This study's object is those factors that affect the defects of photopolymer 3D models. The task addressed relates to identifying the factors that cause the appearance of surface defects and deviations in geometric dimensions in photopolymer 3D models.

The influence of the photopolymer resin temperature on the surface defects appearance and deviations in geometric dimensions, as well as the layers exposure parameters influence on the photopolymer resin temperature, has been revealed. At the final stage of the study, it was found that the exposure parameters of the photopolymer model layers affect the photopolymer resin temperature, which, in turn, increases the likelihood of defects and geometric deviations in the finished model. Provided that the photopolymer resin temperature is kept within the range of 18–26°C, the model dimensions geometric deviation decreases by 0.054 mm along the XY axis and by 0.006 mm along the Z axis. A linear dependence of the size deviations on the exposure parameters and the photopolymer resin temperature has been established.

The process of heat transfer from a UV radiation source to a photopolymer resin has been described. A thermodynamic scheme for controlling the resin temperature based on modeling the heat transfer between the exposed layers and the resin volume, considering the exposure time and UV radiation intensity, has been devised, which makes it possible to predict a critical temperature increase and minimize defects.

While devising a method for controlling products during photopolymer 3D printing, the photopolymer temperature parameter was considered as one of the factors affecting the quality of parts and the level of rejects. Thus, the proposed method for controlling products during photopolymer 3D printing could be used to improve the technological process of manufacturing parts by reducing the number of defects and improving the finished products quality

Keywords: LCD technology, photopolymer printing, additive manufacturing, defects, automated control, thermal model

UDC 004.94:678.742

DOI: 10.15587/1729-4061.2025.335706

DEVISING A METHOD FOR CONTROLLING ARTICLES DURING PHOTOPOLYMER 3D PRINTING

Dmytro Nikitin
Corresponding author
PhD*
E-mail: dmytro.nikitin@nure.ua

Igor Nevliudov
Doctor of Technical Sciences*

Iryna Zharikova
PhD*

Artem Bronnikov
PhD*

Roman Strelets
PhD student*

*Department of Computer-Integrated Technologies, Automation and Robotics
Kharkiv National University of Radio Electronics
Nauky ave., 14, Kharkiv, Ukraine, 61166

Received 29.04.2025
Received in revised form 16.06.2025
Accepted 03.07.2025
Published 30.08.2025

How to Cite: *Nikitin, D., Nevliudov, I., Zharikova, I., Bronnikov, A., Strilets, R. (2025). Devising a method for controlling articles during photopolymer 3D printing. Eastern-European Journal of Enterprise Technologies, 4 (1 (136)), 42–54. https://doi.org/10.15587/1729-4061.2025.335706*

1. Introduction

The introduction of additive technologies into serial and mass production is becoming an increasingly relevant and promising area. This is becoming possible due to three main factors.

Firstly, modules for exposing parts in 3D prototyping machines are being improved. More reliable and cheaper radiation sources are being used, which allow for the formation of a model with higher resolution and have a higher radiation throughput, which makes it possible to faster polymerize parts of the model.

Secondly, every year a larger range of photopolymer resins with different properties for the manufacture of various products appears on the market, for example, photopolymer resins for template molds of products; jewelry photopolymers; dental, and others. All this has created conditions for the emergence of new manufacturers of photopolymer resins, which, within the framework of competition with each other, produce resins in different price ranges.

In general, photopolymer printing products are used to produce master models for casting in jewelry, the medical industry (dental or bone prostheses), in design, mechanical engineering (elements of robotic systems), microelectronics (stencils), architecture (layout). However, photopolymer additive 3D manufacturing, as in any other molding technology [1–3], has its limitations and nuances, namely mass production, and the number of defects. Whereas mass production is enabled by the number of machines, the improvement of specific machine modules, and the use of photopolymers with a shorter exposure time, the issue related to printing defects is more difficult to solve.

Defects can form because of a number of reasons such as machine settings; photopolymer features; printing parameter settings. Whereas the first two factors are quite easy to deal with, determining the influence of photopolymer exposure settings is quite a difficult task because the relevant literature does not fully address the physical features of their occurrence. Identifying factors that cause the appearance of surface defects and deviations in the geometric dimensions of photopolymer products, as well as devising methods to prevent their formation, would reduce the number of defects and reduce production costs.

Photopolymer 3D prototyping technologies are becoming an increasingly promising area. The issue of improving manufacturing accuracy, quality, and minimizing product defects is becoming increasingly acute. The relevance of the topic is due to the prevalence of defects that occur during photopolymer 3D printing, in particular at the layer exposure stage. Insufficient stability of printing parameters, in particular temperature conditions, often leads to the formation of defects, which complicates the use of this technology for the precise manufacture of complex parts. Understanding the physicochemical processes that accompany the curing of photopolymers under the influence of radiation is a necessary prerequisite for further improvement of production processes. This creates a need for scientifically based approaches to reduce defects and increase the reproducibility of printing results.

2. Literature review and problem statement

The scientific literature [4–8] describes three main technologies of photopolymer 3D prototyping. One of the first technologies was Stereolithography (SLA), the principle of which is the sequential polymerization of thin layers of liquid photopolymer resin with a low-power ultraviolet laser beam [4]. The disadvantage of this technology was the high cost and complexity of maintaining the machine.

The principle of operation of the Digital Light Processing (DLP) technology is similar to the operation of a projector, which uses light to project an image of the model layer. The issue of increasing the efficiency of DLP technology was considered in [5]. In the work, in general, the problems of reducing product defects and decreasing printing time were solved by a hardware method, using the technology of digital micromirror devices. The hardware approaches described in the work are based on the use of digital micromirror devices, which have proven efficient for SLA and DLP technologies. In SLA technology, they are used in the scanner system for positioning the laser beam, in DLP technology – for focusing the projection of the product layer. But such an idea is only suitable for DLP technology and is a rather expensive solution that could increase the printing speed but does not improve the surface quality of the products. Due to the hardware modernization of the machines, it is possible to achieve the accuracy of manufacturing the product within ± 0.02 microns. But the hardware solution is quite expensive, so advanced systems based on digital micromirror devices are available for professional machines, which could cost from USD 5000.

Liquid Crystal Display (LCD) technology, which is described in detail in [6], is very similar to DLP technology. But it is based on the use of an LCD screen, with the help of it and a UV matrix, the layers of the model are reproduced: under the action of the UV matrix, the photopolymer is polymerized, and the screen serves to form a cross-section of the product layer. The main disadvantage of this technology is a large number of defective products due to its critical dependence on suboptimal printing parameters.

The model is built only from the bottom up; the screen is located directly under the photopolymer bath. The screen displays the entire layer of the model, revealing bright areas-pixels through which ultraviolet radiation from the LED matrix passes and illuminates the photopolymer.

It is necessary to note some advantages of LCD technology, which were analyzed in [6], namely:

– low cost compared to other photopolymer 3D printing technologies. The initial cost of the machine starts at USD 250 on average;

– ease of maintenance and wide possibilities for modernization. Most of the electronic components are available and standardized; therefore, they are easily replaced and are relatively cheap;

– compared to DLP technology, there is no distortion of the image displayed on the working area. This is due to the fact that the shape of the layer is formed using a screen that fits tightly to the transparent bottom of the bath, which reduces the diffraction of light, thereby reducing the likelihood of defects on the samples and reducing the quality of their surface [7].

The main disadvantages of LCD technology include:

– the dependence of the working area on the size of the screen, the accuracy depends on the screen and its size. Today, there is no screen larger than 10 inches on the market, and even with such a screen with an 8K resolution, it is impossible to obtain a pixel size smaller than 50 microns;

– the location of the screen directly under the bath. The bath consists of an aluminum body and a film 50–150 microns thick, which, if slightly damaged, could leak photopolymer resin. This in turn would get on the screen and electronic components, which could lead to possible damage to the printer.

To address the issues of improving the technology and enhancing the quality of products, a comprehensive approach was already considered in [5] with the possibility of using this approach for all photopolymer 3D printing technologies. The proposal was based on the use of ketocoumarin as a photosensitizer in the photopolymer resin. Based on the authors' conclusions, such a modification of the photopolymer material increases the resolution of the material to 23 microns and makes it possible to print at a speed of 5.1 cm/h. These are quite high indicators, but this approach does not explain the very nature of the occurrence of product defects. A similar concept of improving the composition of the photopolymer material for printing is described in [8, 9]. Modification of the photopolymer with the addition of bimolecular photoinitiating particles makes it possible to improve the polymerization process of photopolymer molecules, carry out the polymerization process of molecules only in more intense radiation zones. But improving the material cannot solve the problems of defects at the technological and physical levels.

