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A MINI REVIEW ON THE EFFECTS OF SURFACE ROUGHNESS IN MICROFIUIDICS CHANNELS

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ABSTRACT

The effects of surface roughness at low Reynolds numbers are more pronounced and critical in microchannels due to the relative size of roughness to channel dimensions. Surface roughness in microfluidic channels originates from the machining process during fabrication. This review examines how surface roughness, resulting from various manufacturing processes, influences the performance of microfluidic devices. Different patterns of surface roughness generated through techniques such as photolithography, etching, precision machining, and 3D printing are highlighted. These techniques yield distinct surface characteristics that affect critical microchannel properties, including fluid flow, pressure drop, and stress distribution. In addition to that, specific fabrication methods can minimize surface roughness, enhancing the performance of microchannels for applications in diagnostics, lab-on-a-chip systems, and small-scale heat exchangers are addressed. The review provides insights into selecting optimal fabrication techniques to achieve desired performance characteristics in microfluidic devices.

Keywords: *Surface Roughness, Microchannels, Fabrication Methods, CNC precision machining and 3D printing.*

1.0 INTRODUCTION

Handling and controlling small quantities of fluid under sub-microliter volume has been in great demand in recent years, primarily in the field of biomedical, environmental and micro-energy harvesting. The Lab-on-a-Chip (LOC) is a miniature device that integrates multiple laboratory functions onto a single chip, exemplifying advanced applications of microfluidic principles [1]. According to Lim *et al.,* these devices hold promise for application in microfluidics in the context of rapid, portable, and cost-efficient analysis of biological samples [1]. Microfluidics circuits are important in these devices because they allow for precise manipulation of biological processes at the cellular level, and they allow miniaturization, which is very important as most of the devices being developed today need to be compact [2]. Also, microfluidics has found significant utility in microheat exchangers. The high surface area to volume ratio of microchannel enhances heat transfer rates, making microfluidic heat exchangers highly efficient for thermal management in various applications [3].

The current microanalytical chemical and biological point-of-need diagnostic test systems, are still in the research and development stage and thus microfluidics is also in the emerging market class [4]. This means that due to the capability of microfluidic systems to handle smaller samples,

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chemical and biological analytical techniques like high-temperature superconductor (HTS) can find usefulness in microfluidic systems. In the pharmaceutical industry, HTS is used early in drug discovery to screen. Thus, millions of potential therapeutic compound candidates are being investigated to evaluate their performance against specific disease biomarkers [5]. Most of the current HTS designs include one or more active robotic systems to select and transfer samples to various testing platforms, such as absorptiometry, or fluorometric systems [6]. Securing these sampling tools at the bottom of each well of multi-well plates allows the sampling of multiple wells simultaneously [7]. Microfluidics also known as lab on chip (LOC) in biochemistry and sample preparation for the detection and movement of fluids through microchannels in a microfluidic device [8]. By applying biochemical principles, and cellular features, and by controlling relative volume, microfluidics will enhance medicine performance [9]. LOC devices offer strategic advantages including reduction and reagent leading to femtomole to attomole sensitivity. This is particularly important because many biomolecules in biological fluids exist at very low concentrations [10]. As previously mentioned, microfluidic devices are well-suited for analyzing small sample volumes [4,11]. Although it is a relatively new field in biochemical analysis, high diagnostic accuracy, gene analysis capabilities, and versatility of microfluidics point to a promising future for this technology.

