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Fatigue strength testing of LTCC and alumina ceramics bonds*

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In this paper the results of fatigue strength tests of ceramic joints are presented. These tests have been performed on the samples subjected to thermal and vibration fatigue as well as on the reference samples without any additional loads. The main goal of the investigation was to determine the strength of hybrid ceramics joints using tensile testing machine. The experiment enabled evaluation of fatigue effects in the mentioned joints. Geometry of test samples has been designed according to FEM simulations, performed in ANSYS FEM environment. Thermal stress as well as the stress induced by vibrations have been analyzed in the designed model. In the experiments two types of ceramics have been used – LTCC green tape DP951 (DuPont) and alumina ceramic tape. The samples have been prepared by joining two sintered ceramic beams made of different types of material. The bonds have been realized utilizing low temperature glass or a layer of LTCC green tape.

Keywords: *ceramic bonds; reliability testing; LTCC; alumina*

1. Introduction

Thick-film and ceramic technology enable the design of various types of sensor, actuators and other micromechanical devices, *e.g.* pressure sensors [1], force sensors [2, 3], microreactors [4]. LTCC (Low Temperature Co-fired Ceramics) is widely utilized in the mentioned applications. Comparison of the parameters of selected ceramics is presented in Table 1. LTCC is able to work up to approximately 700 °C and has relatively low heat conductivity (3.3 W/m·K), which is an advantage or disadvantage, depending on application. In comparison, alumina ceramics containing 96 % Al_2O_3 has higher heat conductivity (24 W/m·K) and is able to work even up to 1500 °C. Good thermal conductivity or capability of operation at elevated temperatures is required in some devices such as heaters or heatsink. The alumina ceramics has also a high Young modulus, by about three times higher than LTCC. In some micromechanical structures a requirement for a high resonant frequency occurs, which is possible to realize due to the high stiffness of Al_2O_3 ceramics. In HTCC (High Temperature Co-fired Ceramics), *e.g.* based on Al_2O_3, some problems with integration of buried high conductivity metallization arise because of sintering at high temperatures. The mentioned problems could be solved by joining two types of ceramics – LTCC and alumina.

Devices made of ceramic materials ensure high reliability, therefore, the reliability testing is very important in producing various devices using such materials. LTCC reliability testing for electronic applications is described in the literature, including electrical, mechanical and thermal tests [5–7].

In this paper the possibility of bonding of the mentioned two types of ceramics and reliability of the bonds have been analyzed. These materials have different coefficients of thermal expansion (CTE), equal to 5.8 for LTCC and 7.9 ppm·K^{-1} for alumina. The mismatch causes thermal stress during temperature change. The goal of the investigation was the testing of fatigue strength of produced bonds. The design of test structures was assisted by Finite Element Method (FEM) simulations in ANSYS FEM environment. The bonds strength was measured for the samples subjected to thermal and/or vibration

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Table 1. Comparison of LTCC and 96 % Al_2O_3 ceramics parameters.

		LTCC [8]	Al_2O_3 96 % [9]
Bulk density	$kg \cdot m^{-3}$	3100	3720
Thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$	3.3	24
CTE	$ppm \cdot K^{-1}$	5.8	7.9
Dielectric strength	$V \cdot m^{-1}$	15×10^6	14×10^6
Dielectric constant		7.8 @ 3 GHz	9.4 @ 1 MHz
Dielectric loss (tgδ)	$(\times 10^{-4})$	6 @ 3 GHz	4 @ 1 MHz
Flexural strength	MPa	320	350
Young modulus	GPa	120	320
Max operating temp.	°C	700	1500

loads and compared with the results for the samples not subjected to any fatigue tests.

2. Testing procedure

The testing procedure consisted in the measurements of bonds strength using a tensile testing machine for some groups of test samples. Under uniaxial tension, a shear stress in the bonding areas of a sample is induced. It is important to design a fixture which exerts only tensile force, without introducing a bending moment. A measure of the strength of the bonds is a force determined at fracture during the tension test. The test samples have been subjected to mechanical and/or thermal loads to evaluate the fatigue effects and existence of cracks and defects in the bonds. Four groups of samples have been tested:

- Samples not subjected to any fatigue loads – only tensile test – reference samples;
- Samples after thermal loads;
- Samples after vibrations;
- Samples after thermal loads and vibrations.

