# Lamination of 3D Structures in LTCC Using Elastomer Bags

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*Abstract*

*Lamination is an important step in the production of three-dimensional structures using green ceramic tapes. A lot of research was devoted to the refinement of the lamination process; a certain number of lamination methods are known from the literature. The present work deals with the evaluation of the method in which elastomer bags are used to carry out the isostatic thermo-compression lamination of green tapes to build 3D structures. With the help of the example of a hot-film flow sensor a technically unsophisticated way to laminate a green tape onto the inner surface of a metal cylinder is demonstrated. Furthermore, test results for lamination of LTCC substrates with cavities of large aspect ratio are presented.*

## 1 Introduction

In certain applications three-dimensional (3D) structures produced with green ceramic tapes (LTCC or HTCC) are needed. Examples of such structures are given by open cavities (e.g. ceramic packages), buried fluidic channels integrated in the ceramic substrate or free standing sensor elements.

The starting point for the presented investigations was a custom 3D sensor design project carried out for an industrial partner. The approximate form of the sensor is given in Figure 1 showing measurement electrodes on its outer surface and the O-ring groove in the rear part of the sensor body. The sensing structures were to be implemented using thick-film pastes on the surface of the cylindrical ceramic carrier.

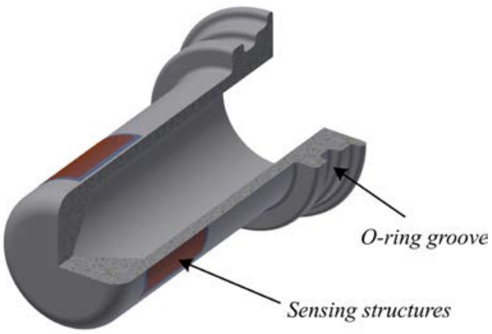


*Figure 1: Principle drawing of the sensor. The rear section of the ceramic body is a part of the hermetical feedthrough assembly with the process vessel wall. Sensing electrodes in the front section would be in contact with the process environment.*

Due to the complex form of the sensor body it was not possible to screen print the structures on its surface directly. The method of choice to produce the sensor was to print the structures on the green ceramic tape and then to laminate it onto the surface of the ceramic cylinder. This also allowed the contacting of the electrodes without breaking the hermeticity of the whole assembly. Still, the main challenge was to implement the lamination process which would join the green ceramic tape with the fired ceramic body and produce a stable 3D structure after firing.

Many studies were devoted to optimizing the lamination process, while aiming mostly to protect the integrity of cavities and channels in the 3D structures and to prevent delaminations, sagging, crushing and cracks. To address these problems different approaches were developed, e.g. using appropriate latex rubber sheets [1], cold low pressure lamination with adhesives [2], cold chemical lamination based on solvents [3], pseudo-isostatic lamination with rubber [4] or low pressure thermo-compression lamination using elastic inserts [5].

The problems emerging during isostatic lamination of 3D structures are well-known. To illustrate their causes an example of the thermo-compression lamination of a green ceramic structure with a cavity onto a prefired ceramic carrier is given in Figure 2. First let us consider a green structure which is inserted into a plastic bag after stacking, the bag being evacuated, sealed and subjected to isostatic pressure in the lamination chamber. The forces shown in Figure 2 (a) would likely cause rounding of the corners or edges of the cavity and deformation of its side walls. If the cavity is not of a quite small aspect ratio, no pressure would be applied to the bottom of the cavity resulting in subsequent delaminations in that part. The plastic bag would probably be broken by the pressure so that the fluid from the isostatic chamber would deteriorate the green structure.

To our knowledge the most widely used way to successfully carry out the isostatic lamination is to place specially formed elastic inserts or relatively thick elastic sheets between the 3D green structure and the plastic lamination bag as shown in Figure 2 (b). This allows

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transferring the external hydrostatic pressure uniformly to the surface of the green ceramics stack.