The fluid flow pattern in the microchannel is predominantly laminar where Reynold’s number is typically less than 100. Although the effect of surface roughness in macro-scale channels may be minimal due to the large channel dimensions relative to the roughness, it becomes significant at the microscale. In microchannels, surface roughness increases friction and pressure drop, altering velocity profiles, enhancing mixing and heat/mass transfer, and potentially affecting flow stability and efficiency. These effects are critical in designing and optimizing microfluidic devices for various applications. This is even more important for the flow within the microchannel due to the inlet and outlet being prolonged when modelization of the surface roughness. Research by Peng *et al.,* reported that the flow of liquid or gas through the microchannels having spherical-shaped surface roughness, causes disturbances in the fluid flow, leading to variations in velocity profiles and phase change of the fluid [12]. Varying levels of surface roughness were reported to affect the heat transfer efficiency and flow behaviour. A study of mixed convection effects on the total heat transfer in rectangular microchannels by Mandev & Manay, revealed that increasing the surface roughness enhances heat transfer by disrupting the laminar boundary layer and hence increases the pressure drop due to higher friction [13]. Lalegani *et al.,* studied the effect of fluid flow across different surface roughness configurations. Four-channel configurations which are rectangular, trapezoidal, elliptical, triangular and complex geometrical shapes were involved in the study [14]. They reported that increasing the height and size of the roughness elements led to higher pressure drop and friction factor values. Conversely, as the distance between roughness elements increased, both the pressure drop and friction factor decreased. The thin layers of liquid or gas that are in contact with the channel walls are the most affected by surface roughness, potentially influencing the entire flow profile. This film is also strongly closely linked to the no-slip boundary condition, where fluid motion decreases at a solid surface. This condition is governed by the surface roughness at the wall which is the contact angle and that affects capillary phenomena [15]. Thus, this is a crucial factor, especially in designing two-phase flows where bubbles of liquid or gas are confined in the channel or flow along the channel wall. Additionally, solid particles or machining residues within the channel can further disrupt the established flow patterns [16,17].

In summary, the effects of surface roughness are more pronounced and critical in microchannels due to the relative size of roughness to channel dimensions and the prevalence of laminar fluid flow profile. Surface roughness in microfluidic channels originates from the machining process during fabrication. Achieving precise control of surface roughness at the microscale in practical applications poses significant challenges. Understanding and controlling the surface roughness is crucial for optimizing the performance of microfluidic devices and ensuring consistent and reliable operation. In the subsequent section, various microfluidic device fabrication methods and their associated average surface roughness magnitudes are highlighted.

2.0 MICROCHANNEL FABRICATION METHODS AND SURFACE ROUGHNESS

2.1 Photolithography and Etching

Photolithography is a highly precise technique that involves numerous processes in the production of micro-devices for the technology industry. [18]. It involves a multi-step process to develop patterns on a photoresist. The basic fabrication process of microfluidic channels through photolithography includes multi-steps. The basic steps involve the preparation of a substrate; photoresist deposition or nanoimprint photoresist on the substrate, and the process of development, baking, and curing respectively [19]. In the end, the desired pattern is achieved by the deliberate removal of the photoresist in certain regions. The manufacturing procedure proceeds by transferring the design onto the glass or silicon substrate by deep etching, which leads to the creation of the microfluidic channel [11]. The thick photoresist (SU8) and dry film photopolymer (DFR) are a negative tone photoresist where the exposed part to UV rays becomes cross-linked and the unexposed part will be washed away during development. This type of photoresist has been traditionally used to develop microfluidics devices and typically has a surface roughness Ra throughout the depth of 151.1 nm [20]. The thin film photoresist on the other hand is used as a template for defining patterns that are transferred onto the substrate typically silicon or glass wafer [21].

Figure 1 illustrates the the photolithography process for fabricating microfluidic devices by Alrifaiy *et al.,* [22]. First, a layer of photo-resist is applied by spinning onto a semiconductor substrate (A). This layer is then exposed to UV light through a high-resolution mask (B). A post-exposure bake follows, after which the photoresist selectively dissolved using chemicals, leaving either negative or positive mould (C).

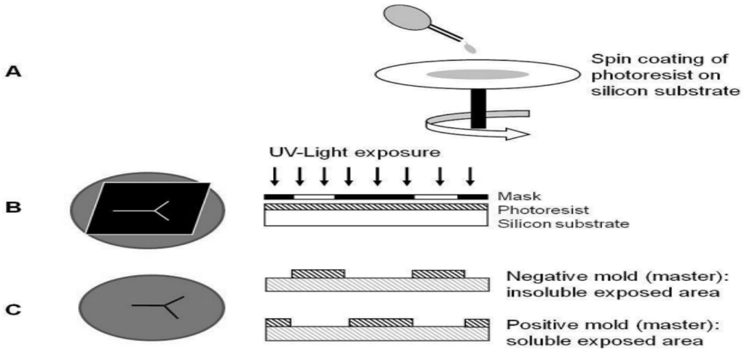

Figure 1: Shows the photolithography process applied in the manufacturing of microfluidic structures [20]. Adapted from Ahmed Alrifaiy, Olof A. Lindahl, and Kerstin Ramser, "Polymer-Based Microfluidic Devices for Pharmacy, Biology and Tissue Engineering," Polymers, 2012, 4(3), 1349-1398. Licensed under CC BY

