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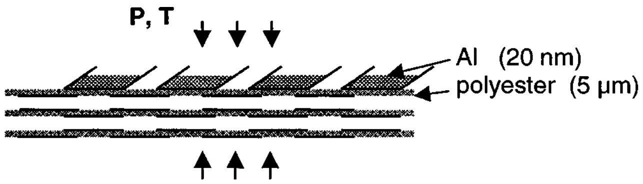
Abstract. A method to fabricate multichannel structures based on micrometre-thick plastic foil is described. In a reel-to-reel process, metallized plastic foil is patterned by laser ablation and stacked. Foil-to-foil joints are established by heating the foil stack under pressure. Expansion of the foil stack perpendicular to the plane of the foils yields a multichannel structure. We have realized structures with many thousands of channels with a diameter of a few hundred micrometres. The multichannel structures can serve for mechanical, optical, electrical as well as chemical functions.

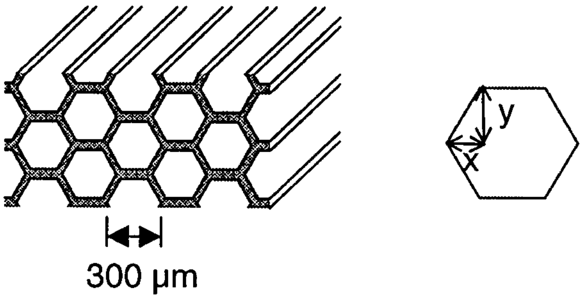
Multichannel structures have applications in many different fields such as mechanical engineering, air filtering, x-ray collimation and DNA sequencing. For micro(electro)mechanics applications we are considering the fabrication of multichannel structures from very thin plastic foils. The main goal is to manufacture structures with many thousands of electrically addressable channels, by a technology suited for mass production. We have focused on the usage of plastic foil material, because it allows for an upscalable reel-to-reel fabrication process. It is a well known principle to make multichannel structures from a stack of sheets, joined with glue at specific locations. However, the formation of joints between plastic foils is non-trivial, because glue tends to spread out when squeezed between the foils. In this paper we will explain how a sealing process can yield foil-to-foil joints with a lateral definition of a few micrometres, suitable for multichannel structures based on micrometre-thick foils.

We selected polyester [poly(ethylene terephtalate)] with a thickness of 5 μm (Mylar-C capacitor grade foil from Du Pont) as the base material for our structures (see figure 1). Polyester foil is readily available in micrometre thicknesses. On both sides, the plastic foil is coated with a metallic layer (20 nm aluminium) by the foil supplier (Steiner, Erndtebrück, Germany). To specify the positions of the joints, we structure the metallic layer with a KrF eximer laser ($\lambda = 248$ nm) under ambient conditions. The energy density of the beam ($\sim$250 mJ cm^{-2}) is chosen as to completely remove the aluminium layer while less than 0.2 μm polyester is removed. The maximum areal patterning speed is 100 cm^2 s^{-1}. The repetition rate was set to 20 Hz. The size and shape of the laser spot are defined with a mask; we used a spot of 150×150 μm^2 as well as a pattern with several lines. On the foil, the overlap between consecutive shots is less than 10%. We selected laser ablation because it fits in a reel-to-reel process. Figure 2 shows a sketch of our winding tool. The two sides of the foil are laser-ablated at different positions. On the final reel (area 20 cm^2) the foil is stacked with a foil-to-foil alignment accuracy better than 10 μm in both in-plane directions. After a sufficient number of turns, the final reel with foil stack is subjected to a sealing process. We apply a maximum temperature of 220 °C (a few tens of degrees below the melting point of the plastic) for about 5 min at a pressure of 2 N mm^{-2}. Inside the stack, there is negligible adhesion where metal-meets-metal or metal-meets-plastic. Where plastic-meets-plastic the adhesion is good, comparable to the heat seals between plastic films in general packaging applications. As a result, we obtain foil-to-foil joints at specific locations inside the foil stack (see figure 1), due to the patterned metal layer, the foil-to-foil alignment and the subsequent sealing process.

Upon foil-stack expansion the foils are deformed into a corrugated shape (figure 1). The expansion is performed at a speed of a few mm s^{-1}. It is very important that the strength of the foils as well as the peel strength of the foil-to-foil joints are large enough to withstand the forces required for expansion of the foil stack. A first-order estimate can be made from a model of elastic deformation. The force, F, per unit channel length, L, required for elastic deformation of a foil with thickness t is given by $F/L = yE(t/x)^3$, where y is the magnitude of the foil corrugation in the direction of stack expansion (cf figure 1(b)), E is the elastic modulus of the foil and x is the x-projection of the foil corrugation (cf figure 1(b)) [1]. The peel strength of a polyester-to-polyester joint was experimentally determined to be larger than 10^3 N m^{-1}, which sets an upper limit to the foil thickness for a given shape of channel cross section. Let us take the honeycomb structure of figure 1. The corner-to-corner distance is 300 μm with a seal width and inter-seal distance of 150 μm. Then $x = 150\cos(60) = 75$ μm and $y = 150\sin(60) = 130$ μm. For a maximum peel force of $F/L = 10^3$ N m^{-1} and an elastic modulus of $E = 4 \times 10^9$ N m^{-2}, we find a maximum foil thickness of 9.3 μm. We checked that polyester foils



(a)



(b)

Figure 1. Fabrication of a foil-based multichannel structure. (a) Stacking of polyester foils with a patterned Al coating. The foil-to-foil joints are established by the application of elevated temperature and high pressure. (b) Resulting honeycomb structure after expansion of the foil stack. The x–y coordinates for the deformation model are shown.

