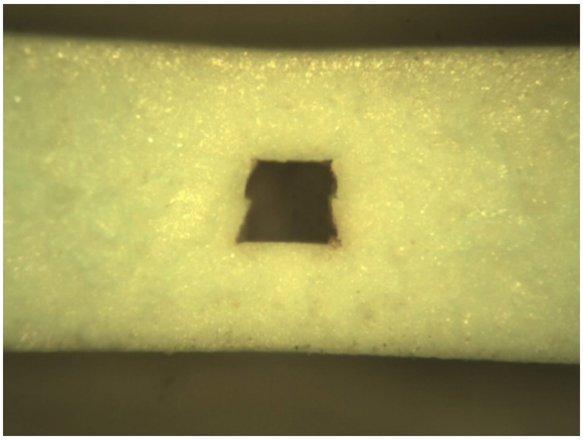

Fig. 1. Two layer channel wall deformation.

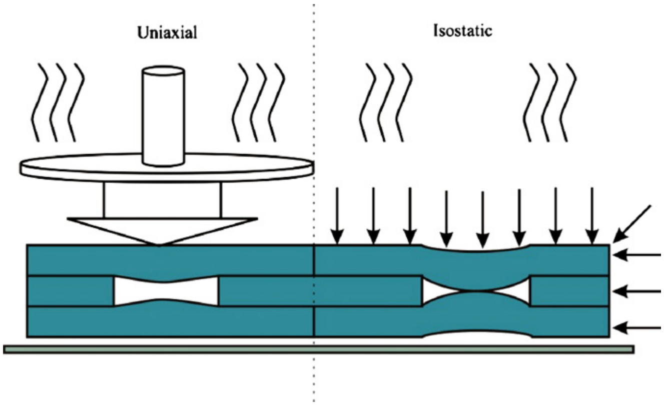

Fig. 2. Uniaxial vs isostatic lamination.

shows a sintered sample of an LTCC stack with an embedded channel which was deformed due to misalignment and laminating pressure, the channel was machined separately in two LTCC layers and aligned afterwards. To avoid deformation, the sheets required to achieve the desired channel height were pre-laminated, followed by laser machining. This pre-lamination process ensures regular cavity walls, even if it is formed across multiple layers.

2.3. *Progressive lamination*

In microfluidic structures with embedded cavities and channels, the lamination phase can prove to be the most problematic. Thermo-compression is a widely adopted technique in which the sheets are laminated under a specific pressure at an elevated temperature. The heat softens the tape by warming the organic solvents and the pressure helps in interpenetration of the micro-particles in the tapes. The temperature is typically set to 70 °C, with a pressure of 200–350 bar for 10 min. A uniaxial or isostatic press serves as the laminating equipment. The uniaxial press exerts the pressure over the entire surface of the stack; it is rotated by 180° half way through the process to ensure uniform pressing across the entire surface. The isostatic press uses warm water which exerts a uniform pressure across the LTCC stack from all directions. The latter is considered a better process owing to this uniform pressure. If no SVM is added it is very hard to prevent the cavities from sagging in isostatic lamination because the pressure is exerted in every direction, however, in the case of the uniaxial press, the pressure is distributed on the whole surface equally, as illustrated in Fig. 2.

