Mechanical behaviour of Low Temperature Cofired Ceramics under biaxial loading: Influence of internal architecture on the fracture response

R. Bermejo[1], I. Kraleva[2], F. Aldrian[3], P. Supancic[1,2], R. Morrell[1,4]

[1]Institute for structural and functional ceramics (ISFK), University of Leoben, Leoben, Austria

[2]Materials Center Leoben, Leoben, Austria

[3]EPCOS OHG, Deutschlandsberg, Austria

[4]National Physical Laboratory, Teddington, United Kingdom

Abstract

In this work, the mechanical response of Low Temperature Co-fired Ceramics (LTCCs) has been investigated under biaxial loading using the ball-on-three-balls (B3B) test, aiming to reproduce a possible loading scenario during service. The influence of the internal architectures of the LTCCs on the strength of the component has been assessed in four set of ≈10 × 10 × 0.4 mm^3 specimens with different features located at the centre of the potential tensile surface of the plate (*e.g.* metal pad, ceramic, metal via). Results have been evaluated using Weibull statistics. The crack propagation behaviour during fracture has been examined on broken specimens by means of a fractographic analysis, aiming to determine the mode of fracture of the components and the role of the internal architecture on the crack path. Results have been compared with bulk LTCCs, taken as reference.

Experimental findings showed different strength values between the tested sets and a different crack path during fracture depending on the inner architecture within 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.

Introduction

Low Temperature Co-fired Ceramics (LTCCs) are layered ceramic based components, which may be used as electronic devices (*e.g.* for 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. 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 such as 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. For instance, the electronics for engine and gear management are installed close to the engine and gears, where temperatures up to 150°C and vibration loads of 50 to 100 times acceleration can be encountered in extreme cases. 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.

In many cases, the exposure of LTCC end components to mechanical stresses may yield different types of failure coming from different parts within the component. 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. Therefore, the understanding of cracking in LTCC components and the response to crack propagation must be assessed if a reliable design is pursued. The estimation of the life time of such components is associated with its mechanical strength and crack growth resistance during service. The strength on LTCC components has been determined using the ball-on-ring (BOR) test [3] or the ring-on-ring (ROR) test [4] on bulk specimens showing the effect of the loading rate and environmental conditions on the mechanical strength. The effect of metallization on the strength distribution has also been assessed using simple architectures yielding a difference not only on the strength values but also on the critical flaw size distribution (Weibull modulus) associated with the presence of vias in the design [5].

In order to further investigate the effect of metallization on the strength of LTCCs, the ball-on-three-balls test has been employed in this investigation [6, 7]. The mechanical behaviour of LTCC components during biaxial bending has been investigated analysing special positions within the part, where the internal architecture may differ from place to place. The

Corresponding author: raul.bermejo@unileoben.ac.at

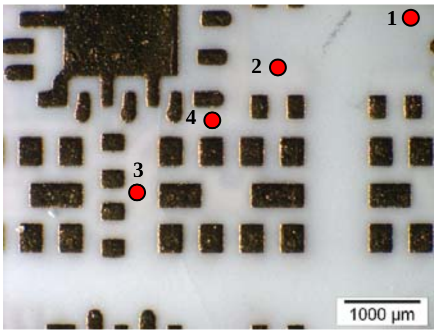
strength has been evaluated using Weibull statistics and a fractography study of broken specimens has been performed to determine the mode of fracture of the components and the influence of the internal architecture on the crack propagation.

Experimental

Material of study

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 testing plates of ca. 10 x 10 x 0.43 mm^3 were cut from each panel (see detail in Fig. 1). The parts were cut in such a way that different locations of the LTCC could be placed in the potential region of maximal stress during testing, thus well defined volumes within the part may be tested. Four series of at least 30 LTCC specimens were selected for the strength measurements (*i.e.* Series 1 to 4). Each series 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 plate (*e.g.* metal pad, glass-ceramic, metal via). An additional series of 30 bulk specimens (without metallisation) was also tested for comparison.

Figure 1. Optical micrograph of a region of the upper side of a commercial LTCC substrate. Strength is evaluated in four different positions.



