Hybrid machining of P20 die steel masters for the development of polymer-based microfluidic devices

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Abstract

Compared to traditional machining processes, a hybrid manufacturing process consisting of mechanical and chemical techniques is advantageous in maintaining dimensional accuracy, surface quality, and form. Hybrid micro-machining methods are considered beneficial in fabricating microfluidic devices as the traditional processes are costlier and time-consuming. In the present work, experiments on P20 die steel are carried out, and the finished products' dimensional accuracy and surface quality are analysed. The dimensional accuracy on the electropolished channel is deterministic as the burrs produced on the edges during micro end milling are removed in the electropolishing process. In the case of surface features, the peak to valley height (R_t) was found to reduce significantly. However, the average surface roughness (R_a) of the finished microchannel was increased when electropolished. Lower R_t value hinders the bacterial growth rate as the breeding sites for the bacteria are curtailed. In this work, 500µm wide microchannels are electropolished to remove the burr on the edges and to reduce the R_t value on the surface. The pre-electropolishing R_t roughness of 13.07µm is reduced to 10.06µm after electropolishing. The microchannels are characterised for their roughness and geometrical tolerance. The geometry and surface roughness determine the fluid flow pattern, and this relation is explored to functionalise the surface for flow separation. The flow separation in the expansion-contraction channels is studied to evaluate the effectiveness of the device.

Keywords: Hybrid machining, micromachining, polymer devices, microfluidics, roughness, microscopy, die casting, peak to valley roughness.

1. Introduction

Microchannels are fabricated in various configurations, elaborately described in Chamka et al. [1]. The authors have done extensive work to determine the configurations of geometries, including rectangular, rib-rectangular, parallel plates, circular and trapezoidal cross-sections. The effect of these geometries on the fluid flow characteristics, the heat and mass transfers, cohesive and adhesive forces acting were reviewed. In an investigative study [2], the effects of the diameter of microchannel on the pressure drop were studied; the experiments show that the microchannels with smaller diameters agree with the literature, whereas the ones with the larger diameter have some interference. Microchannels can be straight [3], and they can be tapered as written by Chen et al. [4].

When we consider the conventional finishing processes like surface grinding, profile grinding, mechanical polishing, and buffing process, residual thermal and mechanical stresses are induced in the sample being finished. As these processes involve the shearing of the material, heat generation can be visualized on the surface. In the case of the thin miniaturized components, this heat plays a critical role as it affects the behaviour of the surface. The surface roughness, in turn, surface energy, is affected by the heat being generated by the process. As an alternative, to avoid the ill effects of heat on the surface behaviour, electropolishing is developed.

Electropolishing is a highly preferred process in enhancing the aesthetic character of stainless-steel components. High-quality, glossy and smooth surfaces are achieved using the EP process. Electro-polishing is an effective method to achieve suitable quality surfaces, especially on free form surfaces.

Finishing free-form surfaces at the microscale is a challenging process since the dimension of the features are smaller than the capability of the grinding tools. The elements with dimensions in the order of a few micro-meters can hardly be ground with the traditional micro-grinding process. Electrochemical grinding, ultrasonic grinding and various other techniques have been found in the literature. But electropolishing proves to be a promising alternative for the mentioned processes. Electropolishing traditionally uses a chemical bath or an electrolytic solution. The device to be electropolished is made the anode, and a graphite rod or a dummy metal piece is made the cathode. A calculated amount of current is passed through the circuit. When the electrons flow through the circuit, the ions on the anode's surface get oxidised, which results in the smoothening of the surface, hence increasing the surface finish of the workpiece. The tips of the surface peaks act as the active centres for charge flow resulting in the non-uniform dissolution of the material. Hence, the tips of the surface peaks get rounded off, and the R_t value of the electropolished surface is comparably lower than the just machined surface [5][6].

The irregularities in surface features act as a barrier for the fluid particles when viewed at microscales. The peaks and valleys visualized in the surface topography can act as barriers to the fluid flow. The pattern can be uniform or non-uniform; both patterns play a significant role in the fluid flow pattern [7][8]. The motion of particles due to the non-uniform features in the microchannels has been explained by Shamloo et al. [9]. These find application in the separation of multi-object flow and multiphase flow. The separation of particles based on the geometry and the surface nature of the channels is very significant in analysing the constituents of mixed fluids [10].

