

Realizing Surface Amphiphobicity using 3D Printing Techniques: A Critical Move Towards Manufacturing Low-Cost Reentrant Geometries

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Abstract

Superamphiphobic surfaces are obtained by lowering the surface energy through changes in surface geometry. These changes can be designed on the surface, altering its wettability, in turn rendering it superamphiphobic. The main geometrical entities behind this phenomenon are reentrant geometries which prevents the solid-liquid interface tension from breaking, thereby resulting in contact angles greater than 150°. The science behind modelling and manufacturing of these reentrant geometries is well established apart from manufacturing them via extrusion based 3-Dimensional printing processes.

This review paper in identifying this scope, summarizes various characterization parameters for surface wettability followed by identifying the role of surface reentrant geometries to introduce superamphiphobicity in polymers. In defining the current state of research in this domain, this compendium identifies that extrusion based 3-Dimensional processes can successfully be used for creation of superamphiphobic surfaces. However, this usually involves addition of a secondary agent which diminishes the role of the surface reentrant geometry. Therefore, a clear route based on extrusion based 3-Dimensional printing of surface reentrant geometry to limit dependency on base substrate has not been fully explored. This opens avenues for testing of new filament-based polymeric materials like PVC and PETG, whose surface properties can be enhanced using reentrant geometries.

Keywords: *Reentrant Geometry, Superamphiphobicity in Polymers, 3D Printing, Wetting Angle*

1. Introduction

Developments pertaining to combined repellency against water and oil using surfactants dates back to 1980s [1]. However, it has been well established that a combination of surface texturing; which also results in changes to surface roughness, and modification of surface chemistry; to induce new interfacial properties, can be attributed as the formative principles behind modifying surface wettability [2–8]. Changes in surface wettability can result in the surface becoming superamphiphobic [9].

An amphiphobic surface is defined in terms of repellency against both polar (e.g. water) and non-polar (e.g. oil) liquids and one which forms a wetting angle (contact angle) that is greater than 90° with the liquid. Similarly, superamphiphobic surfaces comparable to superhydrophobic surfaces are defined in terms of the wetting angle being greater than 150° [10–13]. Superamphiphobicity is a result of low surface energy of the solid-liquid-vapor system formed at the surface [14,15]. Successful superamphiphobic surfaces also exhibit three more characteristics in addition to those listed above [16], these are a) a Low Contact Angle Hysteresis (CAH) to maximize liquid mobility [17], b) high critical

pressure value [18] over which the surface remains stable, and c) a high energy barrier to failure [19] which prevents the liquid from completely wetting the surface grooves.

The key point of this surface characteristic is that it is not material specific [20]. Therefore, based on the specific applications relating to self-cleaning [21], anti-fouling [22], anti-icing [23], anti-corrosion [24], drag reduction [25] and many others, superamphiphobicity may be introduced where metals, polymers and ceramics are used as the base substrates [26]. Another key area of application for superamphiphobic surfaces lies in the self-driving, anti-gravity unidirectional transport mechanisms [27,28] especially in the design of microfluidics transportation where pumping liquids using an external source may not be possible. This kind of surface modification plays a vital role in preserving and enhancing long-term utility of materials where surface coating is not an option and the intrinsic properties of base substrate are required [12]. Some polymers such as polycaprolactone (PCL) [29], polytetrafluoroethylene (PTFE) [30], Polydimethylsiloxane (PDMS) etc. [31,32] have functional groups which naturally exhibit superhydrophobic characteristic. However, where this may not be possible, surfaces can be selectively modified to exhibit self-cleaning behaviour [33–37].

As previously discussed, this requires adding distinctive modifications on the surface structure of the polymer which enables the polymeric chains to exhibit properties which may or may not be characteristic to them [38,39]. Numerous methods for their fabrication with wide ranging results are available throughout the literature [40–42]. While these methods are highly repeatable, and some can be transformed from lab-scale environment into full-scale manufacturing environment [43–45], their utility remains low due to the process complexity and difficulty in achieving complex surface geometries [13,46]. Therefore, new methods which can ease the difficulty in manufacturing of these complex features are being worked upon.

Additive Manufacturing or 3D Printing as it is commonly called, provides a cost-effective solution to the problem of fabricating complex surface geometries to induce superamphiphobicity, which is otherwise not possible with traditional manufacturing techniques[47–49]. 3D Printing techniques with their wide range of available materials[50], direct CAD to product translation and small setup requirements allow for creation of accurate and repeatable geometrical features which are a requirement of these newfound applications [51].

Despite recent advents in 3D printing techniques, the utility of extrusion based additive manufacturing processes remain high [47]. This is because of the ease with which process parameters for extrusion-based processes can be selectively modified for specific materials [52,53]. Due to the subsequent development in extrusion-based techniques, multiple polymeric materials of high commercial importance are readily available for use as a raw material [47,54,55]. With an understanding, that superamphiphobic interaction is not material specific, these extrusion-based techniques can be readily used to develop complex surface geometries on these materials for enhancement of surface properties.

To establish the utility of these extrusion-based 3D printing techniques for creating superamphiphobic interaction, we first begin with an understanding of the basic measurements for characterization of superamphiphobic surfaces. This is followed by defining the role of surface geometry to exhibit superamphiphobicity and how extrusion-based additive manufacturing processes have been successfully used for this purpose. The article concludes on findings from the literature for possible future work in this area.

To move this discussion forward, we start with the definition of the wetting angle as the foremost criterion for characterizing a truly superamphiphobic surface.

2. Wetting Angle

The wetting angle or contact angle is a measure of surface wettability which is defined as the tendency of a liquid to spread on or adhere to a solid surface in the presence of other immiscible fluids [56]. The wetting angle for superamphiphobic interaction is characterized using the Wenzel and Cassie-Baxter Models which define the contact mechanics behind liquid-air interface formed at the surface [57,58]. The principal behind the two models is the Surface Energy; measured as energy per unit area, which results from non-symmetric bonding of atoms/molecules found on the surface directly in-contact with the vapor [59]. The two models are based on the contact angle model formulated by Thomas Young [14] whose initial inspiration came from Galileo's work titled *Discorso intorno alle Cose che Stanno in su l'Acqua* of the 17th Century [60]. The Young's Contact Model is illustrated in Figure 1 and defined by Equation 1.

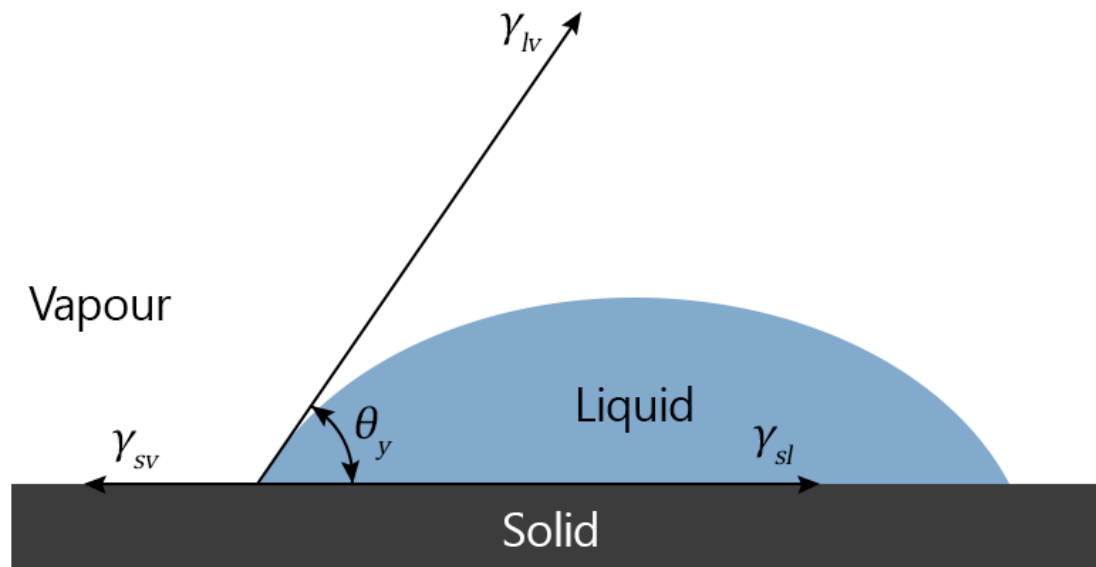


Figure 1: Young's Static Contact Angle Model

$$\cos \theta_y = \frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}} \quad (1)$$

where θ_y is the wetting angle (contact angle) while γ_{sv} , γ_{sl} and γ_{lv} are the solid-vapor interface tension, solid-liquid interface tension and liquid-vapor interface tension, respectively.

Young's first presentation of the solid-liquid equilibrium opened gateways for scholars to further develop their understanding on this concept, where the wetting angle became the basis for defining the wettability or spread of the liquid in the interface. However, this model has one characteristic limitation, which is that it predicts contact angle over an extremely smooth surface (zero surface roughness) which is not representative of any real-life surface [38]. Building up on this theory, Wenzel modelled the role of surface roughness in altering the contact angle and used to introduce a roughness ratio, R defined as the ratio of the actual surface area of the solid-liquid interface to the projected or nominal surface area (where the liquid is actually in contact with the liquid) as shown in Figure 2 and Equation 2 [57]. For ideal scenario where the surface becomes flat or has zero roughness, R is equal to 1 (Young's Contact Model), while for all other cases R is always greater than 1.

