SURFACE FINISH IN MICRO-DRILLING OF PTFE

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ABSTRACT

Surface finish of engineering components plays a key role in their functionality, particularly where the size of the geometric features of the component decreases. This paper reports on such an application – the drilling of micro-holes in PTFE during manufacture of molds for use in the bio-medical field. These molds are used for production of silicone scaffolds requiring very large aspect ratios – typical examples being to produce pillars/columns of 300 micron diameter and 15 mm length. The surface finish of the holes machined in the PTFE becomes critical in order to facilitate extraction of the silicone from the mold without damage. A systematic approach is used to determine the optimum combination of machining parameters with respect to this goal. Furthermore, a novel approach to surface quality estimation is proposed. Direct methods of surface quality assessment in this application are difficult due to the scale of the holes – conventional measurement methods are expensive, time-consuming and require destruction of the mold. In this work, the quality is inferred indirectly through measurement of the force required to extract the silicone from the mold. A simple apparatus to standardize the extraction procedure has been designed and built as part of this work.

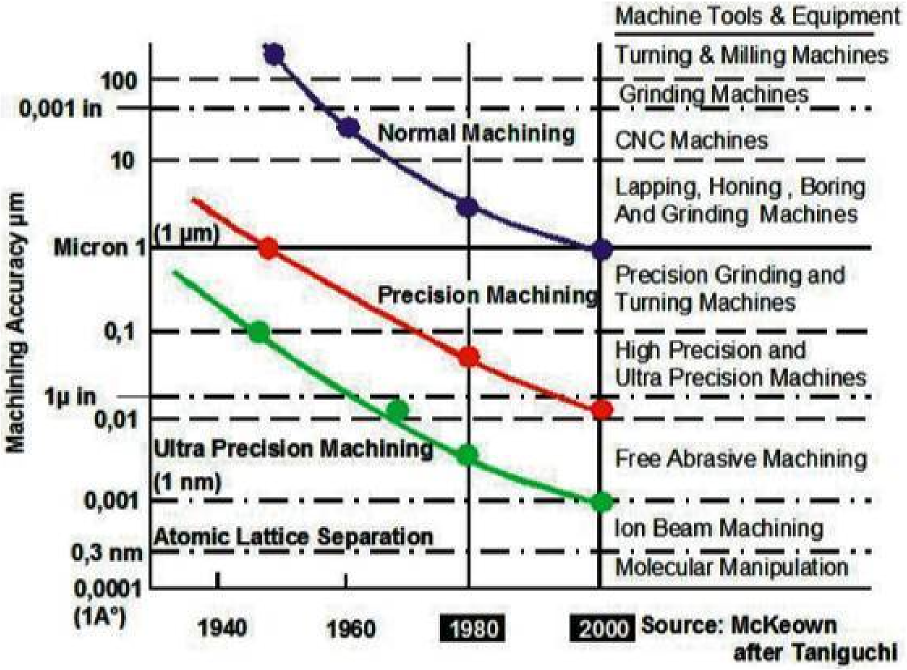
KEYWORDS: Tissue Scaffold, Micro-drilling, surface finish

1. INTRODUCTION

The medical device and diagnostic industry is a cornerstone of the Irish economy, with over 140 companies employing approximately 25,000 people and comprising 10% of Irelands total exports (over €6 BN per annum) [1]. The nature of the industry in Ireland is evolving from principally manufacturing of (relatively) low technology products to a highly complex R&D driven sector. A vast range of products are developed and manufactured in Ireland, from implants to microelectronic devices to diagnostic (e.g. lab on chip) to stents. Increasing amounts of collaboration are being seen between the various agents such as research institutes, universities, government agencies and manufacturing companies. A key feature of many of these products is their small size, which in turn requires the latest knowledge in manufacturing technology to be leveraged.

2. MICRO-ENGINEERING AND MIRCO-MACHINING

With increased capability for precision in machining processes, the manufacture of workpieces that are smaller and more accurate than previously seen becomes reality. The same motivating factors drive this micro manufacture market as its macro counterpart – better performance, higher quality, new applications, and lower costs. It is difficult to put an exact date on the origins of micro manufacturing – around the mid 1960's through to the early 1970's is a widely accepted timeframe [2]. In 1983 Taniguchi quantifies micromaching capability in terms of Taniguchi's unit removal, the amount of workpiece removed during one cycle of process (e.g. one engagement of the tool)[3, 4].