Etching methods are important in microstructure devices because they generate micro channels and other features that regulate and dispense fluid. Both wet and dry etching are utilized in the manufacturing process. These two methods have different characteristics and are suitable for various applications. Thus, academics often employ these approaches to improve complex microfluidic systems for various purposes such as disease diagnostics, chemical analysis, and environment monitoring. The ability to combine multiple etching techniques allows for the development of microfluidic systems to meet functional requirements and performance metrics [11].

2.2 Dry Etching

Dry etching as a term is used to categorize a method that utilizes plasma, chemically reactive gases, or volatile substances in the formulation of vapours to perform the etching process on the substrate surface. Thus, it refers to etching that is brought about by a wide array of stimuli or the processes that they cause. Dry etching is popular in the field of semiconductors [23]. In microfluidic, the most common dry etching techniques include reactive ion etching (RIE), inductively coupled plasma

(ICP) etching, and deep reactive ion etching (DRIE), as well as other etching types which include optical dry etching and ion or electron methods of writing [24]. The etching characteristics, rate anisotropy, temperature, and time play a crucial role in determining the quality and precision of the microchannel after etching thus, these factors directly influence the surface roughness which in turn affects the flow rate of the various fluids and overall characteristics of the fluids inside the microchannel structure [25,26]. The surface roughness in ICP depends on several factors such as the power and the etch rate with the roughness typically between 500 nm to 1000 nm [27].

2.3 Wet Etching

Wet etching is one of the simplest and most versatile chemical etching techniques widely used in microfluidic device fabrication. Its high selectivity in the fabrication of microfluidic devices is also very high similar to chemical compatibility as well as the etch depth and restorable features [28]. In the case of the wet etching process, it is highly selective and is crucial for creating the solution, so it minimizes the noise generated by the etching of different layers [29]. Wet etching is a cost-effective method because the process equipment is simple and the solution can be recycled [30]. Conversely, the wet etching technique is slower on the order of tens of nanometers per second. Similarly, liquid irritation caused by the liquid etchant can compromise the etch stop layer, failing which etching leads to non-uniform etching and significant variation in etch rate. This ultimately affects the impacts of 'depth' or micro-scale structures [31]. The typical surface roughness Ra, for wet etching is 50 nm to 200 nm [32,33]

Photolithography is a technique that has been highly developed for producing large numbers of integrated circuits and microfluid chips [34]. In microfluidics, is essential for defining important for the fabrication and definition of the micro geometry of the structures as microchannels on the polymers, glass, and silicon base [11]. However, while widely used, it can lead to microchannels with rough surfaces on the substrates, which negatively impacts the microchannel's performance and capabilities [4].

The study of Kanioura *et al.* and Chiang *et al.,* both stated that photolithography combined with oxygen plasma etching to a considerable level affects the surface roughness of the microchannels [35,36]. This is because surface roughness negatively influences the velocity of fluid flow and potentially damage cells within the microchannels [35,36]. Hence, it is crucial to find a way of minimizing surface roughness [12]. The surface roughness measurement was investigated using Atomic-Force Microscopy (AFM), and it was manifested that wet etching in an isopropanol or ethanol mixture provided enhanced surface smoothness over the microchannels as compared to the dry etching using oxygen plasma [37]. Specifically, the wet etching process lowered reduced average surface roughness by almost seven times compared to dry oxygen plasma etching [38].

