# Simulation of the Mechanical Stability of Inkjet-Printed Hierarchical Microsieves

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**Abstract:** Porous membranes with pore sizes on the micrometer scale are required in many micro systems dedicated to biological and chemical applications [1, 2]. If their thickness is in the same dimension as the pore diameter they are called microsieves [3]. On one hand the low thickness of the membrane guarantees a small flow resistance for the medium to be filtered but on the other hand its mechanical stability is reduced. A process was developed which allows the preparation of micosieves by inkjet printing [4]. The advantage of this method is the individual positioning of each single pore in a polymer microsieve. Though, a hierarchical arrangement of the pores in the microsieve is possible.

The goal of the presented simulation was to find a compromise between high mechanical strength and high permeability of the microsieve. Various pore arrangements were implemented and their mechanical stability was simulated. By help of a 2D model, the mechanical stability was tested by applying a tensile stress onto the membrane.

**Keywords:** Inkjet printing, microsieve

## 1 Introduction

Inkjet printing is a feasible tool for positioning tiny volumes of liquids precisely and quickly onto a substrate. It has become a common tool for many technical applications beyond graphical purposes.

If the printed liquids comprise nonvolatile solids or can be solidified, then inkjet printing can be used for manufacturing planar as well as 3D structures [4, 5, 6]. Microsieves, which are porous membranes with a thickness smaller or in the same dimension as the pore diameter [3], are required in many micro systems dedicated to biological and chemical applications [1, 2]. Beside MEMS technologies, extrusion processes, etc., inkjet printing offers an interesting and efficient way to manufacture polymer microsieves as well. In Figure 1, the inkjet fabrication process for polymer microsieves is depicted. The intermediate deposition of sacrificial material by inkjet printing is used for the creation of the microsieve's pores. Sessile drops of a water-based liquid are deposited onto a hydrophobic solid support and covered with a thin liquid layer of a polymer solution. The liquid layer solidifies by the evaporation of the solvent, and the sessile drops imprint their shape into it, acting as templates for the creation of pores. Finally, the polymer layer is separated from the substrate, and a freely suspended polymer microsieve is obtained.

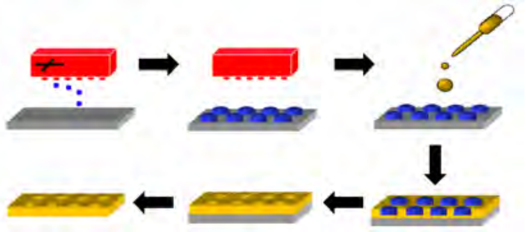

Figure 1: Inkjet fabrication method for polymer microsieves.

Figure 2 shows two typical pores with their spherical shape imprinted by the drops. The pore shape can be regarded as a spherical cap and, depending on the drop volume $V$, the drop's contact angle $\Theta$ and the final thickness of the polymer membrane $h_p$, the drop heigth $h$ and the resulting pore diameter $d$ can be calculated [4]:

$$h = \sqrt[3]{\frac{3V}{\pi(\frac{3}{1-\cos\Theta} - 1)}} \qquad (1)$$

$$d = 2 \cdot \sqrt{(\frac{h}{1-\cos\Theta})^2 - (\frac{h}{1-\cos\Theta} - h + h_p)^2} \quad (2)$$

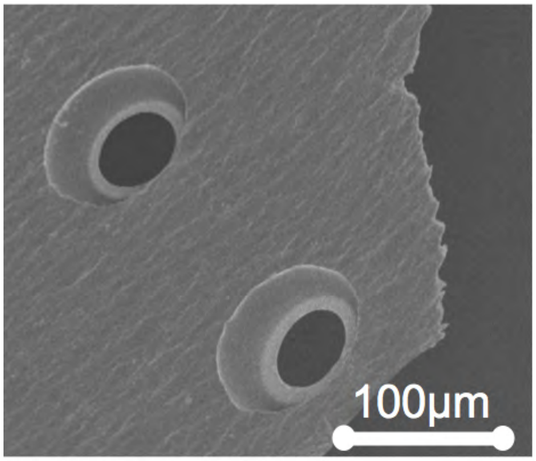

Figure 2: Pores in an inkjet-fabricated microsieve (Scanning Electron Microscopy image, taken from the bottom side of the membrane).

A big advantage of the inkjet process is the possibility to arrange every single pore on a predefined position. This gives the opportunity to overcome a big issue in microsieve fabrication: their mechanical fragility. On one hand a thin membrane — which is characteristic for a microsieve — guarantees a small flow resistance for the medium to be filtered but on the other hand it reduces its mechanical stability. The inkjet process allows to setup porous and non-porous zones in the membrane which creates functional areas for the filtering process and mechanically supporting areas which enhance the mechanical stability of the microsieve. The calculation of the impact of that enhancement was done with a FEM implementation in COMSOL Multiphysics.

