A micro heat exchanger microfabricated from bulk aluminium

G. Scotti¹ and S. Franssila²

¹ Researcher, Aalto University, Department of Materials Science and Technology, Espoo, Finland
² Professor, Aalto University, Department of Materials Science and Technology, Espoo, Finland

E-mail: gianmario.scotti@gmail.com

Abstract. We report a micro heat exchanger microfabricated from a bulk aluminium alloy substrate. The device is comprised of two 18 cm long microchannels, one on each side of an aluminium chip, capped on both sides with a thin self-adhesive polymer film. In spite of a cheap and facile fabrication method, initial experiments with the device show promising results. Area densities from 25000 m⁻¹ to 45000 m⁻¹ have been achieved. Compared to our previous work on aluminium microfluidic devices produced with a similar technology but from a different, less pure alloy, in this study the etched surfaces are significantly smoother, and present less photoresist delamination.

1. Introduction

Micro heat exchangers are miniature heat exchanger devices produced with microfabrication techniques. The advantage of using microfabrication methods for heat exchangers is that the surface/volume ratio (area density) can be made to be very high [1], which is beneficial for heat exchange efficiency. Furthermore, micro heat exchangers can be integrated with other power MEMS devices (such as microreformers or micro fuel cells), with concentrated solar power systems [1], or with electronic components for cooling [2]. Micro heat exchangers require a smaller amount of material to fabricate compared to the traditional, macro-world counterparts, while having the same or better performance [2]. Additionally, the amount of working fluid is typically very small, as a consequence of the small total volume of the microchannels [2].

In [3] micro heat exchangers were made using traditional MEMS technologies and materials: a silicon wafer was etched with TMAH and capped with Pyrex glass by anodic bonding. However, due to robustness and high thermal conductivity, micro heat exchangers are often micromachined from metals: in [4] LIGA was used for micromachining a nickel micro heat exchanger, whereas in [5] microchannels were created in copper by a wire cutting machine. Due to its high thermal conductivity (237 W m⁻¹ K⁻¹), aluminium is also an interesting material [6] [7] [8], but not many devices have been implemented at the microscale: none of the cited works implements microchannels with a hydraulic diameter below 1 mm.

In this work we present a micro heat exchanger made with a modification of the technology previously used for the micromachining of micro fuel cells from bulk aluminium [9] [10]. Unlike in [9] [10] where the alloy used was aluminium 6061, in this work we utilized aluminium 1050A, which...
contains much fewer alloying elements: min. 99.5 w% of aluminium, less than 0.25 w% Si, less than 0.4 w% Fe, and trace amounts of Cu, Mn, Mg and Zn.

2. Experimental

2.1. Micro heat exchanger structure
The micro heat exchanger discussed in this work is formed by two serpentine channels micromachined on each side of a 700 µm thick aluminium alloy 1050A chip. Structurally, this is similar to plate-fin heat exchangers [1]. The microchannels are capped on both sides with a thin polymer sticky film. The arrangement of the inlet holes (figure 1) allows also for the heat exchanger chips to be stacked, though this has not been tested yet. The smaller circles visible on the chip in figure 1(a) indicate the position of the fluidic inlets on the opposite side. Figure 1(b) shows a schematic of the arrangement of the channels and inlet holes on both sides of the chip.

![Figure 1](image-url)  
**Figure 1.** A micro heat exchanger chip. (a) Photograph of chip (capping removed) with human fingers for size comparison. (b) Schematic drawing of the arrangement of the microchannels and inlet holes on both sides of the chip.

2.2. Microfabrication
Our microfabrication process started with priming of the aluminium sheet with HMDS and spinning of common DNQ/novolac resist AZ 5214 on both sides of a mirror polished, 4” x 4”, 700 µm thick aluminium sheet (figure 2(a)). The spinning was done at 4000 RPM for a dried resist thickness of 1.4 µm. After each spinning the resist was soft-baked at 90ºC in an oven. It is important that the resist is carefully soft-baked after the first spinning so that the vacuum of the spinner chuck would not affect the already spinned resist layer. Lithography of the front side was done without alignment, while the back side required back-side alignment (figure 2(b)). After the UV exposure and development, the resist was hard-baked at 120ºC in an oven for 20 minutes. The channels were etched in a commercial anisotropic aluminium etchant (an aqueous solution of 74% H₃PO₄ and 2.5% HNO₃) for 160 minutes at 50ºC, resulting in an etch depth of ~75 µm (figure 2(c)). Both sides of the wafer were etched simultaneously. The aluminium sheet was placed between two dicing frames with a sticky tape.
stretched across (figure 2(d)). This tape acts as a simple capping layer (figure 3). Finally, the chips were diced and separated. Fluidic inlets were obtained by simply punching a hole at the inlet point with a needle or similar tool. Note that the arrangement of the inlets allows one to drill the chip through and have access to the microchannels from the opposite side of the chip (figure 1(b)).

Figure 3 shows a micropatterned aluminium sheet placed between two sticky tapes stretched on dicing frames/rings. After this capping step, one of the dicing frames must be removed before dicing can proceed, otherwise it will be in the way of the rotating blade.

**Figure 2.** Process flow for the microfabrication of the bulk aluminium micro heat exchanger chips. (a) Spinning of photoresist. (b) Lithography (front and back). (c) Etching in isotropic aluminium etchant, to depth of ~75 µm. (d) Capping with sticky tape and dicing.

**Figure 3.** Micropatterned aluminium plate placed between two sticky tapes in dicing frames. After capping, one of the dicing frames must be removed before dicing.

