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COST ESTIMATION OF PHOTOPOLYMER RESIN FOR 3D EXPOSURE OF CIRCUIT BOARDS

The research object in the work is the printed circuit boards (PCB) production technological process using the additive technology of photopolymer 3D printing. The existing problem is that the manufacturing process of single-sided and double-sided PCBs, simple in technology, from the third to the fifth accuracy class, requires the use of a large amount of consumables and technological equipment. In turn, this affects the cost of the product. The research subject is models and methods for manufacturing PCB using photopolymer 3D printing.

In order to reduce the cost of materials: film or aerosol photoresist, as well as reduce the number of technological operations, applying photoresist and for the manufacture of PCBs stencils, it is proposed to use photopolymer 3D printing technologies for the manufacture of PCBs. The paper analyzes the costs of Plexiwire Resin Basic Orange Transparen photopolymer resin for the manufacture of single-sided PCBs and calculates the cost of the consumable (resin) compared to the costs of dry film photoresist. 60 % cost of consumables (photopolymer resin) compared to dry film photoresist for making single-sided PCBs. The work is aimed at determining the dependence of the geometric dimensions of the PCBs topology and the consumption of photopolymer resin on the technological parameters of photopolymer exposure. A regression correlation model of the dependence of resin consumption on exposure parameters has been developed and correlation coefficients have been calculated. It has been established that with an increase in the exposure time of the photopolymer resin, the consumption of the photopolymer resin increases and the deviation of the geometric dimensions of the PCBs topology increases, which in turn negatively affects the quality of the product. Therefore, using the obtained regression model, it is possible to calculate the influence of parameters on the PCB topology and reduce the deviation of conductor sizes and resin consumption.

Keywords: *circuit boards, photolithography, photopolymer exposure, additive technology, DLP, LCD, photo masks.*

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1. Introduction

The rapid development of modern technologies has led to the fourth industrial revolution (Industry 4.0) [1–3]. Industry 4.0 is based on advanced research in the fields of artificial intelligence, robotics, cloud computing, additive technologies, etc. This allowed to improve significantly technological production processes by developing a new in the form of cyber-physical production systems ones (CPPS) [4, 5]. A feature of the CPPS application is the physical and cybernetic world synthesis in a single information eco-space, which allows creating very flexible production lines reconfiguration [6]. One of the CPPS applications promising areas is their introduction into the high-tech electronic products production. Plenty of large corporations, such as Lenovo, Samsung, and order printed circuit boards (PCBs) production from contract electronics companies Jabil Circuit Ukraine LLC, due to cost-effective production, which allows not to create new plants and production lines, but to use existing capacity [7]. PCB production cost consists of many factors: the use and depreciation of machines and installations, the required amount of consumables and resources, the accuracy class of the printed circuit board, the production complexity and much more [8–10]. Thus, the cost of a single-sided copper-based board with dimensions of 40×40×1.6 mm with a dielectric base FR-4 with a minimum hole diameter of 0.25 mm and a step of 0.3 mm conductors varies from 5.4 to 8 dollars. This example demonstrates the need to find an opportunity to reduce the product cost without compromising its quality [11]. A significant advantage of DLP/LCD technology using in the PCB production is, firstly, savings on production facilities, as there is no need for devices for applying film and aerosol photoresists and stencils, and secondly, reduce the consumables cost. Thus, the research theme devoted to reducing the consumables amount in the PCBs production, while maintaining the quality of the product, is an urgent task.

Research object is PCB production technological process using additive technologies of photopolymer 3D printing.

Research subject is models and methods for manufacturing PCB using photopolymer 3D printing.

Research aim is to develop a regression-correlation model of photopolymer resin consumption when creating a PCB topology and regression coefficients calculation.

2. Research methodology

The 3D printers' operation principle using DLP technology is similar to the operation of the projector. The polymer turns into a solid form under the action of visible light. The entire area of the layer is illuminated evenly. Digital light treatment uses a different source of ultraviolet (UV) light [12, 13]. Instead of lasers, DLP printers are equipped with UV projectors that have a system of micromirrors to control the projected light image. Each layer cross-sections images are projected on the work platform and the whole layer is illuminated at once [14].