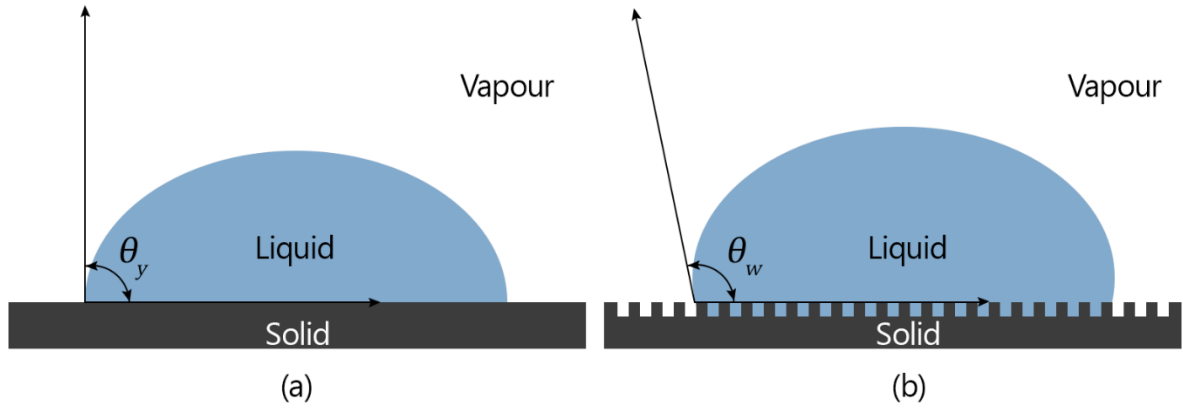


Figure 2: Wenzel Static Contact Angle Model where, a) shows the Young's Static Contact Angle and b) shows the changed Wenzel Contact Angle due to surface roughness where the liquid phase has completely penetrated the surface grooves.

$$\cos \theta_w = R \cos \theta_y \quad (2)$$

where θ_w is the Wenzel contact angle of the liquid droplet on the rough surface, θ_y is the equilibrium contact angle on the smooth surface of the same material. By consideration of this surface roughness, the model assumes that the liquid has penetrated the grooves of the rough surface, thereby being in complete contact with the solid surface. As per theory, this means that the contact angle at Young's state and contact angle at Wenzel state will be different. If the contact angle is hydrophobic in the Young's state, then it will become more hydrophobic in the Wenzel state and if the contact angle is hydrophilic in the Young's state then it will become more hydrophilic in the Wenzel state due to the effect of surface roughness [61]. The Wenzel model pose limitation in that it only accounts for the presence of two phases that is solid and liquid at the contact line, where the solid surface is also taken to be homogenous [62,63]. The Cassie-Baxter model [58] considers the presence of the third phase, that is vapour inside the grooves underneath the liquid which restricts complete wetting of the solid surface as shown in Figure 3. The model is defined based on the following Cassie-Baxter Equation (Equation 3):

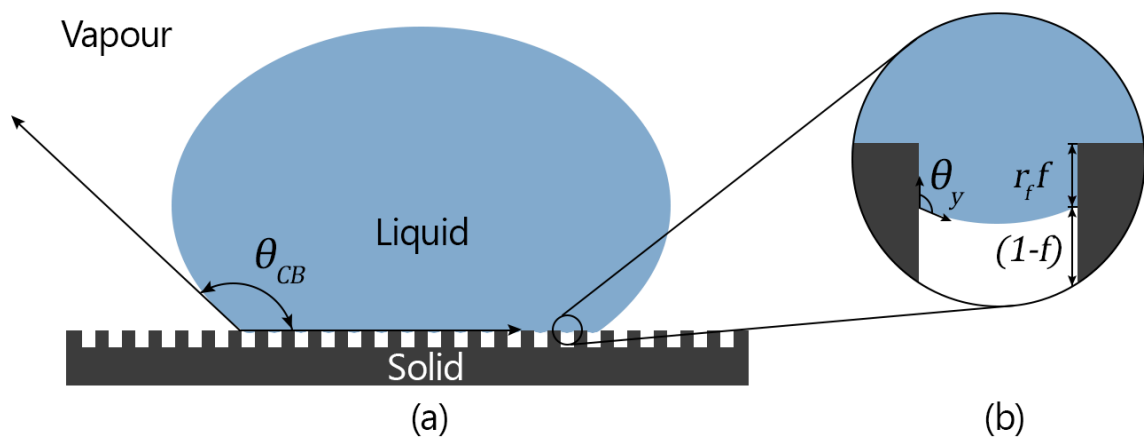


Figure 3: Cassie-Baxter Static Contact Angle Model where, a) shows the Cassie-Baxter state where the liquid droplet rests above the surface due to entrapped air in the surface grooves and b) shows the governing parameters behind the Cassie-Baxter model of Equation 3.

$$\cos \theta_{CB} = r_f f \cos \theta_y - (1 - f) \quad (3)$$

where r_f is the local roughness ratio, f is the fraction of the projected area of the liquid droplet in contact with the solid surface ($0 \leq f \leq 1$), θ_y is the contact angle between the liquid and the solid interface and $(1 - f)$ is the area fraction of the liquid droplet in contact with air trapped in the pores of the rough surface.

It is appropriate to highlight here that while Cassie-Baxter Model is widely used to define a Superamphiphobic interaction, Young's Equation in its true form and Wenzel model are hardly ever used [64]. This is because of the limitation posed by Young's and Wenzel's model equations [65]. As mentioned earlier Young's equation can only be applied to a surface having zero roughness and the Wenzel model while catering for the surface roughness can only be applied to a truly homogenous surface. Only Cassie-Baxter model accounts for surface roughness and heterogeneity. However it is important to note that none of these models account for Contact Angle Hysteresis (CAH) [66], which is an important measurement parameter and is explained later on.

While literature on these 03 contact models is well-defined, evaluation of an analytical solution to find out an estimate of the Contact Angle using the model equations is a tedious task and is based widely on making assumptions [67–70]. However, at the same time empirical results for wetting angle can be easily obtained using Contact Angle measurement [71].

3. Measurement of Wetting Angle

3.1 Static Contact Angle Measurement

Measurement of contact angle can be conducted using an optical instrument such as a Contact Angle Meter which should be capable of photographing a liquid droplet having a volume of less than 20 μ l [72]. Nevertheless, some researchers claim that the ideal size of the liquid droplet should be less than 4 μ l [73–77], where for practical purposes, one should use a slightly bigger volume of liquid say up to 5 μ l and then allow sufficient time for the liquid to evaporate so that the droplet can reduce to this volume [73]. The contact angle is then obtained using a fitting technique such as ellipse fitting [78,79], circle fitting [80,81], Young-Laplace fitting [82,83], polynomial fitting [84,85] and tangent searching mode [86,87] techniques.

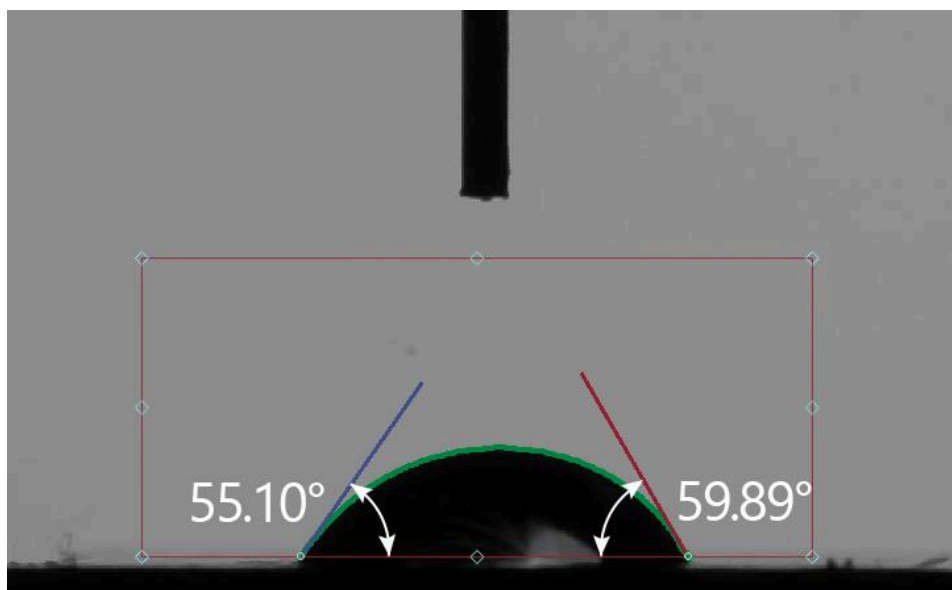


Figure 4: Left and right contact angles measured using Polynomial fitting technique on a 5 μ l droplet suspended over a flat 3D printed surface recorded and analysed using Oscilla Contact Angle Goniometer

Figure 4 shows a standard contact angle measurement software screen with Polynomial fitting technique applied to the droplet shape to decipher contact angles in relation to the flat surface. Moreover, Table 1 provides a quick summary developed by F. Thomsen of KRÜSS GmbH [88] to decide for which fitting technique are applicable for measuring superamphiphobic interaction which depends on the listed parameters.

Table 1: Qualitative Summary for Selection of Curve Fitting Technique for Measurement of Contact Angle developed by F. Thomsen of KRÜSS GmbH (Original Table Truncated to Show Relevant Data)

	Circle	Conic Section	Polynomial	Young Laplace
Measuring Range				
0 – 20°	✓			
10 – 100°		✓	✓	✓
100 – 180°			✓	✓

Therefore, as seen from the Table 1, for a true superamphiphobic interaction where contact angles are greater than 150°, Polynomial Fitting and Young-Laplace fitting techniques are more commonly used.

3.2 Tilt Angle Measurement

However, measurement of this static contact angle does not qualify for a surface to be truly superamphiphobic [89]. A true superamphiphobic surface should rapidly repel liquid without causing any significant distortion to the liquid droplet's bead-like shape [90]. In the Wenzel state the liquid droplet penetrates the grooves of the surface and adheres to them, causing measurable distortion to the droplet's shape and making it difficult to roll off upon tilting [91]. This change in droplet's shape upon tilting gives rise to advancing and receding angles as shown in Figure 5.

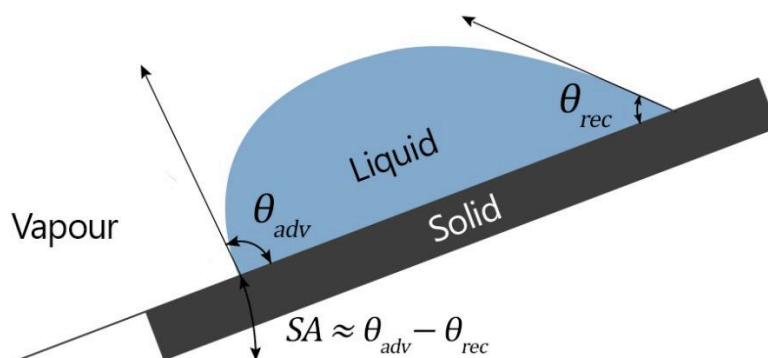


Figure 5: Measurement Method for Tilt (Sliding) Angle where Tilt Angle (SA) approximates to the difference of Advancing (θ_{adv}) and Receding (θ_{rec}) angles

This means that if the surface is truly superamphiphobic it should not allow the liquid droplet to adhere to it and hence the droplet should have small (almost zero) advancing and receding angles upon tilting [20]. Another way of measuring these angles is by slowly varying the volume of the liquid droplet and measuring the difference in the advancing and receding angles as the contact line expands and shrinks as shown in Figure 6. This measurement of droplet's adhesive behaviour gives rise to understanding of the second criterion which needs to be satisfied to characterize a superamphiphobic surface, termed as the Contact Angle Hysteresis [92].