Source: McKeown after Taniguchi

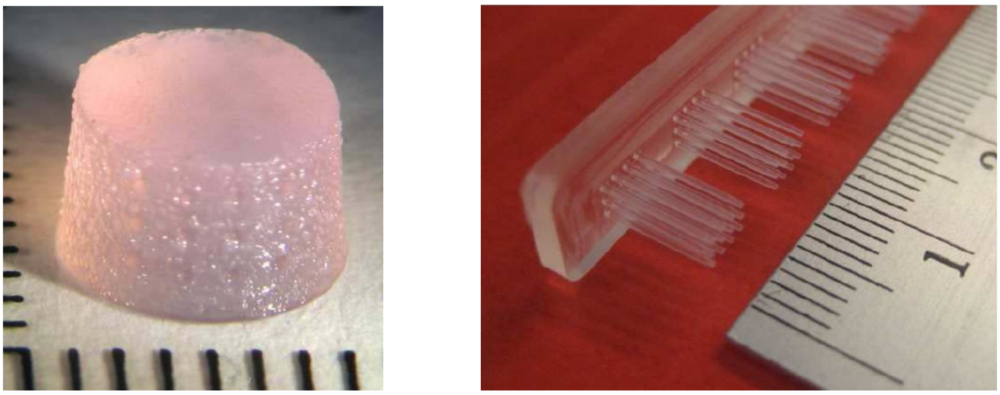
Figure 1. Micromachining capability over time [5]

The motivation for increasingly smaller components parallels the improvements in cutting technology [4]. Demand for reduced weight, reduced dimensions, higher surface quality and part accuracy, while at the same time reducing component costs and batch sizes. Some examples of companies that have lead the way in industry in this field are the likes of; FANUC in robotics and controls, Carl Zeiss in metrology, Mitsubishi Electric in electric devices/products, and Olympus in optics. These companies have invested heavily and consistently in micro-manufacturing technologies over the last fifteen years [5]

3. TISSUE SCAFFOLDS

Scaffold-based tissue engineering is the use of a biocompatible material to either induce the formation or regeneration of new tissue or to act as a carrier or template for implanted cells or other agents [6]. The scaffold or three-dimensional (3D) construct provides the necessary support for cells to proliferate and maintain their differentiated function, and its architecture defines the ultimate shape of the new tissue.

Recent advances in both computational topology design (CTD) and solid free-form fabrication (SFF) have made it possible to create scaffolds with well defined architectures. The benefits of these technological advancements include the enhancement of interconnected porosity which can improve cell seeding and the incorporation of channels to guide cell migration and tissue ingrowth [7]. However, some limitations include the use of toxic binders, poor feature symmetry and limited material choice. Due to these material limitations, researchers adapted SFF techniques to indirectly cast scaffolds with controlled internal and external architecture by means of a lost mold process [8, 9]. Lost mold processes are typically suited to ceramic infiltrates as ceramics are usually sintered to temperatures in excess of 1000°C, thus ensuring complete removal of the polymer mould created through SFF.

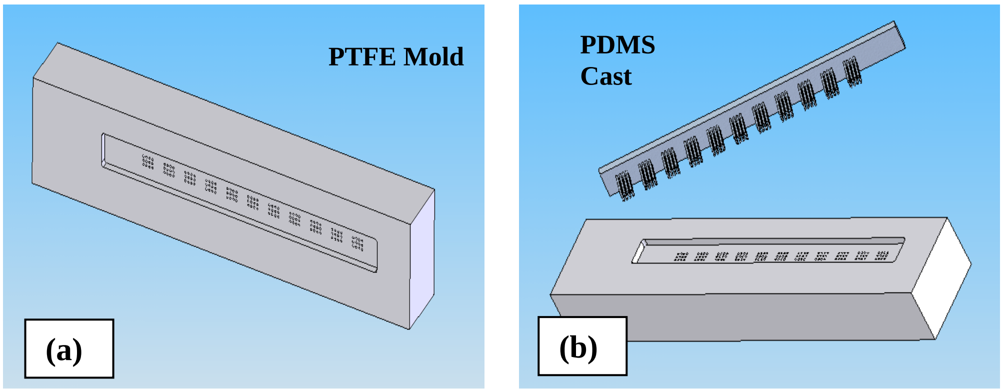


(a) (b)

Figure 1. (a) Chondrocyte encapsulated agarose hydrogel scaffold with a defined array of unidirectional microchannels of diameter 500µm. (b) PDMS 4x3 array pillared mould with 500 µm pillar diameter and 1mm centre-centre spacing, 7mm length.

