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MORPHOLOGICAL COMPARISON OF 3D PRINTED FEED SPACERS FOR SPIRAL WOUND MEMBRANE MODULES

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ABSTRACT: This paper presents the preliminary work done on the fabrication of feed channel spacers with rapid prototyping, 3D printing or additive manufacturing (AM) techniques, involving fused deposition modeling (FDM) and polyjet printing. Feed channel spacers are mesh-like structures placed between membrane leafs in spiral wound modules (SWM) for water treatment applications. AM techniques are employed as tools to fabricate novel feed spacer with complex geometries that maximize mass transfer and minimize feed channel pressure drop and fouling across the SWM. The morphology of the AM printed spacer samples, as well as the dimensional accuracies are examined and compared in this paper.

INTRODUCTION

The spiral wound module (SWM) is one of the most popular module configurations for membrane separation technologies applicable to water and wastewater treatment, seawater desalination, gas separation, concentration and recovery of valuable components for pharmaceutical and dairy industries (Mulder, 1996). Feed channel spacers are important mesh-like structures used in SWM to create channels for fluid flow by separating adjacent membrane leafs apart, hence defining the channel height. The feed spacers serve to facilitate mass transfer and promote mixing of the bulk feed flow through the spacer filaments. However, the narrow spacer-filled channels of the SWM are associated with several issues such as pressure loss, fouling, and maldistribution of flow. First, the presence of the feed spacer in the flow channel hinders the fluid flow, causing a drop in pressure across the membrane module. Second, fouling problems are found to be associated with

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the accumulation of biomass on the spacer. Hence, the optimization of the spacer geometry is significant as it affects the overall economical costs of the membrane separation process (A. R. Da Costa, Fane, & Wiley, 1994).

Previous experimental efforts (Andre R. Da Costa & Fane, 1994; A. R. Da Costa, Fane, Fell, & Franken, 1991; A. R. Da Costa, Fane, & Wiley, 1993; A. R. Da Costa, et al., 1994; Schwinge, Wiley, Fane, & Guenther, 2000) mainly involved commercial feed spacers made via common extrusion method into diamond or ladder-shaped mesh with limited works experimented on complex spacer geometries, for instance, the triple layered spacer made by hand (Schwinge, Wiley, & Fane, 2004). Existing difficulties in fabricating complicated spacer design via the common extrusion method have spurred interest in employing rapid prototyping, 3D printing or additive manufacturing (AM) technologies for spacer fabrication. Some of the very few examples are the multi layered spacer with twisted filaments made by Selective Laser Sintering (SLS) (Li, Meindersma, De Haan, & Reith, 2005) and staggered herringbone and helical spacers made by FDM (Shrivastava, Kumar, & Cussler, 2008). Polyjet printing of spacers may also be examined as tissue scaffolds which had structures akin to the diamond-shaped spacer, were also successfully fabricated by polyjet (Liu, Chou, Chua, Tay, & Ng, 2013; Tan, Chua, & Leong, 2013). AM technology provides the tool to fabricate novel spacers with complex geometries that maximize mass transfer and minimize feed channel pressure drop and fouling. The objective of this paper is to investigate preliminary work done on the geometry design of the spacer, including the replication of commercial diamond-shaped spacer, the triple layered and zigzag spacers tested by previous researchers and morphology of the spacer samples fabricated by FDM and polyjet.

MATERIALS & METHOD

To replicate the geometry of the commercial diamond-shaped spacer, the commercial spacer was examined under transmission microscope to scrutinize the surface structure. The commercial spacer (Figure 1a,b) comprised two layers of polypropylene (PP) materials extruded into filaments. The first layer of filaments (detached filaments) was placed parallel to each other at regular intervals specifically known as the mesh length. The second layer of filaments (attached filaments) was welded at an angle known as the hydrodynamic angle or in this case perpendicularly on top of the first layer. It was discovered that the spacer filaments were not produced as uniform cylindrical rods. Spacer manufacturers reserved their comments on whether the cross-section of the spacer filaments was intended or an inherent error of the manufacturing process. Therefore, the spacer fabricated in this paper took on the assumption that the cross-section of the spacer filaments was circular and uniform throughout the entire filament strand. The designable geometric characteristics of the spacer are defined by its hydrodynamic angle, mesh length and filament diameter. The commercial spacer dimensions were first measured with a digital caliper. A geometric model of the commercial spacer sample at a dimension of 100 mm x 100 mm was then drawn on Solidworks, a Computer-Aided Design (CAD) software. In this paper, the AM technologies investigated for the replication of the commercial spacer were FDM and polyjet.

