Evaluation of the optomechanical effect in coatings made of photopolymers

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Abstract. The study on the optomechanical effect (photostriction) in the material used in 3D printing by layer-by-layer photopolymerization is performed. The calculation - experimental model in the form of a steel console plate with the one-sided photopolymeric coating is developed for studying of this effect. The experimental setup including UV source, the set of irradiated identical consoles, part of which had the photopolymer coating, the speckle-interferometer device for registration of bending micro displacements of the consoles called by photostriction shrinkage of the coating, is collected. The temperature bending of the plate during is irradiation by the UF-source was determined. The Magnitude of the optomechanical shrinkage in comparison with the temperature bending of the plate with a photopolymeric coating at the fixed radiation time is experimentally determined. The technique is developed for calculation and allocation of the optomechanical effect against the background of temperature bending of the plate with a photopolymeric coating and value of earlier undetermined coefficient of linear dilatation of the photopolymer is obtained. Also the residual stresses which generate in the coating owing to optomechanical effect are defined.

1. Introduction

Now we observe the intensive development of technologies of additive manufacturing as they enable rapid and relatively cheap creation of spatial objects of irregular shape with high accuracy and high coefficient of material utilization. The main technologies of additive manufacturing are the threedimensional printing, stereolithography, electrolytic precipitation, winding, selective laser sintering, sputtering, lamination and some others. On this subject, the significant number of papers is published. These papers mainly address the technological aspects of creation of products and their properties. The review of such works is available in [1-4]. There are much less papers with the description of the reasons for which the products gain these or those properties, deviating from the design and how these properties can be changed, having changed the manufacturing process parameters. From the point of view of mechanical aspects of additive production accuracy [5-7] the main problems are the residual (shrinkage) stresses, and the following deviations of the final form of products from the design, that influences strength, stability and durability of final products [8].
One of widespread methods of additive manufacturing of nonmetallic objects is the method of layer-by-layer photopolymerization. Due to specific properties of initial liquid substance (resin) and of the polymerized solid material a separate problem of the process is verification of mathematical models of the final objects [9, 10]. The available theoretical and numerical research data shows that for a closed form model of layer-by-layer additive manufacturing process one should know stresses, deformations and shrinkage in the single elementary layer of finite thickness. At this point the most reliable way of determining these values is experimental study [11]. The possibilities of calculation and compensation of shrinkage stresses negative influence in the course of additive production are considered in [12]. In the present work the shrinkage of objects made of polymeric materials produced by layer-by-layer photopolymerization in a 3D-printer is studied. We also consider the problems of mechanical parameters determination for photopolymer that is necessary for evaluating the mathematical model for bending a two-layer beam consisting of a substrate and a coating. The technique and results of the study of specific effect of shrinkage stresses are presented for the products 3D-printed from a liquid AB 710 B photopolymer in the course of layer-by-layer photopolymerization of substrate at its irradiation by the powerful UF-light source, for example, the mercury-quartz lamp of the 3D-printer. The feature of this effect is also the repeated shrinkage of the final product observed long time after its manufacturing under the influence of the separate weak source of UV-radiation. The similar effect of action of UV-radiation was noted earlier in the film-shaped samples from polymeric materials and samples of biological fabrics [13], some kinds of rubbers [14, 15], in crystals of ferrite of bismuth [16]. Prospects of use of this effect in the optomechanical systems managed by light are noted. As for origins of the optomechanical effect, in the known publications it is noted that in polymeric materials action of UV-radiation interferes with expansion of material due to heating, and the effect of "consolidation" (compression) of the material takes place in microvolumes depending on the nature of the material, its chemical and physical structure [13]. The optomechanical effect in this case is observed reducing the curvature due to temperature-bending of the plate with a coating.