LCD operation principle is similar to the principle of DLP illumination. An LCD display is used as a mask. The photopolymer is illuminated by an LED matrix, on which the image is formed due to the LCD-display, which frame by frame displays the cross section of the molded part.

With 3D printing photopolymer technologies using it is possible to simplify the technological process PCB production compared to the classical stages of photolithography, as well as reduce the amount of technological equipment and consumables (Fig. 1).

The main material for printing in both technologies is photopolymer resin. Currently, there are many manufacturers and brands of photopolymer resins [15]. Their choice of price and quality is usually determined by the accuracy of printing and the minimum allowable layer height and additional characteristics: chemical and mechanical resistance. Also photopolymer resins are chosen based on the possibility of use, for example: to obtain parts of molten models, or biocompatible with the human body (dentures for dentistry), Table 1.

For correct comparison of costs in the PCB Production by the method of film photoresist with DLP and LCD technologies, it is necessary to determine the optimal ratio of exposure conditions and the required product parameters with minimal deviations of the PCB topological pattern.

Preliminary researches of the geometric dimensions deviation of the PCB topology in 3D exposure were performed on 40 samples of photopolymer masks at different values of technological parameters, such as: the thickness of the exposure layer, exposure time and radiation intensity [12].

Photopolymer resin – Plexiwire Resin Basic Orange Transparen was used as a material for obtaining experimental samples. The advantages of this resin are: fairly high mechanical strength of printed parts, short exposure time and relatively low, compared to other analogues, the cost (Table 1). In addition, this resin showed a high level of adhesion to the foil fiberglass blank.

From the results of experiments the following values of conductors width deviations at various parameters of topology exposure were received, Table 2.

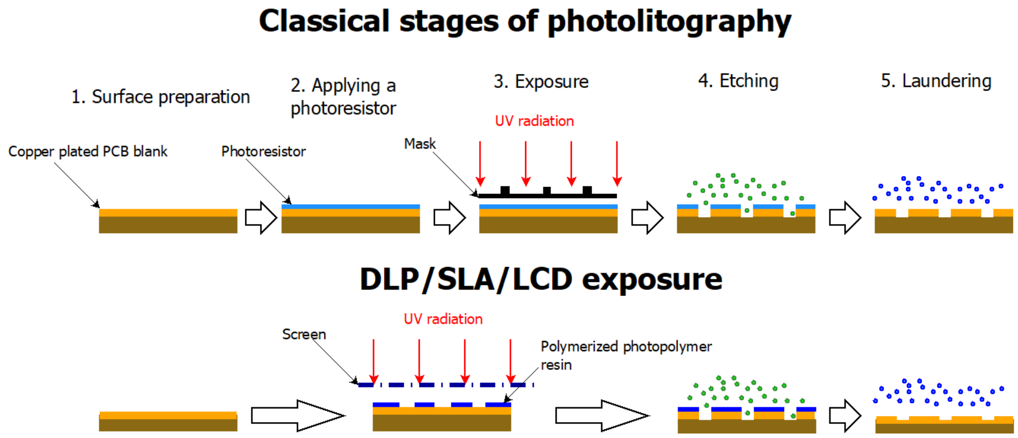


Fig. 1. Comparison of classical stages of photolithography and obtaining a conductive pattern using photopolymer 3D printing

Table 1

Photopolymer resin brands and characteristics

No.	Resin Name	Wavelength range of polymerization, nm	Layer illumination time, s	Layer thickness, µm	Price per litre, dol./l
1	Anycubic 405nm UV [16]	405	5–15	35	47.8
2	Plexiwire Resin Basic [17]	405–450	7–20	35	30.08
3	MonoFilament Basic [18]	405–450	7–25	35	45.13
4	FunToDo [19]	225–415	6–17	20	84.20
5	Wanhao Castable [20]	395–420	8–15	35	56.41
6	BlueCast CR3A [21]	400–410	4–9	10	202.65
7	Elegoo 3D [22]	385–450	3	35	43.87
8	Weistek [23]	385–410	–	50	33.23
9	Tevo [24]	380–420	8–12	50	40.12