Mechanical tests: Ball on three balls

The strength of the LTCC specimens (maximum failure stress) was determined using the ball on three balls test [6, 7]. 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 (see Fig. 2). 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 [3]. The flexural strength was determined from the maximum tensile stress in the specimen during loading, given by:

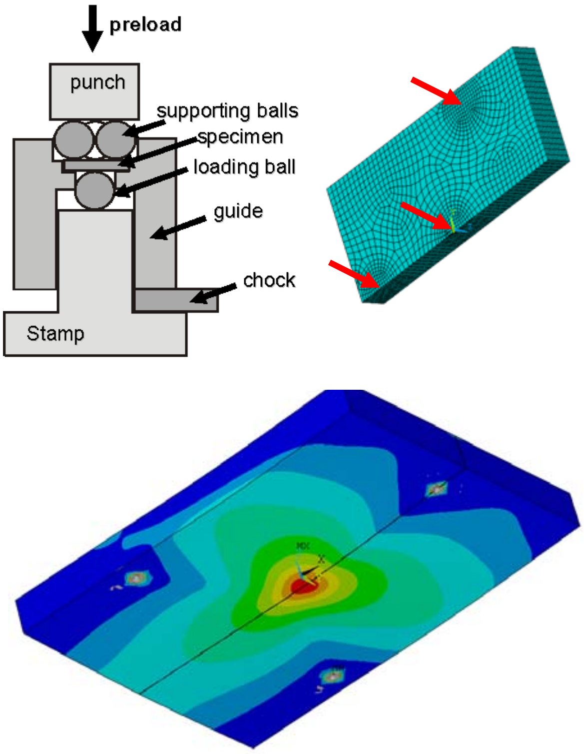
$$\sigma_{\max} = f \cdot \frac{F}{t^2} \qquad (1)$$

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 [8]. A FEM analysis was performed using ANSYS 11.0 for this geometry [9], assuming isotropic elastic properties and a Poisson's ratio of $\nu = 0.2$, in order to determine the f factor, giving as a result [10]:

$$f = 2.58 - 0.67 \cdot \left(\frac{t}{t_0} - 1 \right) \qquad (2)$$

The parameter $t_0 = 0.43$ mm is defined as the mean thickness of the plates. The mesh employed for the numerical analysis and the corresponding stress distribution in the plate during biaxial loading are shown in Fig. 2.

Figure 2. Scheme of the Bal-on-three-balls test for biaxial testing and FE simulation of the stress distribution in the plate during loading.



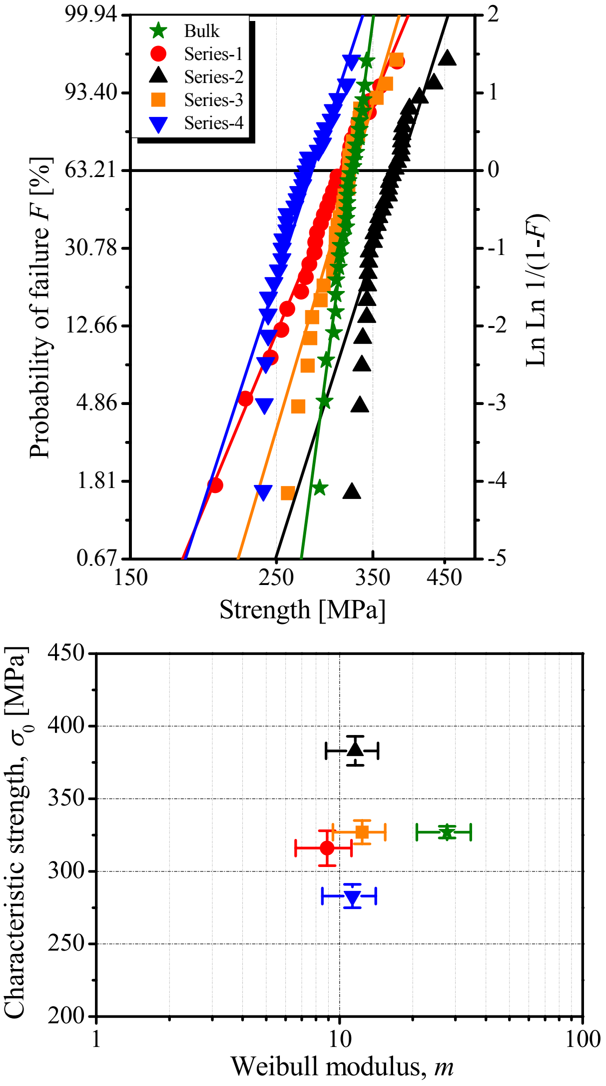
The results are plotted as a Weibull diagram [11], which gives the nominal characteristic strength σ_0 and the Weibull modulus m. A fractographic analysis is also performed using an optical stereo microscope (Olympus SZH10, Austria) for every series to identify the mode of failure and the influence of the internal layered architecture on the crack propagation through the LTCC substrate [12, 13]. The load-displacement curves of the B3B tests were also examined for a better understanding of the fracture process.

