Crack propagation in Low Temperature Co-fired Ceramics under biaxial loading

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ABSTRACT. *Low Temperature Co-fired Ceramics (LTCCs) are layered ceramic based components, which – in recent years - are increasingly used as electronic devices (e.g. mobile and automotive technologies) in highly loaded (temperatures, inertia forces, etc.) environments. They consist of a complex three-dimensional micro-network of metal structures embedded within a glass-ceramic substrate. In many cases, LTCC components are exposed to mechanical stresses, which may lead to crack propagation within the part. In this regard, different types of failure of the end component during service have been reported, coming from different parts within the component.*

In this work, the mechanical response of LTCC components has been investigated under biaxial loading, aiming to reproduce a common scenario during service. The influence of the internal architectures of the LTCCs on the crack propagation has been assessed in $10 \times 10\ mm^2$ *specimens using the ball-on-three-balls test and evaluated using Weibull statistics. Fractography of broken specimens has been performed to determine the mode of fracture of the components and the role of the internal architecture in the crack path. Results show strength dependence as a function of the testing position within the part, which should be taken into account for the realisation of more reliable designs.*

INTRODUCTION

Low Temperature Co-fired Ceramic (LTCC) technology was established in the 1970s as an alternative to overcome conductivity problems with tungsten metallisation in alumina substrates employed in high temperature co-fired ceramics [1]. The low sintering temperature in LTCCs (i.e. below 950 °C) can be achieved by using a glass matrix with a low melting point, allowing a liquid phase sintering of the glass ceramic composite material [2]. This makes feasible the use of excellent conductors like silver, gold or mixtures of silver–palladium, arranged within and/or on the surfaces of the ceramic substrate, forming complex multi-layered structures. Today, they can be found in devices which have to operate under harsh conditions such as high temperatures and mechanical shock. These applications include engine control units, automatic gear box control units, ABS, etc. As the usage of electronic systems increases over time by the *x*-by-wire technology (e.g. brake-by-wire, steer-by-wire) and because such applications have strong safety implications, it is mandatory to improve the reliability of the ceramic substrates.

Even though ceramic multilayer substrates have been used for more than 20 years, insufficient understanding of the production process and the related mechanical loads causes rejection rates during processing, especially due to the formation of cracks. In this regard, different types of failure of the end component during service have been reported, coming from different regions within the part. Therefore, the understanding of cracking in LTCC components (during processing and/or in service) and the response to crack propagation must be assessed if a reliable design is pursued.

In this work, the fracture response of LTCC components during biaxial bending has been investigated. A fractography study of broken specimens has been performed to determine the mode of fracture of the components and the influence of the internal architectures in the crack propagation.

EXPERIMENTAL PROCEDURE

The specimens used for the biaxial strength tests were cut from commercial LTCC-Tapes (panels of ca. 100 x 100 x 0.43 mm^3), provided by the company EPCOS OHG, Deutschlandsberg, Austria. Rectangular plates of ca. 10 x 10 x 0.43 mm^3 were cut from each panel. The strength of the LTCC specimens (maximum failure stress) was determined using the ball on three balls test [3]. The “as-sintered” rectangular plates were symmetrically supported by three balls at one plane and loaded by a fourth ball in the centre of the opposite plane, as seen in Figure 1. The four balls had a diameter of 8 mm. A pre-load of 7 N was applied to hold the specimen between the four balls. The tests were conducted under displacement control at a rate of 0.5 mm/min (Universal Testing Machine, Zwick Z010, Switzerland), to avoid any slow crack propagation effect [4].

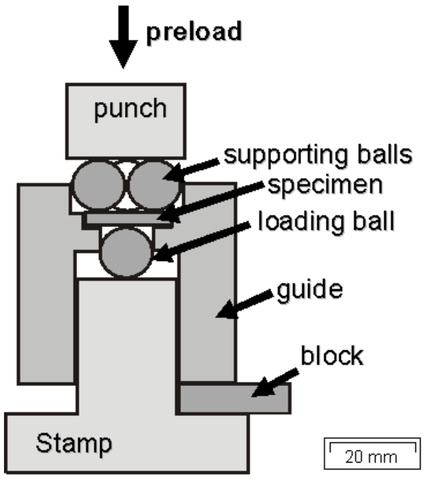


Figure 1. Scheme of a Ball-on-three-balls (B3B) test used for the strength measurements.