Groundwater is categorized by its constituent elements. It is rendered hard if the bicarbonates are present in it, and it is rendered poisonous if arsenic or any other such elements are present in it. Various tests are performed to determine the elements present in water, and ample time and resources are invested. When a microfluidic device is involved, the processing is minimalized, and the resources and time of evaluation are minimized. Microfluidics and microfluidic devices play a significant role in this regard.

Quality and robustness of the microfluidic devices are the utmost characteristics to be considered when the fabrication of these microdevices is considered. In the mass fabrication processes like micro-milling [11], hot-embossing [12], die casting, soft photolithography, injection moulding, the quality of the masters is very essential, as they replicate themselves on polymer-based plastics. Biocompatibility and transparency are crucial in the development of these devices. Polymers like polymethyl methacrylate (PMMA), cyclic olefin copolymer (COC), polycarbonate (PC), and polydimethylsiloxane (PDMS) are the most preferred polymers [13]. The P20 die steel masters are fabricated using micro end milling and further electropolished to obtain appropriate surfaces in the current work. With those masters, PDMS devices are fabricated.

2. Experimentation

2.1. Fabrication of masters for Microchannels

The workpiece considered for the experiments is P20 grade die steel. The properties are detailed in Table 1. Die steel is considered for the experiments because of its availability, machinability, and resilience during the die casting process.

Table 1 Properties of P20 Die Steel

Properties	**Metric**
Density (g/cc)	7.85
Hardness, Rockwell C (HRC)	30
Tensile strength (yield) (MPa)	827-862
Tensile strength (ultimate) (MPa)	965-1030
Thermal Expansion $/^0C$	12.8e-6

The P20 steel is initially milled to dimensions of 60x70mm. The upper surface was ground to obtain a high surface finish as it forms the surface of the finished microchannels. The processing was done to the workpiece to mount on the linear stages of the Miniaturised machine tool and the 5-axis CNC ultraprecision machine as shown in Figure 2 (a).

Thirteen straight columns 0.5mm wide and 30mm in length and two single inlet triple outlet devices are machined using a 5-axis CNC ultraprecision machine. The master and the PDMS device are shown in Figure 1.

2.2 Fabrication of polydimethylsiloxane (PDMS) devices

PDMS devices are fabricated by the normal process. Initially, the PDMS medium and catalyst are mixed in the ratio of 10: 1.5 by volume. The mixture is mixed for 3 minutes. Degassing of the mixture is carried out for 90 minutes; this involves keeping the mixture in a desiccator, and a unit bar vacuum is applied. By this process, the microbubbles of air trapped inside the mixture float to the surface. Vacuum is released such that the mixture is free from air bubbles. The master is cleaned with acetone, and a thin coat of release agent is applied. The greased master is placed on a level platform, and the prepared mixture of PDMS is poured onto the master from one end of the master. The master with the PDMS solution poured on it is placed in the desiccator for 12 hours at room temperature (27^{0}C). The assembly is kept in a desiccator to be free from dust and other airborne impurities.

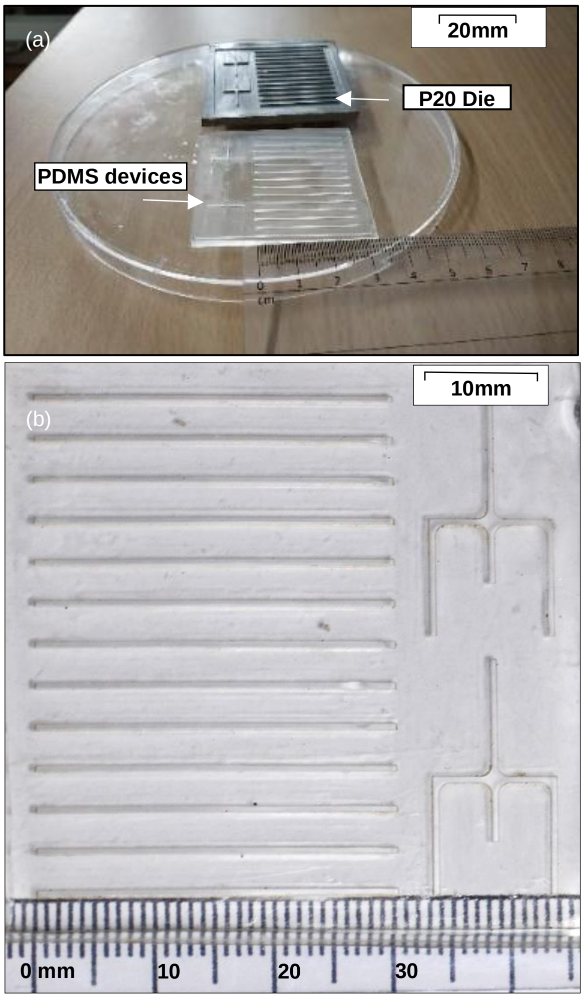

Figure. 1 (a). The die steel mould and the PDMS chip with the straight micro-channels (0.5*0.5*30mm). (b) The PDMS chip bonded onto the polycarbonate glass substrate.

