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NEW NETWORK BASED FINITE ELEMENT METHOD FOR STEREOLITHOGRAPHY PROCESS ANALYSIS

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ABSTRACT: The additive manufacturing technologies have become more popular in the past years besides playing a roll more and more important along the years. In spite of that stereolithography process are still complex, hard to optimize. In addition to that, dimensional distortion and warpening might be evidenced in several cases because of material shrinkage during the curing phase. On the other hand, the current methods for analysis and simulation only considers unidirectional elements and do not considers material diffractions and incidence angle. For that reason, the current work proposes a new finite element method for stereolithography process using network based elements. In this work, the finite element method is introduced and the interaction between polymerization straight lines and between layers were analysed. In this case, the shrinkage ratio and conversion degree were studied as a function of laser intensity, raster velocity, material formulation. By the end, we indicated the suitable process parameter in order to avoid dimensional distortion and warpening.

INTRODUCTION

Researches related to additive manufacturing technologies and applications has growth during the last years (SANGERANO, PALLARO ET AL. 2009; GIBSON, ROSEN ET AL. 2010; GIBSON, ROSEN ET AL. 2010; KOLB, KUMMERLOWE ET AL. 2011; CUNICO AND CARVALHO 2013) Among these processes, it is possible to highlight stereolithography and Mask projection stereolithography which bases its concept on the selective formation -polymer by the use of UV light.

The current methods to simulate SLA processes are mainly based on non matrix unidirectional finite elements and the models ignore angle of laser beam incidence on the resin and light diffraction of material besides polymerization is leaded by penetration depth and critical exposure parameters (JIANG, HUANG ET AL. 2006; SHARMA 2008).

On the other hand, models which are based on polymerization kinetics are generalized and allow us to predict the material behavior as a function of material components tenor, as consequence the material might be optimized (CUNICO AND CARVALHO 2013). For that reason, the present work proposes a novel finite element method for the SLA simulation and the characterization of polymer formation during light exposition.

DYNAMIC FINITE ELEMENT METHOD

This new approach of selective photopolymerization simulation is based on dynamic finite elements method and is mainly divided in 4 steps: energy balance, photopolymerization kinetics, simulation management and results generation. In other methods, the polymerization models are mostly related to penetration depth parameter (Jiang, Huang et al. 2006; Sharma 2008). In these
approach, the understanding of physical-chemical reaction is not clear and the coefficient determination is only defined experimentally or indirectly. Therefore, the effect of material formulation variation cannot be easily predicted easily numerically.

For that reason, this method applied another approach which considers the polymerization rate as main parameter. Additionally, we have also included the analysis of shrinkage factor as a function of degree of polymerization and material formulation. In order to solve the light diffraction, transmittance and energy balance, we assumed that each finite element is composed by transmittance matrix where the light inside such element occurs in longitudinal direction. In addition, the balance of energy considers that the sum of energy inside the element must be null.

That assumption can be interpreted as an expansion of Beer-Lamb Law (Eq. (1)). In Beer-Lamb Law, the absorbed light intensity ($I_{absorbed}$) is a function of input intensity ($I_{in}$), absorbance rate ($\alpha$), thickness (t) and substance/initiator molar concentration ([c]). As consequence, the output intensity ($I_{out}$) is the difference between input intensity ($I_{in}$) and absorbed intensity ($I_{absorbed}$) (Brandrup, Immergut et al. 1999; Andrzejewska 2001; Matyjaszewski and Davis 2002; Fouassier, Allonas et al. 2003; Lovestead, O’Brien et al. 2003; Boddapati, Rahane et al. 2011).

\[ I_{out} = I_{in} - I_{absorbed} = I_{in} - I_{in} \cdot e^{-\alpha t} \]  

(1)

Another representation for these equations can be seen in Figure 1, where a network diagram of the finite element express the energy balance in one, two or three dimensions elements. On the other hand, the energy balance that considers diffraction in two and 3 dimension might been used to characterize either selective composite formation process or SL with charged material.

Figure 1 – Network scheme of Energy balance in one dimension (SLA scheme), considering 1, 2 and 3 dimensions

In this approach, the light flux is determined by the light transmittance (inverse of light resistance) while the absorbed light characterized by a light flux leakage. The energy balance inside the element can be defined according to a transmittance matrix (T), light intensity flux vector (I) and a nodal light intensity difference vector (A), as presented in Eq. (2).

\[ [T] [I] = [A] \]  

(2)

Assuming one element example, the local energy balance equation is represented by transmittance matrix, intensity flux vector and nodal light intensity difference vector is:
Therefore, the light flux and absorbed light can be identified after boundary conditions are applied, such as input node and light intensity. This definition might be described as:

\[ I_x = \frac{K_2}{K_1 + K_2} I_t = I_t e^{-\alpha t} \]

(4)

\[ K_2 = \frac{K_1 e^{-\alpha t}}{1 - e^{-\alpha t}} \]

(5)

And considering that the initiator concentration is proportional to the monomer amount, we can determine the degree of polymer conversion and the absorption coefficient as:

\[ K_2 = \frac{K_1 e^{-\alpha t}[\phi - (1-P)]}{1 - e^{-\alpha t}[\phi - (1-P)]} \]

