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Biomimetic microtexturing for neurosurgical probe surfaces to influence tribological characteristics during tissue penetration

Andreas Schneider [a,*], Luca Frasson [b], Tassanai Parittotokkaporn [c], Ferdinando M. Rodriguez y Baena [b], Brian L. Davies [b], S. Ejaz Huq [a]

[a] Science and Technology Facilities Council, Rutherford Appleton Laboratory, Technology, Micro and Nanotechnology Centre, R18, Harwell Science and Innovation Campus, Didcot OX11 0QX, UK
[b] Mechatronics in Medicine Laboratory, Department of Mechanical Engineering, Imperial College, London SW7 2AZ, UK
[c] Institute of Biomedical Engineering, B 422 Bessemer Building, Imperial College, London SW7 2AZ, UK

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ABSTRACT

For the development of a novel type of neurosurgical probes, surface texturing and various microstructure geometries were fabricated and investigated as to their tribological properties during penetration of a probe into brain tissue. The surface texture and the penetration mechanism under investigation were inspired by the ovipositor of the wood-boring wasp *Sirex noctilio*. Fabrication techniques for microelectronic mechanical systems (MEMS) were employed to engineer this novel biomimetic neurosurgical probe using SU-8 photoresist, Si, and silicone dispersion. Fin- and tooth-like high-aspect-ratio (HAR) side wall microstructures were produced for the surface texture and subsequently integrated into a needle-type probe made by microstereolithography (MSTL). The assembled needle probe with the SU-8 microstructures was used to determine the different bidirectional resistance force during a probe insertion and extraction into soft tissue (including cadaveric animal brain).

1. Introduction

This paper describes surface texturing for novel neurosurgical probes to explore a new method for soft tissue penetration.

Neurosurgical probes are used to remove brain tissue for biopsy in minimally invasive surgery. Conventional probes consist of stainless steel tubes without specific surface texture. These tubes are several centimetres long and comprise channels for optical fibres (illumination, viewing) and a conduit through which miniature surgical instruments can remove tissue from the brain. Such neurosurgical probes have typical outer diameters of 3–6 mm [1,2].

The novel design mimics a wood-boring wasp's ovipositor, which comprises two interlocked halves (valves) with serrated surface textures (see Fig. 1). The valves push into wood with a reciprocating motion. Different bidirectional resistance forces caused by the anisotropic surface texture generate an overall forward movement of the ovipositor. Details of its architecture and reciprocating mechanism are given elsewhere [3]. The current study investigates the motion of similarly textured neurosurgical probes in cadaveric animal brain when external load is applied to the probe.

Photolithography, deep reactive ion etching (DRIE) and polymer casting were used to create the surface texture of the probes. To fabricate three-dimensional structures for the probes such as fins and teeth with under-cut patterns microstructures were produced conventionally on planar Si wafers, subsequently released from the substrate, and assembled into a cylindrical probe.

2. Fabrication of microstructures

Three different wafer-scale methods based on MEMS fabrication techniques for HAR microstructures were exploited to obtain sidewall patterns of tooth and/or fin textures along 75 mm-long strips: (a) photolithography of SU-8 resist, (b) DRIE of HAR structure into Si-on-insulator (SOI wafer), and (c) DRIE of moulds for subsequent silicone casting. For process (a), the substrate was initially coated with a sacrificial layer (lift-off resist Microchem LOR 5B) before SU-8 was thickly applied and directly patterned by photolithography using a photomask and mask aligner (MA6 Karl Suss). After exposure, post-exposure bake (PEB) and development of the cross-linked SU-8, the SU-8 patterns were released from the substrate by dissolving the sacrificial layer. Process (b) is similar to (a), but a thinner resist pattern was exposed and used

* Corresponding author. Tel.: +44 1235 44 5178.
E-mail addresses: andreas.schneider@stfc.ac.uk, a.schneider@rl.ac.uk (A. Schneider).