The flexural strength was determined from the maximum tensile stress in the specimen during loading, given by:

$$\sigma_{\max} = f \cdot \frac{F}{t^2} = \left[2.58 - 0.67 \cdot \left(\frac{t}{t_0} - 1 \right) \right] \cdot \frac{F}{t^2} \qquad (1)$$

with the maximum load at failure, F, the plate thickness, t, and a dimensionless factor f, which depends on the geometry of the specimen, the Poisson's ratio of the tested material and details of the load transfer from the jig into the specimen [5]. A FEM analysis for this situation, assuming isotropic elastic properties and a Poisson's ratio of $\nu = 0.2$, determined the f factor for this case. The parameter $t_0 = 0.43$ mm is defined as the mean thickness of the plates.

Four samples of 30 LTCC specimens were selected for the strength measurements (i.e. sample 1 to 4). Each sample has the same internal ceramic-metal layered architecture. The difference between them lies on the particular feature to be tested, located at the centre of the potential tensile surface of the plate (e.g. metal pad, ceramic, metal via). A sample of 30 bulk specimens (without metallisation) was also tested for comparison. The results are plotted as a Weibull diagram [6], which gives the nominal characteristic strength σ_0 and the Weibull modulus m. A fractographic analysis was performed for every set using an optical microscope (Olympus Austria GmbH, Vienna, Austria) to identify the mode of failure and the influence of the internal layered architecture on the crack propagation through the LTCC substrate [7, 8]. The load-displacement curves of the B3B tests were also examined for a better understanding of the fracture process.

RESULTS AND DISCUSSION

Figure 2 shows a Weibull diagram of the four LTCC samples and the bulk specimens, where the nominal maximum stress (given by Eq. 1) is represented vs. the probability of failure. The nominal characteristic strength σ_0 (i.e. the stress with a probability of failure of $F = 63.21$ %) is also plotted versus the Weibull modulus, m. It can be observed that all samples follow a Weibull distribution. Among the specimens with metal layers, similar Weibull moduli are obtained, ranging between 9 and 12. However, a very high m value is attained for the bulk specimens ($m = 28$). The nominal characteristic strength varies between 280 MPa and 380 MPa.

