SELECTIVE LASER SINTERING OF POLYPROPYLENE FEED SPACERS FOR SPIRAL WOUND MEMBRANE MODULES

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ABSTRACT: Feed spacers are net-like structures present in spiral wound membrane modules (SWM) used for treatment of water and wastewater. Feed spacers require appropriate stiffness to support membrane without damaging and puncturing the membrane surfaces. They also need to be flexible enough to be rolled up around the central permeate tube forming the SWM. Polypropylene (PP) is the commercially used material for feed spacers due to its flexibility and excellent chemical resistance properties. In this paper, Selective Laser Sintering (SLS) is used to investigate the printability of net-typed structures using polypropylene materials to represent feed spacers. SLS processing parameters such as layer thickness, part bed temperature, energy density and scan pattern were studied and net-typed PP spacers were successfully fabricated. However, an analysis on tensile test and dimensional accuracy shows that Young's modulus of the PP material tends to be correlated to the accuracy of the dimensions of the net-typed spacer prototypes.

Keywords: Feed spacers, polypropylene, selective laser sintering (SLS), net-typed structures, additive manufacturing

INTRODUCTION

Additive manufacturing, also known as 3 Dimensional (3D) printing or rapid prototyping is an emerging technology that has shown promising applications in several industries such as

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automotive, aerospace, biomedical, building, consumer and food (Chua & Leong, 2014). It has also begun to attract the attention of researchers in the field of water and wastewater treatment industries for the fabrication of intricate components in membrane modules, such as membrane (Badalov, Oren, & Arnusch, 2015; Femmer, Kuehne, Torres-Rendon, Walther, & Wessling, 2015; Femmer, Kuehne, & Wessling, 2014, 2015) and feed spacers (Fritzmann, Hausmann, Wiese, Wessling, & Melin, 2013; Fritzmann, Wiese, Melin, & Wessling, 2014; Li, Meindersma, De Haan, & Reith, 2005; Shrivastava, Kumar, & Cussler, 2008; W. S. Tan 2014). The current state of art of additive manufacturing is not adequately advanced for direct printing of membranes as the resolution range of 3D printing technology only marginally intersect that of the membrane at 0.1 to 10 µm (Lee et al., 2016). On the other hand, feed spacers with millimeter scale are considerably challenging but possible for direct printing via 3D printing technology. Feed spacers have net-like structures that are used to separate and support membranes while facilitating mass transfer of water across the membrane to achieve higher yield of clean water. Significant problems faced by feed spacers include pressure loss and fouling which may be attributable to the design of the spacer itself. The advantage of employing 3D printing as a tool to fabricate feed spacers lies in the capability of 3D printing in prototyping and manufacturing novel but complex and intricate spacer structures that conventional manufacturing techniques cannot achieve.

The spacer, together with the membrane leafs will eventually be rolled up around the central permeate tube forming the spiral wound membrane modules (SWM) as shown in **Error! Reference source not found.**. The roll-up generates compressive forces and tightening of the spiral will result in further compression of the spacers (Johnson & Busch, 2010). As such, the spacer material has to be both flexible and stiff with high tensile modulus of elasticity. Polypropylene (PP) is the commercially used material for feed spacers due to its low cost, flexibility and excellent chemical resistance properties. Selective laser sintering (SLS) of spacers with polypropylene powder faces challenges in issues such as low tensile strength for thin parts and warping, especially for dense solid structures due to accumulation of heat during sintering. Therefore in this paper, SLS will be employed to fabricate net-typed structures similar to that of a commercial feed spacer using polypropylene powder. As the processing parameters for solid type structures and net-typed structures are different, the optimal processing parameters for printing of net-typed structures using polypropylene materials will be investigated.

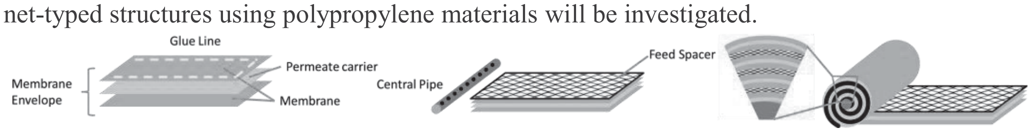

Figure 1: Schematic diagram of the components of a spiral wound membrane module.

MATERIALS & METHOD

Equipment and Material

SLS is a powder-based additive manufacturing technique, commonly used for fabrication of polymer parts. The SLS machine used in this paper is the EOSINT P395 SLS machine from EOS which is illustrated in Figure 2. The 3D geometric model was imported from Solidworks as .stl (stereolithography) format into the EOSINT P395 SLS machine. Files were checked and verified to be error-free using Magics software before loading into the EOS processor which sliced the 3D model into 2D cross sections at the selected layer thickness. The laser beam scanned the 2D cross sections of the model at each layer height to sinter the powder particles together forming the 3D model. The material used was PP powder from Diamond Plastics (Germany) with an average particle size at 60 µm. To fabricate net-typed structures similar to that of a commercial feed spacer, optimising the SLS process is a critical part. Therefore, the SLS process parameters were investigated to obtain the desired spacer characteristics in mechanical strength. The processing parameters of SLS include layer thickness, powder bed temperature, energy density (laser power, scanning speed, scanning distance), and scan pattern.

