ADAPTIVE LAYER HEIGHT DURING DLP MATERIALS PROCESSING

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ABSTRACT: The aim of this research is to show how manufacturing speeds during vat polymerisation can be vastly increased through an adaptive layer heightstrategy that takes the geometry into account through analysis of the relationship between layer height, cross-section variability and surface structure. This allows for considerable process speedup during the Additive Manufacture of components that contain areas of low cross-section variability, at no loss of surface quality. The adaptive slicing strategy was tested with a purpose built vat polymerisation system and numerical engine designed and constructed to serve as a Next-Gen technology platform. By means of assessing hemispherical manufactured test specimen and through 3D surface mapping with variable-focus microscopy and confocal microscopy, a balance between minimal loss of surface quality with a maximal increase of manufacturing rate has been identified as a simple angle-dependent rule. The achievable increase in manufacturing rate was above 38% compared to conventional part slicing.

INTRODUCTION

Industrial adoption of vat based polymerisation has driven this form of Additive Manufacturing to become one of the leading technologies in Additive. Though the method allows for high definition surfaces and geometrical tolerance, the technology is mainly applied in niches where mass customisation and an allowable added manufacturing cost can justify applying the technology for manufacturing. Niches such as the hearing aid industry have been pioneering the industry, and as such, it is estimated that more than 10 million hearing aid shells has been produced through vat polymerisation, with over 90% of all new shells manufactured by vat polymerisation [Wohlers (2015) p.185]. This paper describes research to further increase the competitiveness of vat polymerisation by increasing the manufacturing rate through an adaptive layer height strategy during the manufacturing process. During the manufacture of a geometry with constant cross-section, the layer height affects the surface quality of the manufactured geometry to a minimum, whereas during the manufacture of a variable cross-section geometry, it is imperative to reduce the layer height to reduce staircase effects on the surface topography of the manufactured geometry.An adaptive approach to increasing build-rates has been put into practice by means of a purpose built vat polymerisation system and numerical engine. The Additive Machine Tool has been designed and constructed at the Technical University of Denmark in order to serve as a Next-Gen technology platform. The platform combines vat polymerisation with light modulation done by Digital Light Processing (DLP), as also found in state-of-the-art industrial equipment.

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METHOD

Most industrially available AM machine tools base their operation sequence on a layered approach [Pedersen (2012), p.39-58]. Concern is expressed by the authors that even most state-of-the-art vat polymerisation platforms still slice the manufactured geometry by means of a primitive algorithm by which the geometry is divided intouniform layers. This rudimentary approach to job-planning adds unnecessary manufacturing time, as sections of most geometries can be manufactured considerably faster if the job is planned in a more intelligent fashion. When vertical walls are manufactured, the layer height plays a minimal role in the geometrical tolerances and surface quality of the manufactured geometry, and can thus be increased. In this paper, an approach for dynamically altering the layer height as a function of curvature computed from an analysis of cross-sectional variability is investigated. Figure 1shows the fundamental approach for implementing an adaptive slicing strategy for DLP driven vat polymerisation platforms. At small angles of the angle , , the pixel width governs the approximation quality represented by the red stair-case, whereas at wide angles, the minimal allowable layer height governs the achievable approximation quality. At angles by which the pixel width of the DLP projector are driving the approximation, the layer height can be increased at no loss of quality of the surface structure, thus equating to a loss-less increase in manufacturing rate. This simple rule was included in the slicing engine of the experimental DLP platform. The angle, ,$_{critical}$ at which no further process speed can be obtained, can be described as:

$$\theta_{critical} = 90 - \tan^{-1}\left(\frac{minimum\ layer\ height}{DLP\ pixel\ size}\right) \qquad (1)$$

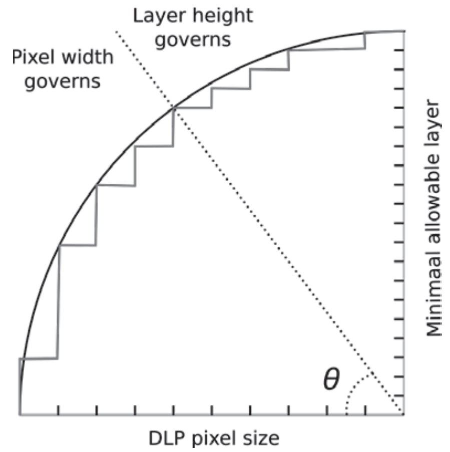


Figure 1 A 2D cross-section view of a quadrant of a sphere. The red staircase indicates the best approximation that can be achieved by a vat polymerisation based machine tool with a given DLP pixel size and achievable layer height.

