Influence of lamination parameters on mechanical properties of low temperature co-fired ceramic tapes

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A B S T R A C T
For the development of force sensors, manufactured in LTCC (low temperature co-fired ceramics) technology for musical wind instruments, the mechanical properties of laminated LTCC tapes were characterized. Since one layer of LTCC tape is not always fulfilling the requirements of the force sensor’s loading capacity, the influence of lamination parameters for different number of layers were investigated. The measurements were carried out with miniaturized (2 × 1 mm²) beam samples of four different LTCC tape materials, namely Heraeus AHT01-005, AHT08-047, CT707; and CeramTec GC. The results of the measurements can be used to determine the proper LTCC tape material, the lamination pressure and the number of layers to allow the development of customized force sensors, not only for musical wind instruments.

1. Introduction

It is intended to carry out case studies on a musical wind instrument concerning the fingering behavior of the musician. Therefore, particular force sensors that are mounted on every hole and key are necessary that accomplish measuring the force of the fingers applied on the instrument’s key-work. The force sensors are based on the strain gauge principle where a beam is bent according to the applied load. This bending is measured by a piezo-resistive thick-or thin-film resistor, respectively. The force sensors will be manufactured in LTCC (low temperature co-fired ceramics) technology since this technology fulfills both the sensory and packaging part of the force sensor.

The mechanical properties of various LTCC tapes with rather large sample geometry (50 × 5 mm²) have already been analyzed using a 3-point bending test [1]. In [1], single- and two-layer samples of the Heraeus CT700 and Ferro A6 tapes and single-layers of the CeramTec GC tape at constant pressures have been investigated. For the application in musical wind instruments, a rather small geometry of the force sensors is required. Preliminary estimations did show that only a beam element (one fixed and one free end, [2]) could fulfill these space requirements. For the development of the sensors, a beam of length l of 2 mm and width w of 1 mm was selected (see Fig. 1); the height h is varying with number of layers and thickness of the tape material.

The strength of only one layer of LTCC tape is not sufficient to be used as force sensor for finger forces on musical wind instruments. The maximum finger force of a single finger was estimated to be around 5 N. Accordingly, in a first step, two layers of LTCC tapes were laminated at different pressures, sintered and characterized. In a second step, the number of layers was increased and laminated with the pressure that was determined as most robust in step one.

2. LTCC sample preparation

Four different LTCC tape materials were compared: the Heraeus AHT01-005, AHT08-047, CT707; and the CeramTec GC. The geometries of the samples were scaled by a factor of 1.253 (the x–y-shrinkage of CT707) to compensate the x–y-shrinkage during sintering. Since every tape material has unique shrinking behavior, the final dimensions had to be considered in the calculation of the mechanical properties. To allow accurate results, the sintered geometries of the beam element (w and h) where measured by an optical profilometer (FT MicroProf, with x–y-resolution of 1 μm, z-resolution of 20 nm). The measured sintered dimensions are summarized in Table 1. For every type of beam, i.e. tape material and number-of-layer combination, the thickness was measured using a distance of 1 mm on the surface of the beam, scanning it in steps of 1 μm and calculating the average thickness. In Table 1, the average values of every 10 beams of one type are
given. These average values were also used for all following calculations of the modulus of elasticity. This approach was used since the thicknesses of the beams of one type were varying by less than ±1 μm.

The samples were cut with a 120 W Nd:YAG-laser, laminated at 70 °C for 3 min with an isostatic press and sintered at a peak temperature of 850°C (Heraeus tapes, dwell time 28 min) and 870°C (CeramTec tape, dwell time 20 min), respectively. The cutting edges of the beams using a Nd:YAG-laser show pronounced glassy seams due to the absorbed laser power. In order to consider this change of the edges of the LTCC material within the mechanical characterizations, the geometry of the final force sensor design was used to measure the mechanical properties.

LTCC tape materials are composites of mainly ceramic and glassy components. This composition yields in a rather weak homogeneity and for this reason there is a wide distribution of the mechanical properties, especially for beams with such small dimensions. To allow comparable results, 10 samples of every combination of material, pressure and number of layers were measured. In the following diagrams the mean values of those measurements together with their minima and maxima are presented.

The complete beam sample with bulk material to the left to mount the structure is shown in Fig. 2. The small radii at the corners were machined to prevent the laser from stopovers and therefore to prevent unwanted additional vitrification at the edges. This step is essential since the maximum stress appears at these fixed ends of the beams. It did show that the machining of the radii does not influence the modulus of elasticity but reduce the flexural strength of the beam and thus complicate the measuring procedure.

### 3. Measurement principles

In order to determine the moduli of elasticity of the different LTCC tape laminates, the beams where deflected by Δz at point (l,0), whereas a constant distance l of 2 mm was used for all LTCC tape materials. When the resulting force F is measured simultaneously, the modulus of elasticity can be determined for known geometry. The modulus of elasticity of a single-side fixed beam is related to the applied force F in z-direction and the deflection Δz by [4]:

$$ E = l^3 / (3l) \cdot \Delta F / \Delta z, \quad (1) $$

where l is the second moment of area. For a rectangular area $I = wh^3/12$.

The Δ in Eq. (1) was used to emphasize that for F and z no absolute values are required but an offset due to the measurement set-up is allowed. The same would not apply when determining the mechanical strength of the material.

In Eq. (1) it is assumed that the LTCC material is in the linear-elastic regime and the modulus of elasticity is isotropic and homogeneous. Whereas the linear-elastic assumption can be considered as fulfilled for ceramic materials [5], the isotropic and homogeneous properties of the LTCC beam do not apply due to material composition, vitrification at the edges and non-ideal laminate interlayer. Nonetheless, this assumption was used and the effective moduli of elasticity were measured to describe the whole beam as one piece of an isotropic and homogeneous ceramic material. This macroscopic assumption allows the engineer to choose the proper material in an easy way.