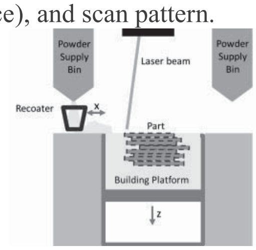

Figure 2: Schematic diagram of the EOSINT P395 SLS machine

Layer Thickness and Orientation

The layer thickness selected for printing spacers was the lowest layer thickness available offered by the EOS SLS machine at 0.100 mm in order to increase the accuracy of the printed spacers. The net-typed structures were oriented such that fine features were positioned flat top down to ensure printability. The orientation and layer thickness may be an important factor to look into since spacers have fine features and typical commercial spacers are considered very thin for 3D printing with spacer thickness in the range of 28 mils to 34 mils (0.7 mm to 0.9 mm).

Powder Bed Temperature

Powder bed temperature refers to the temperature of the powder on the SLS building platform. This temperature is usually set as high as possible but below the melting point of the powder so that less energy is required for the laser to heat up the powder particles during the sintering process. This parameter affects the temperature gradient between the printed part and its surrounding powder. High temperature gradient will result in distortion of parts (Leu, Pattnaik, & Hilmas, 2010; Pham, Dimov, & Lacan, 1999). The PP powder was first tested for the melting temperature and glass transition temperature using Differential Scanning Calorimetry (DSC) before printing. The melting point of the PP powder was determined to be around 163-165°C. Hence, the powder bed temperature range was set between 150°C and 160°C. To determine the optimum powder bed temperature for the selected PP material, a temperature search test was conducted. Curling occurs when the powder bed temperature is too low, causing a high thermal gradient between the sintered part and the unsintered powders. On the other hand, caking will occur when the powder bed temperature is too high, leading to agglomeration of powder particles when powder particle surface starts to melt. For this test, 9 CAD models of T-shape crosses, each of single layer height at 0.100 mm, were uniformly positioned on the building platform of the SLS machine. The building temperature was initially set at 153°C then adjusted in small increments (1-2°C) after noting the number of crosses that curled up after laser sintering. The optimum powder bed temperature was eventually determined to be 157°C.

Energy Density

Besides the powder bed temperature, the other processing parameters also have significant impact on the printability of the PP materials. Continuous printing for several layers may fail when subsequent scanning over the same area causes the sintered part to warp. The recoater will not be able to function properly when hindered by the warped parts and the build will fail. The warping effect can be attributed to the energy density of the laser. The energy density E_L is given by

$$E_L = \frac{P_L}{v_s h_s d_L} \quad (1)$$

where P_L refers to the laser power, h_s is the hatch distance, v_s is the scanning speed and d_L is the layer thickness. These parameters of energy density were varied in order achieve complete bonding of the powder layers and optimal mechanical properties with flexibility and no warpage (Zhu, Lu, & Fuh, 2003).

Scan Pattern

The EOSINT P395 SLS machine requires different parameters setting for different types of scan lines. For fabrication of net-typed structures similar to that of a commercial feed spacer which has millimetre scale dimensions as low as 0.4 mm, the type of scan lines present is the edge lines as seen in Figure 3. Laser power and scan speed were studied in higher levels as they are the two most significant factors that affect the physical properties of the printed net-typed structures. Therefore, in this paper, the edge laser power and edge scan speed values were selected such that the calculated edge energy density will spread over a range from 0.24 J/mm^3 to 2.27 J/mm^3 for a total of 16 runs in increasing energy density.

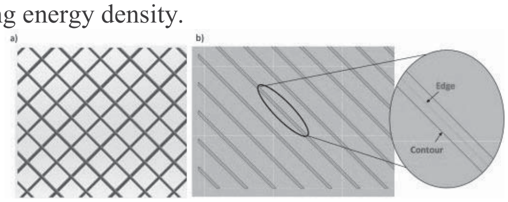

Figure 3: Net-typed structure similar to a feed spacer. a) 3D model b) scan lines of the 3D model at 0.3 mm layer height

Measurement of Dimensional Accuracy and Tensile Testing

The dimensions of the printed net tensile for each run were first measured for the filament diameter and thickness for at least three different positions along the gauge length using digital calliper. The printed net tensile bars were then tested for tensile strength in the Shimadzu universal testing machine. The measurement for each run was repeated at least thrice until consistent results were achieved. There were a total of 16 runs that covered a range from 0.24 J/mm^3 to 2.27 J/mm^3 in increasing energy density. The Young's modulus was calculated using the linear portion of the stress-strain curve for each run.