Hydrogels are a class of scaffold material that are commonly used in cartilage tissue engineering and include alginate, agarose, polyethylene glycol (PEG), polyvinyl alcohol (PVA), pluronics, chitosan, collagen and fibrin as examples. A significant advantage of hydrogels is their potential use as an *in situ* forming scaffold for cartilage defect repair. Existing as a non-solid solution *ex vivo*, such *in situ* forming scaffolds may be injected to the defect site in a minimally invasive fashion. Incorporating discrete architectures into such hydrogel materials is not directly compatible with SFF or RP technologies. The motivation behind this current work is to develop PDMS moulds to incorporate desired unidirectional channelled diameters into cell encapsulated hydrogel scaffolds for cartilage defect repair. The choice of mould material, polydimethylsiloxane (PDMS), is widely used in microfabrication for biological applications and offers biocompatibility, optical transparency, permeability to gases, flexibility, and durability. The creation of such scaffolds with defined architectures and feature sizes offers great potential in the next generation of hydrogel based polymer scaffolds.

An example is shown in figure 2 below of the molds used in the current work



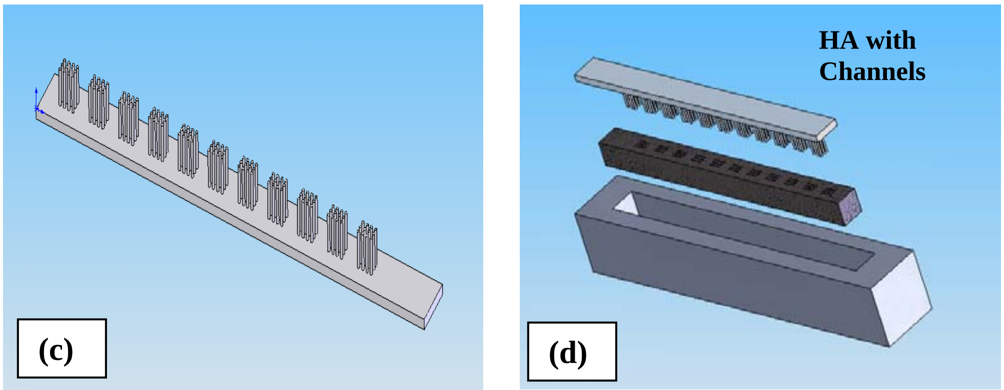


Figure 2. (a) matrix of 0.5mm * 7mm holes in PTFE mold. (b) PTFE mold with cast PDMS. (c) cast PDMS used as mold with Hydroxyapatite slurry (d) final cast scaffold for in-vitro cell culture.

4. EXPERIMENTAL WORK

The individual holes drilled in the mold are 300 microns in diameter and 5 mm deep, in a workpiece of PTFE. This makes conventional surface roughness measurement methods unsuitable – it is impossible to insert a stylus into the holes, and the diameter of the holes and workpiece material means that any efforts to section the piece will, as well as destroying the mold, also obscure any roughness in the original drilled hole itself. The surface roughness of course is not of primary concern – its relevance is in how it may limit the effectiveness of the mold for producing the scaffold device – it being reasoned that higher roughness, and hence higher frictional forces, was responsible for damage to the scaffold device (breakage of individual pillars). It was hypothesised therefore that we would be able to infer the surface roughness indirectly, by measuring the force required to remove the scaffold from the mold.

To investigate this hypothesis, a test-piece was designed (shown in figure 2 below), containing a series of square (6x6) arrays of holes, using different combinations of machining parameters. Each array sits below a small pocket machined in the PTFE, which allows for the inclusion of a removal device (discussed below). These pockets are shown shaded in grey in figure 2 below – the 3 un-shaded squares representing pockets with no hole arrays beneath them, for comparative purposes.