For fabrication using the FDM technique, the geometric model was imported from Solidworks as .stl (stereolithography) format into the Catalyst® EX software of the FDM machine (Stratasys Dimension Elite). Each slice thickness was set to be 0.178 mm. Acrylonitrile Butadiene Styrene (ABS), the most common material for FDM was used to fabricate the sample spacer. The ABS filament stored in a spool was fed into the extrusion head, heated to semi-liquid state and extruded layer by layer from the FDM print head. The extruded material was quickly cooled and solidified

(Chua, Leong, & Lim, 2010). The spacer fabricated by FDM was subsequently soaked in hot alkaline solution to dissolve away the support material. Spacer fabrication using the polyjet involved loading the geometric model into the Objet Studio software of the polyjet machine (Objet Eden350V**)**. The photopolymer material used in this paper was the polypropylene-like DurusWhite RGD430. Each layer thickness was 16 μm. The photopolymer ink droplets were immediately cure by ultraviolet (UV) light when deposited onto the build tray (Chua, et al., 2010). Upon completion of the build part, water jet and brushes were used to remove the support material. Care was taken to ensure minimal or no damage was done to the small and delicate filaments of the spacer.

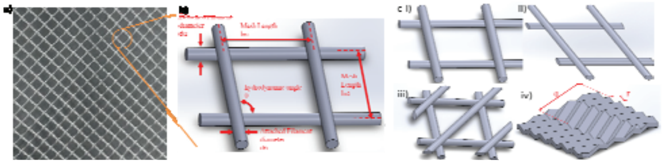

Figure 1: (a) Photograph of the commercial diamond shaped spacer (b) Detailed view of a unit cell of the commercial spacer (c) CAD models of a unit cell of spacer. (i) commercial spacer (ii) diamond-shaped spacer with hydrodynamic angle =120˚ (iii) triple layered spacer (iv) zigzag spacer

Besides replicating the commercial spacer, other spacer geometries examined by researchers in previous publications such as the diamond-shaped spacer with hydrodynamic angle of 120˚(A. R. Da Costa, et al., 1994), triple layered spacer (Schwinge, et al., 2004) and the zigzag spacer (Schwinge, et al., 2000) were also fabricated with FDM and polyjet. The CAD models of the commercial, diamond-shaped with hydrodynamic angle of 120˚, triple layered and zigzag spacers are shown in Figure 1c. The geometry design of the triple layered spacer is the same as that of the commercial spacer but with the addition of a third layer of filaments welded at an angle of 45˚on top of the second layer filaments (Schwinge, et al., 2004). For the zigzag spacer, its geometry is described by the spacer width between the peaks *r*, and the axial distance between the bends *q* of the spacer (Schwinge, et al., 2000).

RESULTS AND DISCUSSION

Dimensional measurements with the digital caliper and micrograph analysis with the scanning electron microscope (SEM) were conducted to determine the accuracy and morphology of the AM fabricated spacers samples. The designed dimensions for each type of spacers are listed in Table 1. The hydrodynamic angle and mesh length for both the diamond-shaped and triple layered type spacers have dimensional errors that are less than 2%. This finding is favorable as both these parameters are vital to the spacer performance in mass transfer and pressure drop reduction. The design parameter with the largest deviation from the CAD models is found to be the filament diameter. It is discovered that for both AM techniques, the detached filaments are larger in diameter that the attached filament despite having the same design size. One possible explanation may be due to the compaction of the bottom layer filaments before they fully solidifies, resulting in the bottom layer having flatter cross-sections and larger diameters. This corresponds to the SEM images of the cross-sectional view of the spacer filaments in Figure 2ii-2 and iii-2. This is less discernible for polyjet as each layer was immediately cured by UV light upon deposition but the effect is apparent in FDM printed spacers as the solidifying speed of the extruded filaments is dependent on temperature, having deposition temperature nearer to the material's glass transition temperature (108˚C for ABS) will allow the extruded material to solidify faster and has better filament shape while higher temperature will result in weaker layer adherence due to thermal shock and filament warping (Cunico, 2013). Dimensional accuracy of FDM printed spacer may also be further improved by using optimization algorithm to get optimal values for CAD model design (Noriega, Blanco, Alvarez, & Garcia, 2013) .

Table 1. Dimensional accuracy of fabricated spacer samples. (a) diamond-shaped spacer (b) triple layered spacer (c) zigzag spacer

a)

		Filament diameter/mm					Mesh length/mm			Hydrodynamic Angle/ °		
Spacer type	AM technique	Designed	Actual (attached)	% error	Actual (detached)	% error	Designed	Actual	% error	Designed	Actual	% error
diamond	Commercial	-	0.40	-	0.40	-		2.90	-	-	90	-
	FDM	0.40	1.06	62.26	1.11	63.96	2.90	2.85	1.93	90	89	1.12
	Polyjet	0.40	0.52	23.08	0.59	32.20	2.90	2.87	1.05	90	90	0.00
	FDM	0.40	1.07	62.62	1.53	73.86	2.90	2.92	0.51	120	118	1.69
	Polyjet	0.40	0.50	20.00	0.52	23.08	2.90	2.98	2.52	120	120	0.00

b)

		Filament diameter/mm							Mesh length/mm			Hydrodynamic Angle/ °		
Spacer type	AM technique	Designed	Actual (1st layer)	% error	Actual (2nd layer)	% error	Actual (3rd layer)	% error	Designed	Actual	% error	Designed	Actual	% error
triple layer	FDM	0.40	1.04	61.54	0.99	5.05	0.93	11.83	2.90	2.87	1.05	90	89	1.47
	Polyjet	0.40	0.54	25.93	0.56	3.57	0.48	12.50	2.90	2.93	1.02	90	90	0.00

c)