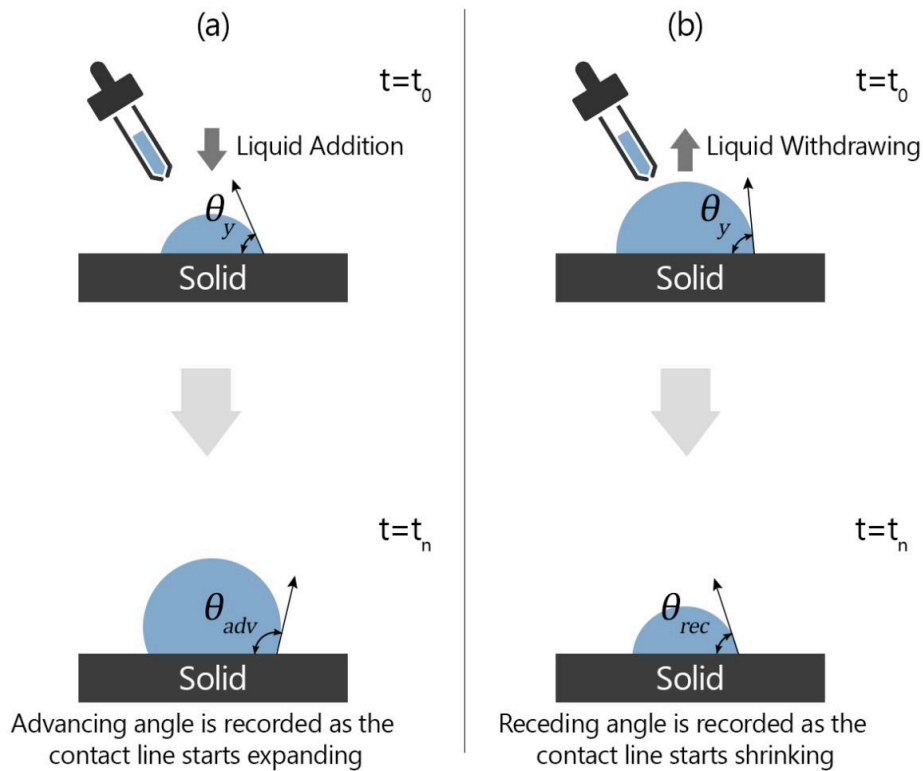


Figure 6: Measurement Method for Advancing (θ_{adv}) and Receding (θ_{rec}) angles where a) shows that the θ_{adv} is recorded at the time where contact line starts expanding while θ_{rec} is recorded when the contact line starts shrinking due to addition and withdrawing of water volume from the droplet.

3.3 Contact Angle Hysteresis

Contact Angle Hysteresis or CAH for short is a measure of the difference between advancing and receding contact angles of a liquid droplet as it undergoes evaporation and cooling. [66]. CAH as discussed earlier is commonly used to quantify surface adhesion. A CAH angle of less than 10° is termed as 'fakir' state [93–95], where vapor (air) is trapped in-between grooves and limits liquid penetration to wet the complete substrate. Examples of 'fakir' state are widely found in nature such as in the Lotus Leaf and Shark's Skin and therefore this effect is also sometimes referred to as the Lotus-leaf or Shark-skin effect [11,12]. A CAH angle of more than 10° is referred to as the Rose-Petal effect, where the liquid completely penetrates and wets the grooves thereby resulting in higher adhesion of the liquid to the surface [96,97]. Low CAH values are indicative of self-cleaning behaviour and are therefore an important parameter for measurement while characterizing superamphiphobic surfaces [73].

Where CAH direct measurement through advancing and receding contact angles may be difficult, an alternate measurement of Tilt Angle (Sliding Angle) may be conducted. Tilt angle is a measure of the critical angle at which liquid tends to slide off when one end of the horizontal surface where the droplet is resting is lifted. While this does not equal the difference between the advancing and receding contact angles, it is usually very close to it as shown in **Error! Reference source not found.** Tilt angle establishes an important parameter for characterization of superamphiphobic surfaces. A tilt angle of less than 10° for both polar and non-polar liquids has been reported as a requirement for the surface to be termed as superamphiphobic [40,73,98,99].

To summarize, Static Contact Angle Measurement, Tilt Angle Measurement and Contact Angle Hysteresis are the 03 most common measurement methods used in empirical study of characterizing a true superamphiphobic surface using CA and CAH.

4. Role of Surface Geometry

With the measurement parameters established, one must develop an understanding of the various physical structures which can be developed on the surface to induce superamphiphobic behaviour. This is important since as previously discussed, physical modification takes lead over chemical modification in demonstrating superamphiphobic behaviour [100] and can help in conversion of any non-amphiphobic surface into an amphiphobic one without any dependence of material [34,39].

This physical modification is usually in the form of protrusions which enables formation of reentrant geometrical features on the surface which is a widely observed phenomenon in nature [101–104], where this behaviour limits sticking up of water and other contaminants on to the surface. Some examples include the Lotus Leaf effect [105–109], Shark skin effect [110–112], Gecko skin effect [113–116] and Peach skin effect [117], named in accordance with the species on which it is observed. Figure 7, Figure 8, Figure 9 and Figure 10 show some high-resolution photographs of these structural features.

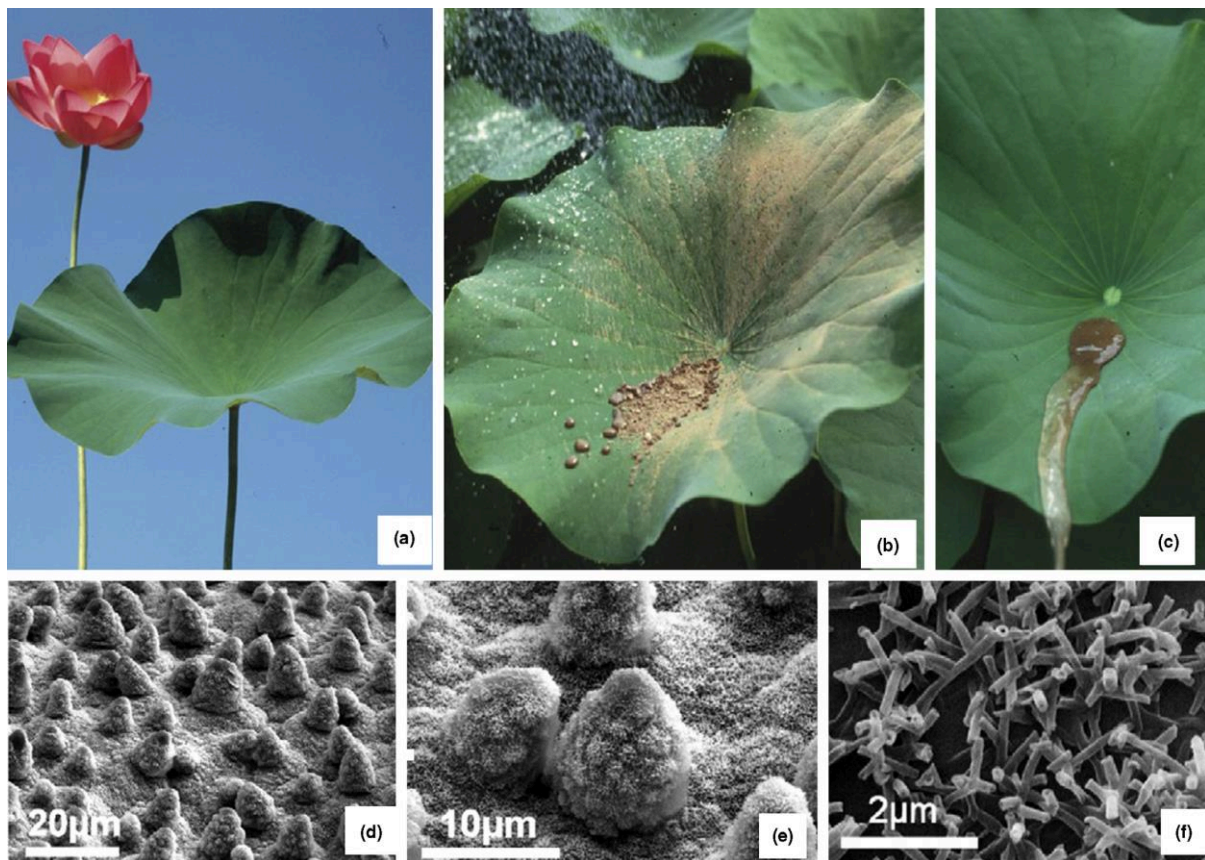


Figure 7: Images of a superhydrophobic lotus leaves (*Nelumbo nucifera*) with self-cleaning properties at different magnifications [107]

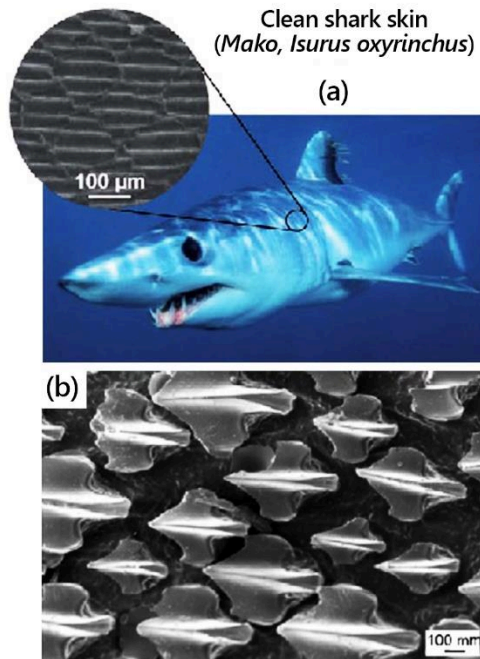


Figure 8: (a and b) Images at different magnifications of underwater shark skin showing characteristic surface geometry for self-cleaning behaviour [101].