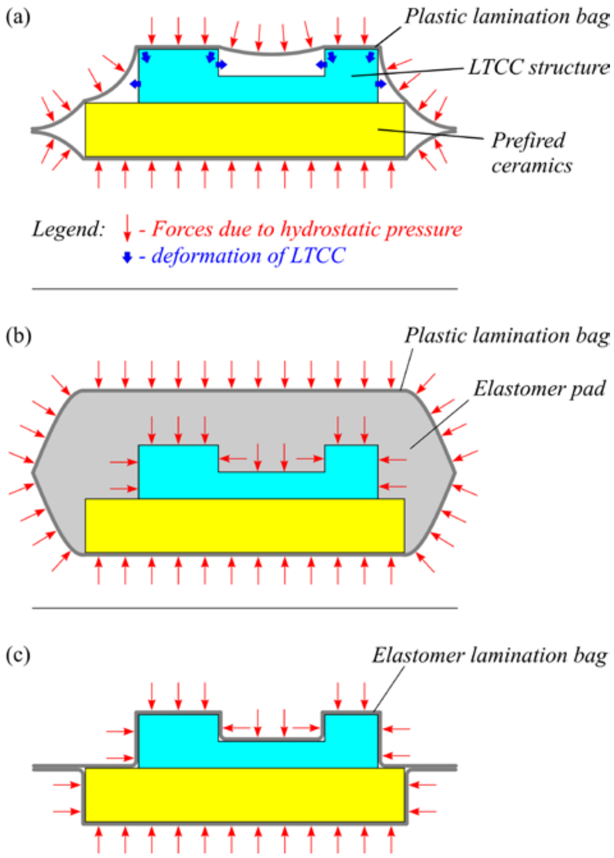


*Figure 2: Distribution of forces during isostatic thermo-compression lamination of a green ceramic structure with a cavity on a prefired ceramic carrier: (a) using a plastic lamination bag, (b) with an elastic insert, (c) in a thin elastomer bag.*

The principle shown in Figure 2 (b) was successfully used to build the prototypes of the cylindrical sensor of Figure 1. However, some issues were found which would complicate using the method in series production, their main reason being the marked 3D form of the substrate. So it was challenging to put the green tape, the ceramic cylinder and the elastomer inserts together prior to placing the assembly into the lamination bag. Defects like folds of the green tape, its being torn or displaced on the cylinder could be observed. All this made the set-up process relatively delicate and time consuming.

Experiments were carried out in our laboratory to overcome these difficulties by eliminating the intermediate medium in transferring the hydrostatic pressure to LTCC and using an elastic bag for the isostatic lamination, as shown in Figure 2 (c). For the successful usage in practice such bags should be thin and easily deformable. They also should efficiently separate the liquid in the lamination chamber from the LTCC. Additionally, it should be possible to evacuate and seal the bags, preferably with standard equipment used for plastic bags.

Our investigations aimed to find suitable elastomer materials and to test whether employing elastomer bags can bring advantages in producing 3D LTCC structures. The results of our experiments proved to be promising not only for the original task of laminating a cylinder structure. A hot-film flow sensor serves as an example of a technically unsophisticated way to laminate a green tape onto the inner surface of a metal cylinder. Furthermore, our first experience in using elastomer bags for lamination of 2.5D LTCC substrates with cavities of large aspect ratio is presented.

## 2 Properties of elastomer bags

Important material properties of elastomers for use in the lamination process are breaking elongation, tensile strength, temperature stability and water permeability. The breaking elongation should be high and the tensile strength relatively low to allow the material to adapt its form simultaneously exerting low deforming forces on the green structure. The material should be stable at least up to about 50°C to 80°C, as the thermo-compression lamination is carried out at that temperature. Additionally it must form a barrier for the fluid (water) during isostatic lamination. The relevant properties of some materials are presented in Table 1.

### 2.1 Elongation stress to a bag

To estimate the typical elongation during lamination of 3D structures in LTCC, the vacuum induced stretching of a latex membrane into a model cavity was measured. The cavity of a square cross-section was used with the width $w = 50$ mm, depth $h = 43$ mm (aspect ratio $h/w = 0.86$) and the radius of chamfer $R = 1.5$ mm (Figure 3).

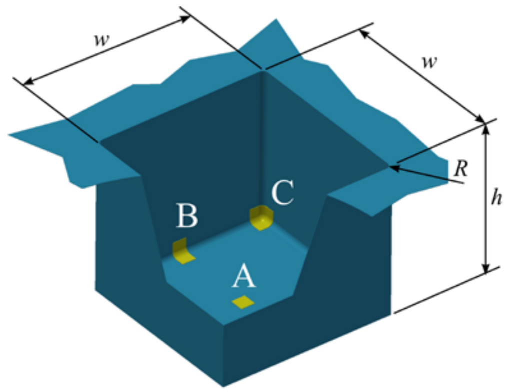


*Figure 3: Locations A, B, and C to measure linear elongation of an elastic membrane in the model cavity with the aspect ratio of $h/w = 0.86$.*