2. Setup and samples for the study of optomechanical effect in photopolymeric coatings

For the study of optomechanical effect in photopolymeric coatings the rigid holder was made, then six substrates were inserted into it - steel console plates (figure 1) of 70 mm long, 15 mm wide and 0.5 mm thick each, onto two of these plates (figure 1, in the center), at the side of UV-source radiation, we applied a photopolymeric coating of approximately identical thickness - in the range of 0.35 - 0.40 mm. For such construction of samples the optomechanical effect had to be seen as bending of the coated plates.

![Figure 1. The mounted samples for the optomechanical effect study - substrates in the form of console plates on two of which (in the center) the photopolymeric coating is applied.](image-url)
The irradiation of plates from the side of the coating was performed by the source of UV-radiation of low power consisting of 8 LEDs with automatic switch-off after 40 seconds of operation. Registration of small bending displacements of plates was done using the electronic speckle interferometer, constructed according to the scheme of Michelson. The scheme of the setup for the study of optomechanical effect in coatings is given in the figure 2.

![Figure 2](image)

**Figure 2.** The scheme of the setup: 1 - speckle interferometer, 2 - console plates-substrates (the substrates with coating are denoted in red), 3 - UV-radiation source.

Here as 1 we designate the interferometer, 2 - the set of samples, part of which had the one-side photopolymeric coating, 3 - UV-radiation source. In the initial state in the absence of radiation by the UV-source the bending displacements of plates, including the ones with coating were registered in spite of the fact that the plates were at natural lighting. This demonstrated the completion of the process of active photopolymerization of the coatings.

**3. Evaluation of the optomechanical effect**

After repeated switching on, and then, after a while, switching off the UV-source the repeating optomechanical effect was observed in the form of bending for the plates with photopolymeric coating. At the same time, the uncoated plates remained still. One of the interferograms of bending of the block of plates at UV-lighting is given in the figure 3. On this interferogram the central plates are covered with a system of the horizontal bright and dark fringes related to the amount of plates bending. The value of bending was determined by a number of the similar fringes at its multiplication on a step of a fringe - a constant value defining difference in bending displacements of the plate between the given and the next closest dark or bright fringe. In our case this was 0.266 microns as long as the solid-state green laser with a wavelength of 532 nanometers was used in our measuring system.

As we observed the process, we noted the unusual features of the optomechanical effect in photopolymer coating: a delay in substrate bending initiation after coating irradiation start, the temporal-nonlinearity of increase in substrate deflection at continuous irradiation combining the periods of increase, decrease and again increase of the deflection, experience of after-effect when after radiation switching off, there often was no automatic reduction of the substrate deflection, but its growth continued, the reverse bending of the console to the side opposite to shrinkage at long period of UV-radiation shutdown. The presence of such features of optomechanical effect indicated that photostretching shrinkage was observed in combination with other types of processes in the coating.
first of all, - with temperature influence forcing the plates to bend to the side opposite to bending at shrinkage.

![Image](image.png)

**Figure 3.** The typical interferogram of block of plates bending at UV-lighting.

4. Separation of the optomechanical effect against the temperature bending for the plate with a coating

It is known that radiation of UV-lamp contains not only light, but also thermal components [13]. For separation of the optomechanical effect it was necessary to estimate the influence of thermal component of UV-lamp radiation on the plates with a coating. For this purpose a thermocouple of a digital thermometer was attached to one of the plates that enabled measuring the temperature variation on the plates during a single phase of UV exposition (40 seconds). Later, instead of the source of UV-radiation, a heat source was installed (a contactless infrared heating element) and the distance between it and the block of plates was picked such that the time of IR exposition was equal to a single phase of UV exposition and that the change of plates temperature was equal to the same at one phase of UV exposition.

After selection of the distance between the heat source and the plates as a result of repeated IR exposition we have registered the interferograms of plates bending with larger number of fringes than in case of the bending of plates under the influence of UV-source. One of such interferograms obtained at heating the plate for a time, equal to one phase of the UV flare is shown in figure 4. In comparison with the interferogram given in figure 3, the difference in fringes for the plates with coating was 2 fringes that corresponded to the change of plate deflection on $\Delta w = 2 \times 0.266 \mu m = 0.532 \mu m$. Therefore, the optomechanical effect created rather significant change in the substrate deflection, reducing its bending due to thermal action.
Figure 4. The interferogram of block of plates bending under the influence of the temperature source.

