euspen's 15th International Conference &
Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Near-net-shape production of sub-mm structures in green/white state porcelain ceramics

Manuel Stompe and Lutz Rissing

Institute for Micro Production Technology, Garbsen, Germany

stompe@impt.uni-hannover.de

Abstract
Manufacturing of ceramic based parts is the main challenge for future application in MEMS for automotive, medicine and mobile technology. To benefit from their superior properties like mechanical strength, high temperature and chemical resistance, high precision and low-cost processes are required.

Keywords: Near-Net-Shape; porcelain ceramics; Dicing; green state machining

1. Introduction

The requirements for an effective ceramic processing are high throughput, low tool wear, simple processing and a maximum material removal rate. Several techniques are used to manufacture near-net-shape ceramics like electrophoretic deposition, displacive compensation of porosity (DCP), selective laser curing, gel casting and 3-D printing. Common ceramics have to undergo a heat treatment to reach their final material properties. For all technologies the geometry is generated during the green or white state of the ceramic. In this state, the hardness is very low and the geometry can be easily manufactured. Most of these processes are accompanied with shrinkage during the heat treatment. The range of this linear one-dimensional shrinkage can vary from 2 % up to 20 % [1-6]. Some technologies can generate near-net-shape structures with reduced mechanical properties [3]. The linear shrinkage is also not constant in the three spatial directions. Material composition, temperature field, geometry and heating conditions can influence the final shrinkage of each work piece [7]. The advanced ceramic used in this work is classified as clay based glass ceramic. The major advantage of this material is the low linear increase <2 % [8]. In some clay based materials like pyrophyllite, the fire clay volume increases during the heat treatment balances the shrinkage and causes a low linear one axis volume increase [9].

2. Experimental Setup

The experiments are done on an ultra-precision dicing machining with a metal bonded dicing wheel. Figure 1 shows the dicing principle and the setup for this experiment.

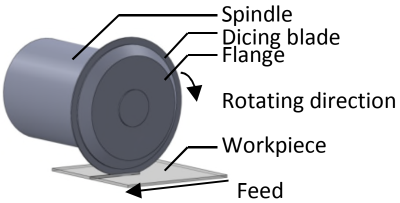


Figure 1. Dicing setup and principle

A nickel-bonded dicing blade with a grit size of 9 µm is selected based on prior studies.
The measurements for structure precision is done with a confocal laser scanning microscope (CLSM, figure 2a) and a high precision scale with 1/1 000 g resolution (figure 2b).

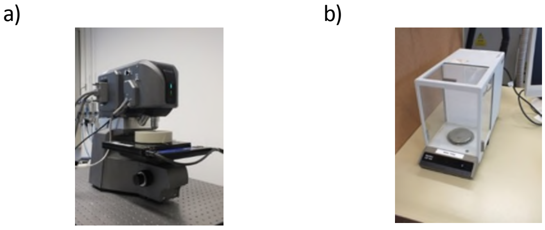
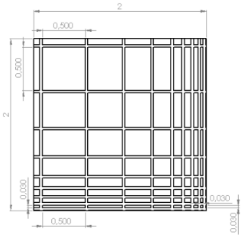


Figure 2. Measurement setup a) CLSM and b) scale

The diced array for structure analysis is shown in figure 3 a) and the separation for aspect ratio analysis is shown in figure 3 b). The cutting depth is gradually increased from 0.25 mm, 0.5 mm, 0.75 mm to 1 mm.

a)



b)
0.5 mm, area 0.25 mm²
0.4 mm, area 0.16 mm²
0.3 mm, area 0.09 mm²
0,2 mm, area 0.04 mm²
0.1 mm, area 0.01 mm²
0.075 mm, area 0.0056 mm²
0.05 mm, area 0.0025 mm²
0.03 mm, area 0.009 mm²

Figure 3. a) Dicing array with separation steps b)

The array is diced in pyrophyllite with different stages of sintering. First stage is unsintered (0h), early drying (6h), advanced drying (10h) and completely dried (14h). These stages offer a low hardness of <500 MPa and an easy machining process, however, in these stages the material is very soft and brittle. It tends to change its mass and volume, causing inner stress after final sintering.

3. Results

The main mass-change and linear volume increase during the final sinter stage (20h) is shown in table 1.

Table 1. Mass and volume change during drying

Time \h	mass change \%	l. volume change \%
0h→20h	7	1.8
6h→20h	4	1.5
10h→20h	2	1
14h→20h	<1	<0.6

Figure 4 shows the results for dicing the array in different drying states plotted against the geometry deviation before and after sintering. 100 % is the ideal geometry.