Results and discussion

Biaxial strength

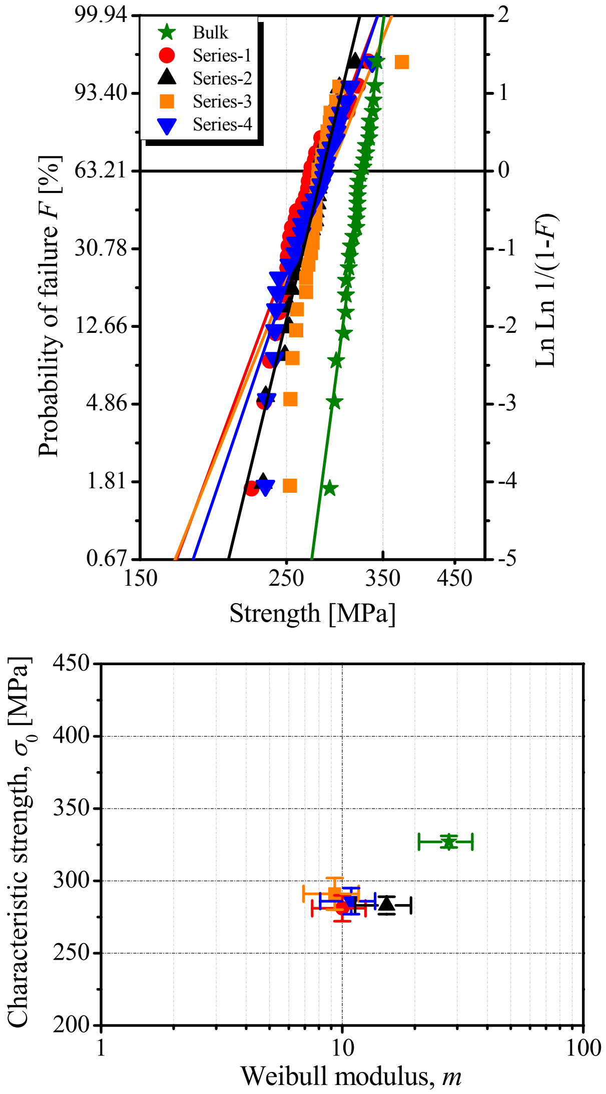
Fig. 3 and Fig. 4 show a Weibull diagram of the four LTCC series, tested with the upper side (shown in Fig. 1) under tension and under compression respectively, where the nominal maximum stress (given by Eq. 1) is represented vs. the probability of failure. The nominal characteristic strength σ_0 (*i.e.* the stress with a probability of failure of $F = 63.21\%$) is also plotted vs. the Weibull modulus, m. The strength results from the bulk specimens are also represented for comparison.

Figure 3. Weibull diagram of four LTCC series (upper side under tension) and bulk material. The characteristic strength, σ_0, is also plotted vs. the Weibull modulus, m.