BENCHMARKING

Given the angular dependency of the influence of layer height and DLP pixel size shown in (1), a hemisphere was chosen as a benchmarking geometry. The geometry, seen inFigure2, was processed through the adaptive layer capable job generator, developed for this research.

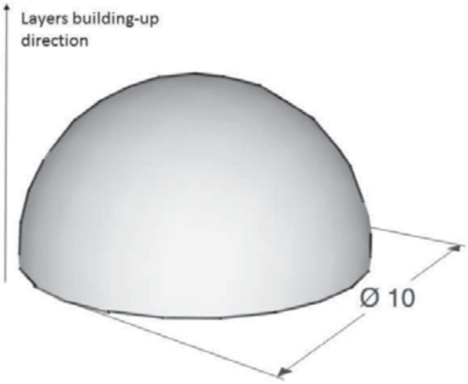


Figure 2 Hemispherical test geometry used to benchmark the adaptive layer generation algorithm

The geometry was processed at an orientation with the flat base of the hemisphere coincident with the build plate of the experimental DLP platform, thus, as the job progresses the cross-section continues to decrease at an accelerating pace. An adaptive slicing was performed taking into account physical process limitations, that occur during any vat polymerisation process. Specifically for the DLP platform used for subsequent validation of the adaptive slicing method, no layer can be less than 10µm and no layer more than 40µm in thickness. The platform is simply not capable of photo-polymerising layers thicker than 40µm due to the opacity of the photopolymer used during experimental verification. The photopolymer furthermore begins to exhibit a non-linear rheological behaviour at layers thinner than 10µm. This in turn defines the smallest permissible layer height. Employing the adaptive layer slicing algorithm with these limitations in mind the build time of the test geometry was reduced by 38.2%, and 191 exposure masks were saved. A table of statistics for the benchmark of the adaptive job generator can be seen inTable 1.

Table 1 Benchmark statistic for the adaptive slicing of a Ø10mm hemisphere

	Traditional slicing	Adaptive slicing
Layer Thickness Range	10µm	10-40µm
Number of exposure masks	500	309

Finally, the build has been illustrated in a graph shown in Figure 4.The green area of the graph is where the layer height is limited only by the capabilities of the DLP platform used for experimental validation, which restricts layers to be thicker than 40µm. The yellow area is where a reduction in layer height occurs as the height is decreased from 40µm toward the minimal permissible layer height, which was set to 10µm. Finally; the red zone is where the build rate is linear, with constant layer height. As a reference, a dashed line indicates the build rate given a constant layer heightof 10µm.

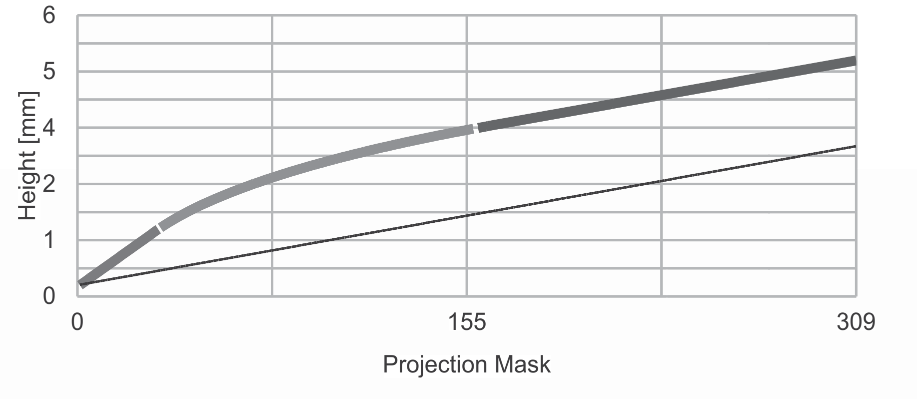


Figure 3 Graph showing the build rate of the test geometry. The growth in height decrease as the cross-sectional variability increases at higher Projection Mask count.

