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Optimization of vat design in open-architecture mask-projection vat photopolymerization platform using Finite Element Analysis.

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Abstract
This work focuses on the vat design optimization in the vat photopolymerization additive manufacturing process. The conducted study presents the influence of the vat's shape and build plate position on the magnitude of stresses occurring on the membrane. Vat photopolymerization (VPP) is characterised by high fabrication fidelity and high resolution. However, one of the challenges of this technology is the short lifespan of the membrane, as for the existing solution it can withstand a very limited amount of fabrication cycles. Therefore, various shapes of the vat of different areas and with different build plate offsets have been investigated. Using the Finite Element Analysis (FEA) software, it was possible to perform simulations and define the most optimal vat shape, which induces the lowest amount of local stresses on the membrane.

Vat Photopolymerization, Additive Manufacturing, Membrane's lifespan, FEA

1. Introduction

Vat photopolymerization (VPP) is a resin-based additive manufacturing technique that has been gaining more interest in the research and development areas since 2004 after the expiration of the original VPP patents [1]. The principle of the manufacturing process involves a vat containing a photosensitive resin and a build plate that is submerged in a liquid polymer at a distance equal to the consecutive layer's height (bottom-up setup). The resin flowing under the build plate is cured by the UV light of wavelength typically in the range 380 – 405 nm, provided by a projector. The layers are chemically bonded by activation of the photoinitiator, which breaks double carbon bonds and merges the monomers, creating branches [2,3,4]. These steps are replicated until obtaining the whole component.

There are two most common VPP configurations: top-down and bottom-up. In the first setup the light source is installed above the container with liquid polymer and the build plate moves downward immersing deeper into the resin. This solution requires a vat with greater height compared to the other configuration. In the bottom-up arrangement, a projector is mounted underneath the vat and delivers light from the bottom. In this case, the direction of the build plate movement is upwards. Moreover, a distinction is made between two types of light sources, such as mask projection (MP), where the whole layer is exposed to the ultraviolet light at the same time (projection mask technology used), and laser writing (LW), where the polymer is cured with a laser beam along the defined beam path [5].

There are many different designs of VPP machines, however, three main modules can be identified among them: the linear stage, the vat, and the light source. Each group has several aspects to improve and develop, such as precision of movement, leakage, quality of light, etc. In this paper, the main focus is put on the self-peeling vat and, in particular, the lifespan of its membrane.

Previous work showed that a coated film is predisposed to cracking after 30 fabrication cycles in a rectangular vat and spilling the liquid resin [2]. Therefore, it is needed to extend the lifetime of the membrane and make it more durable to reduce expenses and waste amount, and to ease the work of machine operators. This issue can be solved by changing the shape of the vat and achieving a lower level of stress, hence making the membrane more resistant to cyclic loads.

Previous research on the influence of the vat's shape on the film endurance included the comparison of two shapes – round and rectangular. Lower stresses were obtained for the offset rectangular vat, achieving approximately 0.43 MPa (max Huber-Mises-Hencky reduced stress) for the applied force of 2.5 N, compared to 2.88 MPa for the same force, in the case of round vat shape [2]. The mentioned study was conducted for the VPP unit with a projection lens of 2.0x magnification and a build envelope of 38.6 x 24.1 mm. However, in the following paper investigation has been performed for the 9.9x projection lens with a maximum build envelope of 192 x120 mm [6], implying significantly bigger manufactured components. Furthermore, four shapes of the vat have been analysed using Finite Element Analysis (FEA): rectangular, triangular, pentagonal, and hexagonal.

The methodology of FEM calculations is presented, explaining the approach used. Results of the simulations are introduced, showing which shape of the vat design exhibits the least stress and therefore is chosen to proceed with in the future design process of a VPP 3D unit.

2. Methodology

The previous study [2], showed that a rectangular vat with the offset is more advantageous compared to the round one in the case of printing in its centre, and achieves signally lower values of stress, hence extending its lifetime. Based on that investigation, the design of a vat has been improved, the part has been manufactured, assembled and implemented in the open architecture high-resolution VPP setup at the Technical University of Denmark. The machine uses a modular double-stage configuration for heavy-duty and ultra-high resolution fabrication and a Visitech LUXBEAM® LRS-WQ-HY projector with an integrated DLP9000 DMD™ UV light engine with a resolution of 2560 × 1600

pixels and 7.54 µm pixel pitch. The overview of the machine is shown in Figure 1a and the cross-sectional view of the vat is shown in Figure 1b. It consists of three main components: a bottom plate, a rectangle plate and a membrane tensioner. There are also applied seals in order to avoid resin leakage, screws to mount the set together, and a PTFE membrane located between the bottom and rectangular plates.