The unidirectional stretching of the membrane observed in the middle of the cavity floor (point A in Figure 3) was approximately 300%; its value was approximately 440% in the middle of the bottom edge (point B) and

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*Table 1: Properties of selected elastomers and thermoplastics: unfilled natural rubber (NR), natural rubber with 25% carbon black filling (NR 25), nitrile rubber (NBR), neoprene rubber with 25% carbon black filling (CR 25), thermoplastic polyurethane elastomer (TPE-U), plasticized polyvinylchloride (PVC-P), low density polyethylene (PE-LD). Data compiled from [6], [7].*

| | NR | NR 25 | NBR | CR 25 | TPE-U | PVC-P | PE-LD |
|---|---|---|---|---|---|---|---|
| **Tensile strength (MPa)** | 24 | 22 | 18.5 | 20 | | 10-25 | 8-23 |
| **Breaking elongation (%)** | 750 | 700 | 510 | 400 | 500 | 170-400 | 300-1000 |
| **Highest service temperature (°C)** | 85 | 85 | 125 | 100 | 80 | 50-55 | 60-75 |

480% in the bottom corner (point C in Figure 3). Comparison of these values with breaking elongations from Table 1 shows that lamination of cavities with aspect ratios of $h/w \approx 1$ should be possible.

### 2.2 Practical implementation issues

While plastic lamination bags are readily available, elastomer bags must be custom-made or an existing object of a suitable form must be used. The majority of our experiments were carried out with balloons and disposable gloves, whereby gloves were better in practical usage due to a wider opening for inserting ceramics.

One of the goals was using standard sealing equipment for evacuation of the bags. Disposable gloves of different materials of several manufacturers were tested; vacuum sealing succeeded with latex (NR), nitrile (NBR) and vinyl (PVC-P) gloves. The sealing of vinyl (thermoplastics) resulted from its melting. The joining in latex or nitrile (elastomers), though there was sufficient adhesion after heating by the hot knife, could be released with some force. Nonetheless, the joining was strong enough to withstand the subsequent lamination process.

## 3 Experimental Results

The usage of elastomer bags for lamination of a green tape onto the inner surface of a metal cylinder and for lamination of LTCC substrates with cavities are discussed in detail below. In general, the obtained results showed that the proposed method can indeed simplify the lamination of complex 3D structures. The choice of the materials and the details of the process can be further optimized.

Our experience with latex, nitrile and vinyl bags can be summarized as follows. Latex showed the best elasticity allowing lamination of structures with high aspect ratio, but occasionally water penetration was observed, strongly deteriorating the result. The used nitrile blend was less elastic, but water penetration did not appear to be a problem. Vinyl showed the best sealing performance and no water penetration, but its elasticity was limited.

### 3.1 Laminating a 3D hot-film flow sensor

A hot-film flow sensor integrated onto the inner surface of a tube segment (see Figure 4) was used as a test to evaluate lamination with elastomer bags [8]. To carry out the flow measurements the tube segment would be a part of a gas pipe. The sensor consisted of six sectors of meander-formed conductive traces (200 µm both width and pitch) evenly distributed on the circumference of the tube. The traces were heated by the electric current from an external circuitry. As the medium (gas) flows through the tube, heat is transferred to it from the traces. The flow velocity of the medium can be determined either keeping supplied voltage constant and measuring the change in electric current through the trace sector, or regulating the temperature of the trace and measuring the supplied power.

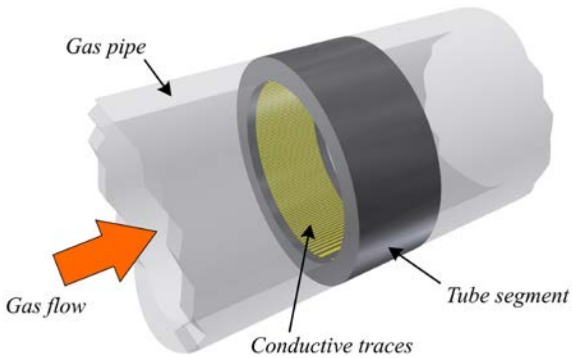


*Figure 4: Principle drawing of the hot-film flow sensor.*

As materials for the tube segment – the carrier – stainless steel 1.4571 (X6CrNiMoTi17-12-2) and 1.4305 (X8CrNiS18-9) were tested. The height of the segment was in the range from 15 to 20 mm, its inner diameter – from 40 to 43 mm. Green ceramic tape (height 12 mm, length of about 135 mm) served as the substrate for the conducting traces. It was first screen printed with meander traces and then laminated onto the inner surface of the carrier.