Table 2

PCB topology geometric dimensions deviation calculation results [12]

Layer width, 20 µm					
Light Flow intensity, 1600 lm					
Polymerization time, s	7	8	9	10	11
Deviation, mm	0.008	0.010	0.011	0.012	0.014
Layer width, 20 µm					
Light Flow intensity, 2800 lm					
Polymerization time, s	7	8	9	10	11
Deviation, mm	0.009	0.01	0.012	0.013	0.015
Layer width, 50 µm					
Light Flow intensity, 1600 lm					
Polymerization time, s	7	8	9	10	11
Deviation, mm	0.009	0.011	0.012	0.012	–
Layer width, 50 µm					
Light Flow intensity, 2800 lm					
Polymerization time, s	7	8	9	10	11
Deviation, mm	0.01	0.013	0.015	0.018	–

In this case, as the initial shift was taken the width of the conductor along the X axis, this was equal to 2 mm. During the increase in the values of the parameters conductor width deviation increased to the greater side (Fig. 2).

After conducting a series of experiments to obtain a PCB topological pattern, data were obtained, which took into account the regression coefficients for the exposure factors of the photopolymer 3D-mask, which affect the deviation of geometric dimensions during printing, Table 3.

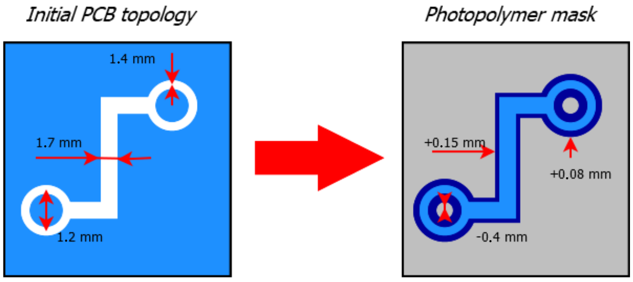


Fig. 2. Conductor width deviation during exposure

Table 3

Regression coefficients calculations

Correlations					
		Deviations	Time	Thickness	Intensity
Deviations	Correlations Pearson	1	0.913**	0.164	0.13
	Meaning (double-sided)	–	0.000	0.313	0.425
	N	40	40	40	40
Time	Correlations Pearson	0.913**	1	0.000	0.000
	Meaning (double-sided)	0.000	–	1	1
	N	40	40	40	40
Thickness	Correlations Pearson	0.164	0.000	1	0.000
	Meaning (double-sided)	0.313	1	–	1
	N	40	40	40	40
Intensity	Correlations Pearson	0.13	0.000	0.000	1
	Meaning (double-sided)	0.425	1	1	–
	N	40	40	40	40

Based on the fact that this experiment investigated the impact of three parameters on one initial change, the regression equation looks like this:

$$y=b_0+b_1x_1+b_2x_2+b_3x_3, \qquad (1)$$

where y – initial variable (PCB topology geometric dimensions deviation); b_0, b_1, b_2, b_3 – coefficients of linear regression of impact parameters on the factor (b_0 – actually regression coefficient); x_1, x_2, x_3 – impact parameters on output variable.

Based on the equation, the regression coefficients b_0, b_1, b_2 and b_3 has next impact on initial variables, Table 4.

Table 4

Regression equation coefficients

Regression equation coefficients	Initial variables	Value
b_0 – actual regression coefficient	–	0.11
b_1	x_1 – exposure time	0.931
b_2	x_2 – radiation intensity	0.130
b_3	x_3 – layer width	0.164

Then it is possible to represent regression equation in next way:

$$y=b_0+b_1x_1+b_2x_2+b_3x_3=$$
$$=0.11+0.931x_1+0.130x_2+0.164x_3. \qquad (2)$$

The obtained results determine the range of further regression model to determine the photopolymer consumption. PCB topology geometric dimensions deviation calculation results are presented in Table 2 [12, 13]. The following printing parameters are used to calculate the photopolymer consumption:

- layer thickness from 20 µm to 50 µm;
- step 5 microns;
- temporary illumination from 7 seconds to 11 seconds.