In order to avoid cavity deformation from the centre, the structure was laminated in stages. This technique is referred to as ‘progressive lamination’ or ‘build-up stack’. The benefits of this process are that each green tape layer is laminated multiple times which gives the stack added strength. The process assists the manual alignment techniques and reduces the risk of misalignment among the layers during lamination. The complete process of this progressive lamination is shown in Fig. 3. Initially, the platform sheets for the structure were laminated and then sheets with etched grooves and cavities were individually added. During lamination a thin metallic slab was placed on both sides of the stack in addition to each inserted layer to distribute the pressure over the entire surface, this metallic slab is removed after lamination and reused with next layer added to the stack. Once the complete LTCC stack was laminated, the covering LTCC sheets were laminated separately and then re-laminated along with the stack. If there is no restriction on the thickness of the finished device, it is recommended that two or more sheets are used as the platform and cover layers to improve the processing repeatability and its structural integrity. The lamination parameters for LTCC green tape with patterned microfluidic structures were optimised through a set of processing trials of varied temperatures, pressures, and durations. It was found that optimum lamination can be achieved by with a lamination pressure of 50 bar and temperature of 80 °C for 20 min. A side view of the embedded cavity shows no sign of de-lamination as shown in Fig. 4. There is, however, a slight bend visible on the top and bottom but this is less than 10% of the thickness, the tapered sidewall artefacts are caused by the laser beam de-focusing as it drills into the material. Steeper sidewall angles can be achieved by refocusing the laser at regular intervals during the drilling process.

3. Fabrication results and discussion

3.1. *H filter*

An ‘H filter’, used to separate different types of particles from a sample, is one of the common elements used in a hybrid microfluidic system. It works on the principle of diffusion and is a useful, compact and lightweight alternative to a centrifuge.[27] The sample is pumped into the filter from an inlet along with the receiver or collecting solution from the other inlet. Small particles in the sample diffuse in the receiver solution in the diffusion chamber and their concentration equalizes in both streams. At the receiving end the separated particles are collected along with the receiver solution from one outlet and the sample with a reduced amount of small particles from the other outlet as shown in Fig. 5. This H filter can be used to precondition a sample. In the case of blood, the hormones and ions can be separated from blood cells. A sample H filter was fabricated using LTCC with a diffusion channel width of 500 μm as shown in Fig. 6.

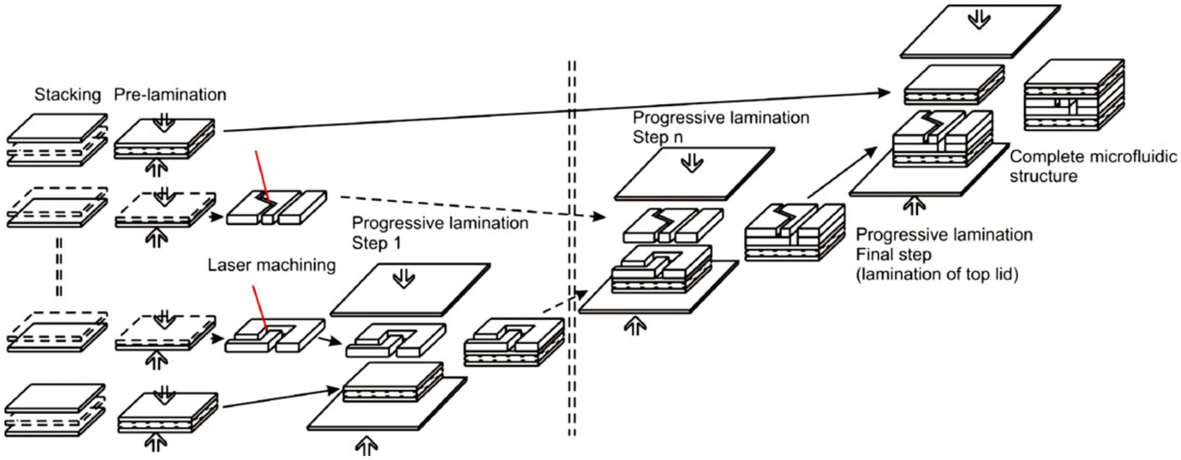

Fig. 3. Progressive lamination for multilayer microfluidic structure.

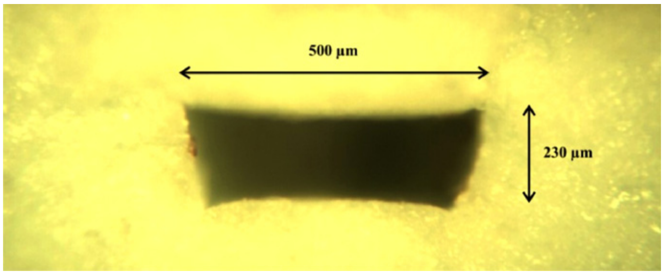

Fig. 4. End view of an embedded microfluidic channel.