(6)

The polymerization rate (RP), which is shown in Eq (7), indicates the variation of monomer concentration or the carbon double bonds as a function of time (t). Therefore the main model controlling factors are the monomer concentration (M) or carbon double bond ([C=C]), absorbed light intensity (I_t), quantum yield of initiation (\( \Phi \)). In addition, k_p and k_t are respectively the constant of propagation and termination (Jacobs 1992; Brandrup, Immergut et al. 1999; Andrzejewska 2001; Matyjaszewski and Davis 2002; Odi 2004; Zhiwei, Jianhua et al. 2006; Huang, Mo et al. 2010; Cunico 2011).

\[ Rp = \frac{-d[M]}{dt} = \frac{k_p}{k_t} [M] \{(\phi - 1)I_t\}^{\frac{1}{2}} = \frac{k_p}{k_t} [C=C] \{(\phi - 1)I_t\}^{\frac{1}{2}} \]

(7)

With respect to degree of conversion ([P]), we might find it by the polymerization rate integration with the time, as presented in Eq. (8) (Andrzejewska 2001; Watts 2005).

\[ [P] = \frac{1}{[M_0]} \int [R_p]dt = \frac{1}{[M_0]} \int \frac{-d[M]}{dt} dt = 1 - ([P_0] - [P]) e^{\frac{k_p}{k_t}(\phi - 1)I_t} \]

(8)

The shrinkage ratio might be correlated with polymer conversion degree and the volumetric shrinkage-strain. The Eq. (9) express a numerical model where the volumetric shrinkage of a monomer is a function of degree of conversion ([P]), monomer functionality (f_i), monomer mole fraction (X_i), monomer molecular mass (M_i) and mixture density (\rho_{mix}) (Watts 2005).

\[ \frac{\Delta V}{V} (\%) = 22.5 \cdot [P] \sum \frac{f_i \cdot X_i}{M_i \cdot Z_i} \cdot \rho_{mix} \cdot 100 \]

(9)

For simulation management, we adopted a routine which is presented in Figure 2.
Material and Methods

For analyzing polymer formation, we used photopolymeric material based on methyl methacrylate (MMA) as monomer (M) (Sigma-Aldrich 2008), Trimethylolpropane triacrylate (TMPTA) (Sigma-Aldrich 2008) as oligomer (O) and the Omnirad 2500 as photoinitiator (PI) (IGM 2005). With respect to the simulated process parameters, we used a Gaussian laser distribution and the main parameters used are presented in Table 1.

Table 1 – Relation of main process parameters used in the numerical simulation

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
<th>Case 8</th>
<th>Case 9</th>
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<tbody>
<tr>
<td>Number of layers</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of layers</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Laser Intensity</td>
<td>100 mW</td>
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<tr>
<td>Laser beam Diameter</td>
<td>0.6 mm</td>
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<tr>
<td>Laser beam light wave length</td>
<td>378 nm</td>
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<tr>
<td>Raster velocity</td>
<td>25 mm/s</td>
<td>25 mm/s</td>
<td></td>
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<tr>
<td>Distance between polymerization lines</td>
<td>0.8 mm</td>
<td>0.8 mm</td>
<td></td>
<td></td>
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<tr>
<td>Layer thickness (substrate) (mm)</td>
<td>0.15 mm</td>
<td>0.15 mm</td>
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Results and Discussions

In Figure 3, simulation results are presented where polymerization profiles are presented for one and two lines of polymerization and one, two and six layers. It is possible to see that the penetration follows a parabolic shape as result of laser beam Gaussian intensity distribution.

In this figure, the degree of polymerization is presented in a transversal section where the maximum polymerization degree was found to be 65%. Otherwise, the analysis of 2 queued layers indicated a peak of polymerization, which is resulted by the cumulative effect and overlap between layers. It is possible to see that although the new layer is about to be formed, the previous layers were also modified, increasing the polymer conversion. In spite of that, when we simulated 6 queue layers, a polymerized area with more than 65% of polymer conversion was found, while the top and bottom layers remain with low polymer conversion degree. Analyzing the simulation of 2 polymerization lines in one and two layer, we could identify that the profile of polymerization remained similar to the previous study cases. Nevertheless, the overlapping area resulted in deeper penetration and polymer conversion. In addition, besides manufacturing issues like warpening and stress concentration might be prevented, the process might be optimized as a function of process strategy, resin properties and equipment parameters.
CONCLUSIONS
Along this work, a novel dynamic finite element method was presented and the simulations of some simple cases were exposed. In this study, it was included new concepts to calculate polymerization profile in SLA processes which is found to be more generalized than current methods. Along this study, the profile of polymerization was seen to be parabolic as expected, even though previous layers was found to be affected by the formation of new layers. This method also proof to be useful to determine stress concentration and simulate manufacturing distortion. However, as this work is still in the preliminary stage further investigations are needed to identify the potential of method and evaluate the accuracy of such methods in comparison with experimental studies.

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