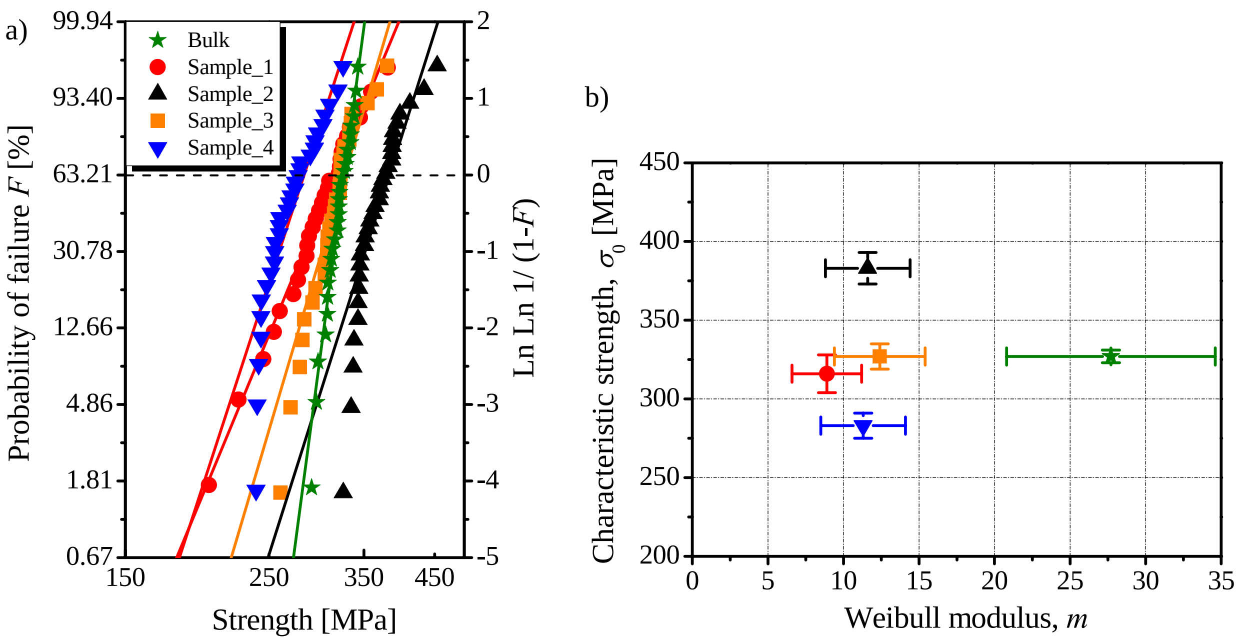


Figure 2. a) Weibull diagram of four LTCC series and bulk material, and b) corresponding characteristic strength, σ_0, plotted vs. the Weibull modulus, m.

The significant difference encountered between the specimens with and without metal architectures might be related to the residual stresses present at the testing surface, associated with the different shrinkage of metal and ceramic parts during cooling down from sintering, since no difference in the defect population could be found.

Some characteristic load-displacement curves of all sets are presented in Fig. 3a. An example of the fractographic analysis is shown in Fig. 3b, where the influence of the internal metal layered structure in the crack path at fracture can be appreciated.

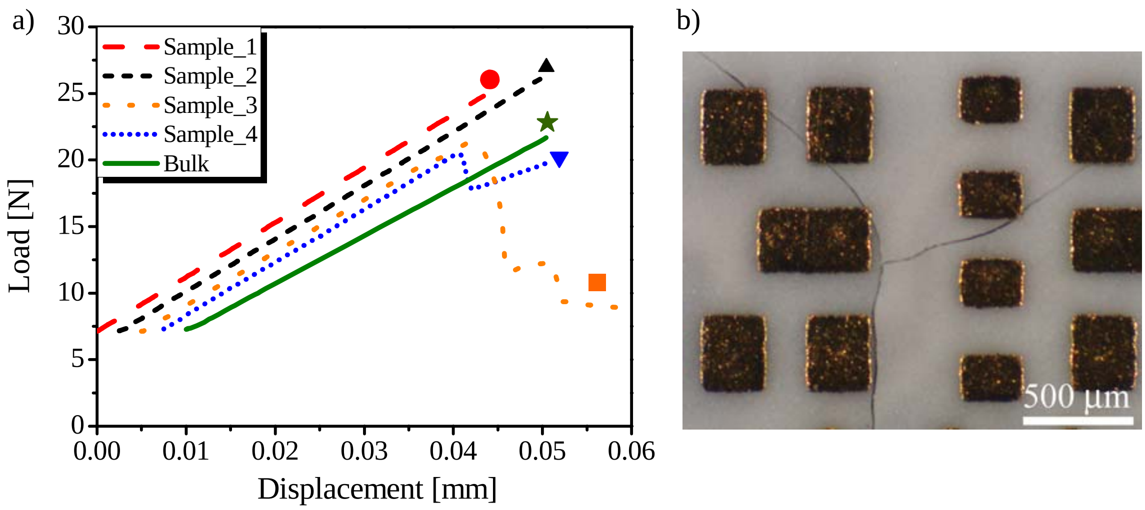
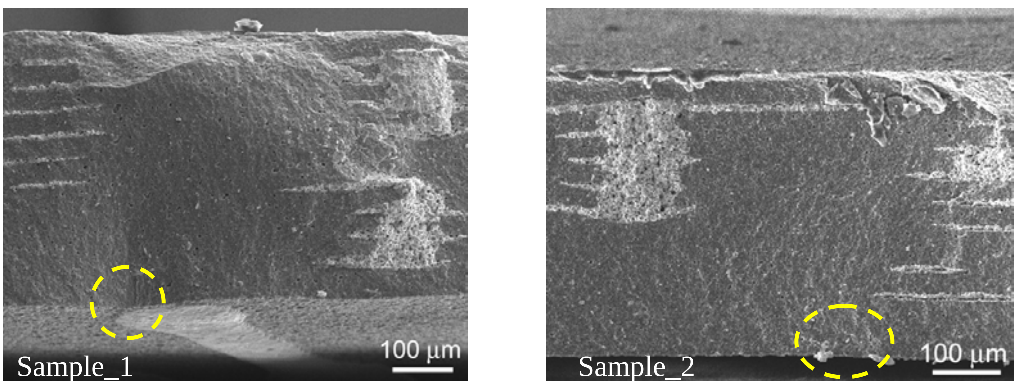