The period of layer illumination – up to 11 seconds – is chosen based on the fact that with increasing exposure time of the photopolymer mask, the deviation of geometric dimensions exceeds 0.015 µm along the X, Y axes.

A 80×72 mm PCB stencil was created for the research in the format of a vector image (*.svg), which was then converted into a format for 3D printing (*.stl). This approach to processing and converting 2D images to 3D objects is necessary to work with the mask in NanoDLP, which can generate machine code sequential command execution (G-code) for DLP/LCD printer, which will set the necessary parameters for printing (Fig. 3).

This program provides the ability to calculate the photopolymer resin consumption during printing a model. Using this option and changing the exposure settings and mask height, the following values were obtained, Table 5.

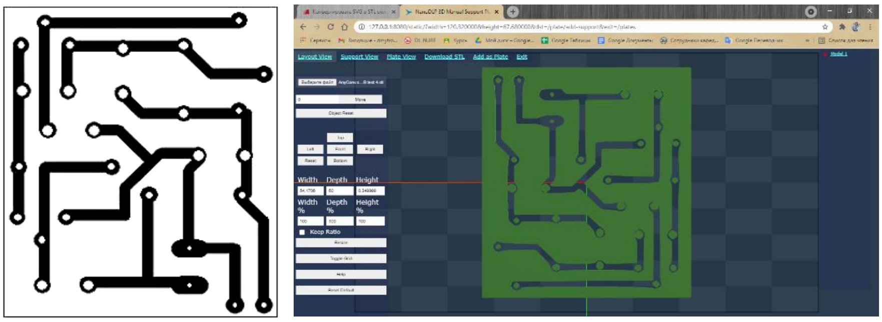

a b

Fig. 3. Vector image processing for 3D exposure: *a* – vector image; *b* – 3D-mask

Based on the fact that for photopolymer resin consumption research two parameters and one initial variable are taken into account, the regression equation may be represented in next way:

$$y=b_0+b_1x_1+b_2x_2, \tag{3}$$

where y – output variable (photopolymer resin consumption); b_0, b_1, b_2 – impact parameters linear regression coefficients on output variable (b_0 – actual regression coefficient); x_1 – exposure time; x_2 – layer width.

The obtained data were processed using IBM SPSS Statistics to perform basic linear regression analysis of exposure parameters [25, 26]. To determine the correspondence between the calculated values of linear regression and the obtained experimental data, it is necessary to determine the value of the coefficient of determination «R». Based on the table «Model Summary^b» (Summary for the model), the coefficient of determination is equal to 0.993, so it is possible to make a decision about the presence of correlation between the calculated and obtained values in Table 6.

Table 5

Polymer resin consumption calculations results

Width, μm	Time, s	Volume, ml	Price, dol.	Width, μm	Time, s	Volume, ml	Price, dol.
0.2	7	0.45	0.011	0.2	8	0.47	0.014
0.25		0.54	0.016	0.25		0.55	0.017
0.3		0.68	0.02	0.3		0.71	0.021
0.35		0.79	0.024	0.35		0.79	0.024
0.4		0.87	0.026	0.4		0.89	0.027
0.45		1.02	0.03	0.45		1.03	0.03
0.5		1.1	0.033	0.5		1.1	0.033
Width, μm	Time, s	Volume, ml	Price, dol.	Width, μm	Time, s	Volume, ml	Price, dol.
0.2	9	0.47	0.014	0.2	10	0.51	0.015
0.25		0.56	0.017	0.25		0.62	0.019
0.3		0.72	0.022	0.3		0.78	0.023
0.35		0.81	0.024	0.35		0.87	0.026
0.4		0.92	0.028	0.4		0.96	0.029
0.45		1.01	0.033	0.45		1.08	0.032
0.5		1.14	0.034	0.5		1.21	0.036