The software approaches described in [5] are based on solving the problem of improving algorithms for constructing contours and analyzing model attachment elements for SLA, DLP, and LCD technologies. And although this is also an effective approach to solving the problem of the quality of photopolymer printed products, the task of eliminating the factors causing model defects is not solved. The basic problem of the image exposure method is in the physics of the light exposure process, namely diffraction phenomena. Since this phenomenon cannot be avoided in the exposure process, approaches to reduce this influence were considered.

But all these approaches in the above works do not take into account the fact that another factor appears in the printing process that affects the appearance of product defects. All these methods consider the manufacture of a photopolymer model as a static process, in which there are only constant manufacturing parameters and non-variable optical phenomena that equally affect the printing process. In our work, it is considered that in the printing process, due to the influence of printing parameters and model dimensions, another factor arises, namely, heating of the photopolymer material after each layer of the product is illuminated. Due to the fact that during the exposure process, the energy of the UV matrix radiation goes not only to the polymerization of the photopolymer but is also spent on heating the photopolymer, this leads to thermal volumetric expansion of the photopolymer resin. And this process affects the accuracy of the exposure of the layers.

There were also software approaches to solving the problem of improving the quality of photopolymer products, which were based on improved algorithms for preparing a 3D model for printing [10]. The process of manufacturing a photopolymer model could be divided into the following stages:

– construction of a 3D model in a CAD system (Fusion 360, Blender, AutoCAD, SketchUp, Tinkercad, and others);

– conversion of the model into a format for stereolithography (stl*., obj*., 3mf*., amf*., and others);

– processing the model in software for dividing it into layers and setting the parameters for printing the sample (such programs are called "slicers"; NanoDLP or Chitubox programs are usually used for photopolymer 3D printing). The main task of such programs is to describe the sequence of commands and printing parameters in the form of a "G-code" code for a 3D printer in order to produce the required model;

– preparation of the printer and printing the product.

Although the process of manufacturing photopolymer products is inherently quite simple and consistent, as in any technological process, defects and product shortages are possible, which could become a significant problem in the production process of parts.

As follows from our review of the literature [11–13], there are quite a lot of reasons for the occurrence of such defects on products, but they can be systematized as follows:

– lack of photopolymer. This factor could cause the following defects: non-adhesion to the platform; increased exposure time of the layer; poor adhesion between the layers of the model;

– failure of printer components. This factor is quite extensive and depends on which component has failed, and which photopolymer printing technology is used. In general, the problems could be divided into failure of electronic components and wear of mechanical components of the machine. It was also found that in LCD technology, the formation of model defects directly depends on the quality of the LCD screen [11]. The appearance of dead pixels would directly affect the detailing of the model and the formation of parasitic illumination of the model or the formation of sinks on the model.

To prepare the photopolymer for printing according to [12], the following requirements are put forward: cleanliness of the photopolymer bath; absence of bubbles in the photopolymer resin; room temperature of the resin 20–22°C before printing. The adhesion of layers and the formation of shells on the surface of the model depend on this.

Incorrect setting of the printing parameters of the model is one of the most critical factors because due to incorrect setting of the printing parameters, there is the greatest probability of defects and product failure, as stated in [13].

Also, the setting of the printing parameters of the model is influenced by such factors as [8, 9]:

– features of the geometry of the product. The more hinged elements in the shape of the product, the greater the need to create additional supports (supports) for these hinged elements. The location of the model on the platform and the angle of overhang of the elements are also very important;

– features of the photopolymer resin. Each photopolymer resin has its own regulated values of the exposure time of the base and main layers, layer heights, and photopolymer polymerization wavelength;

– features of the photopolymer printing technology. Each photopolymer 3D printing technology has a different source for exposing the layer and a different method of building the layer, therefore, the layer setting parameters may be different.

For example, in DLP and LCD technologies, the entire cross-section of the layer is exposed simultaneously, and it is only necessary to specify the exposure time of the base and main layers. And in SLA technology, the laser beam passes along the entire contour of the cross-section of the model layer gradually, therefore, it is necessary to specify the speed of the laser beam.

The printing parameters that affect the preservation of the geometric dimensions of the model, adhesion of layers, and the formation of defects on the surface include exposure time of the base and main layers, s; layer height, μm; radiation intensity, Lm.

Papers [12, 13] indicate that there are quite a lot of reasons for the formation of defects, and it is quite difficult to clearly grade them because the appearance of one type of defect could be influenced by one or more factors.

Practical experience in the production of photopolymer products revealed that most of the causes of defects and product defects are associated with problems in setting printing parameters [12]. To combat most model defects, the following methods could be used: replacing printer elements; selecting a different photopolymer resin; optimizing the model for the features of the printing technology.

Therefore, to correctly set the printing parameters of the model, it is necessary not only to take into account the features of the photopolymer resin, the machine, and the printing technology, but also to understand the physical nature of the occurrence of photopolymer printing defects.

But despite these differences, the polymerization of the photosensitive material occurs with the help of light, which is why light diffraction occurs. This phenomenon occurs in both photolithography and photopolymer printing, and product defects are usually associated with the diffraction of radiation during photopolymerization. The problem of light diffraction was considered in particular detail in [14]. In it, the problem of light diffraction is considered in the process of stencil exposure of the topology image of a multilayer printed circuit board. A similar problem exists when using photopolymer 3D printing.

In photopolymer printing, the appearance of such surface defects as the deposition of excess photopolymer and the formation of surface artifacts is associated with the phenomenon of light diffraction, in other words, the light transmission of the model layers. This phenomenon is explained by the interference of waves at the edges of opaque objects or when waves pass through inhomogeneities between different media. This could be seen most clearly on the example of LCD printing.

The scattering of a light wave is influenced by the following factors: wavelength; width of the gap through which the light flux passes; optical medium through which the light flux passes.

In the case of LCD technology, the radiation source is a UV matrix that emits ultraviolet light with a wavelength of 405–435 nm. To polymerize the photopolymer, the radiation passes through four media that have different optical transmittance and air thickness. This is the distance between the UV matrix and the LCD screen, the LCD screen (0.00135 m), the film of the bottom of the photopolymer bath (0.000125 m), and the photopolymer resin (0.015 m).

The optical transmittance of these media is different, which could also affect the angle of radiation divergence. But for the appearance of pronounced printing defects, the exposure time plays a greater role. This could be explained by the fact that the photopolymer resin polymerizes faster with coherent (directional) radiation than with diffraction radiation. Since the phenomenon of diffraction occurs due to the passage of radiation through all these media, with the divergence of the wave at its edges, the radiation intensity will be lower, or in other words, the energy for polymerization of the photopolymer resin will be lower. Therefore, for the appearance of large deviations in size in areas of excessive polymerization, a longer exposure time of the photopolymer resin is required. Usually, in order to reduce the effect of radiation diffraction, the exposure time and layer height are reduced. With print settings selected taking into account the characteristics of the printing technology and material, these deviations in size do not exceed 100 microns for small models. But when printing large-sized models with a long printing time (from 6 hours), the values of size deviations could reach 2–3 mm. Surface defects of the model also appear at the same values of the printing parameters, so the appearance of defects by light diffraction alone is not enough to explain.

Therefore, it is necessary to consider another physical phenomenon that could cause significant defects in the printing of the model, namely the thermal volumetric expansion of the photopolymer resin during the exposure of the layers.

A detailed consideration of the principle of operation of photopolymer technologies indicates a certain systematicity. All three of these technologies use light radiation, the energy of which is not only directed to the polymerization of the necessary areas of the photopolymer. Part of the energy goes to heating the photopolymer resin itself, in particular due to the temperature coefficient of volumetric expansion of the material (TCVE) [15].

As is known, the temperature coefficient of volumetric expansion of a material (α) determines how its volume changes when the temperature changes and is measured in units of 1/°C (or 1/K). It shows how many units the volume of the material will change due to a change in temperature by 1°C.

The temperature coefficient of volumetric expansion could vary depending on the type of material. The influence of TCVE during the formation of each layer of the model is extremely important since at high temperatures of the resin the coefficient of expansion of the material increases. This could lead to geometric deviations in the layers of the model and cause problems such as parasitic lighting of the layers.

Therefore, it could be considered that all these values of the parameters of the exposure of the layers, to some extent, directly affect the temperature of the heating of the resin during printing, namely TCVE. This causes the appearance of surface defects in the printing and deviations of the dimensions of the product from the initial CAD model.