2. 3. Electropolishing of the master

A chemical bath of phosphoric acid and sulphuric acid in the ratio 1:1 by volume and then diluted to 50ml. The master is made the anode, and a graphite rod is made the dummy. The parameters used for electropolishing are listed in Table 2 and the arrangement of the apparatus is shown in Figure 2 (b) and (c).

Table 2.2. Parameters for electropolishing

Electrolytic bath	H_2SO_4 + H_3PO_4 (2:2ml) in H_20
Volume (ml)	50
Temperature (^{0}C)	27
Electrode gap (mm)	50
Current (A)	0.75
Voltage (V DC)	6
Time Period (min)	5, 15, 20, 25, 30, 35, 40

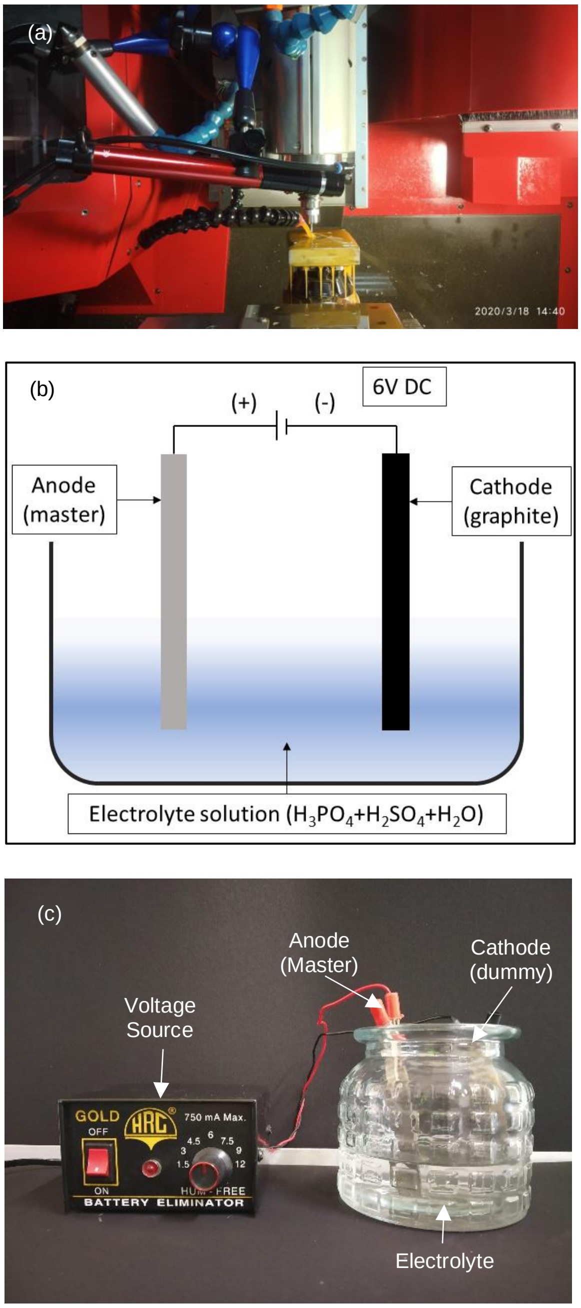

Figure 2. (a) Micro end milling on 5-axis CNC, (b) schematic representation and (c) setup for the EP.

Electropolishing of the calibration strip is carried at various time intervals. The graph of the surface roughness variation with time is as shown in Figure 3.

From Figure 3, it is seen that the least R_t value is achieved at 40 mins; hence, the micromachined master is electropolished for 40mins. The PDMS moulds are fabricated with the electropolished masters as described in section 2.2.

