Investigation of the Effect of the Lighting Step on the Strength of a Ceramic Product in 3D Printing

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Abstract. The subject of this study is to assess the effect of such a 3D printing parameter by the SLA method as the lighting step (the distance between the lines of the beam motion when lighting the layer) on the mechanical properties of a ceramic object. For the study, the lighting step of 50 μm, 75 μm and 100 μm was used. The dependencies such as the Mises stresses, the displacements of the layers of the printed object relative to each other, and also the pressure arising in the layer were compared. To exclude edge effects, dependences were evaluated in the range from 500 μm to 1500 μm of the surface of the object layer, the layer thickness was 100 μm. These studies are necessary to optimize the 3D printing process, to minimize internal stresses and pressures in the printed object. The use of optimal printing parameters will improve the results of heat treatment and obtain objects with the required surface quality.

1. Introduction

Modern companies in leading industries are constantly looking for solutions that allow them to gain an advantage in the global market. The main ways to improve their work may be the optimal planning of production processes based on modeling [1–2] and scheduling, automation and robotics, constant monitoring of production tasks, as well as other technologies included in the Industry 4.0 strategy. One of the increasingly popular technologies is additive manufacturing (AM), especially 3D printing. 3D printing is an example of rapid prototyping technologies (or additive manufacturing), which are becoming increasingly popular because of their practicality and the constant reduction in the price of printing equipment and materials [3]. The fastest prototyping technologies are still under development and are characterized by the high cost of equipment and materials. However, they can produce complex, high-quality, high-strength elements of complex shape, which can be made of various materials with certain properties (for example, various types of plastic, biomaterials, metal, composites, and even concrete [3–4]).

One of the most interesting areas of additive technology is 3D printing with ceramics. This area is interesting for its high strength and temperature properties of the material, as well as a wide range of applications (aerospace, radio electronics, medicine, nuclear industry, general engineering and jewelry industry) [4–5].
Of all the methods for 3D printing with ceramics, the most interesting and popular is laser stereolithography (SLA). The quality of printed parts can be assessed by mechanical or thermal properties, as well as tactile and visual perception [3]. Considering other 3D ceramic printing technologies (FDM, DLP), parts printed using the SLA method have the highest surface quality due to the relatively small thickness of the layers (20–100 μm), high printing accuracy (10-50 μm) and features of the technology of applying the layer (moving the laser beam along the surface of the layer of the future product along a predetermined path) [6].

Problems with the mechanical properties (strength parameters) of printed products are usually associated not only with the mechanical properties of the material itself, but also with the weakness of the interconnection of the layers, uncontrolled shrinkage during cooling, the inaccuracy of the mechanical elements of the 3D printer (moving the platform, laser), as well as directly with print parameters. These parameters include: lighting strategy (strategy of laser beam movement) and interrelated parameters (beam diameter, distance between shading lines, exposure duration, etc.) [3,7,8].

2. Simulation model
Most of the articles devoted to the study of the influence of printing parameters (lighting strategy and related parameters) on the strength characteristics of a product are associated with 3D printing with photopolymers according to the SLA or FDM method, where the product does not require subsequent heat treatment [7–12].

In this paper, using modeling methods, we study the influence of printing parameters on the strength characteristics of the product at the green stage (before heat treatment). The main parameter of 3D printing is the lighting step. In this study we used the lighting step equal to 50 μm, 75 μm and 100 μm. The beam diameter, the distance between the lighting lines, and the exposure duration were unchanged in a numerical experiment. For modeling, we used the following properties of a material based on corundum grade F1000 (fraction 7 μm) and a photosensitive polymer (70% – alumina powder, 30% – liquid photopolymer): density ρ – 3600 kg/m^3, Young's modulus E – 2500 MPa, coefficient Poisson η – 0.26 [13]. 3D models with different printing parameters are shown in Figure 1.

![Figure 1. 3D-models with different lighting step; step: a) – 50 μm, b) – 75 μm, c) – 100 μm.](image)

Hooke’s Law of Linear Elasticity is written as:

$$\sigma_{ij} = \sum_{kl} C_{ijkl} \varepsilon_{kl}$$  \hspace{1cm} (1)

The stress tensor σ and the strain tensor ε are second-order tensors, while the defining tensor C is a fourth-order tensor [14–17]. Due to the symmetry of the stress and strain tensors, Hooke's law can be represented in matrix form. Where the strain tensor ε is written as:

$$\varepsilon_i = \frac{\sigma_i}{E} - \frac{\mu}{E} \sigma_j - \frac{\mu}{E} \sigma_k$$  \hspace{1cm} (2)
\[
\varepsilon_y = \frac{\sigma_y}{E} - \frac{\mu}{E} \sigma_z - \frac{\mu}{E} \sigma_x,
\]
\[
\varepsilon_z = \frac{\sigma_z}{E} - \frac{\mu}{E} \sigma_x - \frac{\mu}{E} \sigma_y,
\]

(3)

(4)

where \(E\) is Young's modulus, \(\mu\) is Poisson's ratio.