Based on our review of three main photopolymer 3D printing technologies, it has been shown that the main defects of products are associated with incorrect printing parameters, optical distortions, and physical properties of the photopolymer. However, the nature of the appearance of defects caused by light diffraction and thermal volumetric expansion of the resin remains insufficiently clarified, which is due to the complexity of comprehensive consideration of optical and thermodynamic effects within the framework of traditional approaches. These limitations could be overcome by constructing more complex models that combine physical, optical, and technological aspects of the printing process. A similar approach is considered in [14], but it is not directly related to 3D printing. All this indicates the feasibility of further research aimed at modeling and optimizing the parameters of exposing model layers, taking into account wave and thermal effects.

3. The aim and objectives of the study

The aim of our research is to devise a method for controlling photopolymer products by determining the influence of the photopolymer resin temperature parameter on the printing process to reduce the risk of surface defects and geometric deviations of products. This will make it possible to develop optimal exposure modes for photopolymer layers of the model during 3D printing of large-sized products.

To achieve this aim, the following objectives were accomplished:

– to determine the influence of the photopolymer resin temperature on the appearance of surface defects and deviations of geometric dimensions;

– to determine the influence of the layer exposure parameters on the photopolymer resin temperature;

– to design a system for controlling the photopolymer resin temperature during exposure of product layers.

4. The study materials and methods

The object of our study is the factors that affect the defects of photopolymer 3D models as the appearance of surface defects and deviations in the geometric dimensions of the photopolymer model negatively affect the quality and functionality of the products.

The hypothesis of the study assumes that temperature is one of the main factors that could affect the appearance of product defects and deviations in its geometric dimensions. This hypothesis is based on the assumption that during the exposure of the product layers, part of the energy from the UV matrix goes to heating the photopolymer resin. This, in turn, changes its temperature coefficient of volumetric expansion.

The principle of operation of the photopolymer 3D printer using LCD technology, described above, used in our research, is shown in Fig. 1.

The occurrence of product defects may be caused by optical phenomena, in particular light diffraction. This process can be schematically depicted as follows, Fig. 2.

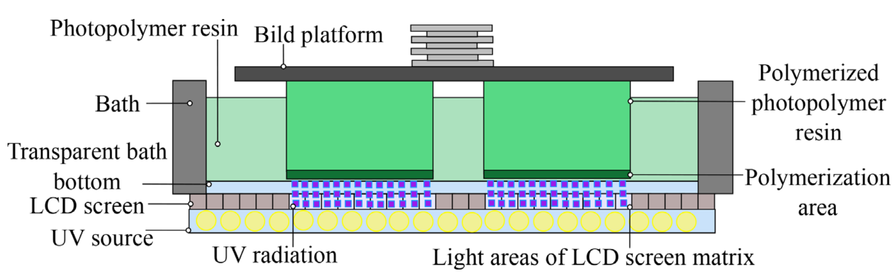


Fig. 1. LCD printer operation diagram

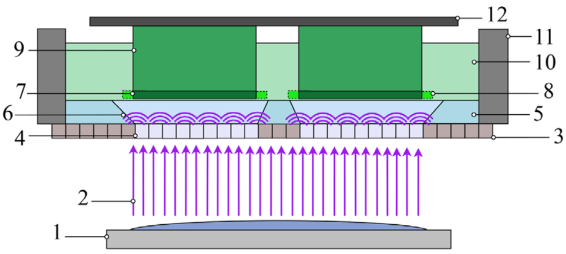


Fig. 2. The principle of printing defects due to light diffraction: 1 – ultraviolet matrix; 2 – ultraviolet radiation; 3 – opaque pixels of the liquid crystal screen; 4 – transparent pixels of the liquid crystal screen; 5 – film of the bottom of the photopolymer bath; 6 – diffraction of ultraviolet radiation; 7 – polymerization of the photopolymer layer; 8 – zone of excessive polymerization due to diffraction; 9 – polymerized photopolymer; 10 – liquid photopolymer resin; 11 – photopolymer bath; 12 – platform for building a model

Fig. 3 shows the basic printing defects that could occur during the manufacture of parts using the photopolymer printing method, obtained during our study.

However, the values of deviations in the geometric dimensions of the model cannot be explained only by optical phenomena that occur during the exposure of the layers and printing parameters. One of the hypotheses of our study is that the printing parameters and the time of manufacturing the model affect the change in the temperature of the resin, thereby creating a new factor for the appearance of surface defects and deviations in the geometry of the product. This process is schematically shown in Fig. 4.

To assess the influence of the temperature coefficient of volumetric expansion on the deviation in geometric dimensions and the emergence of product defects, it is necessary to investigate the following [15]:

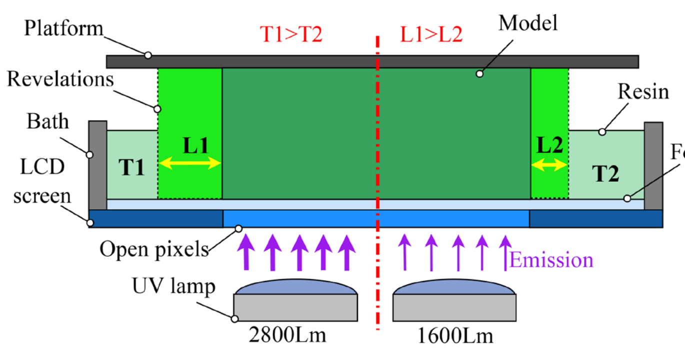
– the degree of influence of the temperature of the photopolymer resin on the appearance of model defects;

– changes in the temperature of the photopolymer resin depending on the layer exposure parameters.

To solve the first task, it was decided to controllably heat the photopolymer before printing the model and print this model at constant layer exposure values. The exposure time of the base layers is 30 s, the exposure time of the main resin layers is 7 s, the layer height is 50 μm, the radiation intensity is 2800 Lm. The model smoothing level and the screen pixel gray level are set to 4, and the time interval between layer exposures is 6 s.

The values of the exposure time and layer height were chosen in such a way as to exclude the possibility of the model peeling off the platform, insufficient layer exposure time and pressing the model into the bottom of the bath. The technological parameters of printing are adjusted using the Chitubox software, and their values were chosen based on the characteristics of the Elegoo Standard Photopolymer Resin brand photopolymer resin, which is used in our study. The polymerization wavelength is 405 nm, the shrinkage coefficient is from 2.76–3.54%, the layer exposure time is 5–10 s, the exposure time of the base layers is 15–40 s. The layer thickness should be 35 μm and 50 μm, the radiation intensity: 1600 Lm and 2800 Lm.

For photopolymer resins, the manufacturers recommend a printing temperature of the product from 18°C to 22°C. In this study, the temperature range varies from 18°C to 40°C, with a temperature increase of 2°C for each measurement. Heating of the photopolymer resin before printing is carried out using a drying chamber.



T1, T2 - photopolymer resin temperature;
L1, L2 - modelling deviations.

Fig. 4. Scheme of defects caused by overheating of the photopolymer resin

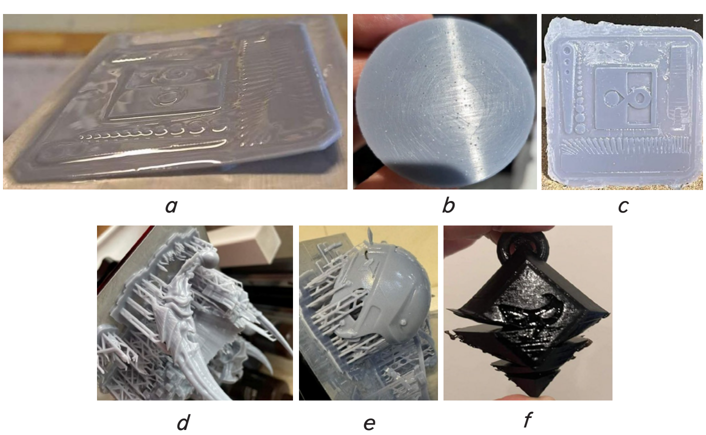


Fig. 3. Defects and rejected parts at photopolymer 3D printing: *a* – sample peeling off the platform; *b* – bubbles on the surface of the model; *c* – pressing the model into the bottom of the bath; *d* – underprinting of elements; *e* – layer stepping; *f* – layer delamination

For the convenience of measurements, a test model of a cube with dimensions of 20 × 20 × 20 mm was selected, which includes various control elements – holes, grooves, and additional geometric shapes (Fig. 5, *a*). The photopolymer 3D printer using LCD technology Anycubic Photon Mono X6Ks and test samples were used for our study (Fig. 5, *b*).