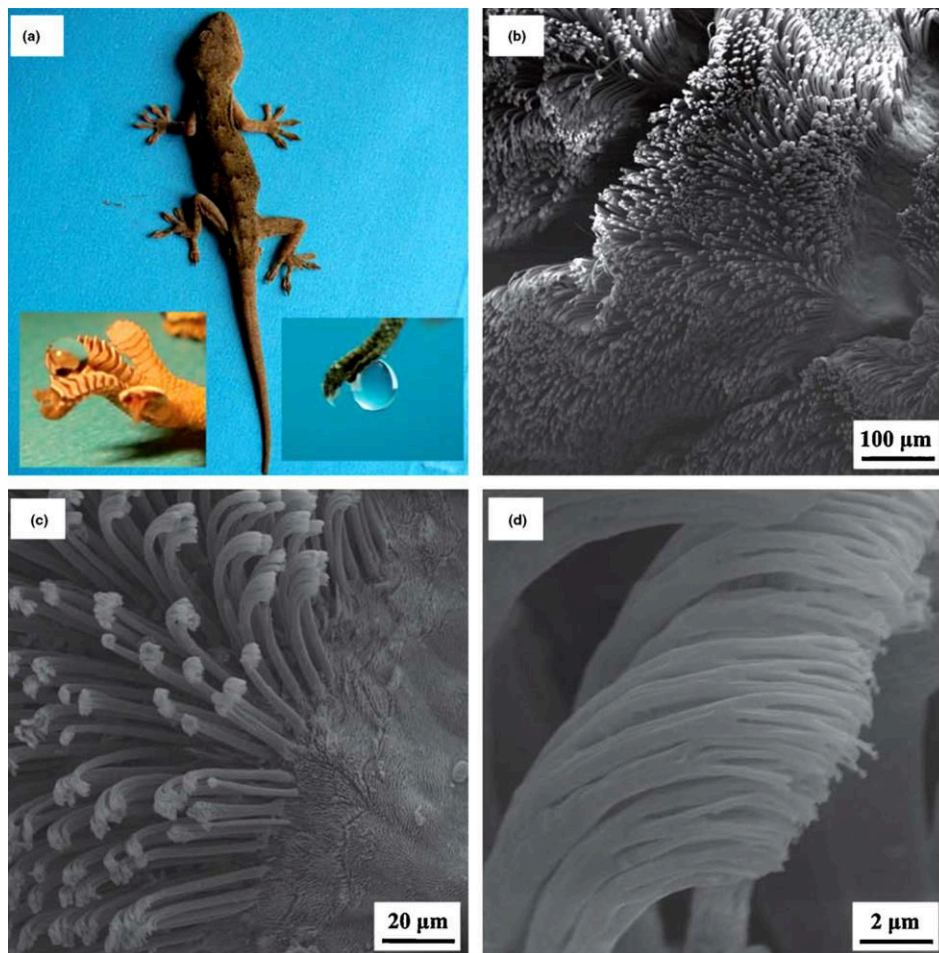


Figure 9: Images of superhydrophobic gecko foot with high adhesion at different magnifications, able to walk on vertical surfaces. [113]

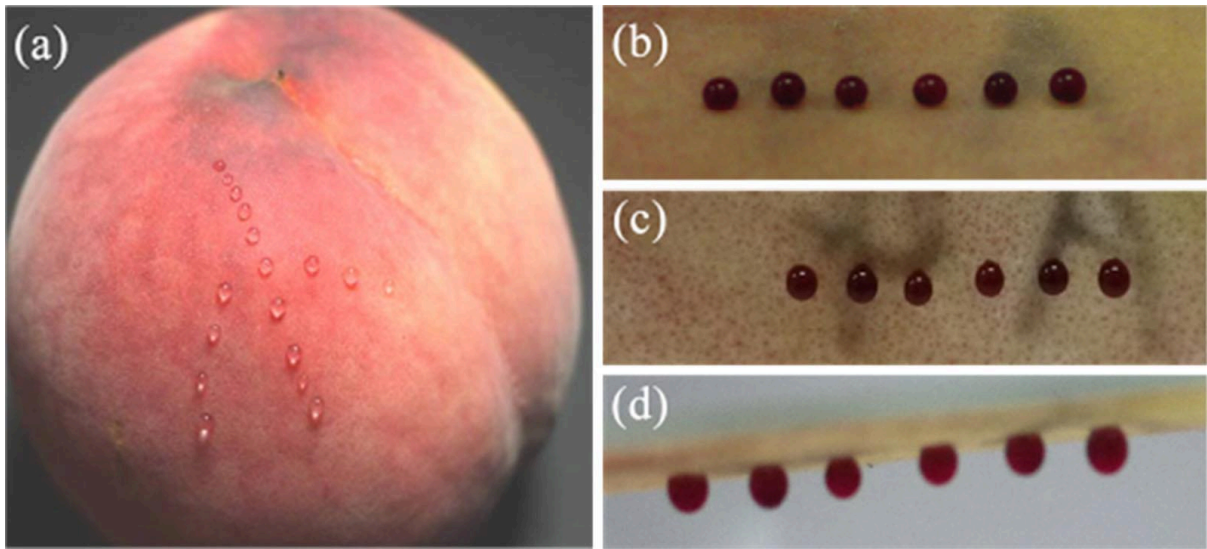


Figure 10: a) Digital photographs of a fresh peach with water droplets on the surface. Photographs of red ink droplets (10 μL) on the surface of peach skin peeled off from a Pinggu peach with different tilt angles b) 0°, c) 90°, d) 180° [117]

Using these and many others as inspiration, researchers have artificially developed and tested various reentrant geometrical features which show this liquid repellent behaviour. Common ones include electrospun fibre structure [118–121], T-structures [122–124], mushroom structure [123,125], Inverse trapezoidal structure [8,126], sphere and microsphere structure [122] among many others.

The guiding principal behind these structures is the reentrant geometry which supports liquid droplets and keeps them away from the bottom surface. This role of reentrant geometry was evaluated by Cao et al. where they demonstrated that for superamphiphobicity to prevail $\theta_{overhang} < \theta_{flat}$ [127] as shown in Figure 11, which is a magnified view of area between 2 reentrant geometries. Wu et al. further explained as to how the structural geometry helps in achieving pressure balance in line with Equation 4 to facilitate superamphiphobic behaviour [128].

$$P_{max} + (1 - f_s)P_{down} \geq 0 \quad (4)$$

Where P_{max} is the upward pressure formulated due to the surface geometry and hence surface tensions γ_{lv} and γ_{sl} , while P_{down} is the combined pressure due to gravitational pull and capillary interaction (Laplace Pressure) of the liquid droplet. f_s is the solid fraction under consideration which includes the reentrant geometries as defined in the Cassie-Baxter state previously. They concurred that if this equation is balanced, the surface will remain completely superamphiphobic.

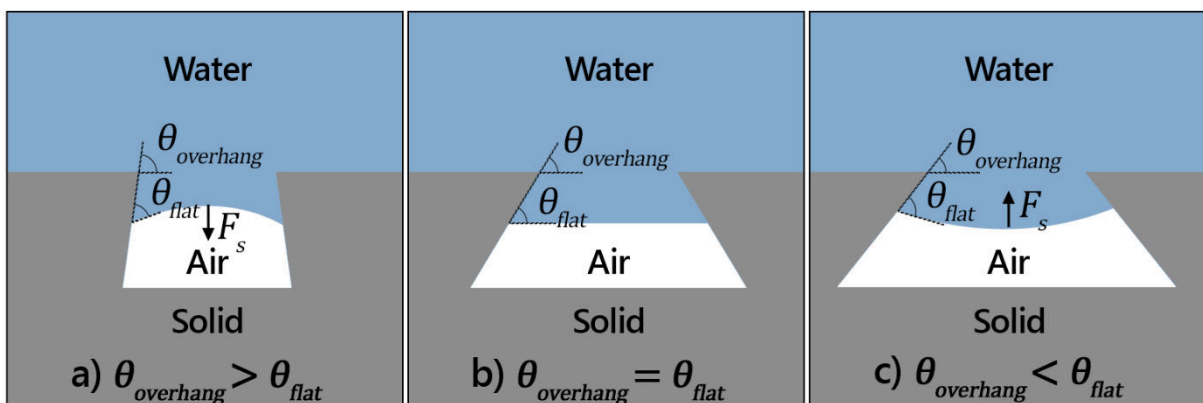


Figure 11: Three cross-sectional profiles of water in contact with a solid surface consisting of overhanging structures where $\theta_{overhang}$ is the angle formed between the sidewalls and horizontal and θ_{flat} is the intrinsic water contact angle. In a)

The meniscus inside the indent is concave when viewed from the water side. The net force (F_s) generated by the meniscus at the water-air interface causes water to enter the indent, completely wetting the solid. In b) The water-air interface is flat and stays at circular intersection of the indent and in c) the meniscus inside the indent is convex which enables the net force (F_s) to point towards the outside of the indent, thereby preventing water from entering the indent. This formation of meniscus is guided by the geometry where the two angles $\theta_{overhang}$ and θ_{flat} are formed. (Image Recreated from Cao et al. [127] for High Resolution Printing)

A derived version of these reentrant profiles is the doubly reentrant structure [16,41,129], so called because it may include more than one reentrant profile in a solid fraction. This geometrical configuration like the reentrant profile is also inspired from nature. These doubly reentrant structures may be created by overlapping one reentrant profile over another [130–132] as shown in Figure 12 or by introducing a much smaller scale structure over the original reentrant structure [133,134] as shown in Figure 13.