Figure 3. a) Load vs. displacement curves of characteristic specimens of the tested samples, b) typical crack pattern of the tensile surface during biaxial testing showing that the cracks do not run straight like in normal biaxial failure due to the influence of metal layers underneath.

In most cases the fracture origin was found at the surface. The crack propagation out of such defects is associated with the layered structure underneath. When the material under the surface is mainly ceramic (Fig. 4, Sample_1, Sample_2), the crack propagates straight, as it corresponds to the case of fracture of brittle materials (e.g. bulk). On the other hand, it can be inferred from the load-displacement curves (Fig. 3) and the corresponding micrographs (Fig. 4, Sample_3, Sample_4) that the presence of metal layers near the surface favours crack deflection, yielding as a result a step-wise fracture response.



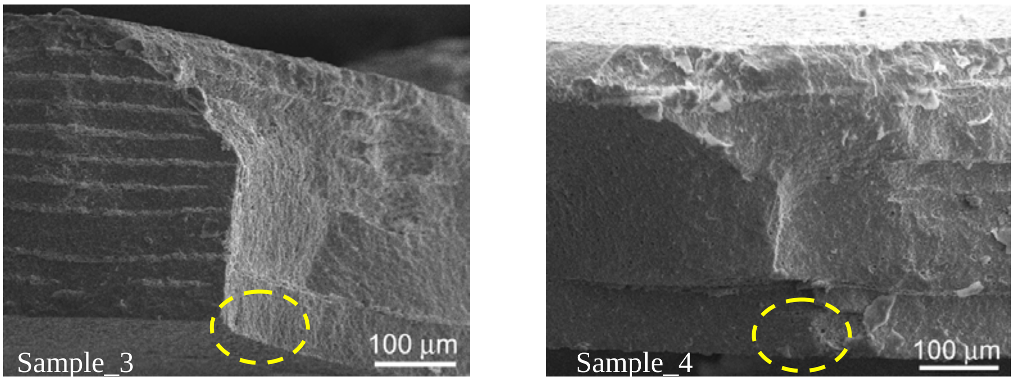


Figure 4. SEM micrographs of the fracture surface of Samples 1 to 4. The tensile surface is placed downwards. The presence of metal layers favours crack deflection and thus step-wise fracture.

CONCLUSIONS

The mechanical response of commercial low temperature co-fired ceramics (LTCCs) has been evaluated using the ball-on-three-balls test. Experimental findings showed that the biaxial strength of LTCCs with internal metal layered architectures is influenced by the surface feature (metal pad, ceramic, via), where the maximal stress is applied during loading. The Weibull modulus ranges between $m = 9$ and 12, which is relative low in comparison with the one obtained for the bulk ceramic ($m = 28$), taken as reference material. A fractographic analysis revealed the source of failure located at the surface. The examination of the fracture surfaces showed a different crack path depending on the inner architecture of the region of maximum stress. While a straight crack pattern was found for bulk ceramics as well as for LTCCs with mainly ceramic content under the tensile surface, a step-wise fracture (load-steps events in the load-displacement curves) could be observed for LTCCs with metallic layers near the surface.

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