RESULTS AND DISCUSSION

Figure 4a shows the images of the printed net tensile bars for each run. The net tensile bar for Run 9 is not shown as the energy density at 0.24 J/mm^3 is too low to be printed. It can also be observed that as the edge energy density of the run increases, the dimensional accuracy of the net-typed spacer structure (Figure 4b) in the middle portion of the tensile bars reduces.

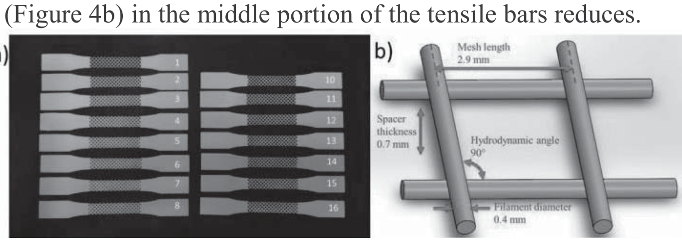

Figure 3: a) EOS SLS printed PP net tensile bars b) Net-typed structure in the tensile bars

The Young's modulus reflects the stiffness of the spacer. A low Young's modulus value would mean low resistance of the material to elastic deformation under load whereas a high Young's modulus would mean having high stiffness. Although there are no study on the specific tensile strength and Young's modulus required for a feed spacer, the feed spacer material must at least be flexible enough to be wrap around a tube. The printed PP net-typed structure for each run showed brittle failure with little or no elongation and hence were concluded as still unacceptable when compared to the commercial feed spacer. The desirable results of the net tensile structures are small dimensional variation, high ultimate strength and considerable young's modulus. Hence, 3D plots of dimensional variation, ultimate strength and Young's modulus (Figure 4) are plotted to give an overview of the results for the 16 runs.

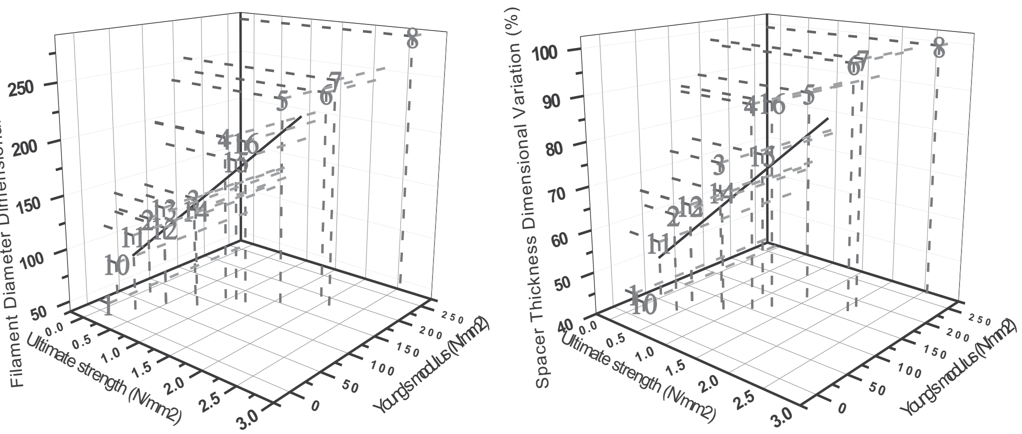

Figure 4: 3D plot of dimensional variation vs ultimate strength vs Young's modulus (left) filament diameter's dimensional variation (right) spacer thickness's dimensional variation

It can be observed that the dimensional variations for printable and handle-able PP net-typed structures are very high with the least being around 40%. Dimensional inaccuracy of the spacers will lead to either a larger or smaller than expected filament diameter and thickness which would affects the flow dynamics in the membrane modules. The effects of the filament size are still debatable because on one hand, larger filament diameters may be lead to lower voidages hence increasing the velocity at membrane surface and enhancing mass transfer. On the other hand, it will also block a larger fraction of the membrane causing lower flux (Da Costa, Fane, & Wiley, 1994; Schwinge, Wiley, & Fane, 2004). Generally, dimensional variations can be reduced by using compensation factors taking into account the laser beam offset and possible linear scaling factors in the x and y direction. However, it may be ineffective for this particular net-typed structure as the laser beam diameter (0.5 mm) is already larger than the filament diameter (0.4 mm).

CONCLUSION

Powder bed temperature search test and parameters optimisation test were conducted to determine the optimal building temperature and process parameters to print PP materials. PP net-typed spacer prototypes were successfully printed via SLS and evaluated for ultimate strength, Young's modulus and dimensional accuracy. It was found that Young's modulus of the PP material tended to be correlated to the accuracy of the dimensions of the net-typed spacer prototypes. This raw PP powder may not be suitable for direct printing of feed spacers with the current setting of process parameters. However, pre-treatment of this PP powder or exploring advanced printing strategies may be investigated in future to improve the mechanical properties.

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