5. Assessment of the parameters influencing the temperature and photostriction bending of the substrate with coating

As a mathematical model of bending the beam with coating at heating it on $\Delta T$ degrees we use the known solution of the thermoelastic problem for a bimetallic plate [17, 18]. According to it the deflection of the two-layer console plate on a fringe which is at a distance $x$ from gripping is described by the formula

$$w(x) = \frac{3h_1 h_2 (h_1 + h_2)(D_1 U_{1\alpha_k} - D_2 U_{2\alpha_k}) \Delta T x^2}{4(D_1 h_1 + D_2 h_2)(D_1 h_1^3 + D_2 h_2^3) - 3(D_1 h_1^2 - D_2 h_2^2)^2 x^2},$$

$$D_k = \frac{1 - v_k}{1 + v_k} U_k, \quad U_k = \frac{E_k}{1 - 2v_k}, \quad k = 1, 2,$$  \hspace{1cm} (1)

where $E_k, v_k, h_k$ - elastic moduli, Poisson’s ratios and thickness of the plate and coating, $\alpha_k$ - the corresponding linear expansion coefficients, $x$ - the coordinate along the beam axis counted from gripping.

For assessment of shrinkage stresses in the two-layer plate under the influence of the radiation of the UV-source we use the approach suggested in [19].

Let’s say the liquid photopolymeric coating is evenly applied to the cantilever fixed substrate of length $l$. After the flare of the UV-source the film of the coating shrinks, that leads to formation of stresses both in the substrate and the coating initiating the substrate bending in the direction opposite to the temperature bending.

Let’s consider first the substrate and the coating in the free, untied state as two independent rods of length $l$ and $l_0$. Accepting that $l > l_0$, we define elongation as $\Delta l = l - l_0$. As $\Delta l = N l_0 / E_2 F_2$, where $F_2$ is the cross sectional area of the coating, $N$ - force which is necessary for the coating elongation by $\Delta l$, we may consider that stresses generated from substrate constraint of shrinkage deformation in
the coating create the equivalent longitudinal force $N$, applied to the joint of the substrate and the coating at the free end of the console. The bending moment from this force is $M = N h / 2$. On the other hand, longitudinal force is expressed through stress $\sigma$ in the coating: $N = \sigma F$, and the bending moment - through the maximum deflection of the console bent by the edge moment of $M$ jointly with the compressive force $N$ [20]:

$$w(l) = \frac{h_l}{2} \left[ 1 - \cos \left( \sqrt{\frac{12 \sigma h_l}{E_l h_l}} l \right) \right]$$

Therefore, having measured the maximum deflection of the rod, we have the opportunity to define shrinkage stress in the coating owing to optomechanical effect.

Calculation on formulas (1), (2) requires the mechanical parameters of photopolymer: elastic modulus, Poisson’s ratio and linear expansion coefficient. The most essential change in time, at different stages of polymerization is known for elastic modulus [11]. On the wide interval of time its value is stabilized at the magnitude of 1.8 GPa according to the tension tests carried out by the authors. The dependence of elastic modulus of photopolymer on time of UV-irradiation is given in figure 5 in logarithmic scale. This result correlates with data of other authors on change of elastic modulus of photopolymers in time [21].

![Figure 5](image.png)

**Figure 5.** Change of elastic modulus of photopolymer in the course of polymerization in logarithmic scale.

Data on Poisson’s ratio for materials for fast prototyping, to which the used photopolymer belongs to, show rather high values: 0.37 - 0.45 [22]. The Poisson’s ratio of our material is in these limits, closer to upper value; according to the results of standard tension tests its value is 0.44.