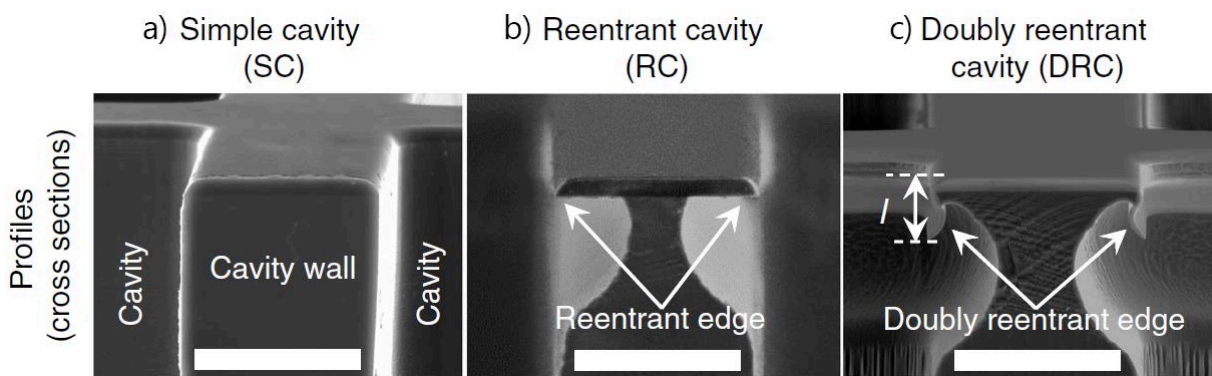


Figure 12: SEM micrographs of three profile cross-sections showing a) Simple Cavity (SC), b) Reentrant Cavity (RC) and c) Doubly Reentrant Cavity (DRC) [130]

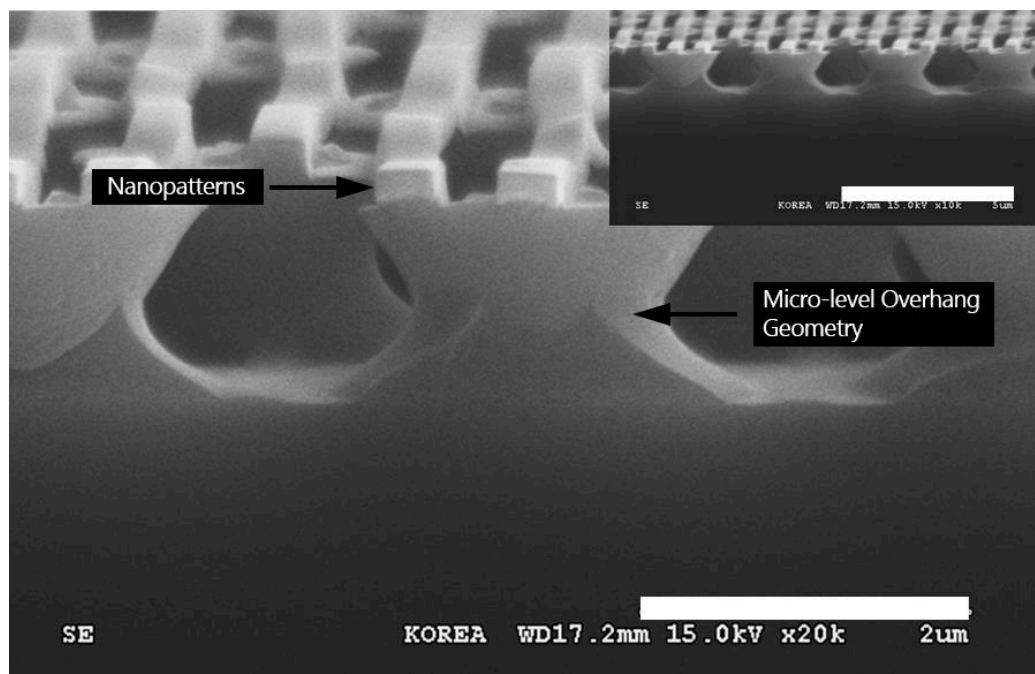


Figure 13: SEM micrograph showing a nanopatterns embedded on top of overhang structures. [133]

These doubly reentrant structures provide a more metastable Cassie-Baxter state by forming multiple $\theta_{overhang} < \theta_{flat}$ angles at various instances, essentially leading to a further increase in the energy barrier to failure [127]. They work by increasing the P_{max} , thereby driving the liquid out of surface indents using the net force or pressure (developed at the meniscus of the water droplet inside the

surface indent) to their favour, hence reducing the wetting potential of the surface and resulting in Low CAH as well as multi-level surface roughness [135].

This goes on to show that physical modification plays a vital role in altering the wetting characteristics of the surface without any dependency on the properties of the base material. However, to ensure this behaviour prevails, a key concern is to make these reentrant and doubly reentrant geometries more durable and reusable which is where selection of materials and manufacturing processes plays its part. This is because that while the naturally occurring surfaces can undergo repair and clean themselves through physical movement of the surface as in the case of muscle movement [136], the same is not easy to achieve artificially. A closer look at this problem suggests that Layer-by-Layer (LbL) deposition [137] and Autonomic / Non-Autonomic approaches [138] of self-healing surfaces can come close to the overall concept of surface regeneration after possible damage or degradation and additive manufacturing techniques provide a way forward in this direction.

5. 3D Printing of Reentrant Geometry

Fabrication of geometrical features which can support amphiphobic or superamphiphobic interaction using additive manufacturing techniques is a forthcoming area of research in polymers. While Guo et al. and Ai et al. have adequately summarized most fabrication methodologies and challenges pertaining to creation of superamphiphobic surface modification on polymers [40,139], this important method remains missing from their review.

Jafari et al. and Yan et al. in a first have addressed this area by reviewing some techniques that have been developed in recent years to achieve superamphiphobicity (including its subsets superhydrophobicity and superoleophobicity) in polymers using additive manufacturing techniques [140,141]. Additive manufacturing techniques follow a layer-by-layer building approach which means that even the most complex of reentrant geometries can be easily fabricated [51,103]. The challenge however remains that protrusions of micro- and nano- scale may not be easy to achieve with all additive manufacturing processes due to limitations in the process itself [47,141]. In the case where this limitation no longer exists as in the case of Two Photon Polymerization (2PP) [142] and Immersed Surface Accumulation (ISA) [51] techniques, the choice of available materials that can be used with them is severely limited and the fabrication setup extremely complicated.

The most commonly used additive manufacturing process is therefore Fused-Deposition Modelling (FDM), an extrusion based technique which falls under the broader heading of Liquid-based techniques for Additive manufacturing defined by Kruth et al [47,143,144]. A similar technique that is used along with FDM and is based on extrusion mechanism is Direct Ink Writing (DIW) [141] or Pressure Assisted Micro-syringe (PAM) [145], which is used with polymers in viscous form. It is important to mention here that both processes follow the same extrusion mechanism and have the most elaborate list of cross-platform generic materials that can be used with them. A major advantage thus of these processes is that if the printing unit allows for adjusting the printing parameters, any material that melts and flows within the working temperature range of the printing unit can be readily used [146]. This is not the case for other additive manufacturing processes like Stereolithography (SLA) which makes use of proprietary resins and hence is highly machine specific [147]. The complete list of materials (to the best of authors' current knowledge) that can be used with these extrusion-based processes is provided in Table 2. As can be inferred from this list, most of these materials are of high commercial importance.

Table 2: List of Materials with their specific natural wetting state(s) due to intrinsic functional groups

S/No.	Material Type	Naturally Amphiphobic (Yes/No/Hydrophobic/Oleophobic)	Reference(s)
1	Acrylonitrile Butadiene Styrene (ABS)	Hydrophobic	[148]
2	Poly Lactic Acid (PLA)	Hydrophobic	[149]
3	PolyEthylene Terephthalate (PET)	No	[150,151]
4	Nylon	No	[152]
5	Polyvinyl Alcohol (PVA)	No	[153]
6	Sandstone (PLA + Ceramic)	No	[154]
7	Wood	Hydrophobic	[155]
8	Metal (PLA with Metal Powder)	No	[154]
9	High Impact Polystyrene (HIPS)	Yes	[154,156]
10	Magnetic (PLA with Iron Fillings)	No	[154]
11	Conductive (PLA with Carbon)	No	[154]
12	Carbon Fiber (PLA with Carbon)	No	[154]
13	Flexible Thermoplastic Elastomers (TPE)	Yes	[157]
14	Polycarbonate (PC)	No	[158]
15	Biodegradable (bioFila)	No	[154]
16	Wax	Yes	[141]
17	Acrylonitrile Styrene Acrylate (ASA)	No	[159]
18	Polypropylene (PP)	Hydrophobic	[160]
19	Acetal (POM)	Hydrophobic	[161]
20	Polymethyl Methacrylate (PMMA)	Hydrophobic	[162]
21	Polyvinylchloride (PVC)	No	[163]
22	PDMS (Used in Combination with another Elastomer)	Hydrophobic	[31,145]
23	Ethylcellulose (EC) (Used with Plasticizer)	Hydrophobic	[145]
24	Hydroxypropyl Cellulose (HPC)	No	[145,164]
25	Hydroxypropyl Methylcellulose (HPMC)	No	[145]
26	Polycaprolactone (PCL)	Yes	[29]
27	Polyvinylpyrrolidone (PVP)	Both Hydrophobic and Hydrophilic Functional Groups Exist/ Oleophobic	[165]
28	Poly(Ethylene Glycol) (PEG)	No	[145]
29	Polyethylene Terephthalate Glycol (PETG)	Hydrophobic	[166]
30	Polyethylene coTrimethylene Terephthalate (PETT)	Hydrophobic	[166]

In any additive manufacturing process, the printing function itself (in this case the motion of extruder and material deposition rate) are machine controlled [167]. However, despite this automation the material deposition method especially in extrusion-based processes brings with it a natural process limitation in that the minimum feature size depends on the diameter of the final orifice and flowability of the material that has to pass through it [168] while maintaining a smooth print acceleration [166]. Furthermore, the layer-by-layer deposition leads to the formation of a natural surface geometry (referred to as the staircase or ladder effect) at the termination point of which layer, which when piled up exhibits its own surface roughness and wetting behaviour [169]. Moreover, an understanding of

the printing process itself enables selective tinkering which can provide benefit in creation of superamphiphobic or its subset superhydrophobic and superoleophobic repellent states.

5.1 Direct Ink Writing (DIW)

In DIW based extrusion setup, an example of this can be seen in the work of Barahman et al who used a 27 gauge (210 μm i.d.) tapered dispensing syringe mounted on a robotic arm [170]. By using the natural dispensing mechanism of the syringe to their advantage, they were able to fabricate ratchet-like asymmetric pyramid posts of poly(dimethylsiloxane) (PDMS) with slopes ranging from 0° to 50° to create a heterogenous superhydrophobic surface as shown in Figure 14. Due to natural adhesion in the polymer, the pyramid tip terminates at a specific angle at the time of disengagement which was used to create this unique ratchetlike geometry. The geometry provided favourable advantage to support directional rolling off of water droplets.