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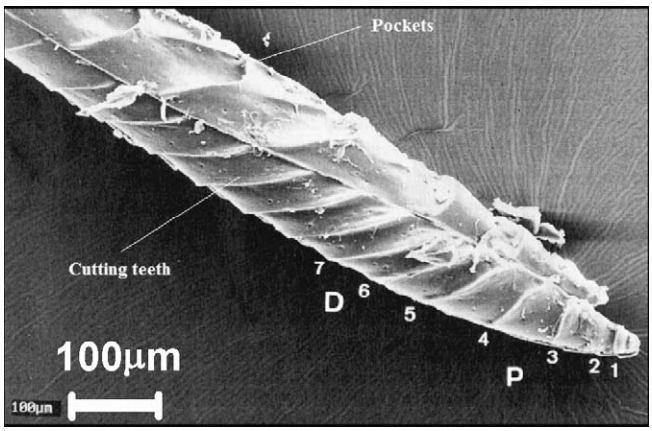

Fig. 1. Micrograph of the ovipositor of *Sirex noctilio*. Numbers and letters indicate "pull teeth" and "push teeth" (Ref. [3]).

as masking layer for etching the microstructures into Si by DRIE. The sidewall profile was etched into the 300 μm-thick Si device layer of a SOI wafer. The 3 μm-thick buried oxide (BOX) layer of the SOI acts as etch stop for DRIE and also as sacrificial layer for release of the etched Si structures.

In process (c), an inverted photomask layout was used to pattern and etch moulds into Si. Subsequently, a thin non-adhesion fluorocarbon polymer film was deposited over the moulds instead of a sacrificial layer, and medical-grade silicone dispersion (MED10-6605) was cast into the mould. After curing, the silicone structures were peeled from the mould.

Microstructures made by the three different techniques from three materials (SU-8, Si, and MED10-6605) were compared regarding their structural quality and dimensions.

SU-8 photoresist [4] is commonly used for fabricating HAR microstructures, so, after optimizing process parameters, free-standing SU-8 strips with sidewall texture (Fig. 2) were fabricated. Process conditions are described in detail elsewhere [5]. For the texturing, a set of samples with thickness ranging from 125 to 525 μm were fabricated. The sidewall structures were protruding from the SU-8 strip by 500, 250, 100, 50, and 10 μm. The pitch of adjacent microstructures on SU-8 strips is 866, 433, 173.2, 86.6, and 17.3 μm, respectively. Good results were achieved for all geometries of 50 μm or larger. With strip thickness less than 250 μm the sidewall inclination angle was smaller than 2.5°.

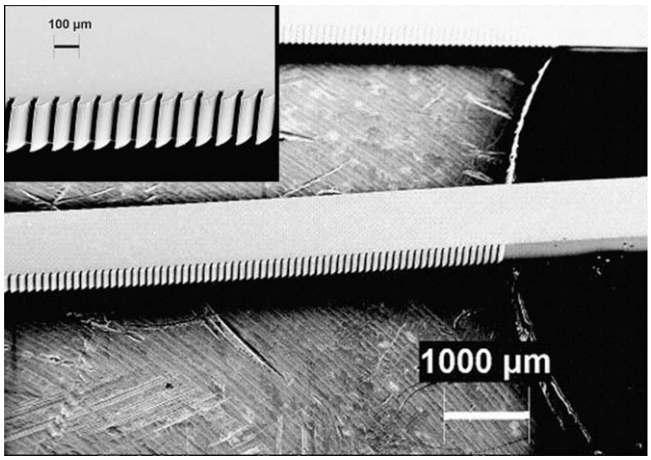

Fig. 2. Individual strip with HAR microstructures on the side wall made from SU-8 photoresist; inset shows detail of the fin structures.

Microstructures protruding 10 μm were visible in scanning electron microscope (SEM) images, but a clear distinction between fin and tooth structures was not possible. Furthermore, the anisotropic feature of 10 μm structures was not reproduced.