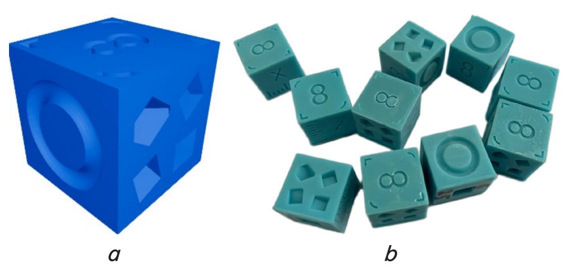


Fig. 5. Test samples for experiments: *a* – test cube; *b* – test samples

During our study, the following parameters were measured:

– deviation of dimensions along the *XY* coordinates (the dimensions of the model along the *X* and *Y* axes are set by the resolution of the pixels of the LCD screen, namely the pixel size. In this printer, the pixel size is 16×16 μm, therefore, the deviation of the dimensions of the model along these axes should be the same. For the convenience of processing the values, we use the average deviation value, taking into account the possibility that the location of the model may be shifted relative to the pixels of the LCD screen);

– deviation of dimensions along the *Z* coordinate (the accuracy of this axis depends on the pitch of the platform screw and is usually considered a constant value, but the temperature value could also affect the size of the model layer);

– the emergence of a special defect in the model, namely bubbles on the surface of the model; underprinting of elements; step-wised layers; influx of layers; delamination of layers;

– formation of artifacts on the model.

To process the statistical data of the research results, a regression-correlation model was built in the IBM SPSS 26 program.

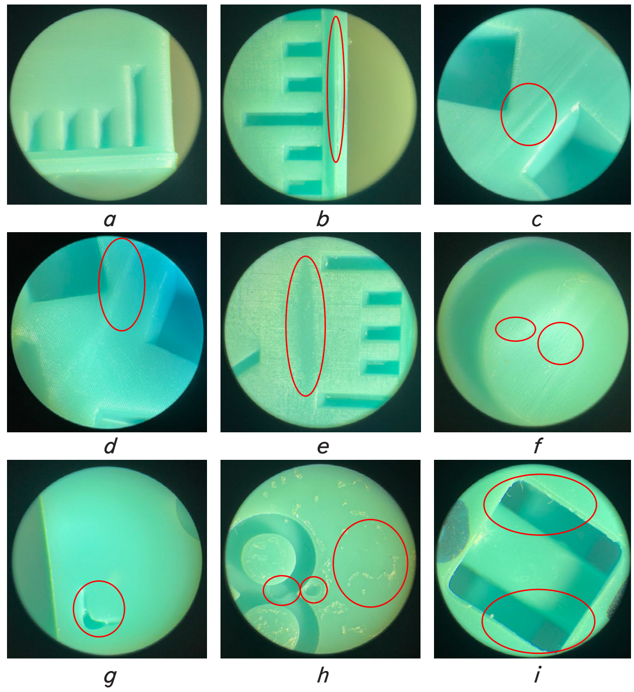


Fig. 6. Defects of test samples: *a* – model surface at 22°C; *b* – model surface at 18°C (crack in the base layers); *c* – model surface at 26°C (layer collapse inward); *d* – model surface at 34°C (layer bending); *e* – model surface at 28°C (layer deposition); *f* – model surface at 20°C (gap); *g* – model surface at 30°C (element deposition); *h* – model surface at 38°C (gaps); *i* – model surface at 40°C (sagging)

5. Results of devising a method for controlling photopolymer products

5. 1. Results of determining the influence of the temperature of the photopolymer resin on the emergence of defects and the geometry of products

Table 1 gives the results of studying the deviations in size and the emergence of model defects.

It should be noted that some samples have several defects at the same time. Fig. 6 shows obvious defects of samples at different values of the temperature of the photopolymer resin.

It can be observed that the hypothesis about the influence of the temperature of the photopolymer resin on the deviations in size and the emergence of model defects does make sense. With increasing temperature, the geometric dimensions of the model increase (Fig. 7).

According to these charts and the results of observations, it could be determined that the optimal temperature range of the photopolymer resin, at which defects and deviations in the dimensions of the model are minimal, is in the range from 18°C to 24°C.

Such an increase in the values of deviations in the dimensions of the samples with increasing temperature could be explained by an increase in the TCVE coefficient of the photopolymer resin.

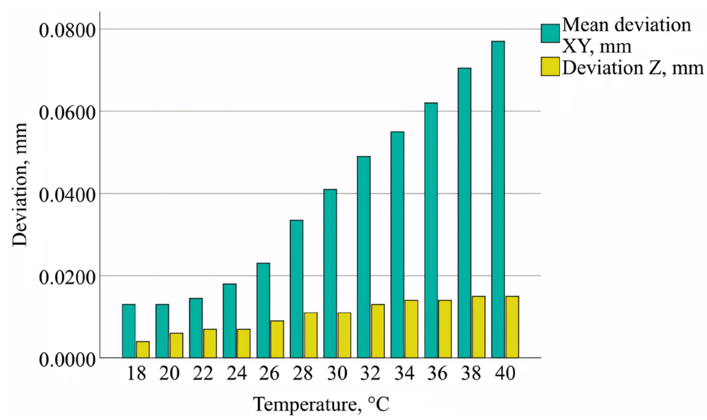


Fig. 7. Chart of sample size deviations versus photopolymer resin temperature

Table 1

Measurement results at different photopolymer temperatures

No.	Temperature, °C	Dimensional deviation by coordinates *XY*, mm			Dimensional deviation at the *Z* coordinate, mm	Emergence of a special defect
		X	*Y*	Mean		
1	18	0.013	0.013	0.013	0.004	Crack in the base layers
2	20	0.013	0.013	0.013	0.006	Gap
3	24	0.018	0.018	0.018	0.007	–
4	26	0.022	0.024	0.023	0.009	Layer collapse inward
5	28	0.034	0.033	0.0335	0.011	Layer surfacing
6	30	0.04	0.042	0.041	0.011	Element surfacing
7	32	0.049	0.049	0.049	0.013	Element surfacing
8	34	0.054	0.056	0.055	0.014	Bending layers
9	38	0.07	0.071	0.0705	0.015	Voids
10	40	0.078	0.076	0.077	0.015	Sagging

5. 2. Results of determining the influence of the parameters of exposure of the product layers on the temperature of the photopolymer resin

Based on the overall dimensions of the reference model, its volume was calculated, which is 8×10^{-9} m^3. The volume of the manufactured experimental samples was also determined in a similar way.

To determine the TCVE coefficient (β) for different printing parameters, it is necessary to determine the change in the temperature of the photopolymer resin for each series of the experiment ΔT:

$$\beta = \frac{\Delta V}{V_0 \cdot \Delta T}, \qquad (1)$$

where ΔV is the change in volume upon heating, m^3; V_0 is the initial volume at temperature T_0, m^3; ΔT is the change in temperature, °C.

The initial temperature was 16°C, with a subsequent increase of 2°C for each subsequent measurement.

TCVE values may vary depending on the composition of the photopolymer resin, the purpose, and desired characteristics set by the manufacturer, namely: main monomers; photoinitiators; additives (plasticizers, stabilizers, pigments, and dyes); fillers; crosslinkers.

Also, the degree of polymerization of the photopolymer resin could significantly affect the presence of defects and deviations in geometric dimensions, so these values may differ for different brands of photopolymers, which is why the coefficients must be selected for each brand separately.

Thus, a chart of the TCVE dependence of the photopolymer resin on temperature was constructed; Fig. 8.

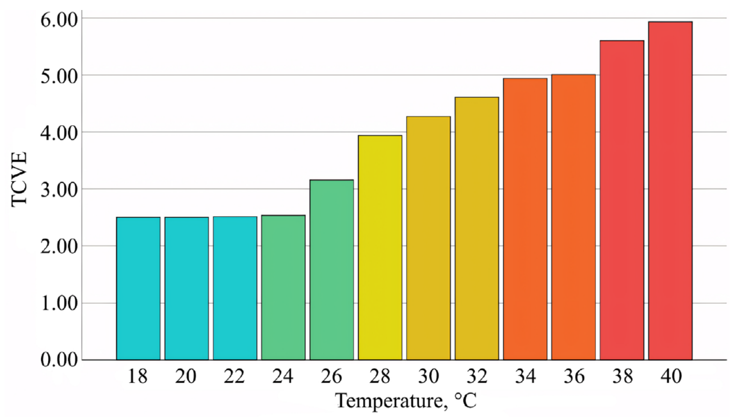


Fig. 8. TCVE dependence on 3D printing temperature

At the next stage of our study, the degree of influence of printing parameters on the heating of the photopolymer resin and the change in the temperature of the photopolymer resin depending on the layer exposure parameters was determined.