Figure 14: Optical microscopy images of asymmetric pyramid shaped PDMS created by selective disengagement at different angles where a) $35\pm 1^\circ$ b) $44\pm 5^\circ$ and c) $50\pm 1^\circ$ [170]

Similarly, He et al. also fabricated an anisotropic porous PDMS film by using a DIW based extrusion setup. They printed lines in parallel and perpendicular directions to create a mesh like porous film volume and developed multiple samples of the same by varying the printing speed and filament spacing. It was observed that the printing speed in turn effects the filament diameter since more material is deposited at lower speeds. The effect of these 03 factors was demonstrated in terms of changing wettability behaviour due to the formation of various geometrical structures as shown in Figure 15 and Figure 16 where the maximum CA of 155° were favourably achieved through their optimization [171].

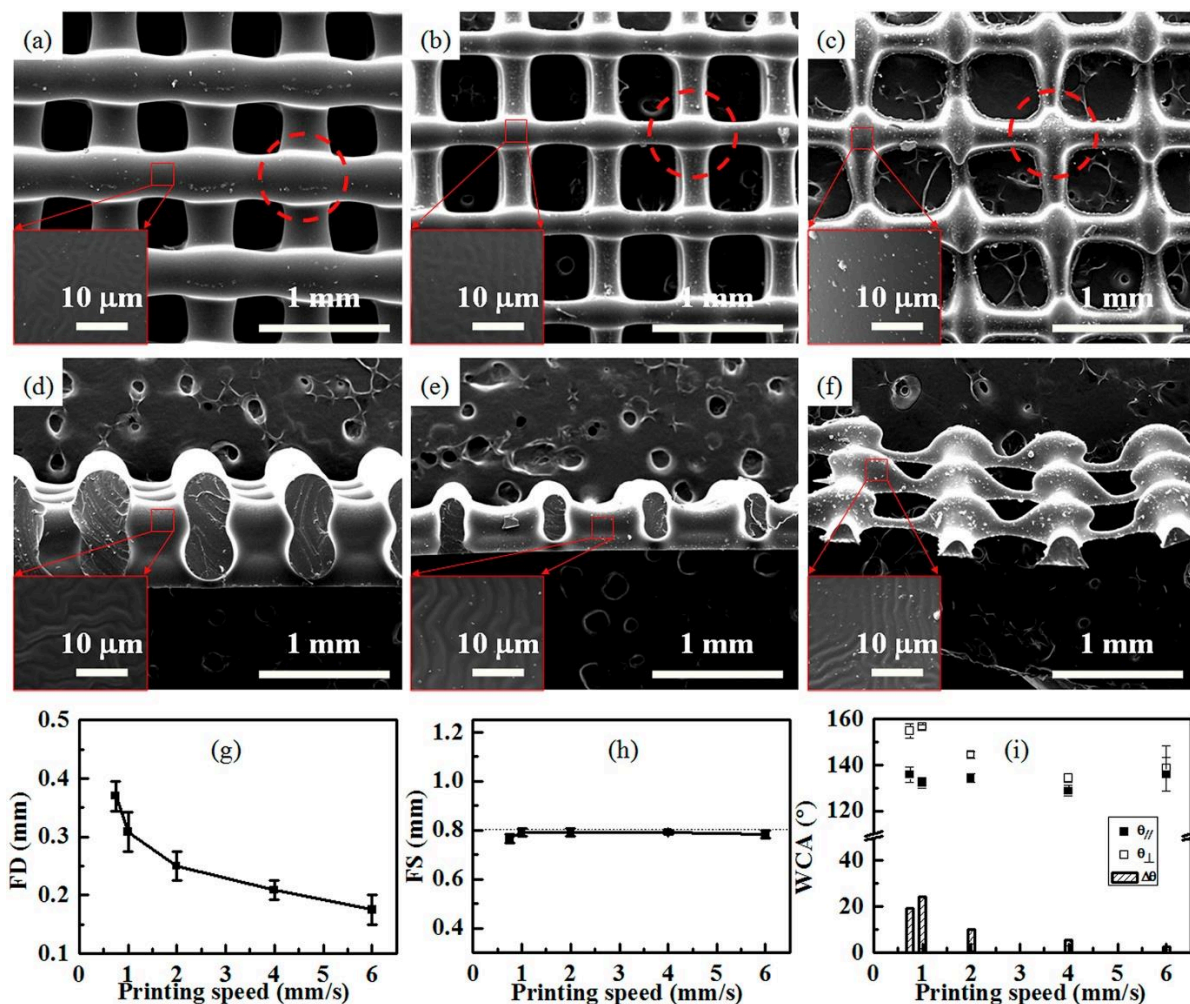


Figure 15: SEM images of surface (a~c) and cross-section (d~f) morphology for samples printed at different printing speeds of 0.75 (a and d), 2.00 (b and e), and 6.00 mm/s (c and f). The insets show the higher magnification images. The edges of cross-points between filaments from neighbored printing layers are shown in red dash circles in (d~f). Filament Diameter (g) and Filament Spacing (h) change with increasing printing speed from 0.75 to 6.00 mm/s. The dash line in (h) indicates the Filament Spacing value which is set by computer program. (i) The averaged Water Contact Angles in perpendicular and parallel directions and their $\Delta\theta$ change with various printing speed. [171]

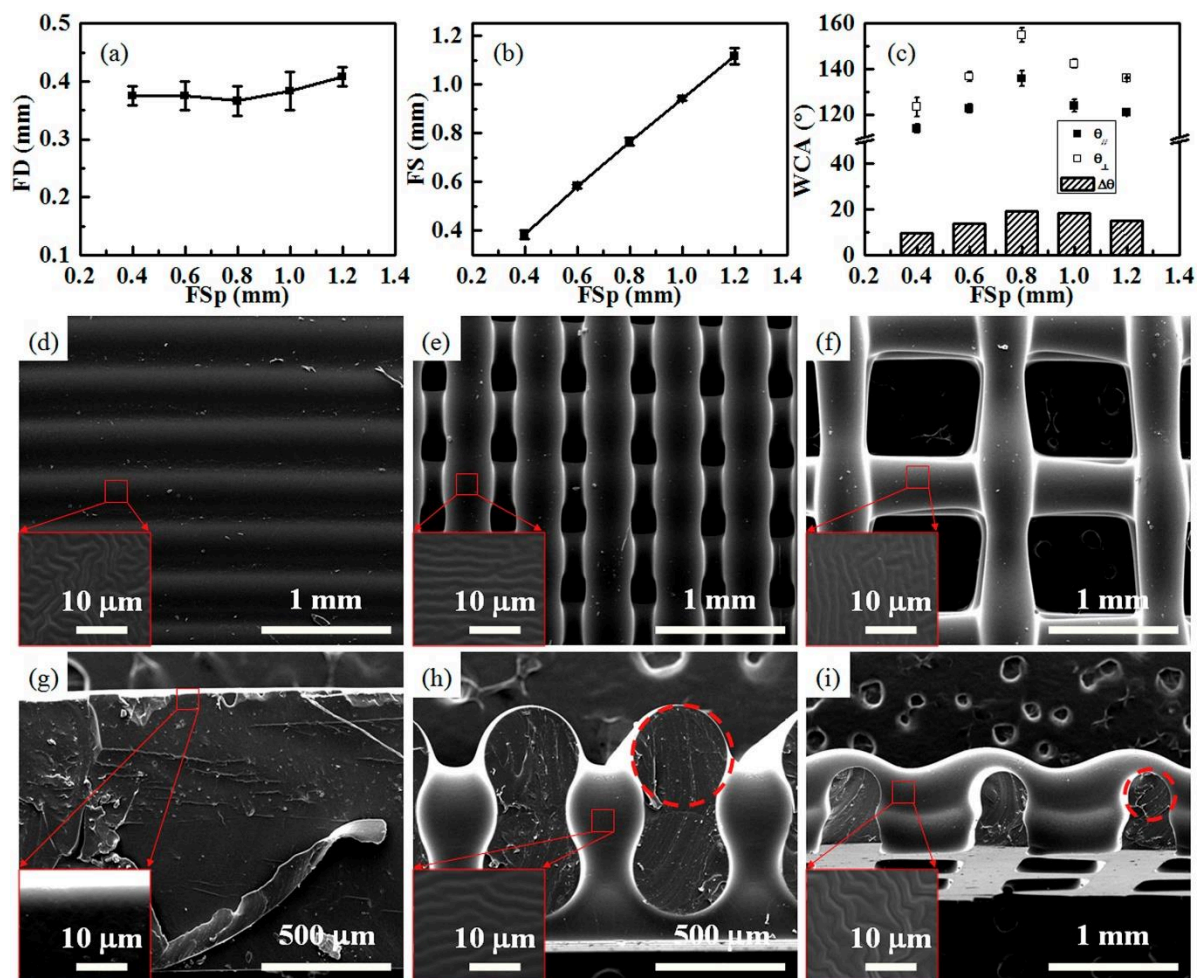


Figure 16: Filament Diameter (a) and Filament Spacing (b) change with increasing FSp from 0.40 to 1.20 mm. The Water Contact Angles in perpendicular and parallel directions and their $\Delta\theta$ change with various Filament Spacings (c). SEM images of surface (d~f) and cross-section (g~i) morphology for samples with various Filament Spacing of 0.40 (d and g), 0.60 (e and h), and 1.20 mm (f and i). [171]

Another facile method of this type was reported by Lv et al. for creating superhydrophobicity with the use of polydimethylsiloxane (PDMS) ink whose flowability (rheological behaviour) was suitably tailored for 3D printing with the addition of hydrophobic silica nanoparticles [172]. Here hydrophobic silica not only enhanced the hydrophobic effect but in turn also provided the mechanical support to the structure to prevent it from premature collapsing. A membrane structure was developed with an average pore size of 0.37 mm. The membrane showed suitable results as an oil-water separation barrier with a high efficiency of 99%. Similar to this, Li et al. used printing ink consisting of a mixture of cellulose acetate (CA), poly(vinyl alcohol) (PVA), and silica nano-particles (SiO_2) to fabricate a highly superoleophobic membrane for oil-water separation with oil contact angles reaching up to 159° underwater [173]. These methods show the ease with which a complex geometry such as that of a membrane can easily be developed in a single-step printing process without any additional modification.

Building up on it, Shin et al. used the DIW technique to create negative sponge templates. These templates were later filled with PDMS and then suitably dissolved to create another oil-water separation barrier especially for use as a sponge to clean marine oil spills [174]. This created a highly superhydrophobic but oleophilic structure with a 3.7 times greater efficiency as compared to the traditional PDMS sponge. Where the sponge structure absorbed and exuded as desired, its reusability over long-term was not gauged which might limit its use, since PDMS is non-biodegradable in nature [175].