No data on linear expansion coefficient (LEC) of our photopolymer was found in sources available to authors. Therefore a specific technique was developed for its measurement.

The linear expansion coefficient measurement was done by means of registration of temperature induced fields of displacements on one of the lateral faces of a cubic sample made of a photopolymer during heating (cooling) of its upper side. The applied setup for photopolymer’s LEC measurement is given in figure 6, denoted: 1 - the sample, 2 - the digital thermometer connected to a thermocouple on the upper side of the sample, 3 - the speckle interferometer, 4 - the IR heater.
Figure 6. The setup for photopolymer's LEC measurement.

Registration of displacements of the lateral surface of the sample when heating its upper side was carried out using the speckle interferometer. The series of interferograms of microdisplacements of the lateral face of the sample at five consecutive stages of sample cooling down is shown in figure 7: from the initial temperature of 28.35 °C down to the temperature of 28.15 °C - in the upper left picture and down to 27.65 °C - in the lower right lower picture. Let's note that registration of interferograms at cooling is simpler as it is a slow process, rather than heating.

Figure 7. Interferograms of consecutive cooling of the sample.

In Table 1 the values of temperature of the upper side of the sample and quantity of the interference fringes registered at this temperature registered on the lateral face of the sample are given.
Table 1. The relation of temperature change with number of interference fringes at sample cooling.

| Interferogram # | Temperature (°C) | Number of fringes |
|-----------------|------------------|------------------|
| 0               | 28.35            | 0                |
| 1               | 28.15            | 2                |
| 2               | 27.95            | 3                |
| 3               | 27.85            | 4                |
| 4               | 27.70            | 5                |
| 5               | 27.65            | 6                |

Evaluating the interferograms of figure 7 and Table 1, we can conclude that the displacement of the lateral face of the sample occurred synchronously to its cooling. Thereof it is possible to evaluate the LEC approximately using the one-dimensional model. Considering that expansion (compression) of the photopolymeric cube takes place in the directions, perpendicular to lateral faces equally, we can use the known formula of temperature lengthening \( \Delta l = l_0 \alpha \Delta T \), where \( \alpha \) - thermal expansion coefficient, \( \Delta T \) - temperature variation. Due to the uniformity of expansion in cube cross-sections we may use the half of the length of his horizontal edge as \( l \).

On the other hand, the value of lengthening can be found as a normal displacement of the chosen cross-section defined through the change of number \( N \) of interference fringes in the known interval of temperatures: \( \Delta l = \lambda N / 2 \), where \( \lambda \) - the wavelength of radiation of the laser used in the interferometer.

The following expression for \( \alpha \) can be obtained from the previous formulas: \( \alpha = \lambda N / (2l\Delta T) \).

Apparently from Table 1, at change of temperature on 0.5 °C six fringes appear on the interferogram: \( N=6 \). Initial length of the cube edge \( 2l = 32 \text{ mm} \), the laser wavelength \( \lambda = 0.532 \mu \text{m} \). With the account of these values for the linear expansion coefficient we will obtain \( \alpha = 14.5 \times 10^{-5} \text{ deg}^{-1} \). A little different from this value turns out and at reversing the formula (1) relative to LEC of the coating.

6. Conclusion
The repeating long-term optomechanical effect consisting in substrate bending owing to photostriction shrinkage of the coating at its repeated irradiation by UV-source was found during the present study. The similar, but opposite bending of the substrate was observed at temperature expansion of the coating that is similar to bending of a bimetallic plate. For separation of thermal bending in the substrate with coating from photostriction bending the series of experiments on remote IR heating of the coating at a level of its heating by the UF-source was performed. Use of the measured values of deflection of the substrate with coating in a model of the non-central bending of the substrate with a coating enabled the definition of the mechanical characteristics of the coating, the magnitudes of shrinkage stresses generated in it and coating thickness which were compared with the data of direct measurements of coatings characteristics on a tensile setup and showed insignificant discrepancy between them.

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