Thus, the results of his work indicate that etching the microchannel surfaces using tetramethylammonium hydroxide (TMAH) solution, isotopic smoothness than using potassium hydroxide (KOH) solution [39]. Moreover, the degree of etching time has an impact on roughness because when the time for etching is prolonged, then the system will end up with a rough surface [39,40]. Studies have also investigated the effects of Phosphoric acid (H_3PO_4) and Hydrofluoric acid (HF) etching solutions on the surface roughness of microchannels [41,42]. For anisotropic etching of the Chromium (Cr) / Gold (Au) thin films, the patterning was done while for the isotropic etching the patterning was done using the H_3PO_4 solution. The recommendation of H_3PO_4 proved better anisotropic etching and better surface of the microchannel as compared to HF state by the analysis of their presented papers showed that [41,42]. However, it was observed that the etching time when using the H_3PO_4 and HF is longer, resulting in comparatively rougher than those achieved when using TMAH and KOH [39,40,43].

Hence, the application of wet isotropic etching liquids on the formation of micro-channels is capable of providing a smoother finish than in the case of dry etching as mentioned by Hakke *et al.,* [44]. Along this line, in the study of [42], the author pointed out that because of the etchant used as H3PO4, the smoothness of the microchannel surface turns out to be better than when using the etchant of HF even with the undercutting effect. Also, the comparison between etching time and surface roughness showed that a higher etching time means a higher surface roughness and compared the obtained patterns in this study with the patterns in the works of [39,40,43].

2.4 CNC Precision Machining

Computer numerical control (CNC) precision machining is used extensively for manufacturing moulds in micro injection moulding for volume manufacturing of micro and nanometer dimensional parts [45]. These microchannels in the automotive components manufactured by CNC precision machining can also be adapted to use in different sectors as fluid control parts. For instance, microchannels are employed as base plates in fuel cells and heat exchangers and applied in the transportation of fluids in inkjet printing [46,47]. CNC precision machining is favoured because of its high precision, facility of the manufacturing process, and cost-effectiveness [11].

The use of CNC precision machining leads the call for mini and universal CNC machines, as well as special-purpose CNC tools. CNC precision machining is attributed to the merits of automated control, high accuracy in dimensions, and high repeatability in production in cases of mass production [48]. Wire Electrical Discharge Machining (EDM), can be used to produce different elongated shapes including circular, rectangular, or 'U-shaped. Under the given criteria, the choice of the finishes machining processes is geared towards high efficiency and accuracy [49]. The fabrication of the micro-grooves and microchannels of such plastic chips is done by employing high-speed micro end-milling, wire EDM, and standard CNC milling accelerating the creation of injection moulds of the polymer microchips [50].

The use of CNC machining makes it possible to machine designs with intricate 3D micro-channel architectures and connect them with other machined geometries on the same workpiece. Four basic categories of CNC machining processes milling and drilling, turning, mechanical grinding, and EDM are commonly employed to manufacture microscale features. Milling generally is the fastest CNC machining method for parallel and step-paid microchannels, while the drilling technique, point-to-point direct cutting is suitable for the simple straight microchannels [51].

2.5 Surface Roughness on CNC Precision Machining Process

Surface finish is the specialized area of the design and manufacturing field. It can influence the fit, function, contact fatigue, wear, and overall performance of the microchannel [52]. The surface with the least surface roughness should be able to account for the least areas that form and waviness deviations [53]. However, micro-milling a common method for producing microfluidic devices is that it leads to some difficulties in surface finish. This is in support of the findings by Kumar *et al.,* and Aurich *et al.,* which both highlighted that surface roughness remains the biggest challenge when manufacturing microchannel [54,55]. To address this problem, choosing and selecting materials to apply in the project. Research by Kumar *et al.,* and Yousuff *et al.,* all made alterations to the cutting parameters in the process of fabricating this microchannel [54,56]

This issue may be shown in Table 1, displays proof of test findings for different cutting settings and roughness of the surface (R_a). Figure 2 shows the verification test by Yousuff *et al.,* with certain random cutting settings and with a fixed tool diameter size of 200 μm labelled as T1 [56].