The casting method of MED10-6605 showed various disadvantages such as shrinkage (~28%), excess material on demoulded structures, and variation in thickness as well as despite the non-adhesive layer imperfect removal, with material adhering to the mould. Fig. 3a shows a micrograph of the sidewall profile of a typical demoulded MED10-6605 sample. A thin film of residue has formed on top of fin structures, and the sample height from back to tip of the fin is not uniform. Furthermore, the sample thickness of ~80 μm at the top of the tip is considerably less than anticipated from a 300 μm-deep mould. In contrast, the height of released Si samples using process (b) is well defined because of specified SOI layer thickness. Small sidewall structures of 10 μm (HAR 30:1) were etched into SOI. However, the sidewall pattern was rough, with some re-entrant etching of the structures close to the BOX layer. In addition, the separation of the Si structures from the substrate at the BOX was incomplete after prolonged HF etching. The sidewall profile of a typical 300 μm-thick Si structure etched by the DRIE process is shown in Fig. 3b.

The SU-8 strips (process (a)) were chosen for assembly into needle-type probes custom-made by MSTL, a rapid prototyping process. Each needle had grooves parallel to the axis to accommodate 12 similar SU-8 strips (Fig. 4). Strips were manually inserted and fixed with epoxy adhesive.

3. Insertion and retraction in brain tissue

To investigate the bidirectional dynamic of an axially moving microtextured probe in brain tissue, the assembled probes (Fig. 4) were inserted into and retracted from cadaveric animal brain by a Testing Instron machine (Dual Column Model 5565) equipped with a 100 N load cell (2525-807 series Drop-through Load Cell). Three cycles of insertion/retraction under constant speed of the probe (1 mm/s) and simultaneous measurement of the applied load were carried out for each probe. The applied load (Fig. 5) was recorded against the relative position between probe tip and brain surface (position zero). Fig. 5 displays the data from the third cycle only. The first cycle was dominated by deformation and cutting forces through the outer connective tissue membrane of the brain, whereas the third cycle allows a better analysis of the pure sliding movement of the textured probe in brain tissue. Only after the tip and untextured neck of a probe was inserted into the brain (~10 mm position), the absolute applied load (negative value for pushing) started to increase almost in the same manner for all probe textures. Reversing load and motion at 30 mm, the needle was pulled out to the initial position (60 mm). At first, the load increases (positive value for pull) approaching different maxima for each geometry of texture. Further retraction reduces the load required because less textured surface area is in contact with tissue. Measurements were made with mixed SU-8 texture protruding 10 μm (10TF), fin (50F) and tooth (50T) microstructures protruding 50 μm, and fin structures (100F) protruding 100 μm, as well as a control probe with a smooth surface. Probes with 500 μm texture were excluded because of causing severe tissue damage. The energy for insertion and retraction was calculated by a numerical integral of the area of the curves. The insertion covers the interval from probe penetration to first load maximum. For retraction, the rest of each curve (load >0) was integrated. In the insertion phase, the required energy rises slightly from 1 to 1.58 mJ with increasing size of the microtexture, but even the smooth probe requires ~1.2 mJ simply owing to surface friction and tissue deformation. Probe insertion is only marginally influ-

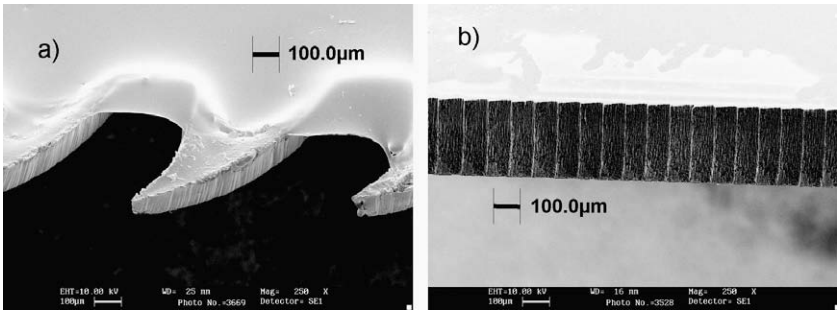

Fig. 3. (a) Silicone microstructure; (b) Si microstructure.