It can be inferred from the figures that all series follow a Weibull distribution. A statistically difference in the characteristic strength of the components is found between the upper side loaded under tension and under compression, *i.e.* $\sigma_0 = 283 \div 383$ and $\sigma_0 = 281 \div 294$, respectively. It must be highlighted the rather constant strength value for the latter, regardless of the location tested. It is also worthy to point out that, in both cases, the strength values are similar to the characteristic strength of the bulk specimens taken as reference, *i.e.* $\sigma_0 = 327$. Nevertheless, the strength distribution between all LTCC series and the bulk specimens is clearly different, independent whether the upper side was tested under tension (Fig. 3) or under compression (Fig. 4). Regarding the Weibull moduli, a slightly difference could be found between both orientations (upper side under tension/compression), being $m = 8.9 \div 12.4$ and $m = 9.3 \div 15.3$ respectively, which are relative low in comparison with the Weibull modulus obtained for the bulk specimens ($m = 28$).

Figure 4. Weibull diagram of four LTCC series (upper side under compression) and bulk. The characteristic strength, σ_0, is also plotted vs. the Weibull modulus, m.

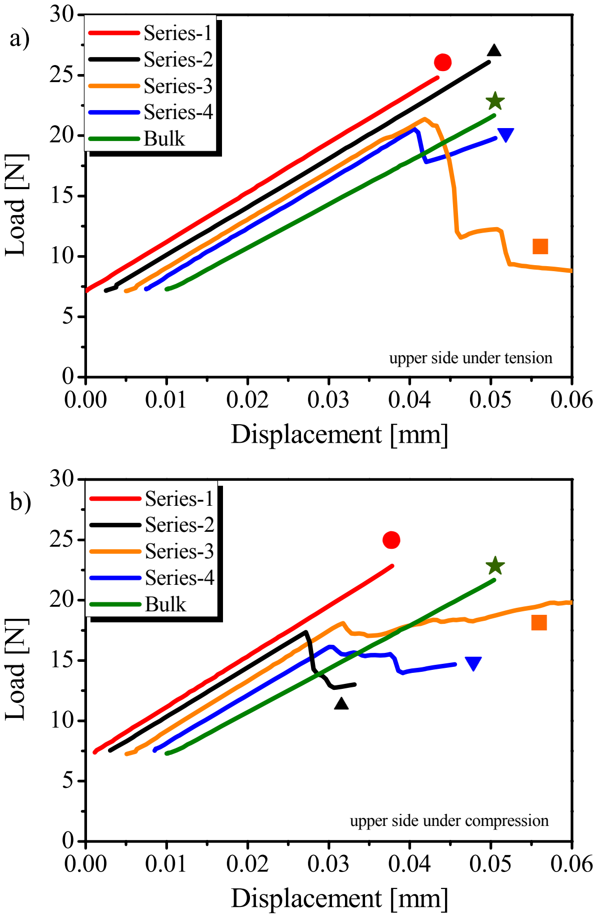


In order to explain the differences between series for the case of upper side under tension (Fig. 3) and the very similar strength distributions for the other case, *i.e.* upper side under compression (Fig. 4), a fractographic analysis is here recalled.

Fractographic analysis of broken specimens

Some characteristic load-displacement curves of all series (1 to 4) for specimens with the upper side either under tension or under compression are presented in Fig. 5a and 5b, respectively. A bulk specimen is also presented for comparison.

Figure 5. Load vs. displacement curves of characteristic specimens of the tested series with upper side under tension (a) and under compression (b).