3. Results and Discussion

3.1 Dimensional Analysis

Dimensional analysis is carried out using an inverted microscope, and the width of the channels was found to vary from 455µm to 480µm. From the images, it is also evident that the burrs are found on the edges of the end milled walls. Walls up to 15-20µm wide from the edges are deformed with burrs on both the edges of the walls. The burr is more evident in the 3D surface topography plots. The edges of the electropolished walls are smoother in comparison with the just machined walls. The contrast of the walls in both cases can be seen in the images shown in Figure 4.

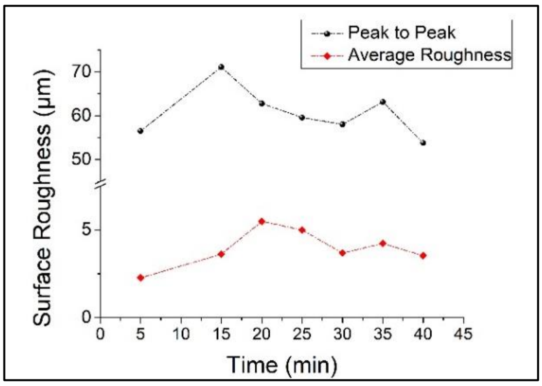

Figure 3. Variation of surface roughness with the duration of the Electropolishing process.

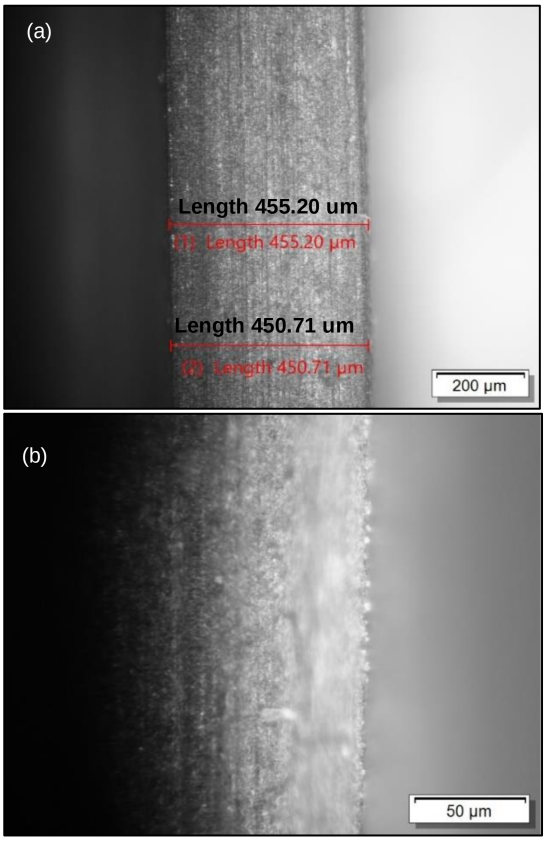

Figure 4. (a) and (b) shows the microscopic images of the just machined walls of masters.

3.2 Surface Analysis

The surface of the masters is analysed using the vertical scanning interferometry technique in the Veeco 3D profiler. The scan length of 50µm is chosen with 687 frames, and the size is set to 736x529 pixels. The 3D topographical plots of the walls are shown in Figure 5. On analysis of the 3D plots, it can be seen that electropolishing increases the average roughness (R_a), and the total height of the roughness profile (R_t)

is reduced. The 3D plot of the surface topography is shown in Figure 5(a). It validates the presence of burrs on the wall edges in the masters, the dimension of the erroneous section of the wall can be seen to be 20 to 25 µm. The peak to peak roughness at a cross-section was taken, and it is found to have reduced from 13.07 µm to 10.06 µm, evident in Figure 5 (b) and (d).