Table 1: The outcomes of the confirmation test concerning various parameters related to cutting parameters with a fixed tool diameter size of 200 μm labelled as T1 including surface roughness (R_a) [56]. Adapted from Caffiyar Mohamed Yousuff, Mohd. Danish, Eric Tatt Wei Ho, Ismail Hussain Kamal Basha, and Nor Hisham B. Hamid, "Study on the Optimum Cutting Parameters of an Aluminum Mold for Effective Bonding Strength of a PDMS Microfluidic Device," *Micromachines*, 2017, 8(8), 258. Licensed under CC BY

Test	Spinning Speed (RPM)	Feed Rate (mm/min)	Depth of Cut (μm)	Tool	Predicted Value of *Ra* (μm)	Experimental Value of *Ra* (μm)
1	20000	100	10	T1	0.23	0.219
2	10000	50	15	T1	0.21	0.211
3	15000	100	10	T1	0.27	0.254

Test	Spinning Speed (RPM)	Feed Rate (mm/min)	Depth of Cut (µm)	Tool	Predicted Value of *Ra* (µm)	Experimental Value of *Ra* (µm)
4	20000	150	5	T1	0.215	0.216
5	20000	50	15	T1	0.25	0.242

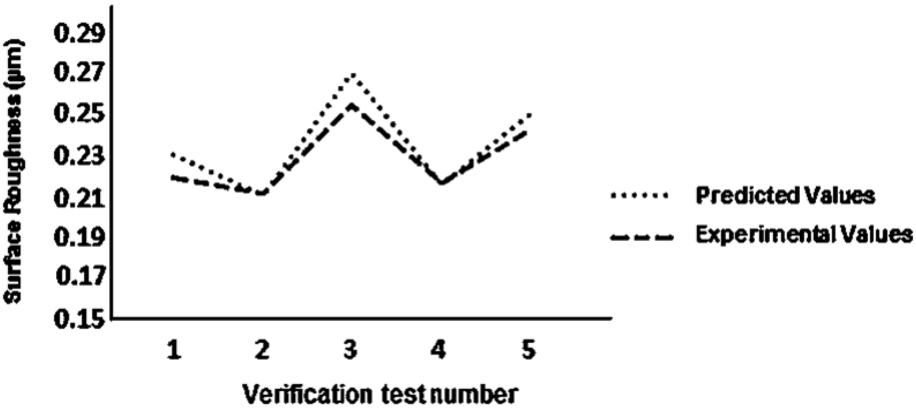

Figure 2: Depicts the verification test with some random cutting parameters [56]. Adapted from Caffiyar Mohamed Yousuff, Mohd. Danish, Eric Tatt Wei Ho, Ismail Hussain Kamal Basha, and Nor Hisham B. Hamid, "Study on the Optimum Cutting Parameters of an Aluminum Mold for Effective Bonding Strength of a PDMS Microfluidic Device," *Micromachines*, 2017, 8(8), 258. Licensed under CC BY

From the study made by Yousuff *et al.,* it was found that improvement of surface roughness in the machining of the microchannel is achievable as the cutting speed increased while decreasing the machine feed rate and depth of cut.

2.6 Three-Dimensional (3D) Printing

In the rapidly changing Industry 4.0, Three-Dimensional (3D) printing, or three-dimensional printing, is a newly developed technology that is progressively more trustworthy and commonplace since it is simple to operate, highly efficient, and affordable to create [57]. 3D printing also known as Additive manufacturing (AM) also realizes products through the additive process of making an object layer by layer based on a computer-generated digital file [58]. As described by, Regassa Hunde and Debebe Woldeyohannes, the 3D printing process typically begins with a conventional 3D printer function which can be obtained from creating the 3D model out of the computer-aided designing (CAD) data which is available from the generated 3D scans or the imagery data for medical use which can be used to obtain the 3D digital information [59]. The computer slices this model obtained using CAD slice the model into thin layers which are each represented horizontally as layers of the 3D model. It also discretely moves up and down to place material into the layer on the 3D printer's print bed. Layer by layer, accumulates and at the end of a process, forms a 3D object similar to digital data. However, cleaning and post-processing are essential to complete the above-stated 3D printing of the object are illustrated in Figure 3.

