Characterization and model-based design validation of 3-D printed cookies

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Abstract
Additive manufacturing is revolutionizing processing in many applications including 3-D food printing. A Fused Deposition Modelling printing method was developed to produce cookies. In order to design food of particular texture, a fine element model was established to predict the mechanical properties of structured products. Cookie structures were engineered to achieve desirable texture properties in silico and dedicated print files were created for 3-D printing. In order to validate the model, the properties of the printed cookies were measured and analysed. Compression tests were performed to determine Young’s modulus. X-ray micro-CT imaging was applied to characterize the 3-D microstructure of the printed cookies samples. Micro-CT imaging provided a better understanding about the effects of the 3-D printing process on cookie structure. Finally, a better fit of the prediction model was obtained by adjusting the model geometry to the scanned printed structure, which indicates the importance of structure integrity for mechanical properties of printed cookies.

Keywords: Structure; 3D food printing; Cookies; Texture; Micro-CT

1 Structure design and 3-D printing
Based on a previous study focused on the relation between the microstructure and texture of cookies, we developed finite element models of mechanical deformation of honeycomb and Kelvin structures to investigate how structural parameters such as cell size, wall thickness and porosity affect the elastic properties of cookies. From this model, an inverse linear relationship was found between the porosity and the effective Young’s modulus of the structures, regardless of wall thickness and cell size as shown in Figure 1 [1].

Print files were generated corresponding to four honeycomb and two Kelvin structures with varying cell size and wall thickness. Those structures were successfully 3-D printed based on the Fused Deposition Modelling (FDM) of cookie dough followed by a traditional baking process.

![Graph showing Young’s modulus (E) of cookies with honeycomb structure and different porosity, wall thickness and cell size: Comparison between the prediction model using the designed and actual cookie structure.](image)

Figure 1 Young’s modulus (E) of cookies with honeycomb structure and different porosity, wall thickness and cell size: Comparison between the prediction model using the designed and actual cookie structure.
2 Characterization of printed cookies

Micro-CT scans were conducted on the entire samples at 17 µm and power voltage of 60 or 100 kV. As represented on Figure 2, 3-D images of cookies were binarized by automatic thresholding using the Otsu method to separate the pores from the material matrix. Then speckles were removed using despeckle and morphological treatments. Those treatments cleaned the binary data without removing the dough porosity of the cookies. A first 3D analysis was performed on the resulting binary data to characterize the microstructure. Then, the data were cleaned again by using a closing operation of larger magnitude in order to remove the dough porosity and only keep the macrostructure induced by the 3D printing. The second 3D analysis was performed in order to compare the actual printed structure to the print file. Then, 3D models were generated which were used as the geometry for the prediction model.

![Picture of printed cookies](image)

Figure 2 Examples of printed cookies having honeycomb and Kelvin structure scanned by micro-CT.

3 Validation of the prediction model Chapter

Compression tests were performed with a maximal strain of 5%. The engineering Young’s modulus was determined from the slope of the linear part of the stress-strain curves of the compression. The measurements were compared to the simulations of the designed structures as well as of the scanned structures. Figure 1 includes (i) the linear relationship between the porosity and Young’s modulus predicted by the model by considering the engineered structure in blue, (ii) the measurements of printed cookies having 3 different honeycomb structures in red and (iii) the validation performed by using the actual cookie structure obtained by tomography in green. The comparison between the measurements and the circled prediction shows divergence due to the deviation of the printed and designed structure. This deviation is due to the spreading of the cookie dough during printing that induces change in wall thickness and cell size. By considering the actual structure, the model fits significantly for two structures. The third structure which is more open, still deviates from the validation experiment. This observation is probably due to experimental variations that were not considered by the model. These variations included the dough porosity influenced by the FDM printing, cracks induced by baking process or moisture content influencing the Young’s modulus of the cookie material [2]. The implementation of these effects into the model should be considered for future improvements.

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References