## 2 FEM Implementation

COMSOL's "Plane Stress" application mode was used for the investigations under static conditions. A membrane size of $2 \times 6\,\text{mm}^2$ was chosen as a compromise between having as many pores as possible and an acceptable computing time. The microsieve's thickness was set to 11 µm, the isotropic material settings of PMMA were applied. As basis for calculation of the pore size a typical inkjet drop volume of 110 pl was taken. With a contact angle of 75° a pore diameter ranging from 85 µm on the bottom to 76 µm on the top side of the microsieve is created. In the 2D model, this spherical pore shape was reduced to cylinders with a diameter of 80 µm. Regarding an 11 µm membrane thickness this results in the same pore volume as in the 3D calculation. To simulate a tensile test, the left boundary of the membrane was fixed and the right one was loaded with 20 MPa (Figure 3).

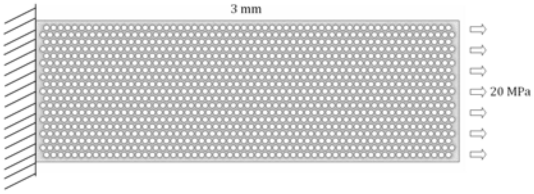

Figure 3: Geometry, mesh and boundary conditions of the 2D model.

As parameter different pore arrangements were selected. With a distance of 100 µm the pores were distributed uniformly (93 pores per mm$^2$), in hexagons of 14 pores each (61 pores per mm$^2$), and in squares consisting of 8 pores each (49 pores per mm$^2$). To evaluate the impact of the pore arrangement, homogenous pore distributions with equivalent pore counts for the hexagonal and squared arrangement were created. In addition, a membrane without pores was simulated as reference.

The mesh was generated using the automatic mesh creator with the "normal" option for mesh size. Depending on the number of pores the FEM mesh consists of 3,008 to 172,316 triangular elements.

## 3 Results and Discussion

Figure 4a shows the von Mises stress and strain behavior of the microsieve fully covered with pores. In the pore area the stress ranges between 0 and 158 MPa whereas the maximum stress is located at the boarders of the pores laying in the flow of forces (Figure 4b). The area between the pores in x direction is nearly unaffected by the force. As result from the stress, the membrane elongates by 131 µm in average (Figure 4c).

For creating the hexagonal and squared pore patterns, certain pores were omitted in the last-mentioned pattern. In relation to the dense-packed pore arrangement the hexagonal pattern has 66 % of the pores and the squared pattern 53 %. Figure 5 shows the results of these simulations.

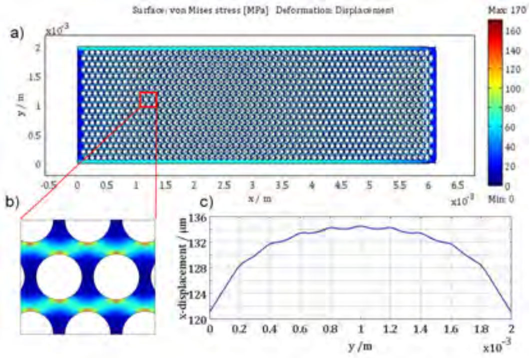

Figure 4: a, b) Von Mises stress and deformation of a polymer microsieve fully covered with pores and c) x-displacement of the right edge of the microsieve.

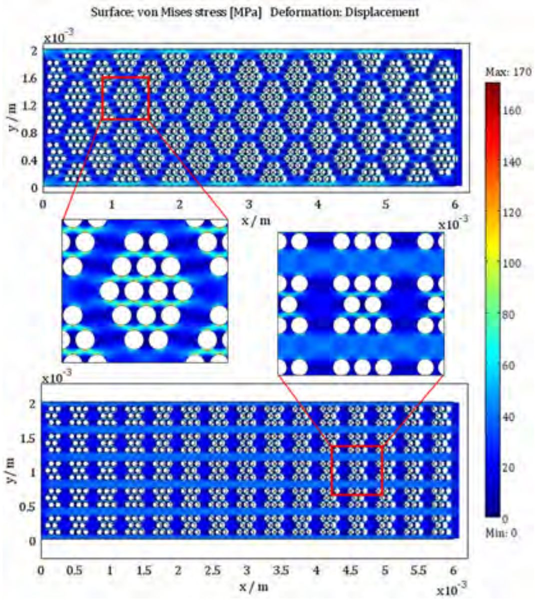

Figure 5: Von Mises stress and deformation of hierarchical pore arrangements (hexagonal and squared) in the microsieve.