The thermal loads were applied in a tunnel furnace at the peak temperature of 400 °C, repeated 20 times (Fig. 1).

According to the method 2005.2 described in [10], vibration fatigue testing should be performed under sinusoidal accelerations at a frequency of 60 Hz and peak acceleration equal to 20, 50 or 70 g in all X, Y and Z directions during 32 hours. It corresponds to approximately $7 \cdot 10^6$ vibration cycles. The time of the testing may be shorted by applying vibrations at higher frequency. In case of the

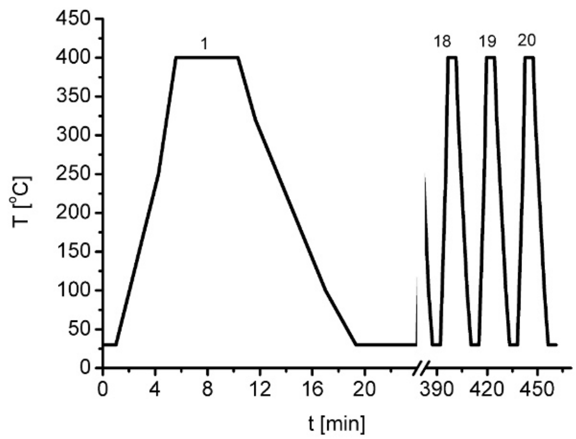


Fig. 1. Thermal cycles applied in the test.

designed test samples, the proper frequency was determined using FEM analyses and set to 400 Hz. Hence, the required number of cycles could be accomplished in 290 minutes. In the experiment, the acceleration only in one direction could be applied because of the designed sample geometry. The acceleration with amplitude of 35 g (24.7 g_{RMS}) was chosen in the tests. The applied mechanical vibrations may be described using Equation (1):

$$A(t) = A_0 \sin(\omega t) \tag{1}$$

where A_0 is vibration amplitude. Corresponding acceleration $a(t)$ is described by Equation (2):

$$a(t) = d^2 \left[A(t)\right] / dt^2 = -A_0 \omega^2 \sin(\omega t) \tag{2}$$

According to (2), the acceleration amplitude can be described by (3):

$$a_{max} = A_0 \omega^2 = A_0 (2\pi f)^2 \tag{3}$$

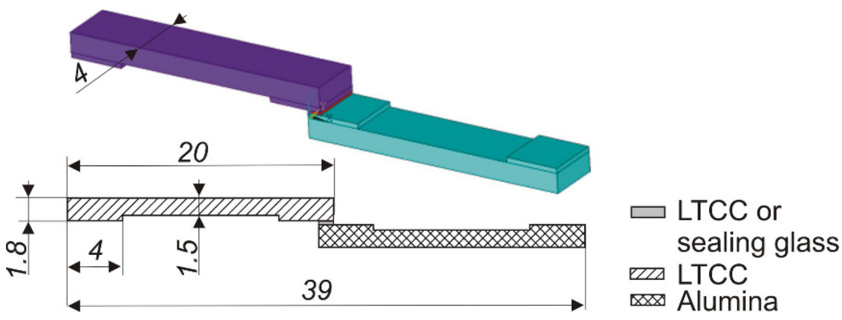


Fig. 2. Test sample geometry.

After simple rearrangement of Equation (3), the required vibration amplitude may be calculated using Equation (4):

$$A_0 = a_{max}/(2\pi f)^2 \tag{4}$$

To obtain the sinusoidal acceleration with the amplitude of 35 g at the frequency of 400 Hz, sinusoidal vibrations with an amplitude of 54 µm should be applied.

3. FEM analysis of test samples

In the design of test samples, technological and testing equipment limitations have been taken into consideration. Test structures consisted of two beams made of various materials, with stepped thickness to facilitate fixing in the tensile testing machine. The view of a test sample model is presented in Fig. 2. The required area of bonding was analyzed using FE modeling. From the point of view of fatigue strength, the bonding areas should be as large as possible – then the strength of the bond is higher than the strength of ceramic material. From the point of view of bond fatigue testing, the fatigue effects proceed faster in smaller bond areas because of the higher stress. In consequence, the smaller the area of joint, the smaller minimal cross-sectional area of beams required to avoid ceramics fracture during tensile strength tests.