The setup was tested with the following green tapes: DuPont 951PT (unfired thickness 114 µm), ESL 41020-T (unfired thickness 115-135 µm) and Kerafol CT 810 (unfired thickness 180 µm). DuPont 951 is a LTCC green tape, the used ESL and Kerafol tapes are designed to be laminated onto alumina and stainless

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steel respectively. The isostatic lamination was carried out using vinyl gloves as elastomer bags at the temperature 55°C, pressure 20 MPa and duration 12 min. The sealed tube segment and the laminated tape are shown in Figure 5.

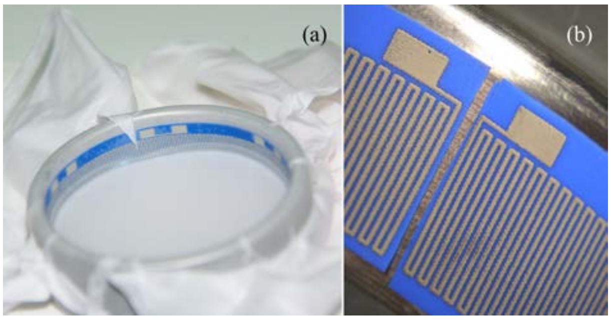


*Figure 5: The tube segment sealed in a vinyl glove (a) and a close-up view of the ESL 41020-T green tape after lamination onto the tube (b).*

Optical inspection of the lamination results revealed that the green tapes did not move during the process and maintained their geometry. It was found, however, that the folds on the elastomer bag, formed due to evacuation, could leave slight impressions on the surface of the tape. These imperfections were most pronounced at approximately half-height of the tube where the opposite sides of the bag join. The effect can be explained as follows: under pressure during isostatic lamination empty pockets indicated in Figure 5 do not completely disappear due to relatively high tensile strength of vinyl. The green tape gets pressed within the remaining small cavities producing a slight impression in the form of a ridge.

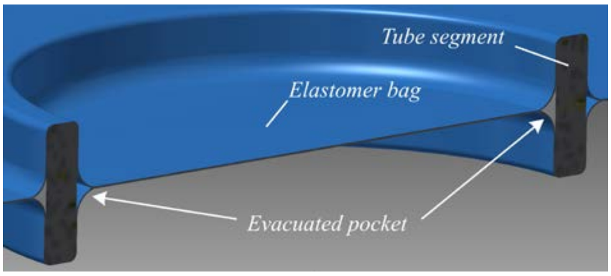


*Figure 6: Schematic diagram showing pockets formed after evacuation of an elastomer bag of a relatively high tensile strength which can leave impressions on the underlying green tape.*

Adhesion to the carrier after lamination showed dependence on temperature and pressure. For the chosen lamination parameters adhesion was good for all three examined tapes as proved by scraping and peeling tests.

The setups with all three tapes were fired at the maximum temperature of 850°C: tubes with laminated DuPont 951 tape in a box furnace using the 3-hour profile from the datasheet; tubes with the ESL and Kerafol tapes in a belt furnace with a 1-hour profile.

As expected, the 951 tape did not survive the firing process because of the large difference in thermal expansion coefficients between LTCC and steel. The best results with the used steel carriers were obtained for the ESL 41020-T tape which delivered a stable and smooth surface after firing (Figure 7).

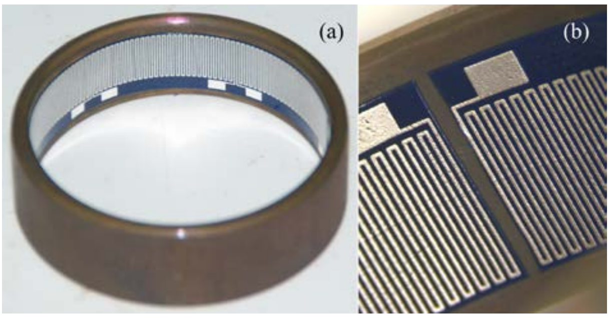


*Figure 7: The overall view of the hot-film flow sensor after firing (a) and a close-up photo of the region where the tape ends join (b).*

### 3.2 Laminating planar substrates with cavities

To examine application of elastomer bags for laminating 2.5D substrates, a test structure with open cavities of different depth was designed. It was built up of nine laser-cut layers of LTCC tape (DuPont 951PT, 114 µm unfired thickness), the total height amounting to nominally 1026 µm. The cavities were arranged in four rows; the lateral dimensions of the cavities being the same in all rows and ranging from 1 mm x 1 mm to 5 mm x 5 mm (see drawing in Figure 8). The depths of the cavities changed between the rows from 228 µm to 912 µm in steps of 228 µm (unfired thickness). The back side of the substrate was left flat.