For this purpose, an average model with dimensions of 21.5 × 21.5 × 36 mm was selected, Fig. 9, which is printed with different parameters of layer exposure, namely:

– resin illumination time: in the range from 2 s to 10 s, with a step of 1 s for each test;

– time interval between layer exposure – 6 s and 10 s;

– number of base layers for all samples – 8;

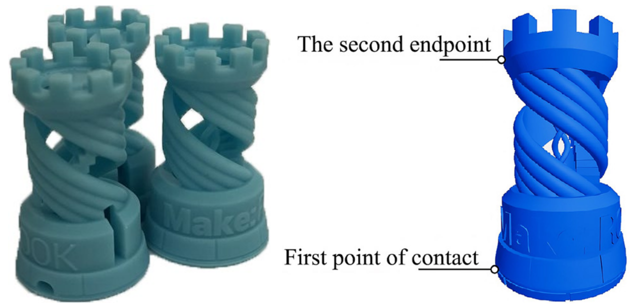
– exposure time for base layers – 30 s;

– layer height – 50 μm;

– maximum radiation intensity: at values of 2800 Lm and 1600 Lm.

These values were selected depending on the technical characteristics of the photopolymer resin. In this case, only those parameters that could directly affect the temperature of the photopolymer resin during printing are changed.

The initial temperature of the photopolymer resin before printing is within 20°C, with a tolerance of ± 0.4°C. This temperature value was selected based on the first study because in the range from 18°C to 24°C, the deviation of the model dimensions is minimal and there are no clear surface defects.



a *b*

Fig. 9. Test samples: *a* – manufactured samples; *b* – sample control points

To check the deviation in the model dimensions, two control points were used: at a distance of 3 mm and 25 mm from the base of the model, which help determine how much the deviation of the dimensions changes at the beginning and at the end of printing.

The chart of dependence of the heating of the photopolymer resin on the printing time of the sample is shown in Fig. 10.

In Fig. 10, the following patterns are observed:

– with an increase in the values of the exposure time, radiation intensity, and time interval between exposure of layers, the average heating of the photopolymer resin increases. On average, the temperature changes:

– at a radiation intensity of 1600 Lm with an interval between exposures of 6 s, the photopolymer resin heats up by 0.86°C with an increase in the layer exposure time;

– at a radiation intensity of 1600 Lm with an interval between exposures of 10 s, the photopolymer resin heats up by 0.82°C with an increase in the layer exposure time;

– at a radiation intensity of 2800 Lm with an interval between exposures of 6 s, the photopolymer resin heats up by 0.95°C with an increase in the layer exposure time;

– at a radiation intensity of 2800 Lm with an interval between exposures of 10 s, the photopolymer resin heats up by 0.77°C with an increase in the layer exposure time.

The results of measurements at the control points of the model are shown in Fig. 11.

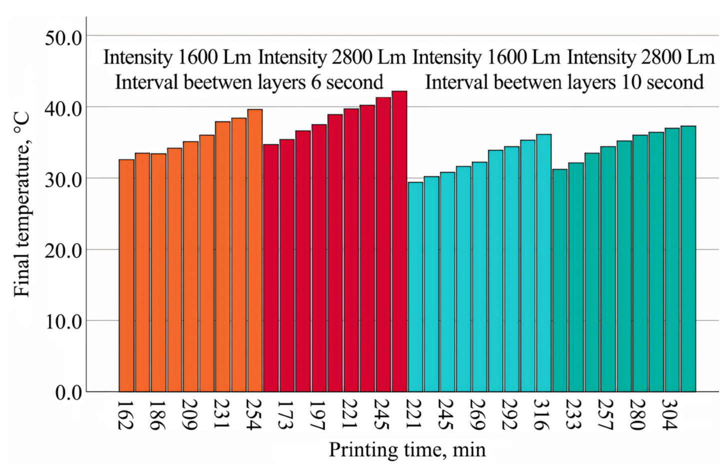
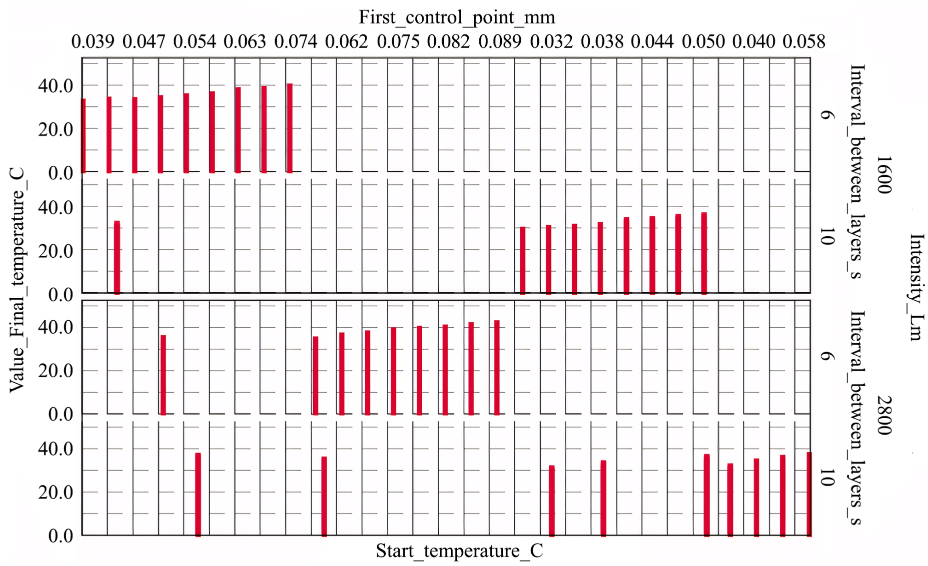
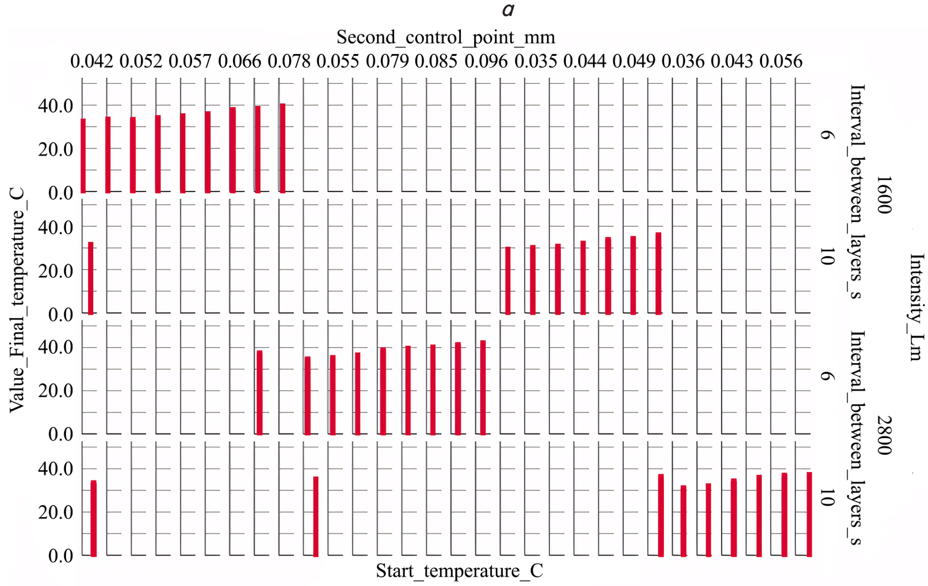


Fig. 10. Dependence of photopolymer resin temperature on printing time



a



b

Fig. 11. Dependence of the influence of the temperature of the photopolymer resin on the deviations in model dimensions: *a* — chart of deviations in the sample dimensions at the first control point; *b* — chart of deviations in the sample dimensions at the second control point

According to the results of statistical processing of our data, the following conclusions are drawn [15, 16]:

– the heating and cooling of the photopolymer resin is most affected by the exposure time of the layer (correlation coefficient 0.726) and the interval between exposures of the layers (correlation coefficient –0.54): the longer the time between exposures, the less the photopolymer heats up);

– the photopolymer temperature parameter really significantly affects the deviation of the dimensions at the control points of the model. For the first control point, the correlation coefficient is 0.952 and 0.955 for the second control point. The smaller value of the coefficient for the first point compared to the second is explained by the fact that at the beginning of printing the photopolymer resin has not yet heated up enough.

It should also be noted that with increasing temperature of photopolymer resin, various defects appeared on the surface of the model, shown in Fig. 12.

From the presence of defects and deviations in the sizes of the samples, it could be clearly judged that with a longer time between exposure of layers and lower values of exposure time and radiation intensity, overheating of the photopolymer resin is less, which, in turn, reduces the probability of deviations in the size of the model and surface defects.

