Vilnius University
Faculty of Physics
Laser Research Center

Laboratory assignment No. MNFT-3

ASSESSMENT OF THE SPATIAL RESOLUTION IN Z AXIS OF THE DIGITAL LIGHT PROCESSING-BASED 3D PRINTING EMPLOYING BEER-LAMBERT LAW

For master students of Laser Physics and Optical Technologies and Laser Technology programmes

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1 The Goal

1. Get acquaintance with the digital light projection lithography and print 3D object.

2 Exercises

2.1 Homeworks:

1. In a group, prepare a resolution 3D model with periodical structure and save it as .STL file. With this resolution model you should be abel to evaluate resolution in XY plane of digital light projection (DLP) lithography machine. With 3D printing software make a several units of your prepared 3D model (scaled-up, scaled-down) in order to determine XY resolution more precise. Note: 3D printing takes time, so your models should not exceed 1x1x1 cm^3 dimensions.
2. Individually, prepare a 3D model you want or need to be printed (for example, small holder for your experimental setup). Note: 3D printing takes time, so your models should not exceed 2x2x1.5 cm^3 dimensions.

2.2 During laboratory assignment:

1. 3D print your resolution model. After it is printed, evaluate size of the printed features: (a) individual features maintain the geometry as it is in .STL file, (b) the features can be distinguished, but the geometry is modified, (c) features in XY plane are not distinguished at all (not printed).
2. Empirically set the „working curve" of one of 3D printing resin and determine resolution in Z axis and optimal exposure duration.
3. 3D print objects for your own needs.

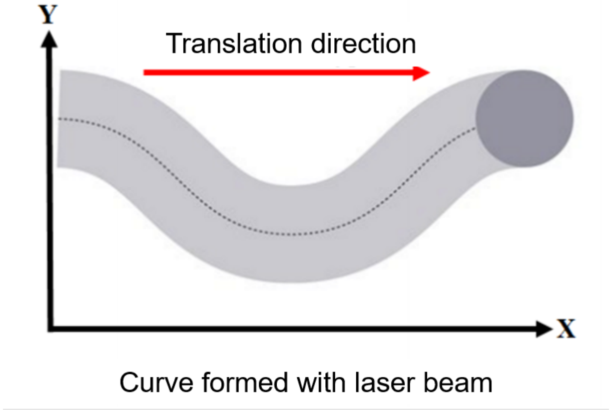
3 Key Questions

1. The principles of the digital light processing-based optical 3D printing.
2. Pros and cons of the principles of the digital light processing-based optical 3D printing comparing it with laser stereolithography.
3. Limits of the spatial resolution and its reasons.
4. Significance of the light penetration depth h_a.
5. Significance of the critical energy dose D_c or critical exposure duration T_c.

4 Theory

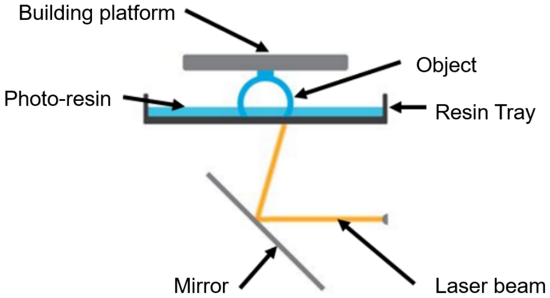
4.1 Stereolithography and its types

Stereolithography (SLA) is an optical 3D printing (O3DP) technique based on photo-polymrization reaction. The reaction mostly is induced with UV light, causing the transform of aliquid photo-sensitive resin into a solid non-soluble polymer. There are two types of the SLA: direct laser writing (DLW) SLA and digital light processing (DLP) SLA. To produce something using one of these techniques, the 3D model of a desired object must be created at first. Typically this step is done employing computer-aided design (CAD) software.Then the CAD model is further processed slicing it into the certain height layers, which are transferred to the 3D printing machine. After that the machine starts the production of the CAD model to the real object in layer-by-layer fashion [1]. The production can be described as a cycle of the following steps: 1) — a building platform is immersed into the photo-resin, which is poured in the resin tray, having a transparent window through which the light exposes the resin, 2) — selective light exposure is applied to the resin and cures it to the solid polymer layer 3) — the cured layer is detached from the resin tray by the movement of the tray and building platform, 4) — a new layer of the uncured resin is deposited on the transparent window, 5) — the building platform is located to the new position where another layer is cured to the previous one. The cycle is repeated untill the whole object is produced [2]. Comparing the DLW and DLP SLA, step No. 2 is performed in different ways. In a case of the DLW SLA the light source is laser diode.

