



**RESEARCH ARTICLE**

**WETTABILITY TUNING OF CANDLE SOOT COATED 3D-PRINTED MEMBRANES VIA LASER POWER CONTROL**

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**Abstract.** Three-dimensional (3D) printing has attracted growing interest for the fabrication of membranes for oil-water separation. While laser power is a key parameter in membrane fabrication, its effect on the wettability of coated membranes is still not well understood, posing challenges for improving membrane performance. This study investigates the effect of laser power on the wettability of 3D-printed polymer membranes coated with candle soot. Membranes were fabricated from virgin polyamide-12 (PA-12) powder using Selective Laser Sintering (SLS) at two laser power settings: 70 W and 80 W and then coated with candle soot. Characterization of membranes involved surface morphology, roughness, water contact angle, mechanical strength and mechanical and chemical stability. Notably, the coated membrane produced at lower laser power of 70 W demonstrated the highest water contact angle ( $150.7 \pm 1.8^\circ$ ), attributed to the lower energy density which led to inefficient powder melting and sintering. In contrast, higher laser power (80 W) produced smoother surfaces and slightly improved tensile strength due to more efficient powder sintering. Mechanical durability remained stable across both settings while chemical stability of the coated membranes showed greater sensitivity to abrasion, likely due to post-printing coating application. These findings underscore the critical importance of optimizing laser power to precisely control membrane characteristics and thereby enhance the efficiency of oil-water separation.

**Keywords:** 3D printing, laser power, wettability, energy density, candle soot coating.

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## 1. INTRODUCTION

In recent years, membrane separation has received a lot of interest [1,2] to its high treatment effectiveness. Diverse chemical substances such as water [1,2] and gas [3] have been demonstrated to be amenable to this approach for separation. Membranes can be fabricated from various types of materials such as metal meshes [4] and polymer-based membranes [1,2,5,6]. Previous researchers [1,2,6,7] focused extensively on polymer-based membranes; its smaller and more controlled pore size result in a better medium for the separation process.

Selective Laser Sintering (SLS) is a three-dimensional (3D) printing method of creating components without supports; the design options are limitless, suitable for fabricating a thin layer of membrane [8] and has the potential to reinvent the present process for producing porous membranes irrespective of geometries with reduced energy usage [9]. The part production process via SLS begins with the spreading of powder material over a build platform. A laser then selectively sinters the powder according to the part's cross-sectional geometry. The process is repeated layer by layer until the final part is fully formed [10]. The SLS process is based on complex fundamental physical mechanisms and behaviours; it encompasses a considerable amount of processing printing parameters [11].

Recently, researchers discovered that the necessity to modify the printing parameters is mostly due to the influence of printing parameters on surface quality, surface roughness and mechanical strength [8-10]. It is challenging to estimate accuracy when creating parts with SLS since it depends on numerous printing factors including hatch distance, layer thickness, laser beam speed, power and platform temperature [12]. The interplay of these printing factors can be explained by evaluating the energy density transmitted to the powder bed by the laser beam during the SLS printing process [10]. Moreover, applying a surface coating can improve the hydrophobic properties of the membrane by elevating the roughness and reducing the surface energy [7].

The key role of the membrane separation is to separate oil-water mixtures; the membrane surfaces must exhibit hydrophobic (repels water) and oleophilic (attracts oil) behaviours, and vice versa. The evaluation of the surface contact angle with the specific liquid can be used to define wettability [13]. In oil-water separation using polymer membranes, hydrophobic surface with contact angle greater than  $90^\circ$  is essential to ensure water repels from the surface while oil goes through the membrane. Surface roughness and surface chemistry are two key aspects that can influence wetting behavior.

In the oil-water separation process, surface coating techniques have been widely explored particularly for enhancing superhydrophobic properties [14]. Candle soot coating is popular among researchers to exhibit superhydrophobic nature of the surface [15,16]; the coating which produces nanostructured, porous carbon particles is a simple and cost-effective way for developing superhydrophobic surfaces. By achieving high contact angles (greater than  $150^\circ$ ) and low sliding angles, these coatings capture air pockets between the water and the surface, resulting in water droplets rolling off and forming beads which mimics the lotus effect. Its superhydrophobic behaviour provides better anti-fouling, water-repellent and self-cleaning characteristics making it suitable for oil-water separation.

Mechanical testing is important for parts fabricated from the SLS fabrication method [7,11]; these studies emphasize the significance of comprehending the printing parameters to maximize the mechanical strength of parts fabricated with SLS. It has been observed that printing parameters such as laser power, hatch distance and scan speed can influence strength of the SLS printed products [8].