A fundamental problem of thermally mismatched materials bonding is the stress caused by temperature changes. In the experiment the bonds were formed at relatively high temperatures. For low temperature sealing glass, the temperature reaches 600 °C and for a layer of LTCC – about 850 °C.

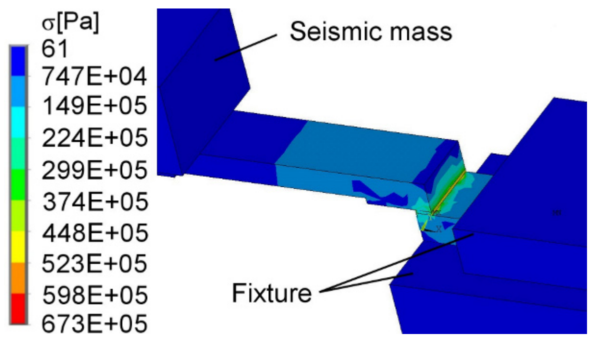


Fig. 3. Simulated stress distribution in the structure bonded using LTCC layer under acceleration equal to 35 g sample with additional 3 g mass (max. 67 MPa).

After cooling down to the room temperature the bonds are highly stressed and a probability of forming cracks and defects occurs. These regions are the sites of expected fatigue effects initiation and the applied thermal and mechanical loads should reveal these fatigue effects. Vibrations should affect the bonds areas inducing a higher stress in these regions than in the ceramic beams. As the stress in the bond areas is too small to introduce fatigue effects, the use of additional mass, fixed on the vibrating beam, was considered (Fig. 3). The comparison of maximal stress versus additional mass for two types of samples is presented in Fig. 4. Assuming a stress at a level of 50 MPa, the masses for the samples with glass and LTCC bonds were determined as 1 and 3 grams, respectively. In the model, a sample is not rigidly attached to the vibrating fixture, but the surfaces of the fixture and the samples are in contact as in the real setup. Therefore, it is possible to evaluate the stress appearance in ceramic beams near

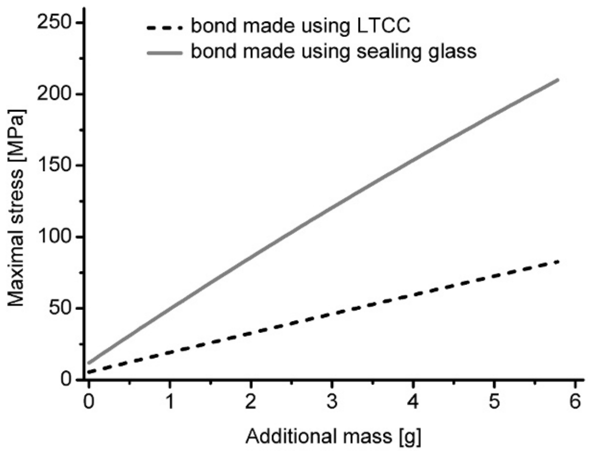


Fig. 4. FEM calculated maximal stress vs. additional mass for the samples under acceleration of 35 *g*.

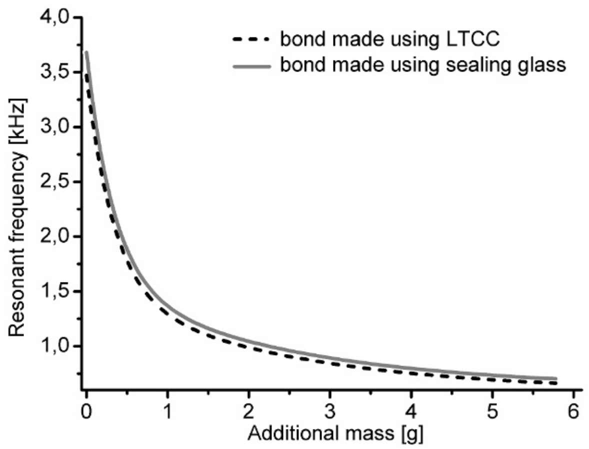


Fig. 5. FEM calculated resonant frequency vs. additional mass for two types of samples.

the fixture when acceleration is applied. It would be impossible in the model where stiff glued fixing is presumed.