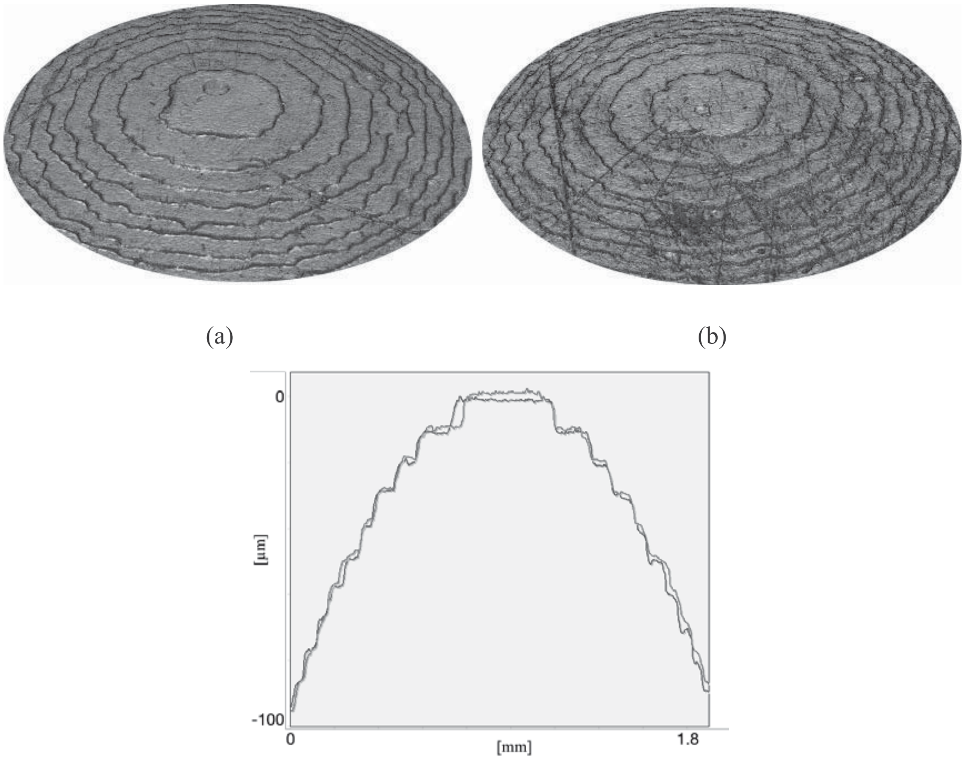
EXPERIMENTAL VALIDATION

The aim of the experimental validation is to prove that the surfaces created using adaptive slicing are similar to surfaces created by using a traditional constant layer approach for manufacturing of a test geometry. Thus, it is the aim to observe that the surfaces of two physical specimen, manufactured by each method are near identical. Experimental validation of the adaptive slicing approach has been focused on a comparison of the surface quality of a hemisphere with reference to an identical geometry manufactured with constant layer height. The photopolymer used is composed of a blend of Acrylate Monomers, and Glycol Diacrylate Monomers with a Phosphine Oxide based Photo Initiator as crosslinking agent. The geometries were manufactured using the settings seen inTable 2. The surfaces were measured by an Alicona InfiniteFocus SL optical 3D microscope.

Table 2 Machine settings during manufacture of test geometry

Machine Settings				
Layer height range [μm]	Burn-in intensity [mW/dm^2]	Burn-in exposure [ms]	Intensity [mW/dm^2]	Exposure [ms]
10-40	234	10000	95	4000

Two areas on the test geometry have been chosen as key areas for a surface topography analysis. The first area is topmost layers of the hemisphere, seen in Figure 4. It is here, as expected seen that there is no noticeable difference between the part manufactured by adaptive slicing (b) and the geometry manufactured by traditional slicing (a). This,given that the layers are within the red zone of the graph in Figure 4, and therefore manufactured with identical parameters. The scratches seen on (b) are from handling the part.