It is clearly visible that less stress is induced into the material. The non-pore areas strengthen the microsieve. This is also reflected by the strain of the sieves. The microsieve fully covered with pores elongates by 2.18 %, the microsieve with the hexagonal arrangement by 1.68 %, and the squared one only by 1.24 %. But this improvement is gained at the expense of the permeability. To investigate the impact of the pore arrangement microsieves with uniformly distributed pores were simulated which consist of the same pore count per area like the hexagonal and squared arrangements (Figure 6).

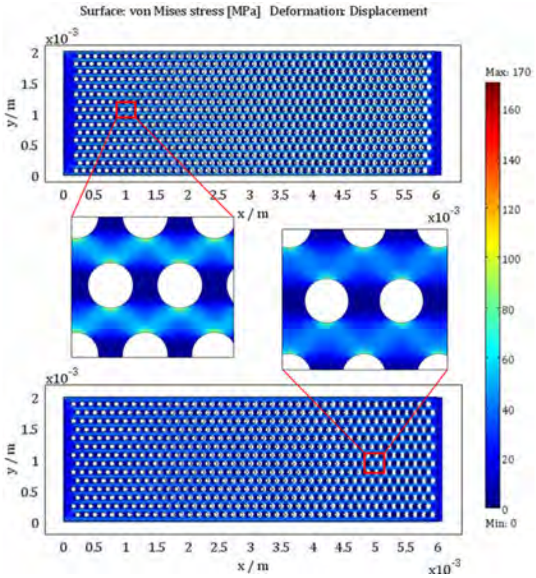

Figure 6: Von Mises stress and deformation of uniform pore arrangements in the microsieve.

The mechanical strength, judged by the strain values, improved slightly in comparison to the hierarchical structures. The membrane stuffed with 66 % pores elongates by 1.46 %, and 1.24 % for the equivalent pore count to the squared arrangement.

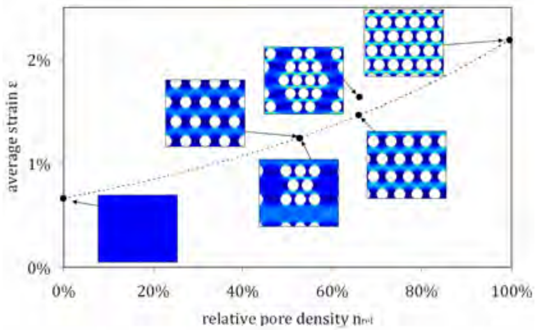

Figure 7: Average strain at 20 MPa load in dependence on relative pore density (100 % = 93 pores per mm$^2$) with the according pore patterns (detail size ca. 0.45 × 0.55 mm$^2$) and an exponential trendline for the homogenously distributed patterns.

Figure 7 shows the average strain plotted over the relative pore density. The embedded images visualize the according pore arrangements. As reference, a membrane without pores was simulated. The main effect of strain increase, i. e. decrease of mechanical stability, is obviously the realtive pore density. The influence of pore arrangement is small and tends to be negligible or directed to a decline of mechanical stability. For the squared pore pattern and its equivalent homogenous pore distribution, no difference in strain could be observed. However, the hexagonal arrangement shows a slight increase in average strain which indicates a decline in mechanical strength. The strain values $\epsilon$ for the homogenous distributions are fitted perfectly ($R^2 = 1$) by an exponential curve (dotted line in Figure 7):

$$\epsilon = \frac{\sigma}{E} \exp(1.2 n_{rel}) \tag{3}$$

where $\sigma$ is the applied stress of 20 MPa and E is the elastic modulus of PMMA (3,000 MPa).

For the tested pore patterns, it can be concluded that the more homogenous the pore arrangement, the higher is the mechanical strength of the microsieve. However, for the application of further support structures, e. g. by inkjet printing [7], a hexagonal or squared pore arrangement can be applied. The omitted pores would be covered by the support structures anyway.

## 4 Conclusion

The mechanical stability of inkjet-printed hierarchical microsieves was investigated. Therefore a 2D model of rectangular microsieves was set into COMSOL Multiphysics and a constant stress onto one boundary was applied. By regarding the resulting strain the mechanical strength could be estimated. The pore density and the pore distribution (distributed uniformly, hexagonally, and squared) were varied and the impact of both was studied.

The main impact onto the mechanical stability has the pore density. With a higher pore density the mechanical stability decreases. By keeping the pore density constant, the tested pore arrangements affect the stability marginally or slightly negatively. If it is intended to apply a further support structure onto the microsieve the hexagonal or squared pore arrangement enhance the mechanical stability.

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