The applied vibration test frequency should be lower than the resonant frequency of the samples. The resonant frequencies vs. additional masses for both types of the samples are presented in Fig. 5. For the assumed mass values, the resonant frequencies for LTCC and sealing glass bond samples are approximately 0.8 kHz and 1.3 kHz. The test frequency has been determined as 400 Hz to avoid large amplitude of the vibrations near resonant frequency.

4. Samples preparation

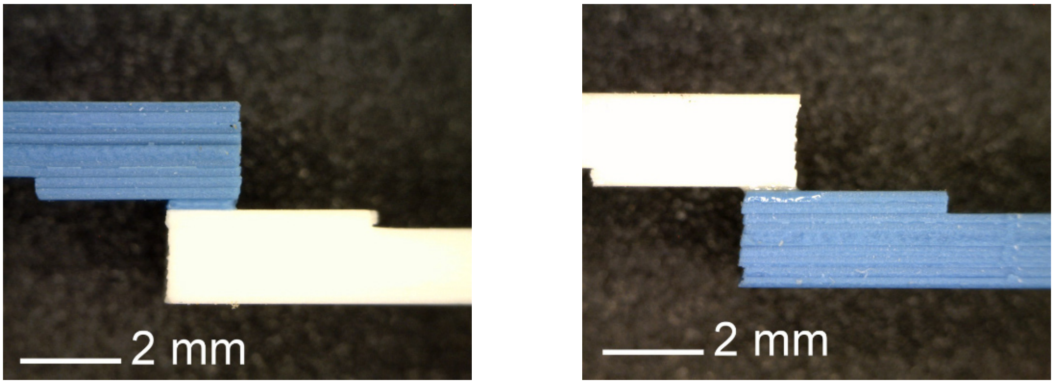
In the experiment, the samples have been made of two types of ceramic tapes – DuPont 951Green Tape™ and alumina tape (96 % Al_2O_3) with unfired thickness of 254 μm and 200 μm respectively. Both materials were machined using laser cutting, stacked and laminated at 70 °C under a pressure of 20 MPa for 10 min. The substrates were separated into beams and fired in proper thermal profiles. The beams have been formed using 9 and 11 layers of material for LTCC and alumina tape respectively. The sintered samples were joined in two ways. For the bonds made using sealing glass, the thick film SG-683K glass composition (Heraeus) was screen printed on the joint areas of both the beams, fired separately, aligned and fired together. The samples joined using LTCC were bonded with a layer of green LTCC tape by a thermo-compressive lamination of properly aligned ceramic beams. The bond areas of both types of the samples are presented in Fig. 6.

For vibration tests, additional masses made of steel were fixed with an epoxy adhesive. The masses dimensions were $5 \times 5 \times 5$ mm^3 and $7.3 \times 7.3 \times 7.3$ mm^3, which corresponds to the masses of 1 g and 3 g respectively.

5. Tests run and results

During vibration test the amplitude has been slowly increased to reach the desired value of acceleration measured with a reference accelerometer. The samples with LTCC bonds have been broken down under acceleration approx. 10 g_{RMS} which corresponds to maximum stress of 27 MPa in the bond region. For these samples, the fractures occurred at the same acceleration level independently whether the samples were subjected to thermal cycling or not. An example of the damaged bond is shown in Fig. 7, where the fracture is visible in the LTCC bonding layer.

The test samples with glass bonds, not subjected to thermal cycling revealed a high strength to vibrations with acceleration of 25 g_{RMS} at 400 kHz. The samples after thermal cycling were damaged at acceleration of approx. 10 g_{RMS}. As it is visible in



(a) (b)

Fig. 6. Bonds formed using (a) a LTCC layer and (b) sealing glass.