In this study, the performance of coated membranes fabricated using varying laser power settings via SLS was investigated. Key analyses included surface morphology, roughness, water contact angle and mechanical strength. In addition, the mechanical and chemical stability of the highest-performing membranes was evaluated. The primary objective was to examine the influence of laser power variation on the wettability (water contact angle) and the durability of candle soot coatings (mechanical and chemical stability). Gaining insight into these relationships is critical for optimizing fabrication parameters to enhance membrane performance in oil-water separation.

## 2. MATERIALS AND METHODS

### 2.1 Fabrication and Coating

Circular specimens with a diameter of 5 cm and square-shaped specimens with a side length of 2.5 cm were fabricated using virgin polyamide-12 (PA12) powder; the thickness for both specimens was 1 mm. The 3D printing parameter settings are listed in Table 1.

**Table 1:** 3D printing parameters settings

Parameters	Values
Laser Power, $P$	70, 80 W
Slicing Thickness, $t$	0.12 mm
Scan/Hatch Distance, $s$	0.30 mm
Laser Beam Velocity, $v$	7.6 m s <sup>-1</sup>

Membrane specimens were coated using a solution of 0.1 wt% candle soot in hexane. Candle soot (0.08 g) was sonicated in 80 mL of hexane for 30 minutes in a sealed container with an ultrasonic bath cleaner. Once the solution was prepared, the coating process began by submerging the membrane specimen in the candle soot/hexane mixture for 40 minutes while sonication occurred. After coating, the membrane was placed in an oven at 60 °C for 10 minutes to facilitate drying process.

### 2.2 Characterization

The characterization comprised four types of testing: surface morphology, roughness, contact angle measurement and tensile testing. Circular-shaped specimens were used in the surface morphology and surface roughness characterization while square-shaped specimens were used in the contact angle measurement. Four distinct types of specimens were evaluated in this study as listed in Table 2.

**Table 2:** Membrane specimens ID

Specimens ID	Description
NCM-70 W	Uncoated membrane; fabricated at 70 W of laser power
NCM-80 W	Uncoated membrane; fabricated at 80 W of laser power
CM-70 W	Coated membrane; fabricated at 70 W of laser power
CM-80 W	Coated membrane; fabricated at 80 W of laser power

#### 2.2.1 Surface Morphology

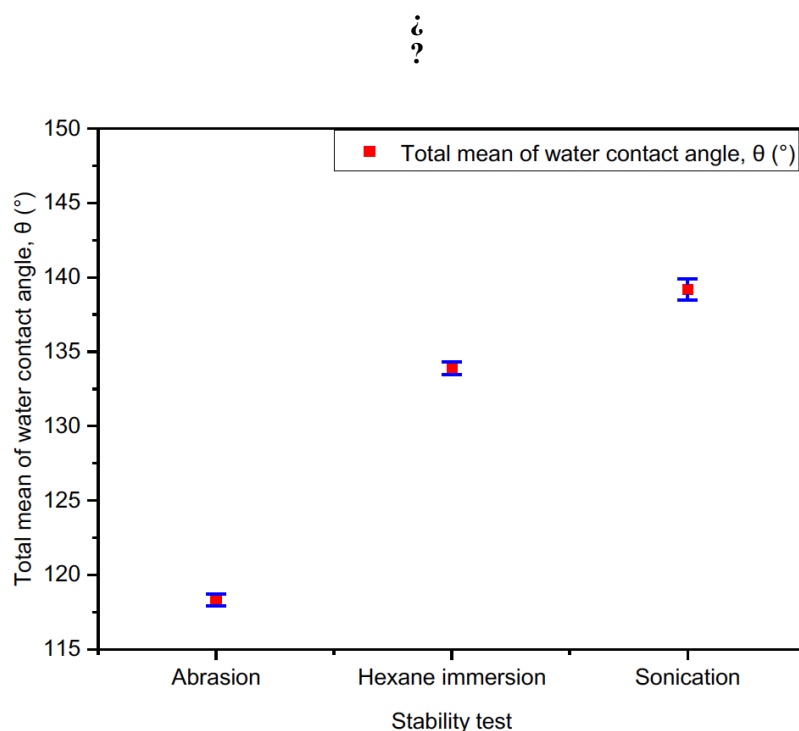
The surface structure of the printed polymer membranes was observed using a Scanning Electron Microscope (JEOL 6010 PLUS), operated in Secondary Electron Images (SEI) mode at two magnification levels: 50× (500 μm) and 200× (100 μm).