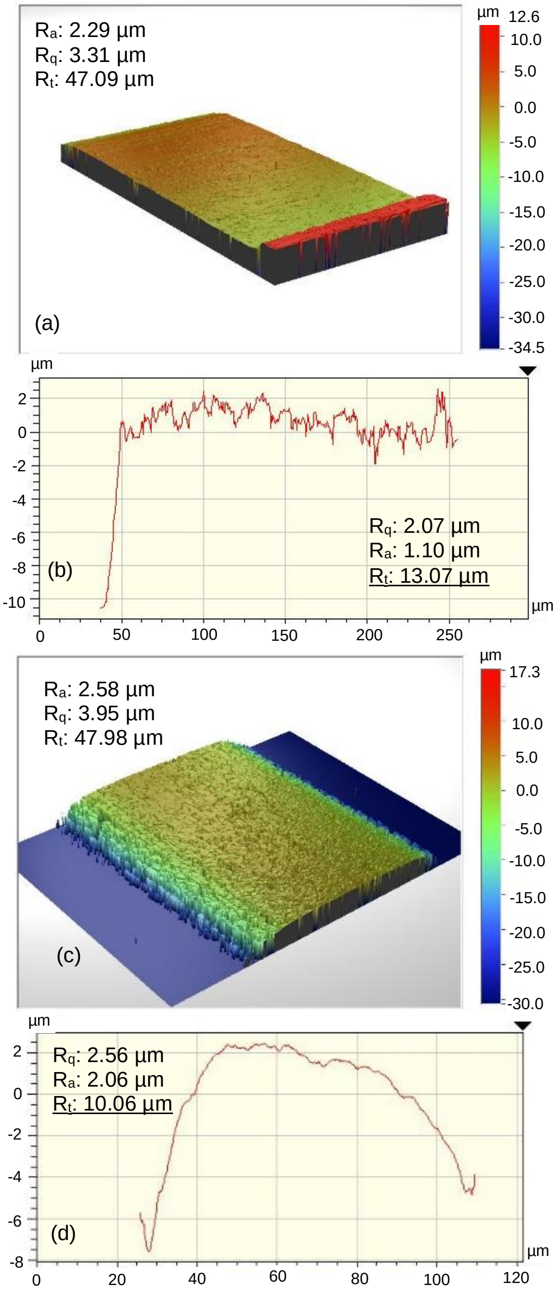

Figure 5. a) 3D and b) 2D surface topography before electropolishing and c) 3D and d) 2D topography after electropolishing process.

4. Conclusions

The hybrid machining technique proves to be a good alternate for fabricating masters for microdevices compared to the existing methods. The process is advantageous in manufacturing high-quality surfaces with higher precision. This technique is very significant in applications that require lower R_t values, as in biomedical devices. The biomedical devices shouldn't have active sites for bacterial growth. A higher R_t value results in higher bacterial accumulation.

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References

[1] A. J. Chamkha, et al., "Review on the nanofluids applications in microchannels - A comprehensive review", Powder Technology 2018, 332, 287-322

[2] G. M. Mala, et al., "Flow characteristics of water in microtubes", International. Journal of Heat and Fluid Flow 1999 20 (2)142–148.

[3] S. M. Hampson et al., "3D printed microfluidic device with integrated optical sensing for particle analysis", Sensors and Actuators B 2018, 256, 1030-1037

[4] K. X. Cheng et al., "Thermal hydraulic performance of a tapered microchannel", International Communications in Heat and Mass Transfer 2018, 94, 53-60.

[5] P. Pendyala, et al., "Evolution of surface roughness during electropolishing", Tribol Lett 2014, 55:93–101

[6] T. Macia, et al., "Parameter selection for electropolishing process of products made of Copper and its alloys". Arch. Metall. Mater. 2014, 62, 3, 1443-1447.

[7] T. Motegi, et al., "Effective Brownian Ratchet Separation by a Combination of Molecular Filtering and a Self-Spreading Lipid Bilayer System", Langmuir, 2014, 30, 25, 7496–7501.

[8] A. v. Oudenaarden, et al., "Brownian Ratchets: Molecular Separations in Lipid Bilayers Supported on Patterned Arrays", Science New Series, 1999, Vol. 285, No. 5430, pp. 1046-1048

[9] Amir Shamloo, Ali Mashhadian "Inertial particle focusing in serpentine channels on centrifugal platform", Phys. Fluids (2018) 30, 012002 1 -13.

[10] T. Maruyama, et al., "Liquid Membrane Operations in a Microfluidic Device for Selective Separation of Metal Ions", Anal. Chem, 2004, 76, 4495-4500.

[11] G. Perozziello, et al., "Microfluidic dialysis device for complex biological mixture SERS analysis" Microelectronic Engineering 2015, 144.

[12] Y. Arcot, et al., "Nickel stamp fabrication using SU-8 lithography for micro hot-embossing serpentine microfluidic channels", International Journal of Precision Technology, 2019, Vol.8 No.2/3/4, pp.298 – 311.

[13] J. Friend, et al., "Fabrication of microfluidic devices using polydimethylsiloxane", Biomicrofluidics, 2010, 4(2), 026502.