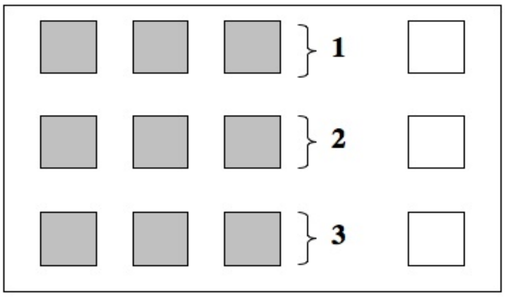


Figure 2. Design of test workpiece

A standard bolt (M6) was used as an insert in each mold to assist in the removal. A locating rig and a removal rig, shown in figure 3 below were used to ensure repeatability in the experimental process. A solution of PDMS resin and curing agent was used to fill the molds, following a degassing phase in a vacuum oven. Once the molds were filled, a further vacuum cycle was used to remove any trapped air and to ensure complete filling of all cavities. At this stage the fixturing bolts were inserted into the mold using the locating rig, before transferral of the entire device (mold and locating rig) to a curing oven for 12 hours. The locating rig was then removed with the individual molded parts ready for removal using an Instron tensile testing machine.

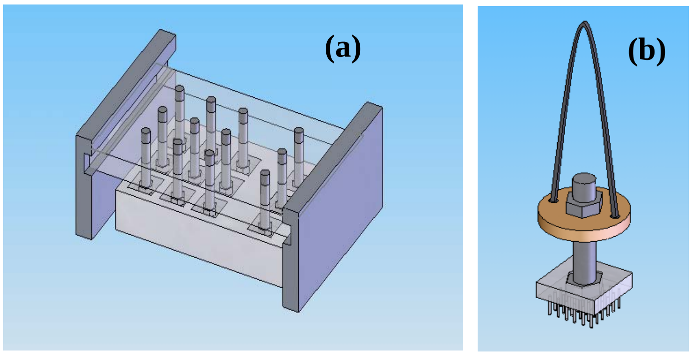


Figure 3. Design of locating (a) and removal (b) devices

A factorial design was implemented for the experimental process, investigating the effect of three variables – the feed rate, the spindle speed and the length of pecking cycle (each hole is drilled in several stages, with the drill retracted at each stage to assist in swarf removal). An initial phase of testing was used to demonstrate an influence, via ANOVA, of machining parameters on the pull-out force required for removal of the part from the mold. A further series of tests was then performed to investigate the interaction effects between the various machining parameters, and the range of input parameter values that permitted removal of all test pieces (24 tests per parameter combination) from the mold without pillar breakage. A final series of tests was run to determine more accurately the interaction effects and the optimum combination of parameters for this operation.

5. RESULTS

Figure 4 shows a typical graph of force required to remove a part from the mold. The maximum force recorded, in region labelled A in the diagram, is used as a proxy for the surface roughness, as discussed earlier. The drop noted in the region labelled B is consistent across all tests (including the reference molds with no pillars), and it is suggested that this is due to tensioning and ‘locking’ of the cable assembly in the removal rig, or to ‘backfilling’ of air beneath the molded pattern – which is vacuum-filled.