5.2 Fused Deposition Modelling (FDM)

Where DIW based extrusion setups have shown credible results, FDM based extrusion techniques are also not lagging behind. In recent years extrusion based FDM technique has been applied to modify a surface wettability behaviour. Two approaches using FDM technique were developed by Kang et al. [176,177] using PLA based moulds for casting PDMS. In their first approach, a simple plate design was printed at increasing angles between 0° to 90° at 10° increment while keeping a fixed layer height. The changing angle resulted in variable surface profiles formed at the termination point of the layer deposition process as shown in Figure 17 and Figure 18. CAs were measured on the surfaces produced and it was seen that while increasing the printing angle leads to a higher CA with water, 70° angle provided the best result in terms of water rolling off or a low CAH.

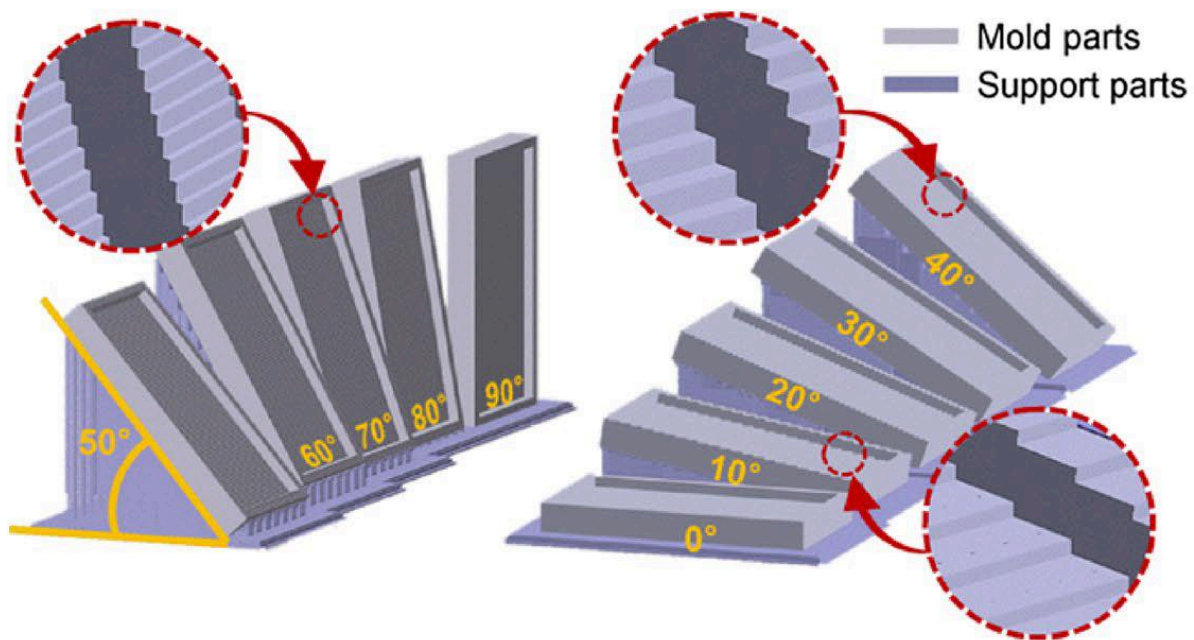


Figure 17: CAD images of main 3D mould parts on support parts with respect to various printing angles [176].

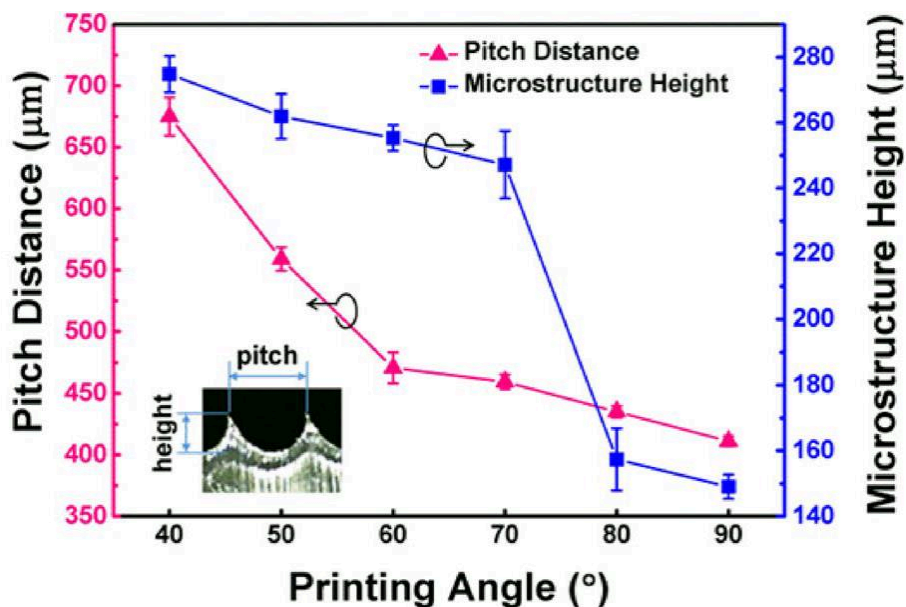


Figure 18: Graph show variation of Pitch Distance and Microstructure Height as a function of printing angle from 40° to 90° [176].

In the second approach, they 3D printed PLA based moulds consisting of inverted pyramid shaped profiles. This time, the layer height was made variable by changing the printing parameters while the

angle of inclination of the pyramid was set at a fixed angle. The roughest surface which was about 300 μm in height attributed the highest CA of 143°.

Furthermore, Milionis et al. [178] and Lee et al. [179] demonstrated the use of a low cost FDM technique to realize superhydrophobicity on relatively non-hydrophobic polymers. Milionis et al. used Acrylonitrile Butadiene Styrene (ABS) while Lee et al. used Polylactic Acid (PLA), both of which are widely used in 3D printing.


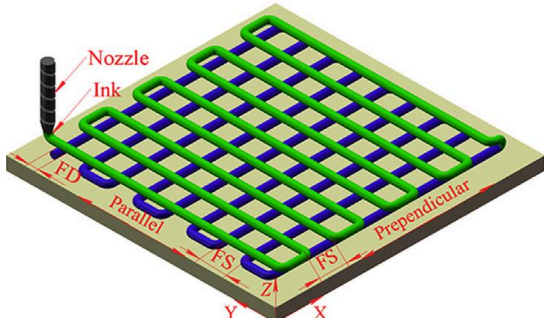
Milionis et al. printed cube shaped heat exchanger designs using ABS and modified their surfaces using dip-coating technique. The samples were pre-prepped using two different approaches where one batch of samples was sputtered with Gold-Palladium particles while the other batch was coated with superhydrophilic rubber coating to act as primer. Both batches of samples were then coated with fluoride based superhydrophobic coating using dip-coating. CAs of 120° and 154.7° were achieved using the first and second approach respectively. The surface geometry of the printed part played little role in determining the superhydrophobic surface properties of the material and the chemical modification can be attributed as the primary reason for this effect.

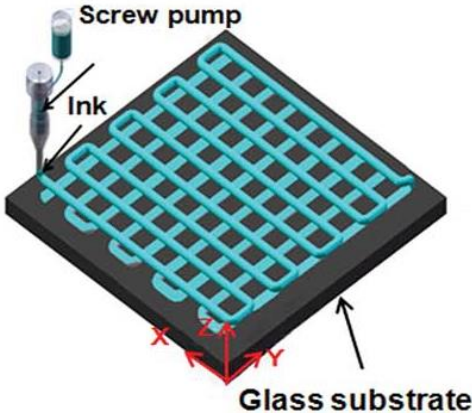
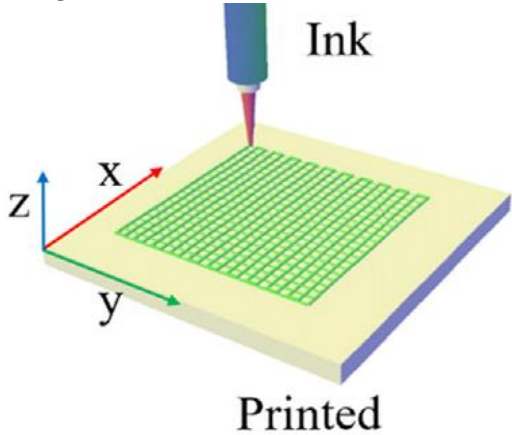
Lee et al. printed a plate design keeping lines as the infill pattern. Two types of line patterns created due to Layer-by-Layer deposition and Tool path (Infill pattern) were then selectively modified by dissolving the top surface in methyl ethyl ketone (MEK) and coating them simultaneously with hydrophobic silica nanoparticles in a single dip coating process followed by drying. CAs of up to 150° were achieved. The technique was also repeated on step and grid patterns with highly favourable results.

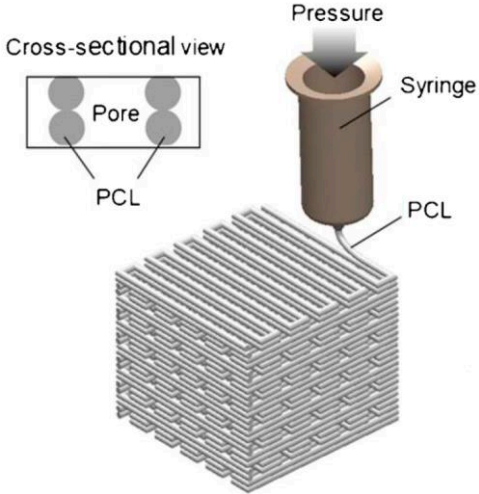
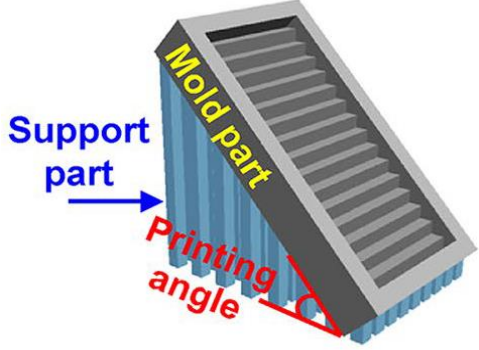
Another low-cost 3D Printing method was employed by Cook et al. to create anisotropic wettability on polymer substrate [180]. Line patterns with channels in between were designed and printed using ABS followed by PLA varying between 250 μm to 1 mm in width and tested for wetting characteristics by measurement of Contact Angle and Tilt Angle in Parallel and Perpendicular direction using water. Samples were then modified in 03 different ways. First set of samples were modified chemically, while the second set of samples was modified by a physical treatment. For the third set a combination of the two was employed. They were able to demonstrate a significant difference in rolling off the water droplet in parallel and perpendicular direction, where the parallel direction facilitated water to flow (hydrophobic) the perpendicular direction made the drop sticky (hydrophilic). The employed treatments greatly altered the wettability behaviour where the physical modification rendered the sample hydrophilic in most cases. While this study provides a way through for using FDM printers for developing hydrophobic polymeric surfaces, it neglects the natural reentrant profile that is created by Layer-by-Layer deposition during the 3D printing procedure. It further also does not specify the effect of pattern height or channel depth, which is an important parameter in this investigation.