#### 2.2.2 Surface Roughness

The average roughness ( $R_a$ ) was measured using a Mitutoyo SJ-410 surface roughness tester over a travel length of 5 mm, in accordance with ISO 4287: 1997. Measurements were taken at three different positions to calculate the mean roughness.

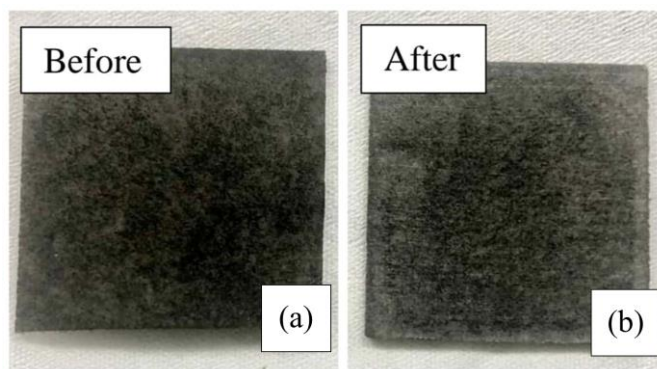
### 2.2.3 Contact Angle Measurement

The wettability of the surface was assessed by measuring the water contact angle (WCA). Using the sessile drop technique, a 5  $\mu$ L droplet of water was deposited on the specimen surface, which setup is shown in Figure 1(a). The average values obtained were calculated from data points taken from five different locations on the specimen. Images of the water droplets were captured using a Digital Viewer Microscope and the contact angles were measured using ImageJ software, as shown in Figure 1(b).



**Figure 5:** Water contact angle after various stability tests (abrasion load, hexane immersion time and sonication frequency)

Among the stability tests, the abrasion test had the greatest impact on the coated membrane surface (Figure 5). The abrasion test was performed to assess the mechanical durability of the candle soot coating applied to the CM-70 W membrane. In this test, the membrane surface was subjected to repeated mechanical friction to simulate physical wear that might occur during handling, filtration or operational use. It was a critical evaluation to determine how well the candle soot layer adhered to the PA-12 particles and whether it could maintain its hydrophobic properties under mechanical stress. After the abrasion process, the water contact angle was evaluated to detect any changes in surface wettability. A significant decrease in water contact angle suggested that the soot layer had been compromised or removed, as shown in Figure 6 where the coated area was visibly faded after undergoing abrasion. Since the candle soot coating was chemically applied after printing, it faded more easily compared to the results reported by Yuan et al. [7], in which the coating material was incorporated into the PA-12 powder before the printing process. However, the membrane remains hydrophobic showing strong mechanical stability after 10 cycles of abrasion test.



**Figure 6:** Membrane specimen (a) before and (b) after abrasion test

The hexane immersion test was performed to evaluate the chemical durability of the candle soot coating on the CM-70 W membrane when exposed to an organic solvent. The membrane was immersed in hexane for a specified duration to simulate potential exposure to harsh chemical environments during use. After immersion, the water contact angle was measured to determine if the membrane retained its hydrophobicity. A minimal change in the contact angle as shown in Figure 5 indicates good chemical stability of the soot coating in organic substances, while a significant drop suggested solvent-induced damage or loss of the hydrophobic layer.

Meanwhile, the sonication test was carried out to investigate the resistance of the candle soot coating to ultrasonic agitation, which mimics mechanical stress under fluidic conditions. The CM-70 W membrane was placed in a sonication bath and exposed to ultrasonic waves for a set period. Following sonication, the water contact angle was measured to evaluate any loss of hydrophobic performance. A notable reduction in contact angle implied that the coating had been partially degraded. All stability test showed a negative impact on water contact angle which explained the candle soot coating can be affected due to external forces. However, the membrane remained in hydrophobic nature showing strong mechanical and chemical stability.

#### 4. CONCLUSIONS

This study investigated the influence of laser power on surface wettability of 3D-printed PA-12 membranes coated with candle soot. The findings indicate that lower laser power (70 W) results in increased surface roughness and higher contact angles, contributing to enhanced superhydrophobicity which is further improved through candle soot coating. A reduction in laser power promotes pore development on the membrane surface which impacts surface quality due to the lower energy density (*ED*) applied during the printing process. On the other hand, higher laser power (80 W) led to smoother surfaces with slightly improved tensile performance due to more effective sintering. As for the coating stability, it was proven to be more sensitive to abrasion, likely due to the coatings being applied after the printing process. Overall, these findings highlight the critical role of laser power in tuning membrane properties for effective oil-water mixture separation.

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## Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

## Disclosure of Conflict of Interest

The authors have no disclosures to declare.

## Compliance with Ethical Standards

The work is compliant with ethical standards.

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