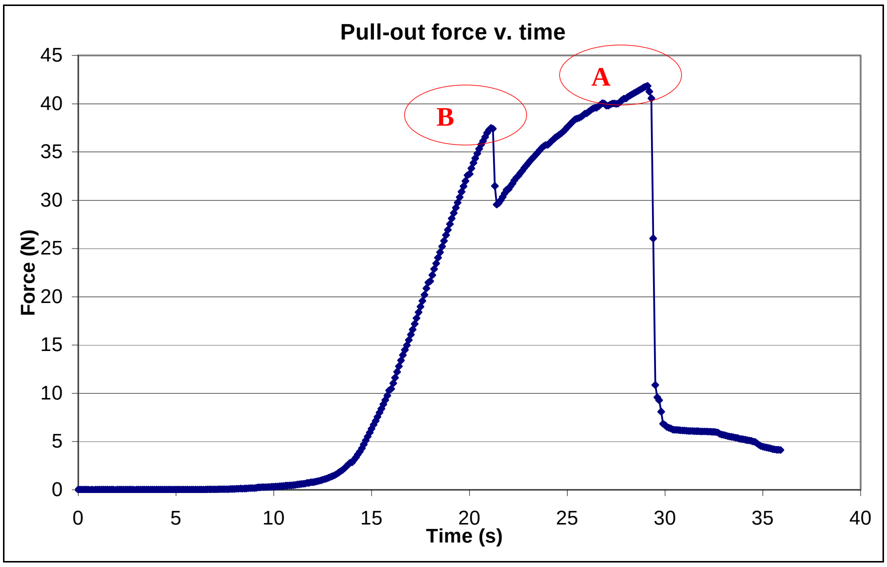


Figure 4. Pull-out force required for part removal from mold

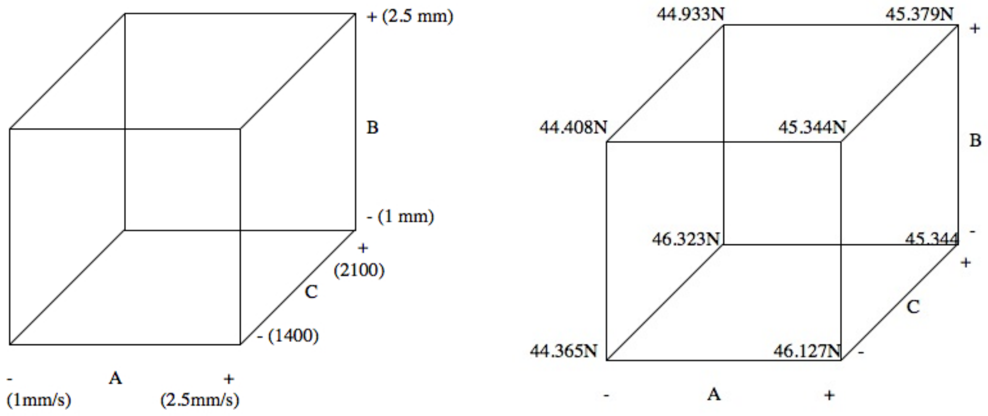
The individual holes drilled in the mold are 300 microns in diameter and 5 mm deep, in a 6x6 matrix; each matrix being machined with a particular combination of machining parameters. A total of 4 molds were used and the positions of the matrices were varied randomly – to ensure that location issues were normalised for. ANOVA testing was performed, with a null hypothesis that the location of the matrix influenced pull-out force. The null-hypothesis was rejected at the 1% significance level – i.e. matrix location did not influence removal force.

A second series of tests was performed, varying the following parameters using a factorial design:

Label	Parameter	Low Value	High Value
A	Feed Rate	1 mm/s	2.5 mm/s
B	Length of Pecking cycle	1 mm	2.5 mm
C	Spindle speed	1400 rpm	2100 rpm

Table 1. Parameter variation for machining tests

The factorial setup of these tests and the measured forces are shown in figure 5 below. A total of 24 tests were performed at each ‘vertex’. A statistical analysis of the results indicates that 2 of the interactions are statistically significant at the 95% level; the AC and the ABC interactions. The implication therefore is that all three input factors should be considered simultaneously in any evaluation or study of this process. Some interesting effects are apparent on closer examination of the AC interaction – increasing the feedrate at high spindle speeds results in a decrease in surface roughness (i.e. less force required for material removal from the mold), while increasing the spindle speed at low spindle speeds results in a rougher surface.



(a) (b)

Figure 5. Factorial design (a) and results obtained (b)

6. DISCUSSION AND CONCLUSIONS

A consistent method of producing scaffold devices with high aspect ration has been demonstrated, with a detailed analysis performed on the influence of the machining parameters on the hole quality. The hole quality has been inferred indirectly by measuring the pull-out force required to remove the cast pattern from the mold. Unsurprisingly the best hole quality was found to result from low feed rates and short pecking cycles, although the influence of spindle speed was less predictable – increasing the spindle speed at these low feed rates actually increased the pull-out force required. The precise implications of the findings reported will depend on factors outside the scope of this paper, such as the influence of the roughness of the cast pillars on the scaffold performance, and the manufacturing costs. However, the information derived in this work will usefully inform any manufacturing decisions as well as providing fundamental insight into the process.

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