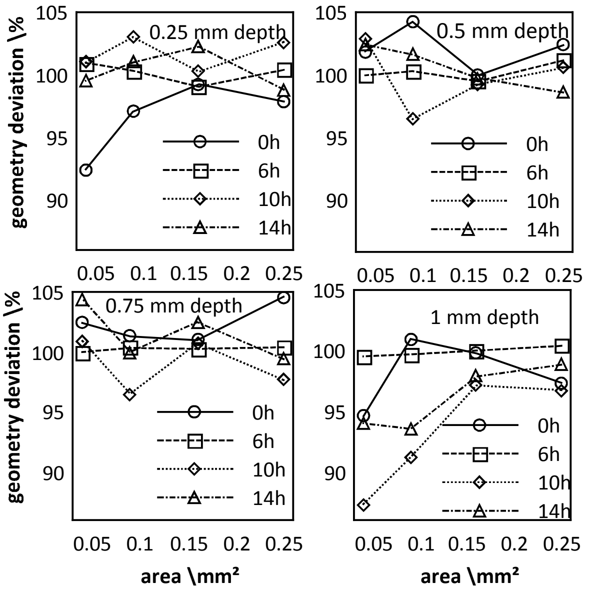


Figure 4. Geometry deviation for different cutting depths

The unprocessed state 0h shows a high deviation from the initial pattern. The 6h dried stage shows with increasing cutting depth a low deviation before and after sintering.

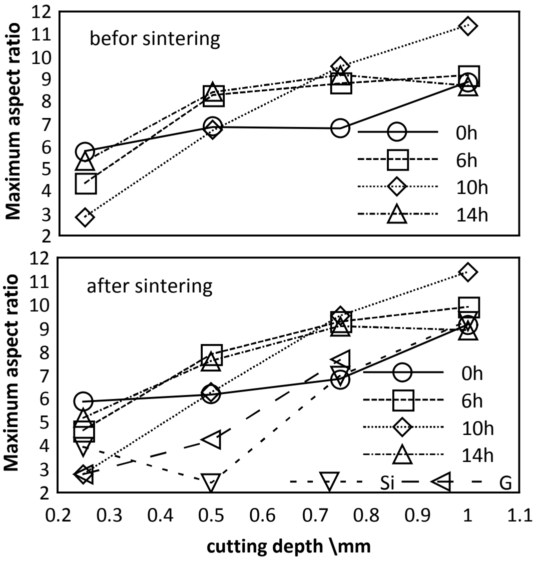


Figure 5. Maximum aspect ratio before and after sintering

In figure 5, the maximum array aspect ratio before and after sintering is shown. The maximum ratio for 10h dried samples is about 1:3-1:11.5. The other stages range from 5-9. With increased cutting depth, the stability of the structures increases because of a better guiding of the dicing blade in the cutting kerf, restricted by the brittleness of the material. In sintered state, silicon (Si) and glass (G) are diced the same way with considerably lower ratios. The area of the smallest diced square is 0.04 mm² and the largest 0.25 mm². A large front side chipping of silicon and glass could be observed during dicing, but nearly none for pyrophyllite.

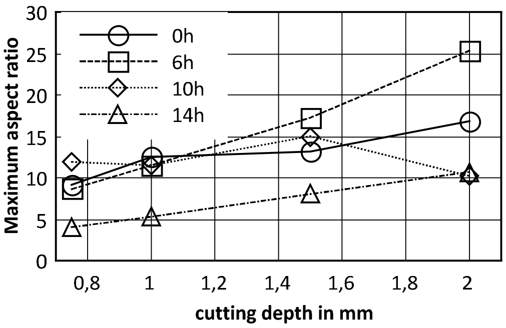


Figure 6. Highest aspect ratio for green/white state pyrophyllite

The highest aspect ratio 1:25 (fig. 6) can be reached for 6h dried pyrophyllite, 5 µm diamond grid and feed < 0.5 mm/s.

4. Conclusion

This work shows the manufacturing potential of pyrophyllite because of its linear increase during sintering of microstructures compared to other substrates like Al_2O_3, HTCC or glass. Prior studies [10] showed the potential for high productive and ultra-precision manufacturing of pyrophyllite in green and white states. The structures were diced in an unsintered state by a Disco dicing saw. Structures down to 30 µm and aspect ratios up to 1:25 were manufactured. A linear increase of 0.5-1.8 % was measured. The processing in the white states (6h, 10h and 14h) generated near-net-shape structures with shape deviations lower than 0.5 %. These near-net-shape processing allows a structuring in a green/white state without post-processing and without to scale down expectations in the final material properties.

Future investigation will concentrate on alternative machining processes because of the predictable low increase and detailed wear measurements for micro structures in unsintered ceramics. The next steps are, to adapt this material for vertical interconnections and low cost substrate for thin film processes.

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