As the temperature of the photopolymer resin increases, the value of the average deviation of the product dimensions increases. This is especially observed at the second control current:

– at a radiation intensity of 1600 Lm with an interval between exposures of 6 s, the average deviation at the first and second control points is 0.043 mm and 0.045 mm with an increase in the layer exposure time;

– at a radiation intensity of 1600 Lm with an interval between exposures of 10 s, the average deviation at the first and second control points is 0.026 mm and 0.027 mm with an increase in the layer exposure time;

– at a radiation intensity of 2800 Lm with an interval between exposures of 6 s, the average deviation at the first and second control points is 0.057 mm and 0.06 mm with an increase in the layer exposure time;

– at a radiation intensity of 2800 Lm with an interval between exposures of 10 s, the average deviation at the first and second control points is 0.032 mm and 0.033 mm with an increase in the layer exposure time.

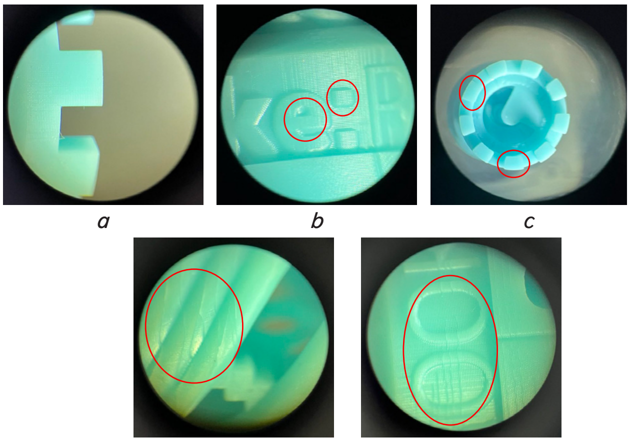


Fig. 12. Defects on the surface of samples at the second stage of research: *a* – reference surface of the model at temperatures ranging from 29°C to 32°C (14% of test samples); *b* – surface of the model at temperatures ranging from 33°C to 37°C – "fuzzy contour" (36% of test samples); *c* – surface of the model at 37°C – "layer deposition" (11% of test samples); *d* – surface of the model at temperatures ranging from 41°C to 42°C – "surface chips" (5.5% of test samples); *e* – surface of the model at temperatures ranging from 38°C to 40°C – "wave" (8.3% of test samples)

5. 3. Results of designing a photopolymer resin temperature control system

From a physical point of view, the process of heating the photopolymer resin and the occurrence of a temperature coefficient of volumetric expansion could be considered a problem of heat transfer in a three-layer wall. The layers of this wall fit tightly to each other, due to the ideal thermal contact on the surfaces at the points of contact they have the same temperature. Considering the features of photopolymer 3D printing using LCD technology, let us analyze in detail the structure of the three-layer wall, as shown in Fig. 13 [16].

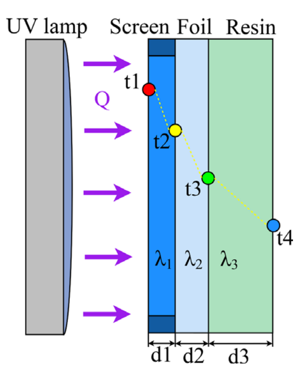


Fig. 13. Heat transfer in the photopolymer LCD 3D printing process

This wall consists of three tightly adjacent layers with the following thicknesses: d_1 (thickness of the LCD screen), d_2 (thickness of the film), and d_3 (thickness of the liquid photopolymer resin). Each of these layers has its own thermal conductivity (λ_1, λ_2 and λ_3, respectively).

The temperatures of the outer surfaces t_1 and t_4 are also known. The thermal contact between the layers is ideal, without mutual gaps and, accordingly, without air gaps. The temperatures at the contact points of the layers are designated as t_2 and t_3.

Since the temperatures of the outer surfaces are constant, the heat flux is constant, therefore, the amount of heat passing through the machine per unit time is unchanged. Under the stationary mode, the specific heat flux Q is constant and the same for all layers. In order to simplify the heat flux equation, we calculate the multilayer wall as a single-layer wall with thickness d_{all} (the sum of all layer thicknesses). In this case, the equivalent thermal conductivity coefficient λ_{eq} is introduced into the calculation, which is determined from the condition

$$Q=\frac{t_1-t_4}{\frac{d_1}{\lambda_1}+\frac{d_2}{\lambda_2}+\frac{d_3}{\lambda_3}}=\frac{\lambda_{eq}}{d_{all}}\left(t_1-t_4\right). \quad (2)$$

Such a description of the heating process is quite simplified since in this model there is only one heat source, which does not correspond to the real technological process of printing. It is necessary to additionally take into account the following factors of heating and cooling of the photopolymer resin, such as [17]:

– heating from the electronic components of the machine (Q_{el});

– heating and cooling from the external environment (Q_v)) and (Q_{fv});

– heating from radiation during exposure (Q_{LCD}) and ($Q_{diod\,(t)}$);

– convection inside the machine (Q_{con}).

The differential equation, which includes all heat flows and relates their effect to the temperature of the photopolymer, takes the following form [18]

$$m_R c_R \frac{dT}{dt}=Q_{diod(t)}-Q_{lcd}+Q_{el}+Q_{con}-Q_v-Q_{fv}, \quad (3)$$

where m_R is the mass of the photopolymer resin in the bath, kg; c_R is the specific heat capacity of the photopolymer resin.

The dynamic model of the process of heating the photopolymer resin during printing could be expressed using the electro-thermal analogy [19, 20]. The circuit has 5 resistors (media through which heat flux losses occur) and four capacitors (media that gradually heat up during the process of exposing the topology image); Fig. 14.

Owing to the components Q_{lcd}, Q_{fv} and $Q_{diod}(t)$, it is possible to control TCVE of the photopolymer resin. The main heating element is the UV matrix, which generates UV radiation. To reduce the risk of overheating of the photopolymer, the diodes on the UV matrix could be turned on in pulses, creating intervals between switching on and off [21]. This allows the resin to cool down, reducing the likelihood of overheating and high TCVE values. Therefore, automated control is carried out through the control over the heat flux $Q_{diod}(t)$.

To test the photopolymer resin heating control system, it is proposed to make the increase in time between exposure of layers adaptive, namely different for different areas of the model.

Based on previous experiments, at the beginning of printing, the photopolymer heating is slow (due to the fact that the heat flux has not yet had time to heat all the media), thus the deviations in size and the number of defects are minimal. Critical values of deviations and the emergence of defects are observed inside and at the end of printing (when all the thermal media have warmed up evenly).

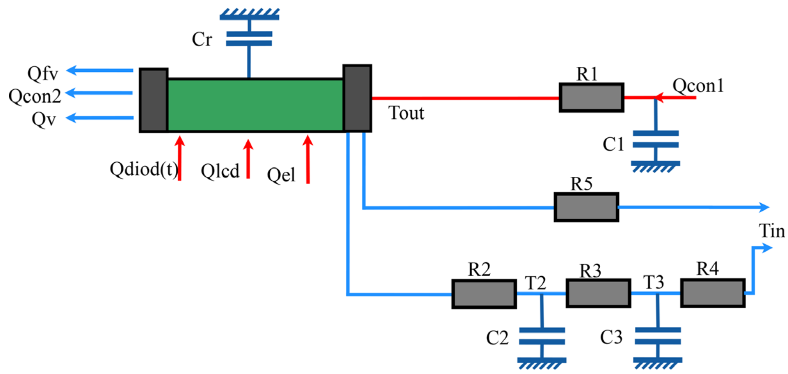


Fig. 14. Electrothermal heat exchange scheme between the photopolymer resin and the heat sinks: Q_{con1} — heat inflow from the room, W; Q_{con2} — heat inflow from the machine body, W; Q_v — heat inflow from natural ventilation, W; Q_{lcd} — heat inflow from the general internal heating of the UV matrix, W; Q_{el} — heat inflow from the electronic components of the machine, W; Q_{fv} — heat inflow due to air infiltration, W; $Q_{diod}(t)$ — heat inflow from one UV diode, W; T_{out} — temperature outside the machine, °C; T_{in} — temperature inside the machine, °C; T_2 — temperature between the UV matrix and air, °C; T_3 — temperature between the air and the LCD screen, °C; C_r — heat capacity of the photopolymer resin in the bath, J/K; C_1 — heat capacity of the materials of the machine body, J/K; C_2 — heat capacity of the fixing lens, J/K; C_3 — heat capacity of the LCD screen, J/K; R_1 — thermal resistance of the housing materials, K/W; R_2 — thermal resistance of the lens material, K/W; R_3 — thermal resistance of the air between the lens and the LCD screen, K/W; R_4 — thermal resistance of the LCD screen, K/W; R_5 — total thermal resistance

Based on this observation, it is possible to make the time between exposure of the first layers less than the time between exposure of the final layers. This approach will reduce the total printing time than under the condition of constant time, when regardless of the stage of printing the model, the time between layers is the same. Such an approach is more optimized in terms of the total printing time and deviations and defects of the model.