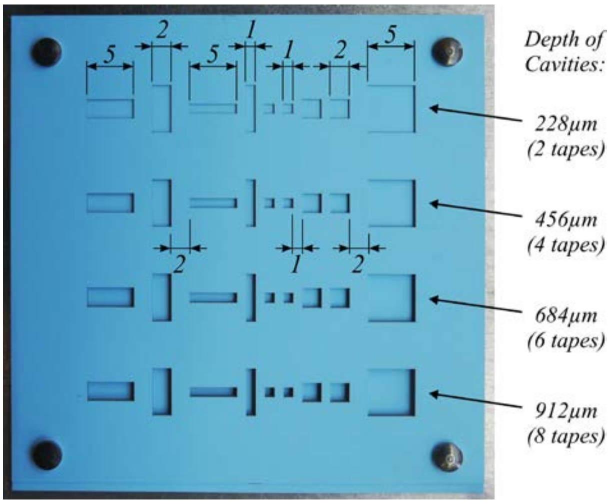


*Figure 8: The test LTCC substrate after stacking on the alignment fixture showing four rows of cavities with different depths. The side of the square substrate is 50.8 mm. Dimensions in the drawing are given in millimeters for the unfired substrate.*

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Lamination was tested with latex and nitrile bags; in the example described below a nitrile glove was used. The LTCC stack was placed on a thick aluminum plate, the backing tape of 951PT served as a release foil between the stack and the aluminum plate. After evacuating and sealing the glove, it was put into the isostatic press and laminated during 8 minutes at a temperature of 60°C and a pressure of 20 MPa. Figure 9 shows the substrate in the glove after lamination.

*Figure 9: The test substrate sealed into a nitrile glove (after isostatic lamination).*

Firing was carried out on a ceramic setter tile using the 3-hour profile with a maximum temperature of 850°C.

As can be seen from Figure 9, the elastomer bag distributes evenly over the surface of the substrate and forms no folds. So it was easy to eliminate the impressions from the bag folds found after lamination of the hot-film sensor.

Two additional effects having an impact on the geometry of the LTCC substrate were found. These were, firstly, the local sticking of LTCC material to the bag and, secondly, the change of planarity of the substrate top surface near the cavities.

The first effect can be described as follows: at locations, where the elongation of the bag was high, some LTCC material stuck to the elastomer and was removed with it. The effect could be seen on the bottom of the cavities with high aspect ratio; it was not observed on the edges of the substrate and on the through holes. The changes due to sticking can be seen in Figure 11 (b) in the height maps of cavities' bottoms, where the row of cavities with depths of 8-tapes is depicted (it corresponds to approximately 710 µm on the fired substrate). From the cross-section height-plot given in Figure 11 (d) the absolute value of the non-planarity can be found: approximately 20 µm in locations indicated by the arrows A. The comparison with Figure 10 shows that the effect did not appear in shallow cavities.

The cause of the local sticking is not quite clear yet and will be subject of further investigations.