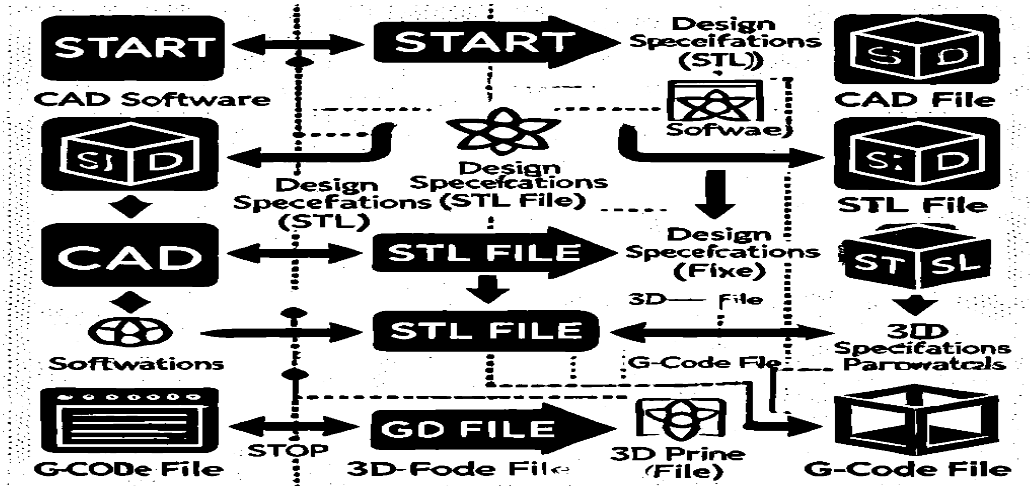

Figure 3: illustrates the process of 3D printing

2.7 Surface Roughness on 3D Printing

One of the difficulties that can be incorporated during fabrication of microchannel using 3D printing is surface roughness. Several factors that influence surface roughness in 3D printed parts such as printing temperature, speed rate of printing, and layer thickness were indicated to affect surface roughness on 3D printed goods [60]. Furthermore, Shirmohammadi *et al.,* stated that the surface roughness of the part can be as low as 11. 319 µm till 15. 8 µm through the use of both the particle swarm optimization and the artificial neural network optimization algorithms [60]. Apart from that, in the fused deposition modelling (FDM) process, temperature is one of the critical factors that affect the parts. It has also been reported that an increase in the temperature can reduce the number of pores in printed components [61]. For example, high temperatures can only solve the problem with the given gap. Kattinger *et al.,* also mentioned that the impact of the print speed itself is accurately reproduced in the irregularities of the thin wall area of the product and the high flat areas of the part are tighter and raised compared to the areas near the plates [62]. However, another aspect of the printing temperature is the flow behaviour, by this approach, the temperature will affect the flow from the hot extruder tip onto the printed surface [62]. The last characteristic of the printing job is layer thickness. Although it is revealed that the reduction in layer thickness enhances the processing time, it doesn't always guarantee a smoother surface finish [63].

3.0 RESULTS AND DISCUSSION

The diverse studies on surface roughness in microfluidic devices can be grouped into three primary clusters. The first cluster addresses fabrication methods and their role in surface irregularities. The second cluster focuses on the impact of surface roughness on fluid flow characteristics, which can disrupt laminar flow by creating localised flow disturbances and increasing frictional resistance. This disruption leads to pressure drops along the channel. This category considers the configuration of surface roughness, particularly distinguishing between sidewall and bottom surface irregularities. These two clusters have been discussed in detail in previous sections. The third cluster encompasses the application-oriented effects of surface roughness. To emphasize the importance of surface roughness in microfluidic devices, this section highlights two critical engineering applications: its impact on heat transfer efficiency and its effect on cell growth rates in cell biology applications.

The effect of surface roughness on the thermal performance of microfluidic devices is evident in applications such as microheat exchangers and cooling devices used for thermal management. Numerical studies on the influence of wall surface roughness in microchannels indicate that roughness can enhance thermal performance and resistance under laminar flow conditions. Lin Guo et. al. conducted comparative research between 2D and 3D wall surface models and revealed that while both dimensions illustrate roughness effects, the 3D model more accurately represents the real rough surface's impact on fluid flow and heat transfer. This study underscores the limitations of 2D models in capturing complex rough surface interactions in microchannels, where the 3D model provides a more comprehensive analysis [64]. Certain microchannels with engineered roughness in liquid cooling applications demonstrate improved thermal-hydraulic performance compared to smooth channels. Yong Guo et al.'s simulation on flow boiling in rough-surfaced microchannels showed that surface irregularities can enhance heat transfer efficiency in liquid cooling, a vital attribute for managing high heat flux applications [65]. Further, counter-flow microchannel heat exchangers (CFMCHEs) also benefit marginally from rough surfaces. A study by Ali et al. examined thermal and hydraulic performance in microchannels with varying geometries, finding that trapezoidal channels with rough walls slightly enhanced thermal performance but at a minor cost to hydraulic efficiency, indicating that surface roughness can optimize heat transfer for specific configurations [66]. In high-efficiency cooling systems, such as traction inverters, strategically designed surface roughness on pin-fin structures has proven effective. Luca Donetti and colleagues observed that increasing the roughness of pin-fin surfaces led to a pressure drop reduction between 4% and 11%, with only a minor thermal performance degradation of less than 2%. These findings indicate that surface roughness can balance thermal and fluid dynamic performance in critical cooling applications [67].