Width, μm	Time, s	Volume, ml	Price, dol.
0.2	11	0.54	0.016
0.25		0.67	0.02
0.3		0.82	0.025
0.35		0.92	0.028
0.4		1.09	0.033
0.45		1.18	0.035
0.5		1.22	0.037

Table 6

Regression analysis results. Cast for model

Model Summary^b										
Model	R	R^2	Adjusted R^2	Standard Error of the Estimate	R^2 Change	F Change	$df1$	$df2$	Significant F Change	Durbin-Watson
1	0.993^a	0.986	0.985	0.0286	0.986	1137.13	2	32	0.000	1.211

Notes: a – Predictor (Constant) Time, Thickness; b – Dependent Variable: Consumption

In Tables 6–8 the values of multiple determination «R^2» are presented, which determines how the parameters included in the equation (exposure time and height of the mask layer) affect the output variable (consumption of photopolymer resin).

In this experiment, the value «R^2» is 0.986, which means that the included factors by 98.6 % affect the value of the response. At the adjusted value «R^2» is equal to 0.985 or 98.5 %.

The standard error of estimation of this calculation is 0.02863, which is within the norm, and can be reduced by conducting a larger series of experiments.

To determine the level of «Significance» and confirm the accuracy of previous results, use the table «ANOVA», which shows that the level of «significance» is less than 0.05, which confirms the accuracy of the results, and the actual regression coefficient of the constructed model (b_0) is 1.864 (Table 7). Correlation of response factors is given in Table 8.

According to the results of the correlation analysis it is possible to deduce the following regularities:

- changing the parameter «layer height» by 5 μm affects the increase or decrease of photopolymer resin consumption with a linear regression coefficient (b_1) by 0.97;
- change of the parameter «exposure time» for 1 second affects the increase or decrease in the resin consumption with a linear regression coefficient (b_2) by 0.215.

Thus, the regression equation of photopolymer resin consumption looks like follows:

$$y=b_0+b_1x_1+b_2x_2=1.864+0.931x_1+0.130x_2. \qquad (4)$$

Table 7

Regression analysis results. Significance calculations results

ANOVA^a						
Model		Sum of Squares	df	Mean Squares	F	Significant
1	Regression	1.864	2	0.932	1137.137	0.000^b
	Residual	0.026	32	0.001	–	–
	Total	1.890	34	–	–	–

Notes: a – Dependent Variable: Consumption; b – Predictor (Constant) Time, Thickness

Table 8

Regression analysis results. Pearson's correlation calculations

Correlations				
		Consumption	Thickness	Time
Pearson Correlation	Consumption	1	0.97	0.215
	Thickness	0.97	1	0.000
	Time	0.215	0.000	1
Significant (1-tailed)	Consumption	–	0.000	0.108
	Thickness	0.000	–	0.5
	Time	0.108	0.5	–
N	Consumption	35	35	35
	Thickness	35	35	35
	Time	35	35	35

3. Research results and discussion

The experimental results in Fig. 4 show the dependence of photopolymer resin consumption on the exposure time of the PCB topology and the height of the 3D mask.