So, the temperature control system will work as follows.

A thermistor is immersed in the photopolymer bath, which polls the temperature of the photopolymer resin every 1000 ms and remembers the initial temperature of the photopolymer resin. The optimal temperature that the system should maintain is in the range of 18°C to 23°C. At the beginning of printing, the interval between layers is minimum 3 s to 6 s, which makes it possible to quickly print the base layers of the model. As soon as the temperature of the photopolymer resin has increased by more than 1°C from the initial temperature, the time between exposures of layers increases by 3 s and the cooling fans of the LCD screen turns on. Thus, with the help of air cooling, there is additional heat removal from the screen and the bottom of the photopolymer bath, which eventually cools the photopolymer resin itself. As soon as the temperature has dropped again by 1°C, the exposure time between layers decreases again and the cooling is turned off.

Thus, using a similar scheme of operation, it is possible to optimize the printing time of products and the heating of the photopolymer resin.

To check the system's performance, two samples with overall dimensions of 18.75 × 30 × 28.75 mm and with small topological elements were printed. One model was printed without temperature control, the other with control. The printing conditions and parameters for these two models are the same: exposure time of the base layers – 20 s; number of base layers – 4; time interval between exposure of layers – 6 s; exposure time of the main layers – 7 s; layer height – 35 μm; radiation intensity – 1600 Lm; initial temperature of the photopolymer resin – 21°C.

The printing control conditions for the second model are a maximum temperature increase of 0.4°C from the initial one. At a temperature of 21.4°C, cooling is turned on and the interval between exposure of layers is increased by 3 s. Fig. 15 shows the results of printing test samples.

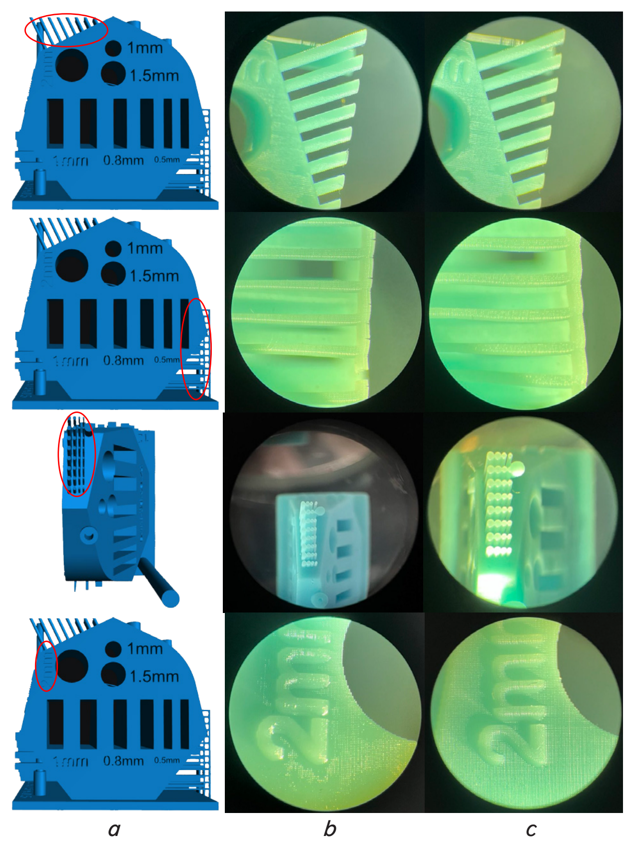


Fig. 15. Results of testing the operation of the photopolymer resin temperature control system: *a* — CAD model of the sample; *b* — sample without photopolymer resin heating control; *c* — sample with photopolymer resin heating control

The tested photopolymer samples show greater detailing of small elements of the product and symmetry of the structure. Also, compared to samples manufactured at critical photopolymer resin temperatures, there is no delamination of the product layers when using a temperature control system.

6. Discussion of results based on examining the influence of temperature characteristics of the photopolymer resin during the exposure of layers on the quality indicators of the product

Our results demonstrate the influence of changing the temperature of the photopolymer resin on the quality of the product and the accuracy of the geometric parameters of the model. In particular, it has been experimentally confirmed (Table 1 and Fig. 7) that with increasing temperature of the photopolymer resin, the number of defects on the surface of the product and the values of dimensional deviations along the XY coordinates increase. This is explained by the fact that an increase in temperature leads to an increase in the temperature coefficient of volumetric expansion of the resin TCVE (Fig. 8), which causes deformations in the polymerized volume.

Also, our experiments (Fig. 10, 11) showed that during printing the model, the temperature of the resin changes depending on the duration of exposure, radiation intensity, and the interval between the illumination of the layers. This is confirmed by the results of measurements of 36 test samples: in the cases of increasing exposure time and radiation intensity, the average heating of the resin is up to 0.95°C, which is critical for models with parts less than 0.5 mm.

The optimal exposure parameters (time 2–10 s, interval 10 s, intensity 1600 Lm) allowed us to minimize the heating of the resin and, accordingly, reduce the probability of defects. Correlation analysis (coefficients 0.726 and –0.54) confirmed that the exposure time and the interval between printing layers have the strongest impact on temperature fluctuations and on the accuracy of the product (Fig. 10 and Fig. 11). The presence of defects and deviations in the size of the samples makes it possible to conclude that increasing the time between exposure of layers and reducing the exposure time and radiation intensity contribute to less overheating of the photopolymer resin. This, in turn, reduces the probability of dimensional deviations of the model and defects on its surface.

One of the advantages of the proposed method of product control, which is based on changing the temperature of the resin of photopolymer products, is that the problem of printing defects is considered at the physical and technological levels. The method is based on a comprehensive approach that simultaneously takes into account optical phenomena of diffraction [14] and thermal processes occurring during polymerization. This approach is more systematic and effective as it makes it possible to minimize the number of defects without significant costs.

Our devised method of product control is based on a comprehensive approach to analyzing the causes of defects, taking into account not only optical phenomena that occur during the exposure of product layers but also the temperature properties of the resin. The implementation of such a method is less expensive compared to previous approaches to solving the problem of the quality of photopolymer products.

Unlike hardware solutions [4], which require the use of expensive digital micromirror systems (equipment cost from USD 5000), the proposed approach makes it possible to avoid significant costs for modernization of the machine. It does not require changes in the printer design or improvement of the material, as in the cases described in [6, 7]. Also, unlike software methods [5], focused on optimizing contours or building hinged elements, without taking into account variable physical factors, the proposed method is based on thermal heating of the resin during printing. This makes it possible to explain the emergence of defects even with a correctly configured exposure algorithm. At the stage of literature review, it was determined that most existing approaches to improving the quality of photopolymer 3D printing ignore dynamic changes in the physical state of the material during printing of the product. The proposed solution, which involves controlling the heating of the photopolymer resin, partially eliminates this drawback.

Taking into account the thermal effect that accumulates during long-term printing (especially for large-sized products, Fig. 11, 12) makes it possible to explain the causes of deviations that cannot be eliminated by conventional approaches. Thus, our study not only resolves the identified problem but also offers a practical way to overcome it through dynamic temperature control.

In further studies, it is planned to determine and collate a temperature change in photopolymer resin for other photopolymer 3D printing technologies. The designed temperature control system for LCD technology could already be used for the production of photopolymer models.

Based on the results of designing a photopolymer resin temperature control system, it could be judged that the proposed method is effective in reducing the likelihood of surface defects in the model. This is explained by the fact that by increasing the time between exposure of layers and additional cooling of the bottom of the photopolymer bath, the photopolymer resin has the opportunity to cool down to suitable printing parameters. At these temperature values, minimal deviations in dimensions are observed and the likelihood of surface defects in the product is reduced.

Therefore, a method for product control has been proposed, taking into account resin heating, which involves increasing the time between exposure of layers with an increase in temperature of more than 23°C and forced heat removal from the photopolymer bath. Although the appropriate control system could increase the total printing time (4 h 53 min – printing time without temperature control compared to 5 h 27 min – with control of photopolymer resin heating), it minimizes the occurrence of defects or even product failure, which would reduce costs in the production process.

One of the limitations of our study is that the influence of temperature phenomena identified in this work is relevant for large-sized products with a long printing time of 12 hours or more. On small models with a short printing time, the photopolymer resin does not have time to heat up the photopolymer critically, so temperature could already insignificantly affect the emergence of surface defects and deviations in the size of the product.

