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Fracture Toughness (K_{IC}) of Lithography Based Manufactured Alumina Ceramic

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Abstract. Precision shaped ceramic components can be obtained by an emerging technique called Lithography based Ceramic Manufacturing (LCM). A green part is made from a slurry consisting of a ceramic powder in a photocurable binder with addition of dispersant and plasticizer. Components are built in a layer–by-layer way by exposing the desired cross-sections to light. The parts are subsequently sintered to their final density. It is a challenge to produce ceramic component with this method that yield the same mechanical properties in all direction. The fracture toughness (K_{Ic}) of of LCM-alumina (prepared at LITHOZ GmbH, Austria) was tested by using the Single-Edge-V-Notched Beam (SEVNB) method. Notches are made into prismatic bend-bars in all three direction X, Y and Z to recognize the value of fracture toughness of the material in all three directions. The microstructure was revealed with optical microscopy as well as Scanning Electron Microscopy (SEM). The results indicate that the fracture toughness in Y-direction has the highest value (3.10 $MPam^{1/2}$) that is followed by the one in X-direction which is just a bit lower (2.90 $MPam^{1/2}$). The Z-direction is found to have a similar fracture toughness (2.95 $MPam^{1/2}$). This is supported by a homogeneous microstructure showing no hint of the layers used during production.

1. Introduction

Preferably, the production of sintered ceramic component has to be carried out to near-net shape. This is due to the fact that machining is time consuming and expensive (because diamond tools are required). Another problem is that components with complicated geometries are not possible to be manufactured with conventional methods [1]

Components usually are designed by computer aided design (CAD) and it is expected also that ceramic components can be manufactured directly from CAD information. Additive Manufacturing (AM) is a new method that makes it possible to manufacture parts with a complex geometry [2-7] without subsequent machining. Additive manufacturing is a process during which the three dimensional (3D) object is produced by sequential assembly of layers. The information on the layer geometry comes directly from CAD. The AM technology is well established for metal and plastic processing and lately has been successfully introduced for ceramic, especially for customized designs or complex parts [8].

Several technologies for AM ceramics have been developed. At Lithoz GmbH (Vienna, Austria) the Lithography-based Ceramic Manufacturing (LCM) is employed. Alumina is one of the typical ceramic that can be produced by using LCM [9].

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In lithography-based ceramic manufacturing (LCM), the design is prepared for 3D printing. The green parts are manufactured from alumina slurries (commercial Al_2O_3 powders + dispersing agent) by digital light processing (DLP). The dispersing agent contains reactive monomers, solvent, and a photoinitiator. The photoinitiator reacts under LED as an external energy source. The initiator is excited to create radicals that react with the monomers in the mixture. The desired matrix (acrylate monomers) is formed by chain reactions than bind ceramic particles in the desired shape. The process occurs in a short lapse of time. Specific parameters of light intensity and exposure time are chosen. The individual cross section (layer) of the part being manufactured is created by using dynamic masks (digital mirror device) and high performance LEDs as light source. The fabrication of the part is done in layer-by-layer. Fresh slurry is applied for each individual layer in the vat through a dosage system with subsequent vat rotation. The building platform is lowered (around 25 µm) into the slurry, such giving the thickness of one layer in the green body [8].

In this research, the effect of the orientation of the layers on the fracture toughness (K_{IC}) has been investigated by using single-edge V-notch beam fracture toughness test (ISO/FDIS 23146:2008(E) Standard). The microstructure has been revealed and fractographic investigation have been conducted to provide information to be related with the fracture toughness value of the material base on layer orientations [10].

2. Experimental procedure

The material was alumina that was produced through LCM method from Lithoz GmbH (Vienna, Austria). The fracture toughness test samples were prepared by diamond grinding following the schematic shown in Fig. 1. There were 3 types of fracture toughness samples based on the position of the beam with respect to the layers, namely sample-X, sample-Y, and sample-Z. Microstructure observation was conducted at X-direction and Y-direction as can be seen in Fig.1. Optical microscopes as well as scanning electron microscope (SEM) were utilized for the purpose of microstructure observation. The fracture surfaces were investigated by with SEM to be related with the fracture test result.

The V-notching process for fracture toughness test samples was conducted by using a razor blade machine (EXAKT Advanced Technologies GmbH, Germany). The diamond paste was added on the surface of the razor blade. The length of the V-notch was measured by using an optical microscope. The diameter of the tip should was also recorded. Fig. 2 is a typical V-notch that was used for fracture toughness testing in this research.