3.2. Bio-particle separator

A bio-particle separator prototype was fabricated using four LTCC layers in Fig. 8. The inlets for fluids are on different layers. In the centre of the structure there is a separation chamber where a membrane can be placed for the separation of particles. This type of structure has the flexibility to integrate not only a membrane between the separation channels but also a ferromagnetic material can be screen printed on top or bottom of the structure for magnetic bio-particle separation as illustrated in Fig. 7.

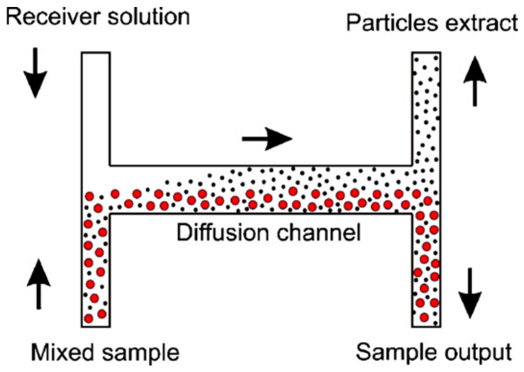

Fig. 5. Working principle of an H filter.

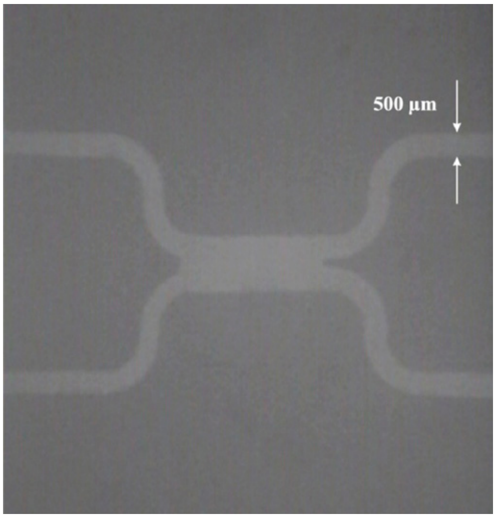

Fig. 6. X-ray photograph of the fabricated LTCC H filter.

3.3. Microfluidic mixer

Microfluidic mixers are used for mixing different liquids on-chip. The liquid is pushed into the mixer using pumps and there is an optimum length for a mixing chamber which allows these fluids to mix properly before being fed to subsequent elements. An example of a microfluidic mixer fabricated using LTCC is shown in Fig. 9. A channel width of 500 µm was machined using the laser.

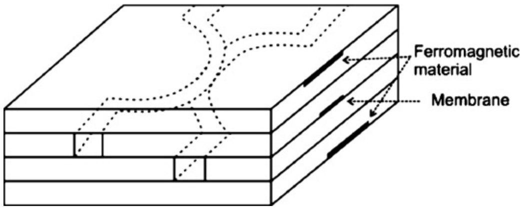

Fig. 7. Illustration of magnetic bio-particle separator.

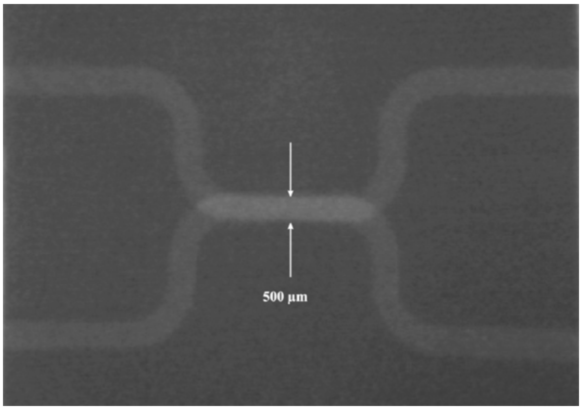

Fig. 8. X-ray photograph of bio-particle separator with broadside separation mechanism.