In our study, one could note a drawback relating to the fact that additional checks are required for other photopolymer 3D printing technologies, such as SLA and DLP, since they have certain differences in image exposure. Therefore, the heating values of the photopolymer resin may differ from the results reported here. In addition, the devised method requires further improvement with a larger sample of experiments.

7. Conclusions

1. Based on the results of our research, it was determined that:

– during printing of the product, the parameters of the exposure of the sample layer have a significant impact on the emergence of model deviations and printing defects;

– the temperature of the photopolymer resin could be attributed to external factors that affect the failure of the photopolymer product.

2. Most of the UV radiation during exposure of the model layer goes to heating the photopolymer, which in turn affects TCVE. Thus, physical thermodynamic factors are added to existing methods for improving the quality of photopolymer products (hardware, chemical based on the improvement of the photopolymer resin, and software approaches). Based on our results, it is possible to draw the following conclusion that the deviation of the geometric dimensions of the test samples is significantly affected by the use of a photopolymer temperature control system. Without controlling the overheating of the photopolymer resin, the size deviations average 0.04 mm along the *XY* coordinate.

3. According to the results of analysis of our data, it could be assumed that the control of the printing temperature of photopolymer resin is a rather important parameter. The studies prove the assumption that with an increase in the exposure time of a photopolymer product, the phenomenon of not only the overexposure of layers occurs, caused by light diffraction, but also the expansion of the photopolymer resin during the exposure of the layer. The energy from the ultraviolet radiation source is spent not only on polymerization but also on heating the photopolymer resin itself, which causes the emergence of surface defects and deviations in the geometric dimensions of the product. The effect of temperature could be especially critical not only for small elements of the product but also under the condition of long-term printing of large models, in particular with a printing time of more than 10 hours. Thus, under the condition of using a photopolymer resin overheating control system, the deviations in the dimensions of the product are on average 0.032 mm, i.e., the deviations in geometric dimensions are reduced by 20%.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

The team of authors expresses sincere gratitude to the Head of the Educational and Scientific Laboratory "3D Prototyping", Associate Professor at KITAR Department, KhNURE, PhD, Associate Professor, Yevheniy Razumov-Fryzyuk, for consultations and for providing the opportunity to conduct experimental research at the laboratory.

References

1. Nevliudov, I. Sh., Zharikova, I. V., Perepelitca, I. D., Reznichenko, A. G. (2014). The analysis of the electronic devices substrates roughness testing methods. Eastern-European Journal of Enterprise Technologies, 2 (5 (68)), 25–30. https://doi.org/10.15587/1729-4061.2014.21864
2. Polozova, T., Romanenkov, Y., Sheiko, I., Buiak, L., Murzabulatova, O., Ponomarov, S. (2024). Industrial Development in the Era of Digital Technologies: a Comparative Analysis of EU States. 2024 14th International Conference on Advanced Computer Information Technologies (ACIT). Ceske Budejovice: IEEE, 419–422. https://doi.org/10.1109/acit62333.2024.10712520
3. Nevliudov, I. Sh., Chala, O. O., Botsman, I. V. (2021). Determination of technological process modes for surface formation of substrates for functional components of microoptoelectromechanical systems. Functional Materials, 28 (2), 381–385. https://doi.org/10.15407/fm28.02.381
4. Zhao, X., Zhao, Y., Li, M.-D., Li, Z., Peng, H., Xie, T. et al. (2021). Efficient 3D printing via photooxidation of ketocoumarin based photopolymerization. Nature Communications, 12 (1). https://doi.org/10.1038/s41467-021-23170-4
5. Jacobsen, A., Jorgensen, T., Tafjord, Ø., Kirkhorn, E. (2015). Concepts for 3D print productivity systems with advanced DLP photoheads. Emerging Digital Micromirror Device Based Systems and Applications VII. SPIE, 9376, 937605. https://doi.org/10.1117/12.2084962
6. Shafique, H., Karamzadeh, V., Kim, G., Shen, M. L., Morocz, Y., Sohrabi-Kashani, A. et al. (2024). High-resolution low-cost LCD 3D printing for microfluidics and organ-on-a-chip devices. Lab on a Chip, 24 (10), 2774–2790. https://doi.org/10.1039/d3lc01125a
7. Nevliudov, I. Sh., Nikitin, D. O., Strilets, R. Ye. (2025). Rozrobka systemy avtomatyzovanoho keruvannia fotopolimernym 3D-drukom. Avtomatyzatsiia ta kompiuterno-intehrovani tekhnolohii – 2025. Kyiv: KPI im. Ihoria Sikorskoho, Vyd-vo "Politekhnika", 86–87.
8. Fiedor, P., Pilch, M., Szymaszek, P., Chachaj-Brekiesz, A., Galek, M., Ortyl, J. (2020). Photochemical Study of a New Bimolecular Photoinitiating System for Vat Photopolymerization 3D Printing Techniques under Visible Light. Catalysts, 10 (3), 284. https://doi.org/10.3390/catal10030284
9. Tomal, W., Pilch, M., Chachaj-Brekiesz, A., Ortyl, J. (2019). Development of New High-Performance Biphenyl and Terphenyl Derivatives as Versatile Photoredox Photoinitiating Systems and Their Applications in 3D Printing Photopolymerization Processes. Catalysts, 9 (10), 827. https://doi.org/10.3390/catal9100827
10. Livesu, M., Ellero, S., Martínez, J., Lefebvre, S., Attene, M. (2017). From 3D models to 3D prints: an overview of the processing pipeline. Computer Graphics Forum, 36 (2), 537–564. https://doi.org/10.1111/cgf.13147

11. Nikitin, D. O., Balabanov, I. V. (2024). Doslidzhennia vplyvu temperatury fotopolimernoi smoly na zberezhennia heometrychnykh rozmiriv modeli pid chas 3D druku. Science of XXI century: development, main theories and achievements. Helsinki: International Center of Scientific Research, 197–203. Available at: https://previous.scientia.report/index.php/archive/issue/view/26.01.2024
12. Nevliudov, I., Razumov-Frizyuk, I., Nikitin, D., Badaniuk, I., Strelets, R.; Linde, I. (Ed.) (2023). Practical results of the study of photopolymer exposure of printed circuit board topology. Information Systems in Project and Program Management. Riga: European University Press, 262–280. https://doi.org/10.30837/mmp.2023.262
13. Nikitin, D. (2024). Development of a model for controlling the temperature of photopolymer resin based on LCD 3D printing technology. Control, Navigation and Communication Systems, 1 (75), 31–37. https://doi.org/10.26906/sunz.2024.1.031
14. Born, M., Wolf, E. (2013). Principles of optics: Electromagnetic theory of propagation, interference, and diffraction of light. Elsevier, 836.
15. Reddy, J. N. (2014). An Introduction to Nonlinear Finite Element Analysis: with applications to heat transfer, fluid mechanics, and solid mechanics Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199641758.001.0001
16. Ruban, I., Horenskyi, H., Romanenkov, Y., Revenko, D. (2022). Models of adaptive integration of weighted interval data in tasks of predictive expert assessment. Eastern-European Journal of Enterprise Technologies, 5 (4 (119)), 6–15. https://doi.org/10.15587/1729-4061.2022.265782
17. Salcedo, J., McCormick, K. (2020). SPSS Statistics for Dummies. Hoboken: John Wiley & Sons. Available at: https://www.wiley.com/en-us/SPSS+Statistics+For+Dummies%2C+4th+Edition-p-9781119560821
18. Keviczky, L., Bars, R., Hetthéssy, J., Bányász, C. (2019). Control Engineering. Advanced Textbooks in Control and Signal Processing. Singapore: Springer, 532. https://doi.org/10.1007/978-981-10-8297-9
19. Ziaziun, I. A. et al. (Eds.) (Suchasni informatsiini tekhnolohii ta innovatsiini metodyky navchannia u pidhotovtsi fakhivtsiv: metodolohiia, teoriia, dosvid, problemy). Kyiv-Vinnytsia: TOV firma "Planer", 39, 514. Available at: https://library.vspu.net/items/e39efe6a-1bd9-445a-af11-eb357fdba890
20. Hahn, B. H., Valentine, D. T. (2017). Essential MATLAB for Engineers and Scientists. Academic Press. https://doi.org/10.1016/C2015-0-02182-7
21. Díaz-Rodríguez, I. D., Han, S., Bhattacharyya, S. P. (2019). Analytical Design of PID Controllers. Cham: Springer International Publishing, 302. https://doi.org/10.1007/978-3-030-18228-1