The K_{IC} tests were performed and the values were calculated based on the ISO/FDIS 23146:2008(E) standard [10] following the schematic in Fig.3 and Equations 1 and 2. The force (F) was applied to the beam specimen with the average initial crack size α until the sample fractured. The value of α was obtained by averaging values of measurement of the initial crack length (a) at 3 different locations on the specimen's fracture surface. The graph of force vs. displacement was recorded to ensure if the material is linear elastic.

$$K_{IC} = \frac{F}{B\sqrt{W}} \cdot \frac{S_1 - S_2}{W} \cdot \frac{3\sqrt{\alpha}}{2(1-\alpha)^{1.5}} \cdot Y^* \quad (1)$$

$$Y^* = 1.9887 - 1.326\alpha - \frac{(3.48 - 0.68\alpha + 1.35\alpha^2)\alpha(1-\alpha)}{(1+\alpha)^2} \quad (2)$$

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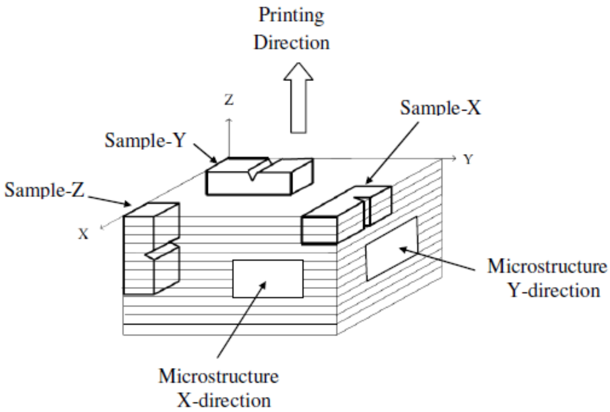

Figure. 1. Schematic of specimen types and micrographs with respect to the printed layers

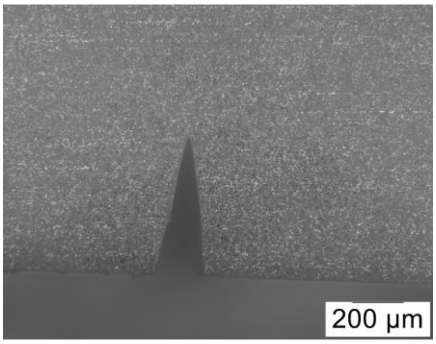

Figure 2. V-Notch for fracture toughness test

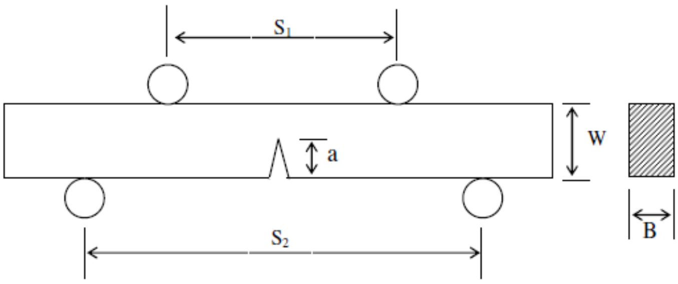

Figure.3 Schematic of four points bending single edge V-notch beam fracture toughness test

3. Result and discussion

The results indicate that the fracture toughness in Y-direction has the highest value (3.10 ± 0.13 $MPam^{1/2}$) that is followed by X-direction which has just a bit lower (2.90 ± 0.11 $MPam^{1/2}$). The Z-direction is found to have a similar fracture toughness (2.95 ± 0.10 $MPam^{1/2}$). It should be noted that the graph of force versus displacement during the fracture toughness tests shows some deviation from the one expected for a linear elastic material (Fig. 4, 5, and 6). Changes in the slope of the curves at low forces may be attributed to alignment of specimen and testing jig and/or settling of the testing jig. No decrease of specimen stiffness with increasing load, which would indicate stable crack growth prior to fast fracture, was observed. Near the point of fracture, all specimens behaved linear elastically.

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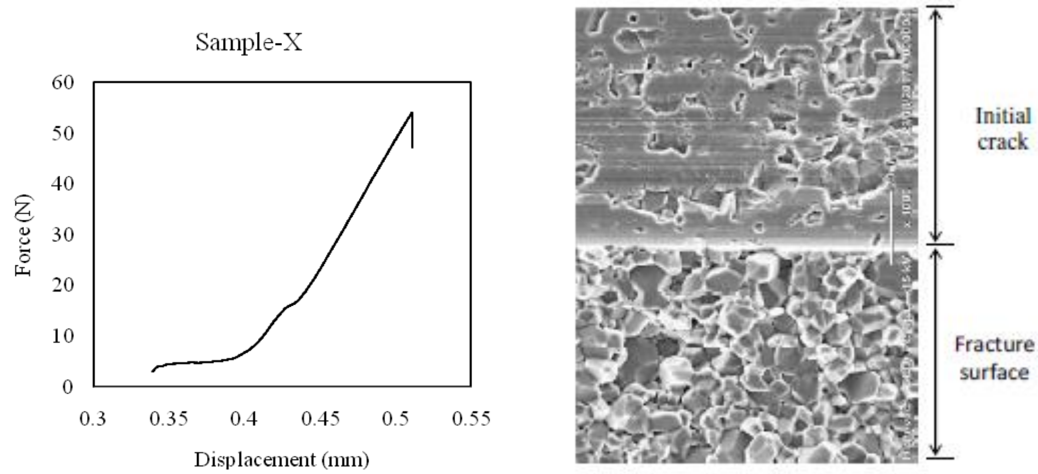