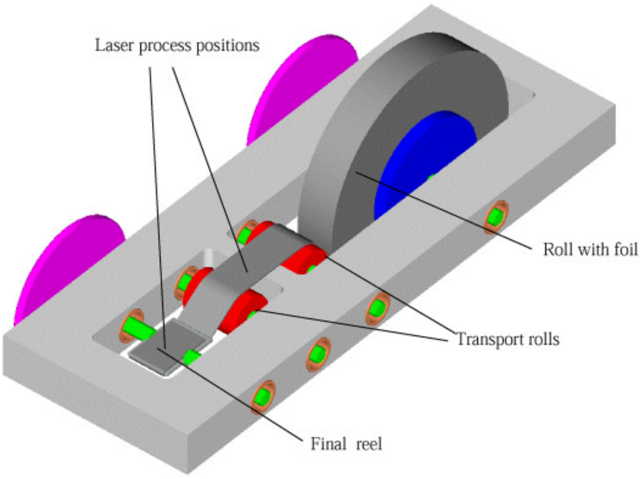


Figure 2. Schematic diagram of the reel-to-reel foil processing tool.

with a greater thickness (20 μm) showed rupture along the joints upon expansion of the foil stack.

Figure 3 shows images of an expanded structure made of polyester foil with a thickness of 5 μm. A regular honeycomb is obtained with straight walls. Detailed images show that the radius of curvature at the bending points is about 20 μm, which leads to the conclusion that inelastic deformation has taken place at the hexagon corners. This is in agreement with the fact that relaxation and hysteresis are seen in force-versus-expansion curves. The largest samples that we have made so far contain more than 20 000 channels with a length of 2 cm. We note that the geometry of the channels is given by the geometry of the foil-to-foil joints as well as the expansion step. Conical as well as curved channels can be made with suitably chosen patterns of metal removal.

In conclusion, we have shown that regular multichannel structures can be made from micrometre-thick polyester foil.

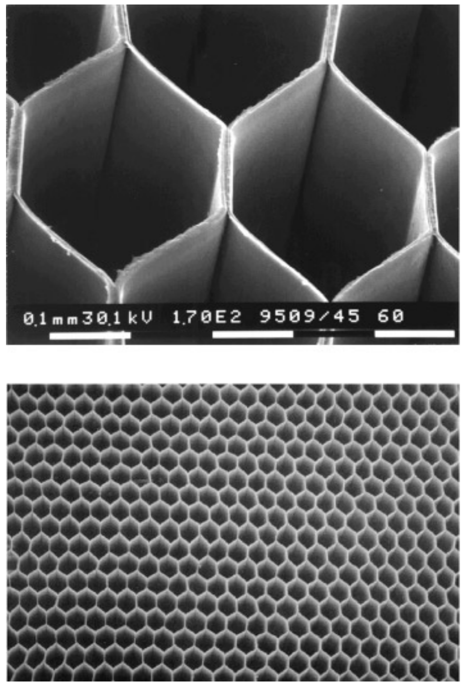


Figure 3. Scanning electron micrographs of a foil-based honeycomb made of polyester foil with a thickness of 5 μm covered by 20 nm Al. The width of the foil-to-foil joints is 150 μm.

The structures are made in a reel-to-reel process followed by a single heat sealing and expansion step, holding promise for high-volume and low-cost production. The force required for expansion of the foil stack sets a minimum to the channel diameter; we expect that hexagonal channels with a diameter of about 10 μm can be made from foils with a thickness of around 1 μm.

The scope of applications of our foil-based technology is large. The multichannel structures can, for example, be engineered for optical effects (collimation, reflection, absorption, etc) when suitable optical coatings are applied inside the channels. In more sophisticated applications, voltages can be applied to the metallic coating that is present inside the channels. This makes the structures interesting for the development of multicell microactuation devices (see, for example, [2]). As a next step we are developing an interconnect and voltage-driver technology to be able to supply voltage signals to every channel individually. This will yield microelectromechanical devices with a high density of channel-like cells. Using electrostatic, electrophoretic or electrochemical principles, interesting opportunities arise to make devices with a high density of ultra-low volume cells, for example for combinatorial materials synthesis or DNA sequencing.

References

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[2] Yamaguchi M, Kawamura S, Minami K and Esashi M 1993 *Proc. IEEE Micro Electro Mechanical Systems (Fort Lauderdale, Florida, 7–10 February 1993)* (Fort Lauderdale, FL: IEEE) p 18