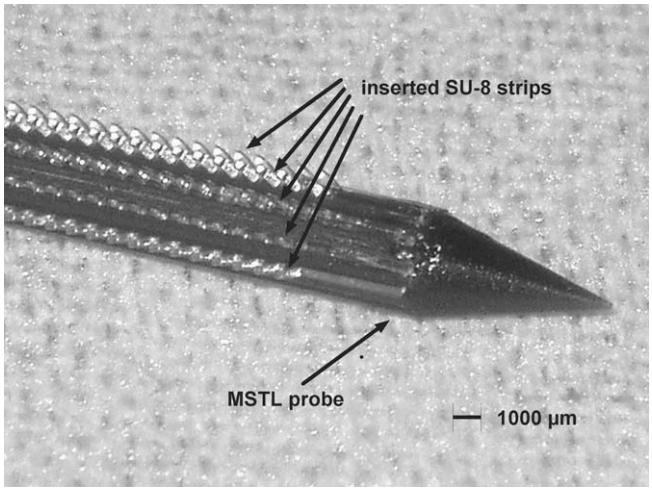

Fig. 4. Assembled MSTL probe with 12 SU-8 strips (fins protruding 500 µm from surface).

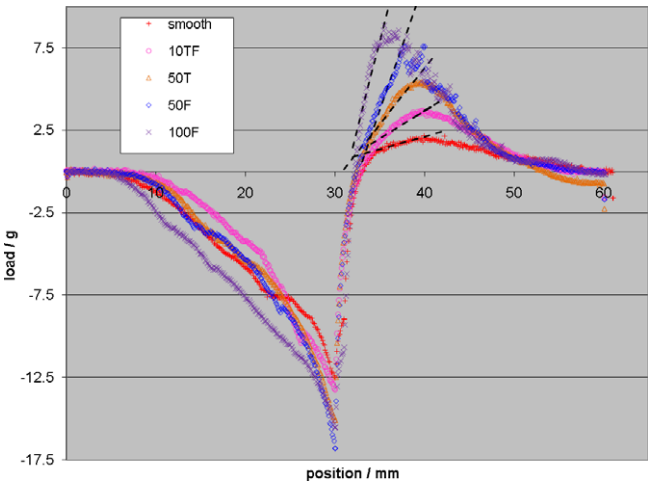

Fig. 5. Load–displacement diagram for insertion and retraction of assemble probe into brain tissue; dotted lines indicating linear increase of load during probe retraction.

enced by surface texture. However, larger differences are observed for retraction. The smooth probe requires the least energy (0.29 mJ); the 10 µm structures require slightly more (0.43 mJ) whereas larger structures require twice as much at least (50T, 50F, and 100F require 0.6, 0.69, and 0.81 mJ, respectively). The larger the texturing structures are, the more energy is required for retraction, indicating an increase in resistance during backwards motion. Additionally, the gradient of load increase during retraction is more rapid for larger microtextures (Fig. 5). Taking the error for load and position into account, the energy can be measured within an accuracy of 2%. Therefore, the energy difference between different geometries (50 µm fin and teeth) during retraction is small but substantial. Generally, the energy necessary for probe retraction of large texture geometries is slightly less than required for their forward motion. Therefore, forces between pull and push are almost balanced. Hence it should be feasible to design a neurosurgical probe with reciprocating mechanism which easily moves forward by a slight axial push.

4. Conclusion

The anisotropic bidirectional resistance forces during reciprocating movement of a novel neurosurgical probe were investigated for two types of texturing (tooth- and fin-like microstructures) at various dimensions (10–500 µm). Microstructures with textured sidewalls were produced from SU-8, Si, and silicone (MED10-6605). Ultimately SU-8 structures proved suitable for load–displacement experiments on animal brain tissue. Structures larger than 100 µm cause severe tissue damage and can be excluded for prototype development. For microstructures in the critical range of 10 µm exceeding HAR of 20, fabrication limits mean that no distinction between tooth and fin structures and their orientation was possible. However, they still affect force and energy needed for extraction of the probe.

With probe surface morphology of 50–100 µm, the net energy difference between forward and backward motion becomes small enough to reduce the force required for the axial push of the probe. Thus, a novel neurological probe axially split into two segments mimicking an insect's ovipositor should be able to move forward with minimal axial push during reciprocating actuation.

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