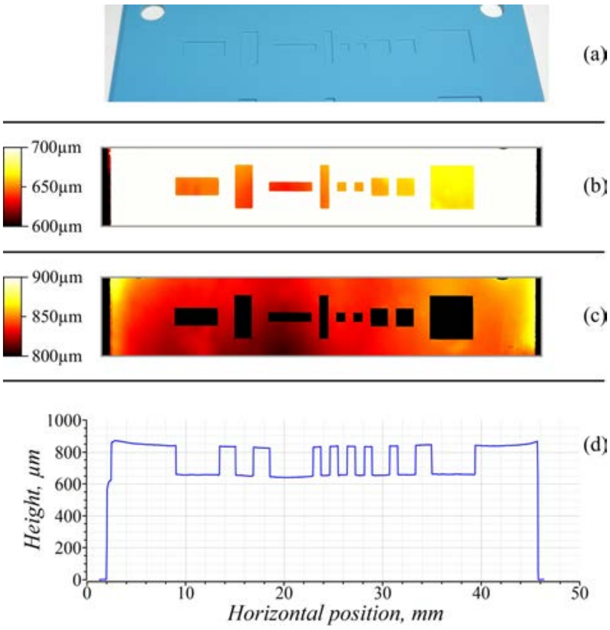


*Figure 10: The test structure after firing; the region with cavities of the least depths is shown: an overview photo (a), height maps of the surface (b) and (c), the height profile through the cavities' midpoints (d). The scales of the height maps are given on the left and indicate the absolute height relative to the bottom of the substrate.*

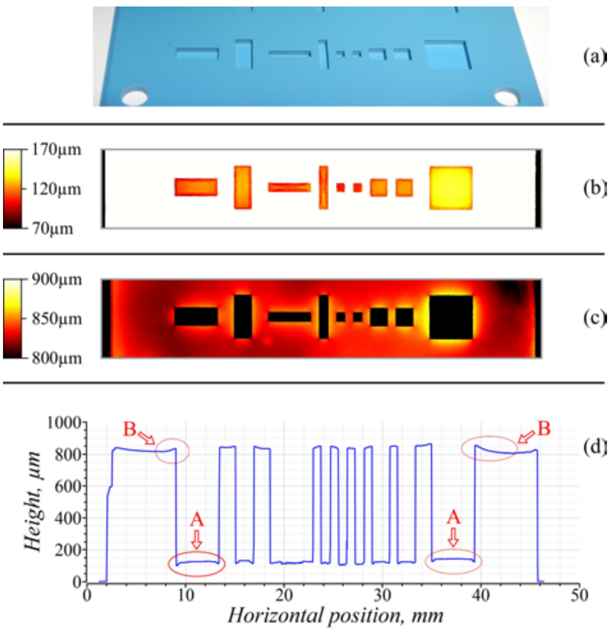


*Figure 11: The test structure after firing; the region with the deepest cavities is shown: an overview photo (a), height maps of the surface (b) and (c), the height profile through the cavities' midpoints (d). The scales of the height maps are given on the left and indicate the absolute height relative to the bottom of the substrate.*

The second effect manifests itself in the elevation of the substrate top surface in proximity of the walls of the cavities as the height map of the surface in Figure 11 (c) illustrates. Arrows B in Figure 11 (d) indicate this elevation in the height-plot; it amounts to up to 50 µm over the undistorted surface. Once more, this effect is negligible in the shallow cavities, proved by comparison with Figure 10.

Explanation of the effect lies presumably in the tensile stress distribution within the elastomer: in the corners the stress is higher due to higher elongation, so less pressure is transmitted from fluid to the LTCC during lamination.

Several further general observations gained from the experiments can be given:

- Even though no release foil between the green ceramics and the elastomer bag was used, only local sticking was observed (in places where the elastomer bag was strongly stretched).
- Except for the LTCC loss due to the local sticking effect the floors of the cavities of all depths remained flat.
- The side walls of the cavities with depths of 6 and 8 tapes had a certain structure which resulted from the tolerances during stacking. This structure was retained after lamination and firing.

## 4 Conclusions

The obtained results showed that using elastomer bags for the isostatic thermo-compression lamination of complex 3D structures can simplify the production process in certain applications. The method can be especially useful for lamination of non-planar (e.g. cylindrical) assemblies, like the ones described in the paper.

In the practical implementation of the discussed examples elastomer bags in form of disposable gloves made of latex, nitrile and vinyl were tested. They could be processed using standard equipment for isostatic lamination and showed satisfactory performance in the application. Latex occasionally exhibited water penetration; vinyl had limits in respect to the highest possible aspect ratio of the structures. It is intended to test further elastomers and thermoplastics as materials for the lamination bags.

Experiments on 2.5D LTCC structures with open cavities also brought positive results concerning the possibility of employing elastomer bags for the isostatic lamination instead of plastic bags with elastic inserts. Two effects causing distortion of the ceramic structure were revealed: the local sticking of LTCC material to the bag and the change of planarity of the substrate surface near the cavities. The substrate thickness change due to these effects was about 50 µm at most (for the substrate of 43.7 mm fired size). This value can be tolerated in many applications.

## Acknowledgements

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