		Spacer width between the peaks / mm			Axial distance between the bends / mm		
Spacer type	AM technique	Designed	Actual	% error	Designed	Actual	% error
zigzag	FDM	1.73	1.48	16.89	10.39	9.85	5.48
	Polyjet	1.73	1.41	22.70	10.39	10.14	2.47

The SEM images of the fabricated spacer samples are shown in Figure 2. Spacers fabricated using polyjet are in better geometrical agreement with the CAD models compared to FDM. This outcome is expected as polyjet machines have better resolution at 16 μm layer thickness compared to that of FDM machines at 0.178 mm. Although better, the cross-sectional views of polyjet fabricated spacers were still unsatisfactory as ellipsoidal instead of circular cross-sections (Figure 2cii-1 and ciii-1) of the spacer filaments were produced. On the other hand, FDM could not print a cylindrical spacer filament as shown in Figure 2cii-2, ciii-2 and civ-2. Each cylindrical filament was printed out in several thin layers, resulting in a flat spacer filament. For the zigzag spacer (Figure 2bv and cv), polyjet is able to produce the zigzag shaped of the spacer with the peaks and bends visibly defined. In the case of FDM, the peaks and bends of the zigzag spacer were flatted out by the extruded strand. These effects of FDM process can be explained by the staircase effect (Galantucci, Lavecchia, & Percoco, 2009) where each layer is influenced by the angle between the vertical axis and the surface tangent, causing the presence of seam lines between each layers. The problem may be solved if the FDM processing parameters can be altered. The porosity and surface finish of the printed parts can be affected significantly by adjusting process parameters, specifically the air gap and raster width (Ahn, Montero, Odell, Roundy, & Wright, 2002; Ang, Leong, Chua, & Chandrasekaran, 2006; Galantucci, et al., 2009). Chemical treatment of the printed ABS material with polar solvents (Galantucci, et al., 2009) was also proven as a simple alternative method to reduce the staircase effect of the FDM printed parts.

Despite having better precisions, the SEM images of polyjet printed parts demonstrated high surface roughness at the microstructure level as compared to the smooth surface of the FDM extruded filament strand. The roughness of the polyjet printed spacers may be attributed to the incomplete removal of support material as some interior parts of the unit cell were inaccessible to cleaning or it may be associated with the printing pattern of polyjet. Surface roughness of the spacer can be detrimental to spacer fouling as rough surface provides a favorable platform for foulants to attach on. Hence, there is a need to improve the surface quality of polyjet printed parts by ensuring complete removal of support materials through more efficient and easier means.

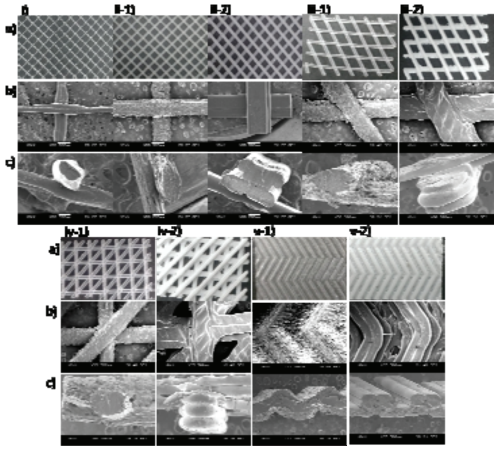

Figure 2. Photographs of (a) fabricated spacers and SEM images of (b) plan view of spacers and (c) Cross-sectional view of spacers where (i) commercial spacer (ii) replicated commercial spacer (iii) diamond-shaped spacer with hydrodynamic angle = 120˚ (iv) triple layered spacer (v) zigzag spacer which are (1) fabricated by polyjet (2) fabricated by FDM.

In this paper, spacer fabrication is limited to FDM and polyjet techniques. The choice of the AM techniques was based on the current availability of AM machines with the feasibility to fabricate polymeric parts in the lab. Other AM techniques including SLS will be considered in future work. The second limitation in this study is the type of material used. The most common material used to make the commercial feed spacer is polypropylene (PP) due to its good pH range and excellent chemical resistance to many solvents. However, due to the restriction of the use of materials by the AM machine manufacturers, the materials used to fabricate the spacer were not yet considered in this paper. The third limitation in this study is the inability to alter the process parameters of FDM machine (Stratasys Dimension Elite) to achieve better accuracy and surface finish.

CONCLUSION

The morphological comparison of 3D printed feed spacers via FDM and polyjet printing was studied in this present paper. Both AM techniques are able to produce similar geometrical structures as the designed CAD models. FDM fabricated spacers portrayed smoother surface at the microstructure level than polyjet despite its staircase effect. However, the accuracy of FDM printed spacers is inferior to that of the polyjet. In comparison, polyjet printed spacers demonstrated good resolution and accuracy but rougher surface at the microstructure level. The effect of microscale roughness of the spacers will be characterized in terms of channel pressure drop, and surface drag effects in membrane filtration experiments. The future plan will include investigation of other AM techniques such as SLS to determine the best production method for fabricating spacers in both geometry and material design.

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