### 2.3. Characterization

For the heat exchange characterization we placed the capped chips in a polycarbonate jig with fluidic fittings (figure 4).

Two peristaltic pumps pumped hot water through one side of the chips, and cold water through the other side. Both flows were set to 50 µL min⁻¹, which is close to the maximum attainable with the available peristaltic tubes. Temperatures were measured with an Amprobe® infrared thermometer, by temporarily removing the fittings and letting the water (first at the inlet, then at the outlet) leak onto a patch of cleanroom wipe. When the wipe was sufficiently wet, the infrared thermometer was pointed at it and the temperature was recorded. The ambient temperature was 20°C. The cold water was obtained by having water and ice mixed in a beaker, while hot water was taken from a beaker placed on a hotplate at 80°C.
3. Results and discussion

The measured temperatures of the water on the “hot” side were 21°C at inlet and 18°C at outlet. On the “cold” side, the temperatures were 16°C at the inlet and 18°C at the outlet. Due to the method used to measure the temperature of the water, it is certain that some thermalisation of the water with ambient air took place, and that the temperature differences of the water going in vs. flowing out of the micro heat exchanger must have been larger. While the temperature measurement methodology is far from optimal, the experiment demonstrates qualitatively the validity of the design.

A separate set of results of the experiment relate to the microfabrication itself:

- The etched surfaces resulted in much smoother etched surfaces compared to the ones obtained in previous work [9] [10], with RMS roughness ~550 nm vs. ~960 nm
- The etch rate is about half that found in [9] [10]: ~0.45 μm min⁻¹ vs ~0.85 μm min⁻¹
- The photoresist adhesion appears to be significantly improved; the angle between the etched surface and the horizontal plane of the aluminium sheet is very close to 90°, and it is fairly sharp compared to what was obtained in [9] [10]. It can be concluded that no resist delamination occurred.

The first two effects can be easily attributed to the choice of aluminium alloy — 1050A in this work vs. 6061 in our previous works. It is known that aluminium etching is affected, and in fact catalyzed, by impurities [11]. Furthermore, the fact that 1050A has much fewer insoluble alloying elements, causes a much lighter (in fact, invisible/not noticed) patina to be deposited on the etched surface. As a consequence, roughness caused by the non-etchable patina should be smaller than in the case of aluminium 6061.

We do not know, at this point, what is the cause for the better photoresist adhesion. This important aspect will require further research.

Figure 4. Micro heat exchanger chip with capping inserted in measurement jig. Fluidic fittings are threaded into the polycarbonate blocks.

Figure 5. Scanning electron microscope images of microchannels. (a) Microchannel on one side, and channel profiles on both sides, are imaged. (b) Close-up of one channel near the dicing point. The undercut is equal to the etch depth, ~75 μm.
4. Conclusions
The micro heat exchanger presented in this work is still a work in progress, but in spite of a less-than-ideal characterization method, it shows promising heat exchange characteristics. The very cheap and facile fabrication process opens many new possibilities for power MEMS applications, especially considering the improved results obtained with aluminium 1050A compared to our previous work.

The device can be improved by using other capping methods; attempt to thermocompressively bond aluminium chips to form a capped stack is a worthwhile research. Other channel topologies, e.g. parallel, should be better suited for heat exchange, and experimenting with narrower channels to further increase surface density, should be attempted. Improving the characterization method is very important as well. Finally, it would be of great value to discover the reason for better photoresist adhesion to aluminium 1050A.

References
[1] Li Q, Flamant G, Yuan X, Neveu P, and Luo L 2011 Compact heat exchangers: A review and future applications for a new generation of high temperature solar receivers Renew. Sust. Energ. Rev. 15 4855–4875.
[2] Kew P A and Reay D A 2011 Compact/micro-heat exchangers & Their role in heat pumping equipment Appl. Therm. Eng. 31 594e601.
[3] Munkejord S T, Mæhlum H S, Zakeri G R, Nekså P, and Pettersen J 2002 Micro technology in heat pumping systems Int. J. Refrig. 25 471–478.
[4] Harris C, Despa M, and Kelly K 2000 Design and Fabrication of a Cross Flow Micro Heat Exchanger J. Microelectromech. S. 9 502-508.
[5] Jiang P-X, Fan M-H, Si G-S, and Ren Z-P 2001 Thermal-hydraulic performance of small scale micro-channel and porous-media heat-exchangers Int. J. Heat Mass Tran. 44 1039-1051.
[6] Antohe B V, Lage J L, Price D C, and Weber R M 1996 Numerical characterization of micro heat exchangers using experimentally tested porous aluminum layers Int. J. Heat and Fluid Flow 17 594-603.
[7] Omri M, Barrau J, Riera S, and Fréchette L G 2012 A novel hybrid microchannel heat exchanger configuration aiming for uniform wall temperature Proc. PowerMEMS 2012 (Atlanta, USA) pp. 407-411
[8] Fernando P, Palm B, Ameel T, Lundqvist P, and Granryd E 2008 A minichannel aluminium tube heat exchanger – Part I Int. J. Refrig. 31 669–680.
[9] Scotti G, Kanninen P, Kallio T, and Franssila S 2012 A high-power micro fuel cell microfabricated from aluminium Proc. PowerMEMS 2012 (Atlanta, GA, USA) pp. 375-378
[10] Scotti G, Kanninen P, Kallio T, and Franssila S 2014 Bulk-Aluminum Microfabrication for Micro Fuel Cells J. Microelectromech. S. 23 372-379.
[11] Catotti A J, Grad P P, and Cohn H, "Process of etching aluminum foil for electrolytic capacitor," US Patent 2,853,445, 1958.