Figure 4. Graph of force vs. displacement for a sample-X to be related with fracture surface

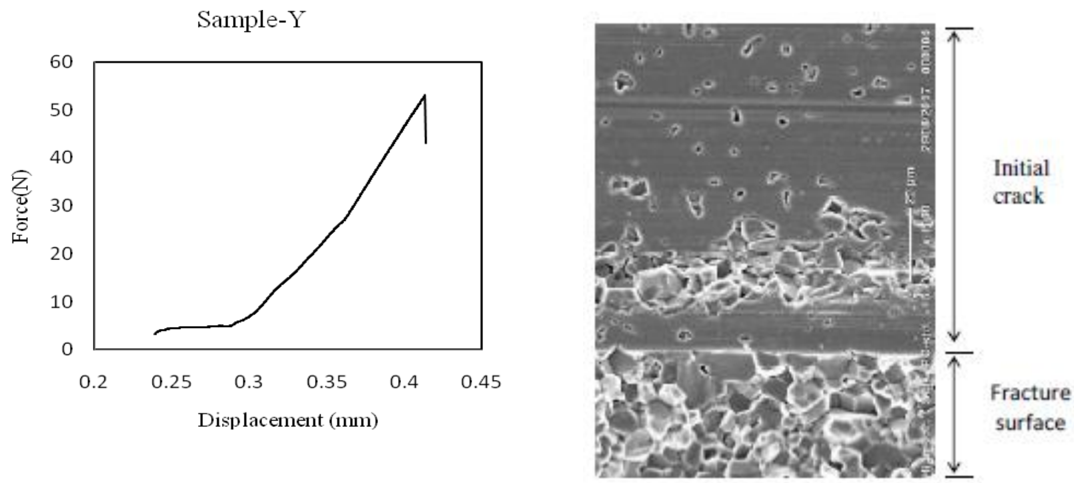


Figure 5. Graph of force vs. displacement for sample-Y to be related with fracture surface

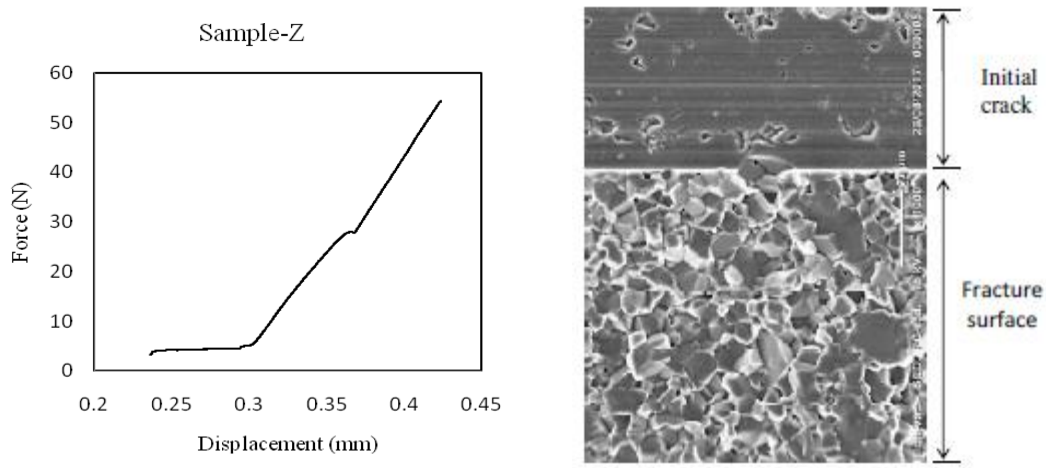
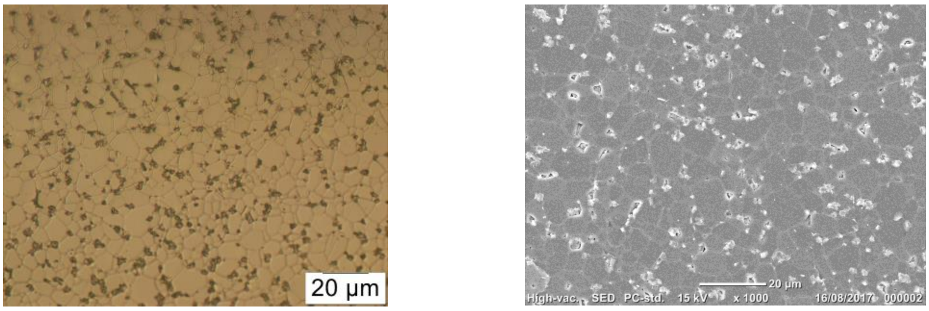