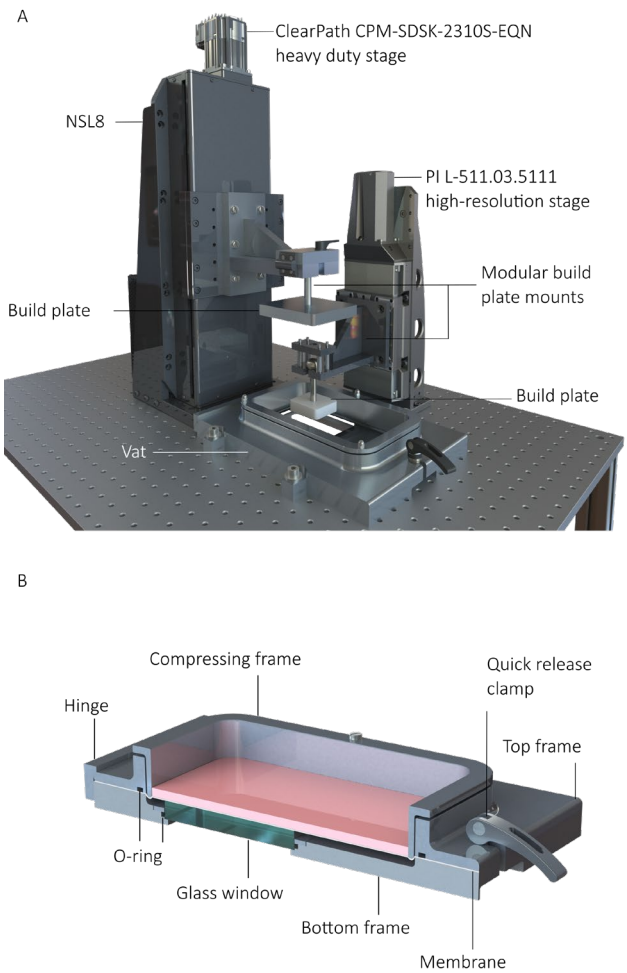

Figure 1. Open architecture VPP platform at the Technical University of Denmark. A: Overview of the modular double-stage setup, B: cross-sectional view of the rectangular offset vat [4]

In the following study, maximum Huber-Mises-Hencky (HMH) reduced stresses have been obtained for the considered four shapes of the vat: rectangle, triangle, pentagon, and hexagon, in order to decide which of them is the most durable.

Each shape has two different areas of 545260 mm^2 and 215600 mm^2 (called the *bigger* and *smaller* area, respectively). Additionally, every instance has two part offset configurations. In total, there are 16 simulations carried out in the first set, and three in the second set (Table 2), where investigation has been conducted for cases with the same offset to height ratio. This ratio describes the location of the simple part with rectangular cross-section on the centreline of the membrane. Maximum build envelope is defined as 192 x 120 mm for the 9.9x projection lens, according to the Visitech's specifications [5].
Simulations have been performed considering a PTFE membrane of 76e-3 mm thickness, a yield strength of 480 MPa and Poisson's ratio of 0.4, which is fixed and loaded as presented in Figure 1b. Load acting on the coated film is selected to be 2.5 N as considered in [2]. The offset is defined as the distance between the part and the vat as presented in Figure 2. In specific, in this paper, it is the length of a line perpendicular to the left edge of the cross-section of the part, which starts from the middle point of that edge and ends at the vat's left edge.

A possible limitation of this approach is that the model is simplified as it contains only one component, where the adhesive bonding between the part and the membrane is neglected. This assumption might lead to discrepancies between the data obtained from simulations and the results from experiments. Even though variations between simulations and experiments are expected, the numerical model will still be a useful tool to pinpoint the best combination, between vat shape and offset, to generate the lowest stress on the membrane during fabrication.