(a) (b)

Figure 4Top: (a) part manufactured by constant layer height. (b) reference part manufactured with adaptive slicing. Bottom: Red marks the profile of the adaptive part. Blue marks the reference.

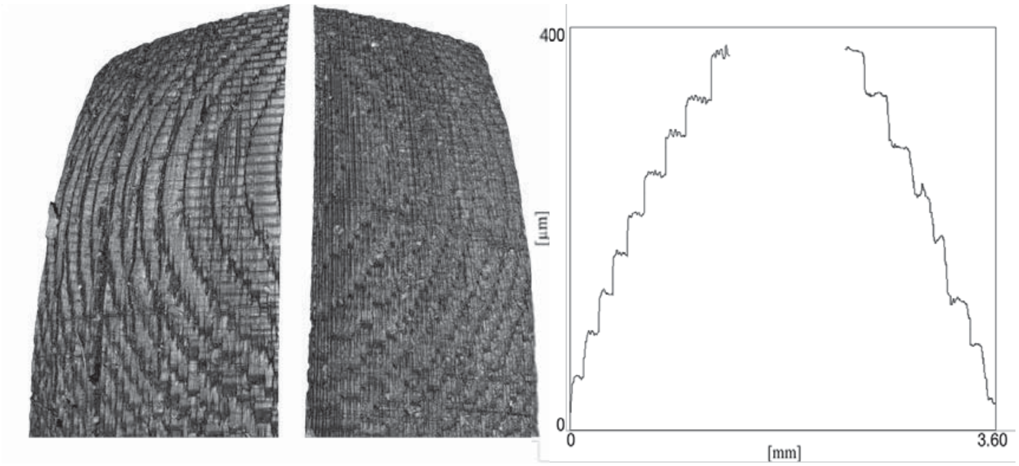
The step height of the studied areas were obtained from the histogram of the area (for the topmost layers) or the profile (for the base); the results are listed in

Table 3. Both studied areas produced by the two methods show identical step height considering the standard deviation.

Table 3 Step height of the studied areas

Step height (µm)	Traditional slicing	Adaptive slicing	Major factor
topmost layers	9.80 ± 0.80	10.03 ± 0.75	Layer thickness
the base	51.23 ± 8.24	50.97 ± 2.62	Pixel size

The second area, seen in Figure 5(left), is along the base of the hemisphere. It is here that the most significant difference between the two specimens can be expected. The adaptive manufactured specimen will in this area be comprised of layers four times thicker than the reference geometry. Nonetheless, the surfaces are remarkably similar, this is the main contribution to the surface structure is from the DLP pixel size and not the layer height. It is evident, by a closer study of the surface profiles of the specimen on Figure 5(right), which in this area has two orders of surface structure. A low amplitude, high frequency, that can be linked to the layer height, and a dominant high amplitude, low frequency surface that is the perceived and functional surface of the component.



(a) (b) (a) (b)

Figure 5Left: (a) reference part manufactured with constant layer height (b) part manufactured by adaptive slicing. Right: (a) marks the profile of the reference part. (b) marks the adaptive.

CONCLUSIONS

The aim of this research has been to shed light on the capabilities of adaptive slicing for DLP based vat polymerisation machine tools without reduction of surface quality. It was documented how an improvement of more than 38% in manufacturing speed was achieved while retaining surface fidelity while printing a hemispherical test specimen. By studying the most critical area of the geometry; the near vertical side walls; it was noticed that two distinct orders of surface structure was present. The high amplitude and low frequency structure being the dominant was near identical on the adaptive surface and the reference surface. This concludes that it is not so that the one surface is better than the other. There is merely a slight difference in the superposed height frequency pattern given from the nature of the individual layers of each component. It is therefore believed that adaptive slicing for DLP manufacturing may play a key role in future development of fast and competitive technology platforms.

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