3. Analysis of the results

The results of 3D modeling are shown in Figures 2–4. The dependences of the Von Mises stresses, displacement, and pressure between the first and second laser beam paths along the surface of the third layer were considered.

As can be seen in Figures 2, the Von Mises stresses dependence varies from 1.25 to 5.49 GN/m². You can see that there is a significant difference in the Von Mises stresses between a step of 100 μm and 50–75 μm. If at a step of 100 μm, we observe Von Mises stresses ranging from 5.43 to 5.48 GN/m², then in a step of 50–75 μm we see stresses in the range from 1.27 to 1.55 GN/m².

**Figure 2.** Von Mises stress versus sample length plot; step: 1 – 50 μm, 2 – 75 μm, 100 μm.

Consider the displacements that occur, which are shown in Figure 3, with a different lighting step. We see a similar situation, as with von Mises stresses. At a step of 100 μm, we observe a significant displacement. At a lighting step of 100 μm, the plane displacement varies in the range from 65.8 μm to 67 μm. The displacement at a lighting step of 75 μm varies from 20 μm to 25 μm, and at a step of 50 μm, on average, is 18 μm. We can draw a preliminary conclusion that the lighting step of 100 μm is not permissible, however, for an accurate conclusion, it is necessary to analyze the surface pressure arising between the layers.

The pressure between the first and second line of the laser beam along the surface of the third layer is shown in Figure 4. On the one hand, at a filling step of 100 μm, the surface pressure is not stable and varies over a wide range from -2.97 to -2.88 GPa.
Figure 3. Dependence of displacement on sample length; step: 1 – 50 μm, 2 – 75 μm, 100 μm.

On the other hand, at a lighting step of 50-75 μm, we observe a different degree of pressure values. At a lighting step of 75 μm, the pressure values range from -0.9 to -0.8 GPa, and at a step of 50 μm, the pressure is on average -0.7 GPa.

Figure 4. The dependence of pressure on the sample length; step: 1 – 50 μm, 2 – 75 μm, 100 μm.

4. Discussion
To assess the effect of the lighting step on the mechanical properties of the 3D printed product, the following dependences on the sample length were examined: von Mises stress (Figure 2), displacement
(interlayer) (Figure 3), and pressure (Figure 4). The total length of the sample in the study is 2000 μm, however, to exclude edge effects in the experiment, the range from 500 μm to 1500 μm was taken into account [18–22].

Based on the obtained dependencies, the following facts can be distinguished:

- When analyzing the stress plot of Von Mises, it can be seen that the sample with the lighting step of 50 μm has the lowest stresses, which is associated with better polymerization of the layer due to the superposition of the beam (a new beam passage affects the previous half the beam diameter).
- The smallest absolute value of the displacement, as well as the amplitude of its change, indicates the most optimal 3D printing results when using this lighting step (50 μm).
- At a lighting step of 50 μm, the pressure is higher than at 75 μm, but the pressure is almost the same over the entire length of the sample.
- The cardinal difference on the plot for the 100 μm lighting step is associated with the smallest number of intermolecular bonds arising between the beam paths, and a sharp pressure jump at several points on the plot indicates that by the middle of the sample a small number of these bonds affect the pressure increase.

5. Conclusion

Based on the results obtained during the simulation, it was concluded that the lighting step of 100 μm is not suitable for 3D printing of products, since the studied dependencies for this step are much higher and not stable depending on the area of the 3D printed object.

On the other hand, the dependences obtained for the lighting step of 50 μm are smallest in size (the smallest magnitude of the stresses and displacement, the minimum amplitude of the pressure change). Using a 75 μm lighting step can increase the speed of building an object. However, the difference in printing speed is insignificant (20-30%), while the stresses that occur in the object with a lighting step of 75 μm can provoke cracks, leashes and subsequent destruction of the printed object at the stage of heat treatment. Thus, for the material composition used (ceramic paste based on alumina powder and liquid photosensitive polymer) on an AF 200 Universal 3D printer (software used on a 3D printer - Triangulatica), a 50 μm lighting step is the most optimal and will improve the strength characteristics of the object at the stage of “rown stage” (finished product after heat treatment).

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