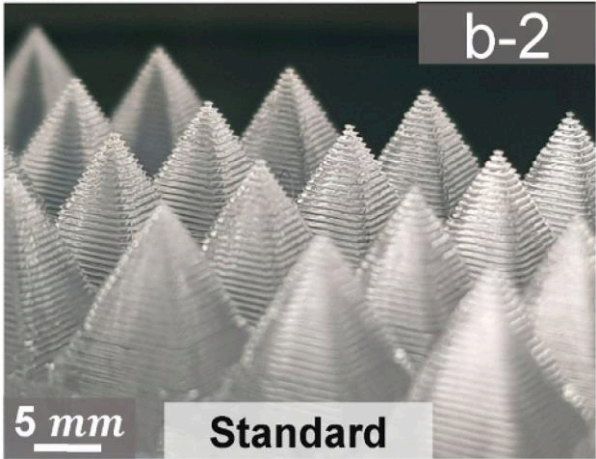
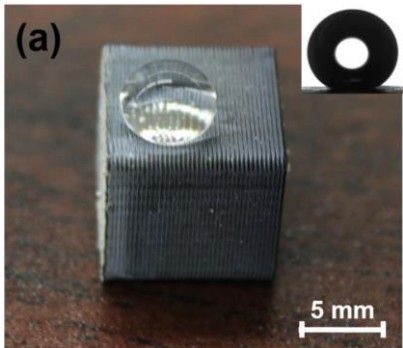
Table 3 provides a summary of the findings in this review. As can be deduced from the table, most researchers when using either DIW or FDM based approaches have relied on materials that already exhibit repellency against a liquid. Whereas, materials like Polyvinylchloride (PVC) and Polyethylene Terephthalate Glycol (PETG) which are the most abundantly used polymers for handling liquids have never been worked upon. The efficacy of reentrant geometrical features on their surfaces and the parameters that govern the printing process itself in these extrusion-based techniques is therefore a novel area of research.

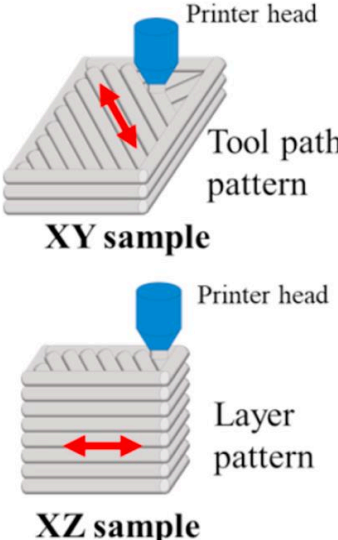
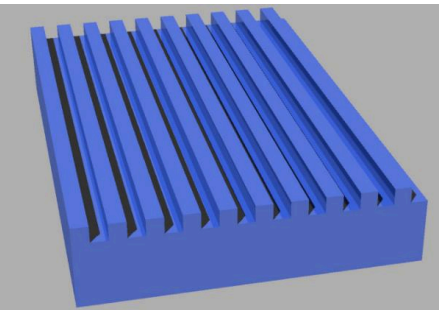
Table 3: Summary of Extrusion-Based Methods used to develop Amphiphobic Surface Modification in Polymers

S/No.	Profile	Type of Extrusion-Based Method	Materials		Material(s) Already Hydrophobic or Oleophobic?	Role of Reentrant Geometry Well Defined?	Highest Contact Angle Achieved	Ref
			Printed Materials	Final Materials				
1	<p>Profile Description: Ratchet-like Anisotropic Posts as shown in Figure 17.</p>  <p>Figure 19: Optical Microscopy Image of DAP-35-20 Specimen showing a post angle of roughly 35° [170].</p>	DIW	PDMS	-	Yes	Yes	170 (With Water)	[170]
2	<p>Profile Description: Film developed in mesh form due to overlapping lines in Parallel and Perpendicular Direction deposited layer-by-layer as shown in Figure 20.</p>  <p>Figure 20: Schematic of 3D printing process of anisotropic porous PDMS film using a home-made DIW setup [171].</p>	DIW	PDMS	-	Yes	Yes	155 (With Water)	[171]

3	<p>Profile Description: Membrane structure in mesh form developed by overlapping lines in Parallel and Perpendicular Direction deposited layer-by-layer as shown in Figure 21.</p>  <p>Screw pump Ink Glass substrate</p> <p>Figure 21: Schematic of the 3D printing of a porous membrane using nanosilica-filled PDMS ink [172].</p>	DIW	PDMS + Hydrophobic Silica Nano Particles	-	Yes	Yes	157 (With Water)	[172]
4	<p>Profile Description: Membrane structure in mesh form developed by overlapping lines in Parallel and Perpendicular Direction deposited layer-by-layer as shown in Figure 22.</p>  <p>Ink Printed</p> <p>Figure 22: Schematic of the 3D Printing process of the Composite Membrane [173]</p>	DIW	PVA + Silica Nano Particles + Cellulose Acetate	-	Yes	Yes	159.14 (With Oil)	[173]

5	<p>Profile Description: Cubic Mesh formed due to overlapping lines in Parallel and Perpendicular Direction deposited layer-by-layer as shown in Figure 23.</p>  <p>Figure 23: Schematic of the 3D Printing process using PCL [174].</p>	DIW	PCL	PDMS	Yes	Yes	143 (With Water)	[174]
6	<p>Profile Description: Plate design (mould) as shown in Figure 24 with an intrinsic triangle pattern printed by varying printing angle which creates a different staircase at the termination point of each layer.</p>  <p>Figure 24: Schematic of the FDM 3D printing process employed by Kang et al [176].</p>	FDM	PLA (Mould)	PDMS (Cast)	Yes	Yes	160 (With Water)	[176]

7	<p>Profile Description: Hydrophobic pyramid shapes developed by 3D printing of inverted PLA pyramid mould which results in natural layer-by-layer ladder structure on the sides of the casted PDMS pyramid as shown in Figure 25.</p>  <p>Figure 25: Optical image of the hydrophobic 3D pyramidal structure shape at standard resolution obtained by casting PDMS from 3D printed PLA mould [177].</p>	FDM	PLA (Mould)	PDMS (Cast)	Yes	Yes	143 (With Water)	[177]
8	<p>Profile Description: Staircase structure formed on the sides of the 3D printed ABS Cube due to natural layer-by-layer deposition process in FDM as shown in Figure 26.</p>  <p>Figure 26: 3D printed and dip-coated ABS cube, where the water droplet forms a spherical shape characteristic to superhydrophobic surfaces [178].</p>	FDM	ABS	ABS (Dip-Coated with Hydrophobic Fumed Silica and Acrylic Fluoropolymer)	Yes	Yes	159 (With Water)	[178]

9	<p>Profile Description: Naturally induced Layer and Tool Path patterns formed in FDM based 3D printing process as shown in Figure 27.</p>  <p>XY sample</p> <p>XZ sample</p> <p>Figure 27: Schematic of 3D printing induced patterns, where Layer pattern is synonymous to the staircase effect [179].</p>	FDM	PLA	PLA (Dip-Coated with PDMS)	Yes	Yes	160 (With Water)	[179]
10	<p>Profile Description: Lines and channels pattern which results in directional hydrophobicity of 3D printed ABS and PLA patterns treated with FAS as shown in Figure 28.</p>  <p>Figure 28: CAD model of Line and Channels pattern [180].</p>	FDM	ABS	ABS (Treatment with Fluoroalkyl Silane (FAS))	Yes	Yes	147 (With Water)	[180]
	PLA	PLA (Treatment with Fluoroalkyl Silane (FAS))	Yes	Yes	142 (With Water)			

6. Conclusion:

This structured review presents a new forthcoming use of additive manufacturing techniques for inducing superamphiphobicity (including superhydrophobic and superoleophobic) in surfaces. It goes on to show how surface wettability can be suitably designed in the system by additive manufacturing of reentrant surface structures that limit dependency on the base material and are responsible for a smooth transition towards achieving a heterogenous wetting state (Cassie-Baxter).

The most established additive manufacturing techniques are extrusion based Fused Deposition Modelling (FDM) and Direct Ink Writing (DIW) or Pressure Assisted Micro-syringe (PAM) processes which have an extension range of freely available, cross-platform compatible materials of high commercial importance.

While reviewing the articles in this area (See Table 3), it is clearly observed that researchers have previously used materials which already exhibit repellency against a liquid which overshadowed the role of surface reentrant geometries in their design. Furthermore, in doing so they have neglected the full range of materials (See Table 2) especially those of high commercial importance like PVC and PETG whose surface wettability states can be redefined using reentrant structures. This means that an established route for design of reentrant geometries using the layer-by-layer deposition approach of these extrusion-based techniques is not available. To establish this route, one requires a clear understanding of process specific characteristics like the orifice diameter of the nozzle and material flowability including the movement of the extruder (print acceleration) which would determine as to how these parameters can be selectively exploited for generation of a complex set of reentrant features for superamphiphobic applications.

Reentrant geometry holds immense importance in modification of wettability behaviour where a pure amphiphilic surface can be rendered amphiphobic (or its derived state) with the formation of a correct reentrant geometry. Through this review it has been identified that with a background knowledge of parameters defining the reentrant geometry, an endless array of geometrical features can be easily designed in a CAD software and 3D printed to control surface wettability. Where extrusion-based additive manufacturing processes due to their simplicity and wide-range of material choices need to be explored further.

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