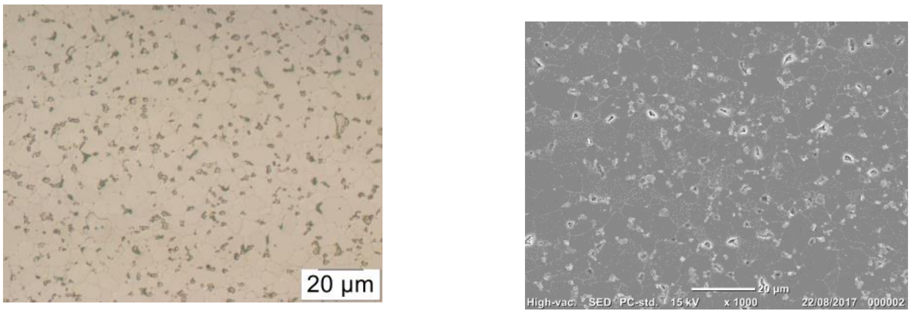
Figure. 6. Graph of force vs. displacement for sample-Z to be related with fracture surface

The results of observations on microstructures are presented in Fig. 7 and Fig. 8. It is found that no indications of the layered structure can be found in X-direction as well as Y-direction. LCM-alumina is produced layer-by-layer and the thickness of each layer is approximately 25 µm [4]. This means that alumina that is produced by the LCM method by Lithoz GmbH can reach a level of homogeneity of the microstructure similar to that of ceramics made by conventional processing methods. Defects like the one shown in Fig. 9 are due to the specific productions route. Reducing the size of such pores or avoiding them generally is a challenge for future developments of the process.



(a) (b)

Figure 7. Microstructure of LCM alumina observed on X-direction. a. Optical microscope, b. SEM micrograph



(a) (b)

Figure 8. Microstructure of LCM Alumina observed on X-direction. a. Optical microscope, b. SEM micrograph

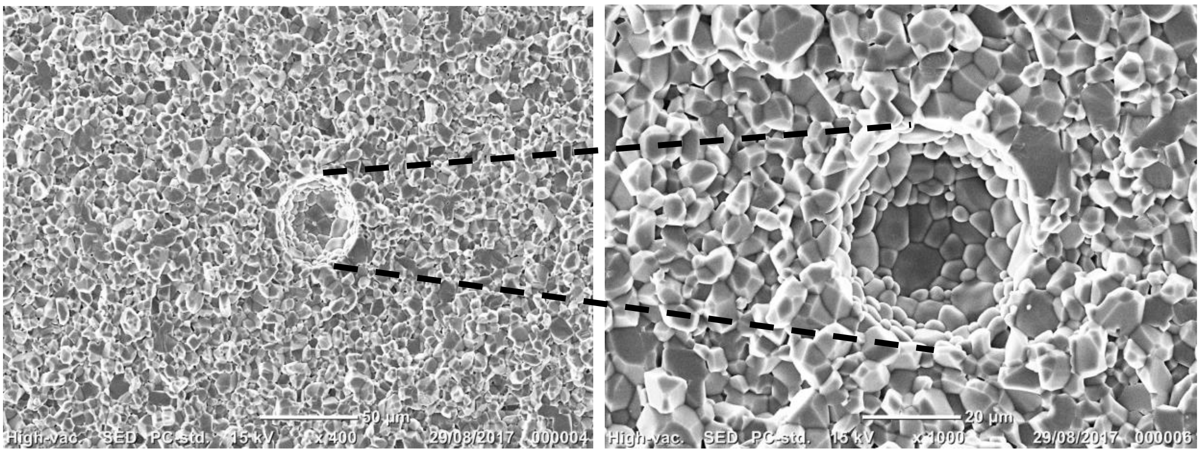


Figure 9. Small spherical defect that is found in the LCM alumina specimen

4. Conclusion

The alumina that is produced by the LCM method by Lithoz GmbH shows a level of microstructural homogeneity similar to the one of ceramics made by conventional processing routes. This is confirmed by the fact that the fracture toughness is approximately 3 $MPam^{1/2}$ in all directions with respect to the layer orientation. This value is in the same range as for conventional fine grained alumina ceramics. For the future work, LCM method will be introduced to other types of advance ceramics.

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