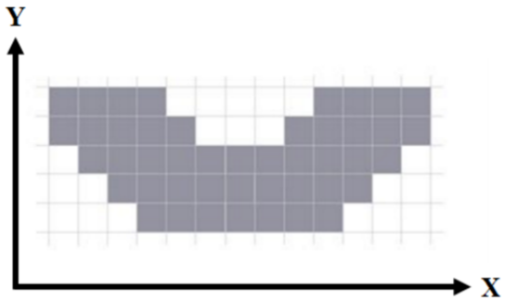


1 Fig. A layer is formed using a raster scanning of the laser spot [3].

Laser beam is focused to the photo-resin and cures the desired height layers (Figure 1). The beam is scanned using the movements of two galvanometric mirrors all over the cross-section of each layer. One mirror controls X axis, other – Y axis. The polymerization reaction is induced within the focal spot and the resin becomes cured. The principle scheme of the DLW SLA is depicted in the Figure 2.



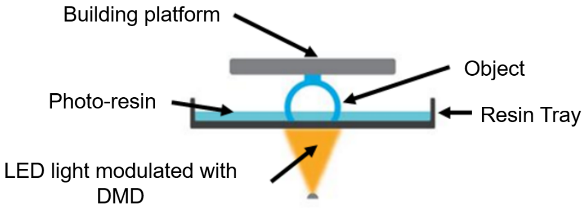
2 Fig. The principle scheme of the DLW SLA [3].



Curve formed with squared pixels

3 Fig. Selective exposure employing DLP. Layer is formed out of squared pixels [3].

In a case of the DLP SLA the light source is light emitting diode (LED), which generates I of dozens of mW/cm^2 on the building platform. LED irradiation is modulated via micro-electro-mechanical technology, using digital micromirrors device (DMD). In contrast to the DLW SLA, this time the whole cross-section of the layer is exposed at ones. Absence of the scanning allows to accelerate the whole manufacturing process. The micro-scale mirrors forms the projections of the layers out of squared pixels (Figure 3). The mirrors are diagonally allocated semiconductor chip. They have two states: on and off. While in the on state, the light is reflected to the photo-resin (corresponds to the grey color in Figure 3). While in the off state – light is reflected away from the resin (white color). The dimensions of the micromirrors can be only a few micrometers, for e. g., 5,4 µm [4], which are depicted as pixels in dozens of µm size.



4 Fig. The principle scheme of the DLP SLA [3].

The principle scheme of the DLP SLA is presented in the Figure 4. The exposed area size and the achievable spatial resolution in XY plane depend on the size of the micromirrors, distance between them and optics.

The companies producing the DLW SLA O3DP are: „Formlabs“, „3D Systems“, „DWS Lab“, „XYZ Printing“ and etc. The typical laser spot is 140–300 µm. Other companies („Asiga“, „MoonRay“, „Autodesk“, „B9CreatoR“, „UNCIA 3D“, „Morpheus“, „Kudo 3D“, „CoLiDo“ ir kt.) produce DLP SLA O3DP. Mostly a single pixel size does not exceed 100x100 μm^2. These parameters (spot and pixel size) defines the spatial resolution in XY plane. However, there is a big importance of the spatial resolution in the third axis – Z. It defines a single layer height, which usually is between 10–200 µm and depends on the light absorption in the material.