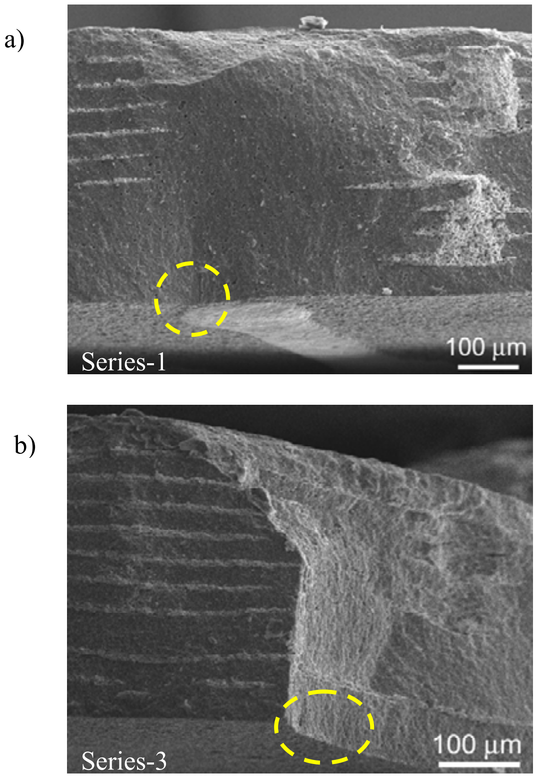


The different load-displacement curves between bulk specimens and certain series (with metal architectures) suggest the effect of such metal layers on the crack propagation through the LTCC. The examination of the fracture surfaces showed a different crack path depending on the inner architecture under the tested region.

An example corresponding to this fractographic analysis is shown in Fig. 6, where the influence of the internal metal layered structure in the crack path at fracture can be appreciated. While a straight crack pattern was found for bulk ceramics as well as for LTCCs with mainly ceramic content under the tested surface (such as in Fig. 6a), a step-wise fracture (load-steps events in the load-displacement curves from Fig. 5) could be observed for LTCCs with metallic layers underneath the surface (as shown in Fig. 6b), which favoured crack deflection.

A fractographic analysis of the broken specimens revealed the source of failure located at the surface under tension. However, the identification of natural flaws (*e.g.* pores, agglomerates, etc.) as fracture origins was in most of the cases not possible. In some cases, the failure origin could be identified at the interface ceramic-vias, most likely associated with stress concentrations, as also reported in literature [5].

Figure 6. SEM micrographs of the fracture surface of two specimens corresponding to series 1 (a) and 3 (b) with the upper side tested under tension. The tensile surface is placed downwards.



Further interpretation of the strength results presented in Figs. 3 and 4 can be then completed with the fractographic observations of the corresponding fracture surfaces of the broken specimens. On the other hand, the four LTCC series which have metal architectures showed Weibull moduli ranging between $m = 9$ and 12 and between $m = 9$ and 15 for the upper side tested under tension and under compression, respectively. In terms of characteristic strength, series 1 corresponds to LTCC specimens with a characteristic strength similar to the bulk specimens (Fig. 3). The architecture under the surface with maximal stress is mainly ceramic (see Fig. 6a). On the other hand, series 3 or 4 have metal layers at a distance of approx. 100µm from the surface. This may lead to the "*banana-shape"* in the Weibull diagram, which is related to the fact that large cracks might be arrested by the first metal layer, thus yielding a unique minimum failure stress value ("threshold stress"), similar to the case encountered on other layered ceramic architectures (see for instance [14-16]). In this regard, the difference between series 4 and 2 could be speculated to be associated with the corresponding distance of the metal layer to the surface of the specimen, thus yielding a different minimum failure stress, as reported in other particular ceramic-ceramic systems [17, 18].

The role of the metal layers on the strength and crack propagation in these materials should be further investigated, in order to design more reliable LTCC components.

Conclusions

The mechanical response of commercial low temperature co-fired ceramics (LTCCs) was assessed using the ball-on-three-balls test, which allowed the evaluation of biaxial strength at specific locations in the component.

The specimens tested with the upper side under tension and under compression showed a statistically difference in the characteristic strength, *i.e.* $\sigma_0 = 283 \div 383$ and $\sigma_0 = 281 \div 294$, respectively, being similar to the characteristic strength of reference bulk specimens, *i.e.* $\sigma_0 = 327$. Regarding the Weibull moduli, a slightly difference could be found between both orientations (upper side under tension/compression), being $m = 8.9 \div 12.4$ and $m = 9.3 \div 15.3$ respectively, which are relative low in comparison with the Weibull modulus obtained for the bulk specimens ($m = 28$).

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.