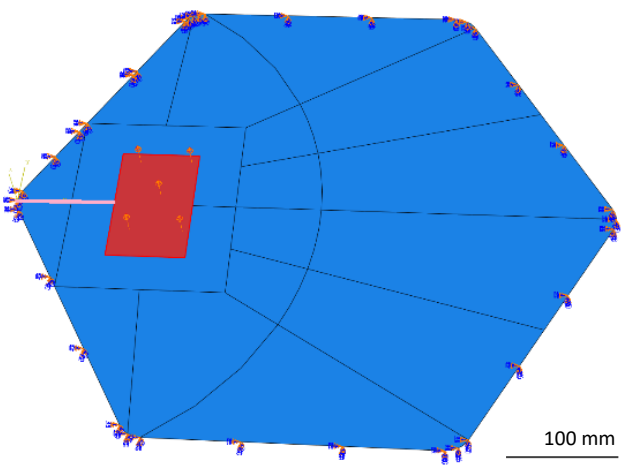

Figure 2. Example of the considered membrane model (blue) with fixing and load methods. The pink line and the red rectangle represent the offset and the maximum part cross-section area, respectively

Table 1 Input data and results of the first simulations set.

Shape	**Rectangular**				**Pentagonal**				**Triangular**				**Hexagonal**			
Vat area [mm²]	545260		215600		545260		215600		545260		215600		545260		215600	
Offset [mm]	100	200	50	100	150	250	100	150	200	300	180	250	150	250	100	200
Offset to height ratio [-]	0.10	0.20	0.09	0.18	0.17	0.29	0.19	0.28	0.21	0.32	0.31	0.43	0.17	0.28	0.18	0.35
Max Reduced Stress HMH [MPa]	3.114	2.120	3.865	2.690	3.152	2.273	3.450	2.335	3.710	2.805	3.959	2.815	3.020	2.147	3.259	1.661

3. Results and discussion

Simulations have been divided into two sets. The first one contains 16 cases of the membrane with four different shapes, two different areas, and two different offsets. Four instances representing each shape, with the least advantageous results (smaller area and smaller part offset) have been shown in Figure 3. It is observed that stress level lowers with a higher number of edges. However, in this batch, the ratio of the offset to height of the membrane is different for each case, therefore, after obtaining the results, three cases with the lowest magnitude of stress have been chosen to be considered further. Hence, the second simulation set contains the mentioned three instances (one rectangular membrane and two hexagonal) with the same offset to height ratio.

Results of the second set of simulations have been obtained and presented in Table 1. Additionally, the stress maps of cases with the highest and lowest values are shown in Figure 4. It is observed that for each shape, the use of a smaller vat area leads to a higher level of stress. Moreover, for greater offsets, lower magnitudes of stress are achieved. It can be further seen, that stress concentration occurs on the edges of the membrane and in the area of the cross-section of the part.

The lowest HMH stress values have been obtained for two hexagonal membranes: the one of smaller area, with 200 mm offset (1.661 MPa), and the one of bigger area with 250 mm offset (2.147 MPa). Moreover, a low stress level was also obtained in the case of the rectangular-shaped vat with the biggest area (995 x 548 mm^2) and greater offset (200 mm) stress magnitude is 2.120 MPa. For these three instances it has been decided to conduct a further investigation setting their offset to height ratio at the same level of 0.35.

The results of the second simulation batch are shown in Table 2. Furthermore, stresses maps of instances with the smallest and the greatest stress level are introduced in Figure 5.

After setting the offset to height ratio to the same level, in other words placing the part at the same location on the membrane, it turns out that the most optimum solution (1.447 MPa) has been achieved by the biggest hexagonal vat, whereas the worst by the rectangular (2.307 MPa). Nevertheless, it will be necessary to conduct validation experiments on the actual stresses that occur on the membrane and its resistance to cyclic loads.

As expected, the higher stress concentration occurred in the proximity of the part as well as at the edges of the membrane on the side of the highest length of the feature. The exact forces are further expected to change depending on the cross-sectional dimensions of the fabricated parts, therefore a subsequent study on the relationship between the shape of the part and shape of the membrane would further add to the machine design aspect.