The measurement principle used to obtain the modulus of elasticity E of the laminated LTCC beam is shown in Fig. 3. The corresponding set-up is shown in Fig. 4. A commercial semiconductor force sensor is moved towards the mounted sample beam and thus a force is applied. Concurrently, the deflection is

### Table 1

<table>
<thead>
<tr>
<th>Tape material</th>
<th>Tape thickness t in μm</th>
<th>Sintered width in μm</th>
<th>Sintered thickness h in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHT01-005</td>
<td>135</td>
<td>922</td>
<td>118 215 325 412</td>
</tr>
<tr>
<td>AHT08-047</td>
<td>115</td>
<td>972</td>
<td>99 180 270 351</td>
</tr>
<tr>
<td>CT707</td>
<td>240</td>
<td>1000</td>
<td>155 289 429 567</td>
</tr>
<tr>
<td>GC</td>
<td>300</td>
<td>1011</td>
<td>235 462 690 920</td>
</tr>
</tbody>
</table>
measured contactless by a linear variable differential transformer (LVDT). This method allows the concurrent measurement of force and deflection with negligible mutual influence.

The samples themselves were mounted with a clamp. When mounting the beam five times, the calculated modulus of elasticity was repeatable in the range of less than 2 GPa.

4. Results

4.1. Variation of pressure

In a first step, the lamination pressure was varied. Two tapes of every LTCC material were laminated at pressures of 7 MPa, 9 MPa and 11 MPa, respectively. The pressures were selected as a trade-off between manufacturer data sheets and published data (see, for example [6,7]).

The measured moduli of elasticity are summarized in Fig. 5. All Heraeus LTCC tapes (AHT01-005, AHT08-047 and CT707) show increasing moduli of elasticity (maximum at 11 MPa in each case). In contrast, the CeramTec GC LTCC tape shows decreasing moduli of elasticity (maximum at 7 MPa). Scanning electron microscope (SEM) analyses did not show any differences in the cross sectional view of varying lamination pressure (see Figs. 6–9). There are some arbitrarily distributed voids that could be observed, but a qualitative optical analysis was impossible with SEM due to the fact that only 2-D images could be taken. However, etching of the glass phase could lead to further information about the lamination interface.

4.2. Variation of number of layers

In a second step, the number of layers was varied. For every type of material, 1–4 layers were laminated and characterized.

For the CeramTec GC tape a pressure of 7 MPa and for all Heraeus tapes a pressure 9 MPa was used for sample preparation. The reason why the pressure for the Heraeus tapes was not 11 MPa, the
optimum, is that the used isostatic press already represents a hazard at those pressures.

The single layer types of the Heraeus tapes have a sintered thickness of only 99–155 μm. Since they are very brittle at these thicknesses, they additionally were mounted on an alumina substrate by a low temperature sealing glass paste (ESL 4022-F) to avoid deflections of the bulk material. For the remaining combinations there were no differences in the measurements of the modulus of elasticity when they were mounted on alumina and thus it showed to be unnecessary. The measuring results of the moduli of elasticity are shown in Fig. 10.

5. Discussions

For the lamination pressure variation of two-layered LTCC beams, the result can be interpreted in that way, that enclosed voids are reduced with increasing lamination pressure for Heraeus tapes. The CeramTec GC tape seems to already show increasing delamination behavior at those pressures. But this interpretation still has to be proven by using enhanced analysis tools.

For the number-of-layers variation at constant pressures, all four types of LTCC tapes show monotonically decreasing moduli of elasticity with increasing number of tapes. This is what was expected since every lamination layer contributes as non-ideal intermediate layer. For that behavior a model has to be established that is valid for an arbitrary number of layers. Ideally a model could be found for which only a single- and a double-layer LTCC laminate has to be manufactured and measured and the effective modulus of elasticity of an n-layer LTCC laminate could be calculated. Also, the supposed ease of measuring the actual thickness of the laminate is not a trivial task, since each LTCC material has its unique surface properties. Since the calculated modulus of elasticity depends on the third order of the laminate’s thickness, this is a challenging task.

6. Conclusions

For the application in miniaturized force sensors, different kinds of LTCC tape materials where compared concerning their moduli of elasticity E. The influence of the lamination pressure on E was determined. The Heraeus AHT01-005, AHT08-047 and CT707 each showed increasing E with increasing pressure, whereas the CeramTec GC tape material showed decreasing E. The reason for that behavior is still an open question for the future.

Further, the decrease of the modulus of elasticity was measured in dependence on number of laminated tapes. For an adequate correlation between E and number of layers, further measuring is required and a model has to be established, where an useful approach could be that one in [8]. In this article the authors make the assumption that an Euler–Bernoulli-beam consisting of two layers of arbitrary linear, isotropic and homogeneous materials are non-ideally laminated. A model is established to take into account this non-ideal behavior by defining a constant slip modulus as interlayer. From measurements of the modulus of elasticity of a single layer and the effective modulus of elasticity of a twolayer-laminate the corresponding slip modulus could be calculated and used to simulate an n-layer-laminate by means of finite element simulations. In the model the fact has to be considered, that the thickness of an n-layer LTCC laminate is not exactly n times that of the thickness of a single layer.

In the next step, possible piezo-resistive thick- or thin-film pastes together with applicable conductor pastes have to be tested for their compatibility with the LTCC tape materials to allow the set-up of the electrical part of the force sensor.

References