Both DLW and DLP SLA have increased the resolution of the 3D printing, specially compared with the fused-filament-fabrication, where a melted plastic is deposited as layer. Due to high precision SLA technologies are efficient and consume low amount of the material. Thus it makes SLA attractive in a such fields as jewelry and design, microfluidics and senors [5, 6], medical modeling, production of the surgical guides and dentistry [7, 8].

4.2 Linear optical absorption in the materials

In the previous section, it was mentioned that spatial resolution in Z axis matters. It defines what height layers can be produced in the certain photo-resins. In other words, it defines what the thinnest positive features (for e. g. membranes) or the smallest negative features (holes, microchannels, voids) can be formed. It might essential in such applications, as microfluidics [9]. In this section, a mechanism of limits of spatial resolution in Z axis will be explained [10].

The height of the single cured layer depends on how deep the light can penetrate the material. Absorption coefficient α defines this limit. α describes the light traveled distance in the substance, after which an initial irradiation intensity I_0 reduces e^{-1} times. α has a measuring unit of μm^{-1}. Inversely proportional parameter h_a defines a depth which the light can penetrate:

$$h_a = 1/\alpha. \tag{1}$$

If I_0 is known (W/cm^2), then according to the Beer-Lambert law the intensity I after distance z will be:

$$I(z) = I_0 e^{-z/h_a} \tag{2}$$

Multiplying this equation by the exposure duration t_p, we can calculate an energy dose (J/cm^2), which was transfered to the material. To induce the polymerization reaction and start curing of the layer, a critical energy dose D_c must be achieved. If D_c is not achieved, no polymerization occur. A certain polymerization depth z_p can be cured only after applied particular t_p required to obtain D_c:

$$D_c = t_p I_0 e^{-z_p/h_a}. \tag{3}$$

Knowing I_0, a critical exposure duration T_c can be caculated, which defines the duration, required to reach D_c to cure a zero thickness layer (z_p=0):

$$T_c = D_c/I_0. \tag{4}$$

Having these equations, desired z_p can be expressed as:

$$z_p = h_a ln(\frac{t_p}{T_c}). \tag{5}$$

The derived equations are good for monochromatic light source or for the constant α all over spectrum of the light source. However α is a function of wavelength $\alpha(\lambda)$, and most of the real light sources emit are polichromatic irradiation, which I also depends on λ: $I_0(\lambda)$. According these assumptions, the energy dose can be expressed as:

$$D(z,t) = t\int_0^\infty I_0(\lambda)e^{-\alpha(\lambda)z}d\lambda. \tag{6}$$

The equation can be normalized to the energy dose by the surface of the material (D(0,t)), before the absorption occur. In a such way we can calculate normalized energy dose D_n(z), describing the decrease of the energy in the material, as the irradiation penetrates it.

$$D_n(z) = \frac{D(z,t)}{D(0,t)} = \frac{\int_0^\infty I_0(\lambda)e^{-\alpha(\lambda)z}dz}{\int_0^\infty I_0(\lambda)dz}. \tag{7}$$

The equation can be easily fitted with the function [11]:

$$D_n(z) = ae^{-z/h_a} + c = 1 - a(1 - e^{-z/h_a}). \tag{8}$$

c = 1-a, when $D_n(0) = 1$. Parameter a defines photo-resins aborption spectrum overlap with the light source emission spectrum. If the spectra overlap well, then a = 1 and can be express as:

$$D_n(z) = e^{-z/h_a}. \tag{9}$$

According reference [11], polymerization depth z_p can be calculated more accurately:

$$z_p = h_a ln(\frac{t_p a}{a(T_c + t_p) - t_p}). \tag{10}$$

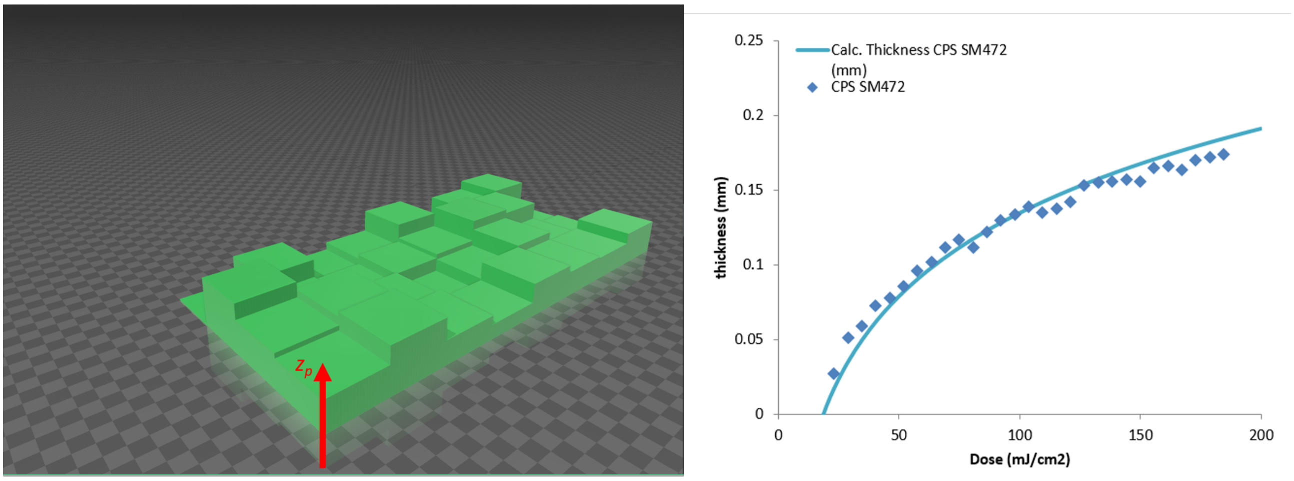
When a = 1, we come back to the (5) equation.

Now it is clear, that to assess what height layers can be printed, it is mandatory to know light penetration depth h_a and critical energy dose D_c (or critical exposure dose T_c). For example, these parameters for the commercially available photo-resins can be as follows: „PR48“ – h_a = 80 µm, T_c = 0,7 s, „PlasClear“ – h_a = 120 µm, T_c = 0,4 s, „FSL Clear“ – h_a = 320 µm, T_c = 0,5 s [10], „MakerJuice G+ Black“ – h_a = 270 µm, „Formlabs Tough“ – h_a = 160 µm.

4.3 Working Curve Measurements for the Optical 3D printing and Assessment of the Optimal the Exposure Dose

3D printing community practice open sourcing, in order to make 3D printing affordable and user-friendly technology, o simply – hobby. Thus there are tons of various users provided information available on the websites, articles, blogs and elsewhere how to start, perform and enhance 3D printing. One of the examples is Autodesk Ember user provided method to achieved optimal exposure dose for the photo-resins. Most common it is called Working Curve Measurement (WCM). A detailed description of it can be find here [13]. Briefly, it sounds like that:

Let assume, that a fixed area of the photo-resin is evenly exposed with the known I irradiation. The area is divided into separate segments, which obtain different amount of the exposure dose D by controlling the exposure duration t_p. It means, that each segments will be cured to a different polymerization depth z_p. z_p is measured and plotted as a function of t_p or D (Figure 5).



5 Fig. Left – fixed area of the photo-resin, divided into 32 segments and exposed evenly (I constant all over the area) varying t_p for each segment, resulting to the varied z_p. Right – measured, plotted and fitted z_p.

The fit of the z_p graph defines h_a and D_c (or T_c) parameters. h_a is an inclination of the fitted curve and D_c (or T_c) is an intersection with abscissa at z_p=0. When those two parameters are assessed, there is no problems to evaluate required D (or t_p) for the desired z_p. To sum up, you have to do these steps: expose 3D resin with different exposure duration, assess the height of the polymerized structures, plot measured heights vs exposure duration, fit the graph with equation 5, calcute, what exposure duration is required to print 25, 50, 75, 100, 125 and 150 µm height layers and provide data in table.

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