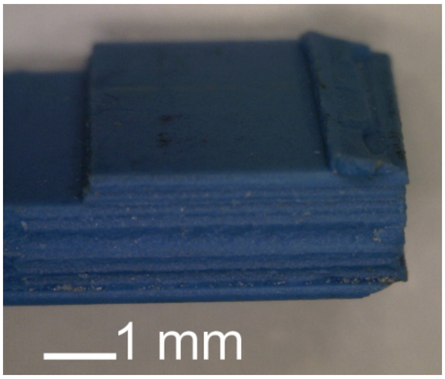


Fig. 7. Fracture in LTCC bond occurred during vibration test.

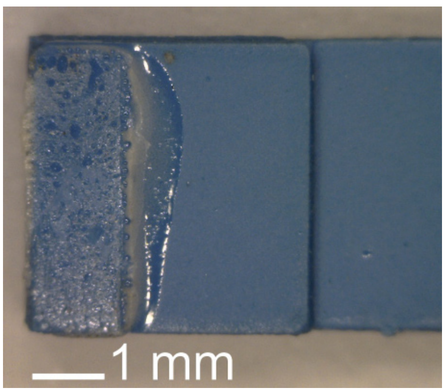


Fig. 8. Heterogeneous structure of glass.

Fig. 8, the structure of the glass contains bubbles and grains, which after thermal cycling reduce the bond strength.

The tensile strength tests revealed higher strength of the bonds than of the LTCC material. During these tests, the fractures occurred in the LTCC beams near the bond region, for both LTCC and glass joints (Fig. 9), no matter weather the sample was subjected to additional tests or not. The fractures occurred at an average force of 75 N $\pm$ 15 N measured with a tensile strength machine, and according to FEM analysis this force corresponds to approx. 160 MPa maximum stress in the bond region (Fig. 10).

6. Conclusions

The tests performed on the bonds of ceramic materials revealed high strength of these joints. In case of LTCC bonds, fractures occurred only in LTCC beams or through the joints layers. The separation between the additional ceramic layer and beams surfaces did never happen and this method of joining could be utilized in further research. The samples joined using low temperature glass had a good strength at assumed 25 g_{RMS} acceleration. Thermal cycling had a significant influence on this type of bonds. The performed tests can be considered as a preliminary research. In further experiments other glass compositions and different temperatures in thermal cycling should be studied. In testing of LTCC bonds, lower stress level should be assumed because of limited strength and brittleness of this material.

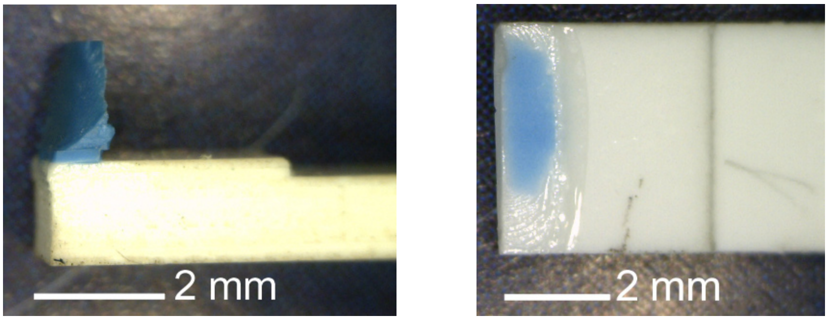


Fig. 9. Samples fractured in uniaxial tensile test for (a) LTCC and (b) glass bond.

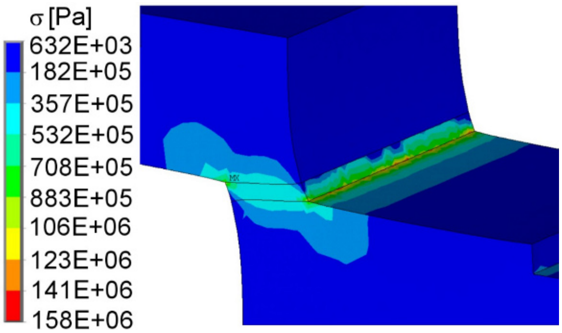


Fig. 10. Simulated stress in LTCC bond under uniaxial tension with force 75 N – (max. stress 158 MPa).

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