Surface roughness also plays an important role in cell biology applications. For instance, surface roughness can influence bacterial adhesion, crucial for designing surfaces that promote or inhibit microbial growth. Pandit and Samuel's work on PDMS-based microfluidic devices to study the effect of surface roughness on bacterial activity demonstrated that smoother surfaces with electropolished finishes (Ra = 2.29 nm) reduced bacterial attachment compared to rougher surfaces (Ra = 2.59 nm). This reduced anchoring capacity on smooth surfaces is likely due to fewer irregularities. Consequently, this makes it more challenging for bacteria to establish footholds. Such insights are valuable for developing polymer-based microfluidic devices in biomedicine, where controlling bacterial activity and cell adhesion are critical for creating artificial growth environments [68].

In general, the research on microchannel fabrication methods emphasizes the critical role of surface roughness in determining the flow characteristics within microchannels. This review identified key fabrication techniques, including photolithography, etching, CNC precision machining, and 3D printing. Each method produces distinct surface roughness, influencing fluid behaviour differently. For instance, wet etching results in smoother surfaces than dry etching, leading to more predictable fluid flow. CNC precision machining offers high accuracy and reproducibility, making it a preferred method despite concerns over surface roughness. These microchannels find applications in various fields, such as disease diagnosis, chemical detection, and environmental monitoring. Future efforts to improve microfabrication technologies will focus on achieving precise control of surface roughness, conducting complex multiphase flow studies in rough channels, and developing better visualization tools for microscale fluid dynamics. Such advancements will further expand the applications and effectiveness of microfluidic devices in numerous scientific and practical fields. Table 2 depicts the surface roughness values associated with different fabrication methods.

Table 2: The surface roughness values associated with different fabrication methods

Microchannel Fabrication Methods	Surface Roughness (R_a).
Photolithography	151.1nm
Dry Etching (ICP)	500-1000 nm
Wet Etching	50-200 nm
CNC Precision Machining	0.21-0.27 µm
3D Printing	11.319-15.8 µm

This table signifies the surface roughness of various fabrication techniques, which define their influence on the functioning options of microchannels. As illustrated, wet etching yields the smoothest surfaces, while 3D printing generally creates relatively rough surfaces. The unevenness of each method affects the movement of the fluids through microchannels. Choosing the correct fabrication techniques is crucial for the given purpose and for creating the desired surface roughness.

3.0 CONCLUSION

As concluding remarks, this review highlights surface roughness as a critical factor influencing fluid dynamics within microchannels, directly impacting pressure drop, friction, and flow consistency. Variations in surface texture stemming from different fabrication techniques significantly alter flow characteristics, especially at the microscale where surface effects are amplified. Methods such as photolithography, wet and dry etching, CNC precision machining, and 3D printing each yield unique roughness profiles, affecting the functionality and efficiency of microfluidic devices. Minimizing surface roughness is essential for applications like lab-on-a-chip systems, micro heat exchangers, and cell biology studies, where smooth channels ensure predictable flow patterns and affect biological cells' growth rate and surface adherence. Future work should focus on refining fabrication methods to achieve controlled surface finishes and further exploring roughness impacts on complex fluid behaviours, ultimately enhancing the design and reliability of microfluidic devices. In the future, efforts to enhance microfabrication technologies for precise control of surface roughness, complex multiphase flow studies in rough channels, and better visualization tools for the microscale fluid dynamics analysis

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