Table 2 Inputs and results of the second set of simulations

Shape	**Rectangular**	**Hexagonal**	
Vat area [mm^2]	545260	545260	215600
Offset [mm]	348	313	200
Offset to height ratio [-]	0.35	0.35	0.35
Max reduced stress HMH [MPa]	2.307	1.447	1.661

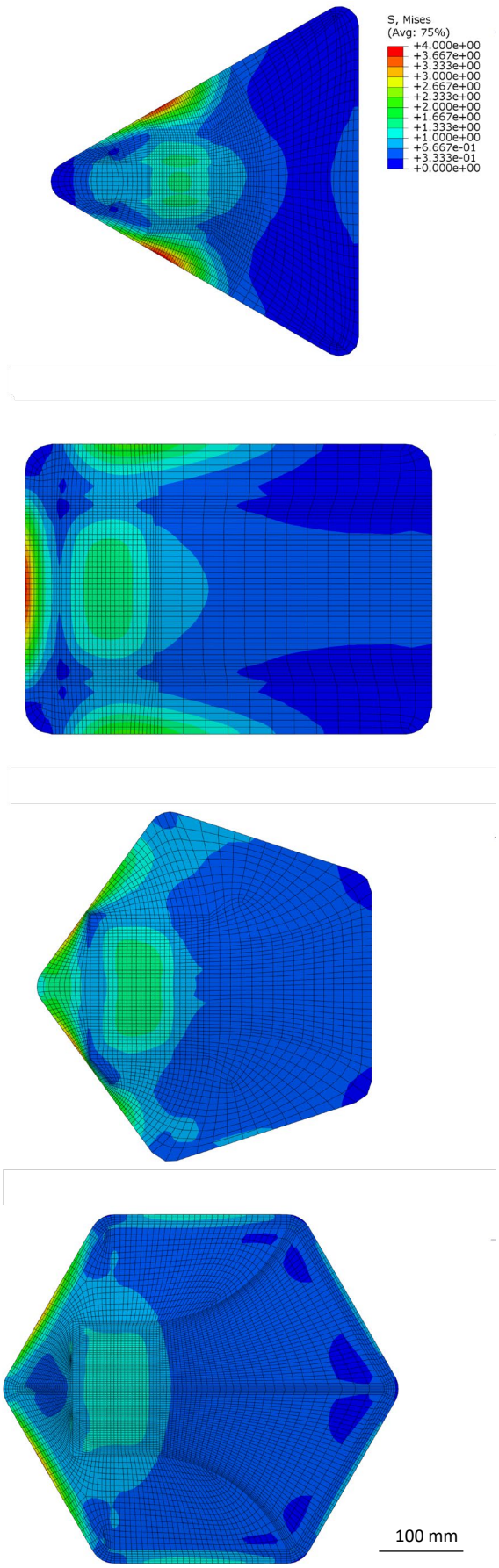

Figure 3. Stress maps of the highest stresses from the first simulation set (from the top): smaller triangular membrane with an offset of 180 mm, smaller rectangular membrane with an offset of 50 mm, smaller pentagonal membrane with an offset of 100 mm, smaller hexagonal membrane with the offset of 100 mm