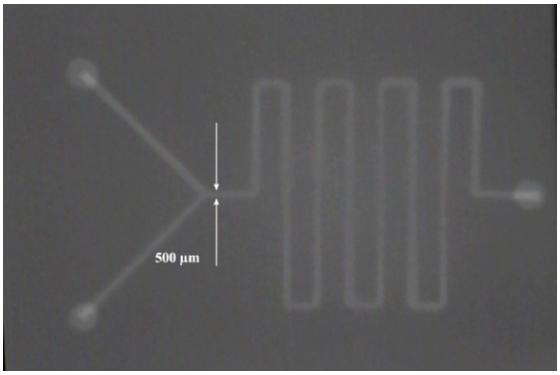

Fig. 9. X-ray photograph of the microfluidic mixer.

3.4. Microfluidic reservoirs

Microfluidic reservoirs embedded between various LTCC layers were realised in an LTCC substrate as shown in Fig. 10. These reservoirs, or buffers, have dimensions of 500 μm × 500 μm × 460 μm and are used to hold fluids which could be later pumped to the desired location using the channels and valves. An X-ray photograph of the embedded channels realised in LTCC is shown in Fig. 11.

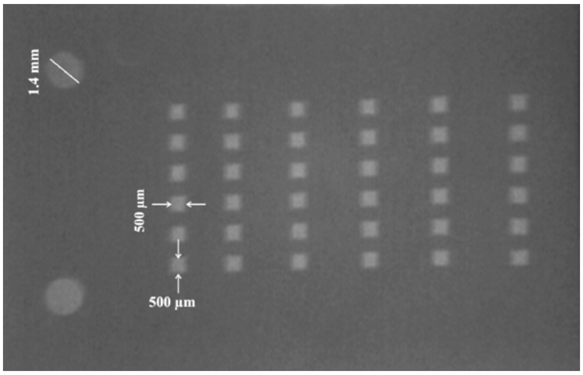

Fig. 10. X-ray photograph of a fluid reservoir array: each reservoir measures 500 μm × 500 μm × 460 μm.

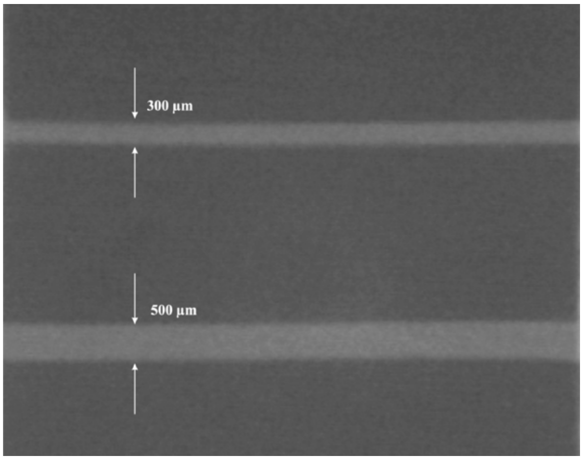

Fig. 11. X-ray photograph of two embedded microfluidic channels of widths 300 μm and 500 μm.

Fig. 12. Cross-sectional view of an embedded channel after firing.

4. Conclusion

Various microfluidic structures have been demonstrated using LTCC technology and laser machining of embedded cavities. These cavities were embedded inside the structure and a progressive lamination technique has been used to avoid the deformation of cavities without requiring the use of a sacrificial volume material. X-ray images have been presented to confirm that no cavity has collapsed during the processing of these structures. The uniform contrast of X-ray photographs presented earlier shows that all of the embedded cavities were in good condition and there was no sign of deformation or sagging. The cross sectional view of an embedded channel with a height of 230 μm justifies this observation as shown in Fig. 12. A wide range of functional microfluidic structures has been presented which were successfully fabricated using the laser ablation machining technique along with controlled lamination process.

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