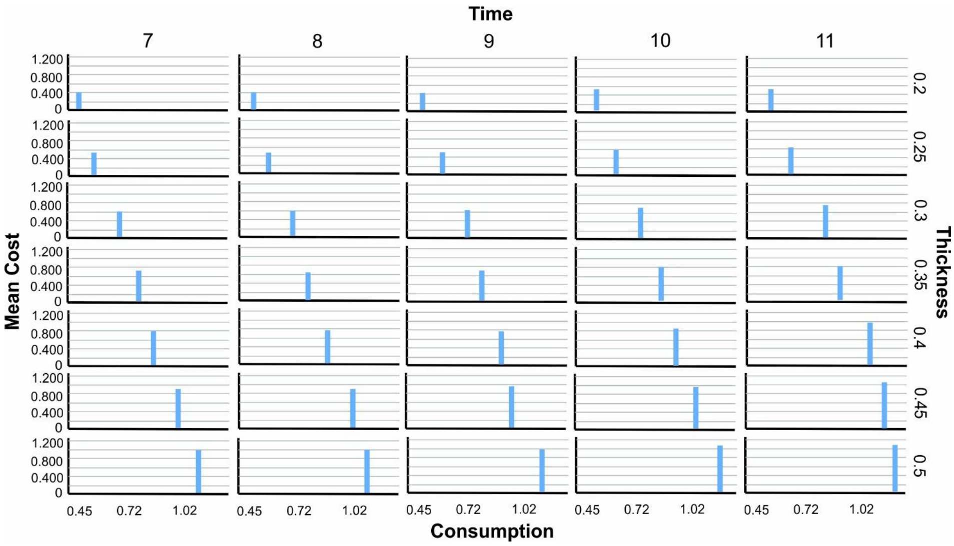
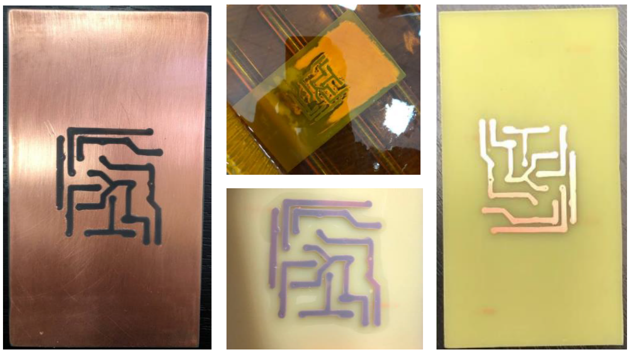


Fig. 4. Graphic representation of photopolymer resin consumption impact on exposure parameters

From the 35 produced samples, one with the smallest deviations of the topology during printing and etching of the board ±0.011 μm was selected. This sample was obtained at an exposure time of 9 seconds, the height of the mask layer of 0.25 μm (Fig. 5).



a *b* *c*

Fig. 5. PCB production by 3D exposure technology:
a – polymer photo mask; *b* – PCB etching in a solution of ferric chloride ($FeCl_3$); *c* – PCB ready topology

During the production of this sample 0.56 ml of photopolymer resin brand Plexiwire Resin Basic was used. If to analyze such samples, it is possible to find that with increasing time by one second, at the same layer height of 0.25 μm, the volume of resin consumption increases by an average of 0.17 ml. This also increases the geometric deviations of the width of the conductors by an average of ±0.0125 μm.

Thus, using 100 ml of photopolymer resin, it is possible to make 178 PCBs with dimensions of 80×72 mm, at a price of 3 dollars per 100 ml, the cost of polymer resin for one 3D mask is 0.017 dollars. Eleven standard 300×200 mm sheets (0.75 USD per sheet) will be required to make this number of PCBs using Riston-200 photoresist film. In total, the cost of PCB production with photopolymer exposure is 3 dollars, with the classical method of printing using photoresist film 8 dollars 27 cents. The difference in cost is 5 dollars and 26 cents.

These researches can be used not only to create a PCB photopolymer topology, but also to create photopolymer 3D models. But this requires taking into account exposure parameters impact in order to design a model taking into account the geometric deviations in printing.

4. Conclusions

During the experiments, data were obtained that allowed to develop a regression-correlation model of photopolymer resin consumption in the creation of the PCB topology and regression coefficients calculation. This makes it possible to reduce the cost of consumables for the PCB production by the method of photopolymer 3D masks and gives a positive economic effect from use in enterprises within the concept of cyber-physical production systems.

According to the results of research, it can be concluded that in the PCB production with dimensions of 80×72 mm photopolymer exposure, the exposure time was 9 seconds at a layer height of 0.25 μm. Savings on consumables are 62 % compared to the production of the same PCB on photoresist film technology. This proves the feasibility of using photopolymer 3D printing for the PCB production.

This manufacturing technology makes it possible to combine in one process the bringing on and exposure of the topology on the workpiece, which significantly reduces the duration of production and reduces the amount of process equipment in the structure of the process. In addition, the proposed approach allows more efficient use of production space in enterprises, as well as demonstrates the economic benefits of using additive 3D printing technologies in the PCB production.

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