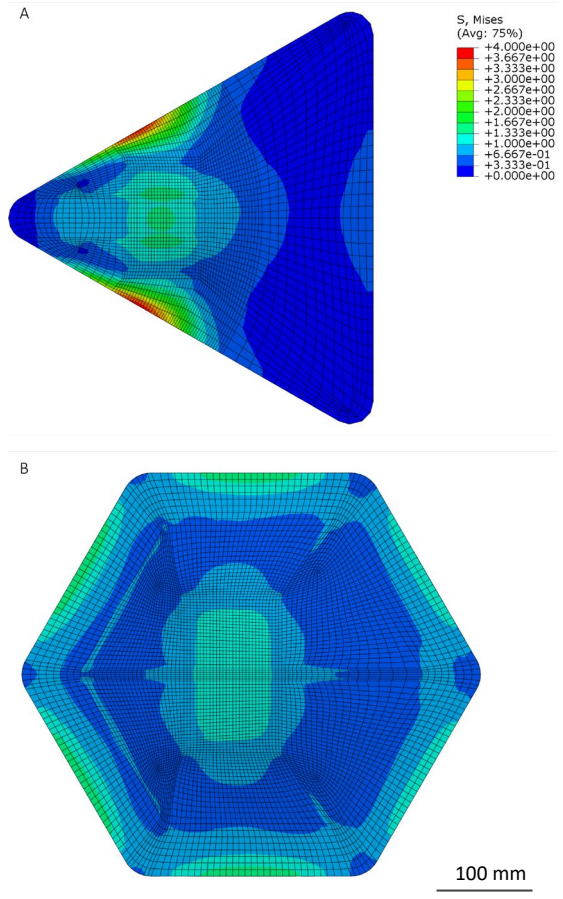

Figure 4. Stress maps of the worst case. A: smaller triangular membrane with an offset of 50 mm (above). Stress maps of the best case. B: smaller hexagonal membrane with an offset of 200 mm (below)

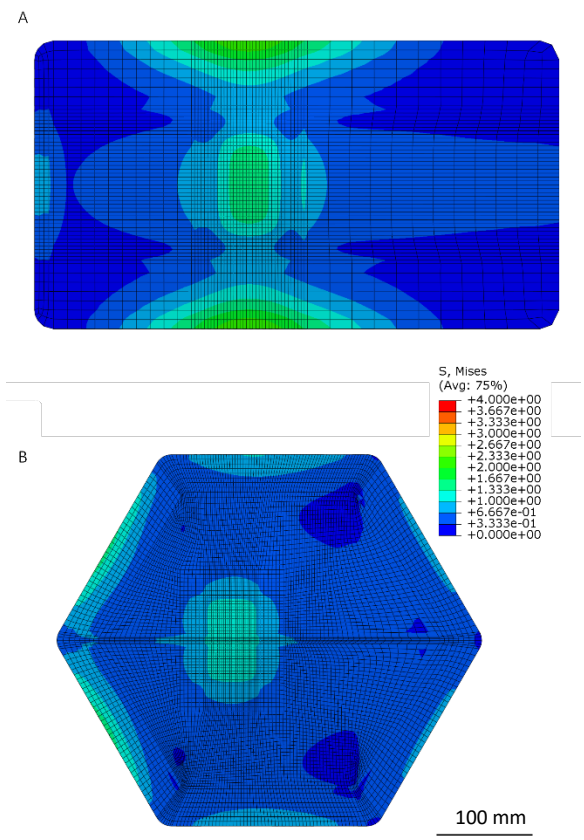

Figure 5. Stress maps of the worst case (up – bigger rectangular membrane with an offset of 348 mm) and the best case (down – bigger hexagonal membrane with an offset of 313 mm)

4. Conclusion

This investigation was intended to define the influence of the vat's shape and build plate position on the stress magnitude of the membrane in order to extend its lifetime. Four shapes were proposed: rectangle, triangle, pentagon, and hexagon. The most optimum combinations between vat shape and part offset, i.e. the lowest stress level, was achieved by the hexagonal vat. Moreover, the study showed that a bigger area of the membrane lowers the magnitude of reduced stresses. In addition, the influence of the offset has been confirmed and it is concluded that an increase in the offset, results in a decrease of stress. However, it is to be mentioned, that, in order to keep different peeling angles around the cross-section of the part, and therefore obtain a non-mechanical tilting effect, the manufactured part in the vat, cannot be placed in the middle of the membrane. It was further observed that stresses are lower for the membrane of the shape with a higher number of edges.

In the previous study [2], the approach differed as the offset was not used in the circular vat, as these vats were compared on a different level. Additionally, mentioned paper shows importance of the use of an offset, rather than influence of the shape in particular. In the current work however, it is shown that the offset has a significant influence on the results of reduced HMH stresses, thereby confirming the first research, and more importantly, in case of the same offset, the more corners a vat has, the lower stress values are obtained, stating that shape has a significant influence. Further work providing analyses of circular, oval and elliptical vats will help to define the influence of the shape better. Another difference is that in [2] a specific case was considered, whereas this research is more general.

The carried-out work presents valuable indications on how the geometry of the vat and the position of the build plate should not be considered as trivial aspects when dealing with the design of a vat photopolymerization system. An optimal combination between the vat shape and offset of the fabricated part can lead to a reduction of the stress, improving the quality of the manufactured part and the overall life of the membrane. This will result in a reduction of costs and an increased efficiency during manufacturing. In future works, experiments will be carried out to validate the results of the numerical model.

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