Acknowledgements

Financial support by the Austrian Federal Government (in particular from the Bundesministerium für Verkehr, Innovation und Technologie and the Bundesministerium für Wirtschaft und Arbeit) and the Styrian Provincial Government, represented by Österreichische Forschungsförderungsgesellschaft mbH and by Steirische Wirtschaftsförderungsgesellschaft mbH, within the research activities of the K2 Competence Centre on “Integrated Research in Materials, Processing and Product Engineering”, operated by the Materials Center Leoben Forschung GmbH in the framework of the Austrian COMET Competence Centre Programme, is gratefully acknowledged.

References

[1] Imanaka, Y., Multilayered low temperature cofired ceramics (LTCC) technology, New York, NY 10013, USA (2005).

[2] Ewsuk, K. G.: Ceramic-filled-glass composite sintering. Ceram. Trans. 15 (1990) 279-295.

[3] Dannheim, H., Schmid, U. & Roosen, A.: Lifetime prediction for mechanically stressed low temperature co-fired ceramics. J. Eur. Ceram. Soc. 24 (2004) 2187–2192.

[4] Tandon, R., Newton, C. S., Monroe, S. L., Glass, S. J. & Roth, C. J.: Sub-Critical Crack Growth Behavior of a Low-Temperature Co-Fired Ceramic. 90 (2007) 1527-1533.

[5] Dannheim, H., Roosen, A. & Schm, U.: Effect of metallization on the lifetime prediction of mechanically stressed low-temperature co-fired ceramics multilayers. J. Am. Ceram. Soc. 88 (2005) 2188–2194.

[6] Danzer, R., Supancic, P. & Harrer, W.: Biaxial Tensile Strength Test for Brittle Rectangular Plates. J. Ceram. Soc. Japan 114 (2006) 1054-1060.

[7] Danzer, R., Harrer, W., Supancic, P., Lube, T., Wang, Z. & Börger, A.: The ball on three balls test – Strength and failure analysis of different materials. J. Eur. Ceram. Soc. 27 (2007) 1481-1485.

[8] Börger, A., Supancic, P. & Danzer, R.: The ball on three balls test for strength testing of brittle discs: stress distribution in the disc. J. Eur. Ceram. Soc. 22 (2002) 1425-1436.

[9] Guide to ANSYS User Programmable Features. ANSYS Release 11.0 (2007).

[10] Bermejo, R., Kraleva, I., Antoni, M., Supancic, P. & Morrell, R.: Influence of internal architectures on the fracture response of LTCC components. Key Engineering Materials 409 (2009) 275-278.

[11] ENV 843-5, Advanced Technical Ceramics - Monolithic Ceramics - Mechanical Tests at Room Temperature - Part 5: Statistical Analysis. 1997, pp. 40.

[12] Morrell, R., Fractography of Brittle Materials. Measurement Good Practice Guide No. 14, Teddigton, UK (1999).

[13] Danzer, R.: Mechanical Failure of Advanced Ceramics: The Value of Fractography. Key Engineering Materials 223 (2002) 1-18.

[14] Lugovy, M., Slyunyayev, V., Subbotin, V., Orlovskaya, N. & Gogotsi, G.: Crack arrest in Si_3N_4-based layered composites with residual stress. Comp Sci Tech 64 (2004) 1947-1957..

[15] Sglavo, V. M., Paternoster, M. & Bertoldi, M.: Tailored residual stresses in high reliability alumina-mullite ceramic laminates. J. Am. Ceram. Soc. 88 (2005) 2826-2832.

[16] Bermejo, R., et al.: Threshold strength evaluation on an Al_2O_3–ZrO_2 multilayered system. J. Eur. Ceram. Soc. 27 (2007) 1443-1448.

[17] Bermejo, R., Torres, Y., Sanchez-Herencia, A. J., Baudín, C., Anglada, M. & Llanes, L.: Residual stresses, strength and toughness of laminates with different layer thickness ratios. Acta Mater. 54 (2006) 4745-4757.

[18] Bermejo, R., Pascual, J., Lube, T. & Danzer, R.: Optimal strength and toughness of Al2O3–ZrO2 laminates designed with external or internal compressive layers. J. Eur. Ceram. Soc. 28 (2008) 1575-1583.