Prediction of the properties of photopolymer prototypes

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Abstract. The study of the mechanical properties of photopolymer material SI500. For the manufacture of experimental samples used the method of rapid prototyping stereolithography. The effect of process parameters on tensile and compression strength was studied. It was found that the mechanical strength of the samples is influenced by the layer thickness, exposure time, and additional processing in an ultraviolet chamber. The values of maximum tensile stresses, which are achieved when the layer is exposed for 30 seconds and additional processing, are determined. Changing the layer thickness does not significantly affect the values of maximum tensile stresses. The maximum is in the range from 53.4 MPa to 55.4 MPa. Values of maximum mechanical strength during compression of the samples is achieved with a flash of 10 seconds. The maximum compressive stresses range from 229 MPa to 230 MPa. Changing the layer thickness does not significantly affect the compressive strength.

1. Introduction

Modern rapid prototyping technologies are used to create new equipment. Technologies can reduce manufacturing time, check the manufacturability of the design and functionality of the prototypes.

Stereolithography technology is one of the promising methods for manufacturing functional prototypes. Details have high quality indicators, which are not inferior to reference samples.

Layered curing of materials is carried out by exposure to ultraviolet radiation [1, 2]. The transmission of radiation occurs due to the laser or video projectors initiating the polymerization reaction in the liquid layer of the polymer composition. In the process of layer-by-layer shaping of the prototype according to computer data, it is necessary to achieve the required degree of polymerization to form a given accuracy, surface quality and mechanical properties.

In the process of layer-by-layer construction of the prototype under the influence of ultraviolet radiation, the achieved degree of polymerization of the prototype is 50 - 80%. To increase the degree of polymerization up to 90%, additional processing is used in a chamber with ultraviolet radiation [3,4,5]. At the same time, the mechanical properties of the prototypes are stable.

The presence of uncured volumes in the prototype leads to disproportionate shrinkage. Prototypes have low mechanical properties. On the surface of the prototypes, warping of the form occurs [6,7].

In the process of stereolithography, photopolymer materials based on acrylic, epoxy and ether are used [8-11].
The authors' studies [12] are aimed at studying the influence of SLA parameters - the process during the construction and post-processing of prototypes.

The research results showed that thermal post-processing of the sample after building the prototype can reduce the level of residual stresses caused by shrinkage of the material [13].

The authors of [14] used different modes of laser radiation power when constructing a prototype using the technology - SLA. The results of the work allowed to reduce the curing time, to reduce the degree of shrinkage, warping and to increase the accuracy of the prototype.

The authors of [15,16] made an attempt to improve the surface finish of SLA prototypes. The results are achieved by adjusting the angle of the laser beam to the scanned surface.

Prototypes made using stereolithography technology are widely used in the aerospace, automotive and manufacturing industries. They are used as functional models in bench tests. Therefore, the strength of prototypes has an important role [17]. In [18, 19], the effect of process parameters on the strength of the manufactured prototype was studied using standard mechanical tests. It was found in the works that the strength of the prototypes is influenced by the thickness of the layer, the orientation of the models and the cured area. In this case, the main parameters is the layer thickness, which allows to increase the strength of the prototype.

The results presented by the authors were obtained using samples made by classical stereolithography. A laser beam was used to illuminate the cross sections. The work describes the exposure process using the image mask created by the projectors. The flare region extends to the entire cross section of the experimental sample. Therefore, the degree of cure and strength indicators will have different values. The development of the direction of strength analysis depending on the parameters of the non-classical stereolithography process is an urgent scientific and technical task.

It is important to determine the effect of key process parameters on the degree of cure of the photopolymer material. The results will allow the manufacture of prototypes with desired mechanical properties.

2. Materials and methods

To study the mechanical properties, a SI500 acrylic based photopolymer composition was used. The material is in a liquid state prior to construction. After exposure to light with a wavelength of 350 to 500 nm, the material experiences a phase transition. The increase in mechanical rigidity occurs due to the formation of transverse and longitudinal polymer chains. Stereolithography uses crosslinked acrylic polymers. The physical and mechanical properties of the SI500 photopolymer composite material are presented in Table 1.

| $E^a$, GPa $\sigma_p$, MPa $\epsilon^c$, % $\sigma_y$, MPA $G^e$, GPa $T_g$, °C $\rho_{lig}$, g/sm$^3$ $\rho$, g/sm$^3$ | 2.68 | 78.1 | 4.39 | 65 | 2.5 | 61 | 1.1 | 1.2 |
|---|---|---|---|---|---|---|---|---|

$^a$Tensile modulus.
$^b$Tensile strength.
$^c$Relative strain at break.
$^d$Bending Strength.
$^e$Shear modulus.
$^f$Glass transition temperature.
$^g$Density in the liquid state.
$^h$Density in solid state.

Samples for mechanical analysis were made by stereolithography using an Envisiontec Perfactory XEDE rapid prototyping unit. The main difference from the classical method of stereolithography is the method of exposure. In the process of exposure, a mask is used to project the section of the model. Used projectors with lamps can increase the speed of construction and detailing of prototypes. The digital processing method of the prototype cross section is shown in Figure 1.
Figure 1. Scheme of digital light processing (DLP): 1 - projector; 2 - photomask; 3 - polymer alignment mechanism; 4 - bath with a liquid polymer; 5 - lowering base; 6 - is a cured polymer model.

For the analysis of mechanical properties, samples were constructed in accordance with GOST 11262-2017 (ISO 527-2: 2012) (Figure 2.)

Figure 2. Samples from SI500 photopolymer material.

Additional processing of the samples was carried out using an ultraviolet camera UVACUBE (2000 W). The maximum power of exposure to light for 1 minute is selected.

The parameters of the process of constructing samples for conducting strength analysis are presented in table 2.

| № | Mode | Layer thickness, mm | Layer exposure time, s | UV light |
|---|------|---------------------|------------------------|----------|
| 1 | 0,05 | 10                  | +                      |          |
| 2 | 0,05 | 10                  | -                      |          |
| 3 | 0,05 | 20                  | +                      |          |
| 4 | 0,05 | 20                  | -                      |          |
| 5 | 0,05 | 30                  | +                      |          |
| 6 | 0,05 | 30                  | -                      |          |
| 7 | 0,1  | 10                  | +                      |          |
| 8 | 0,1  | 10                  | -                      |          |
| 9 | 0,1  | 20                  | +                      |          |
| 10| 0,1  | 20                  | -                      |          |
| 11| 0,1  | 30                  | +                      |          |
| 12| 0,1  | 30                  | -                      |          |
The dimensions of the working part of the samples were controlled by a MK-25 micrometer in accordance with GOST 6507-90. The measurement of mechanical properties was carried out on a universal testing machine MI-40KU. The speed of movement of the working beam of the installation is 3-5 mm / min.

3. Results and discussion

The experimental samples were built in accordance with the modes indicated in table 2. In each series of the experiment, three samples were used. Based on the obtained data, histograms of the average values of tensile and compression strength were plotted (Figure 3-6).

Figures 3-4 show the tensile strength of the samples, depending on the exposure time and the use of additional processing in an ultraviolet chamber for 1 minute.

**Figure 3.** The dependence of tensile strength of samples with a layer thickness of 0.1 mm.

Figure 3 shows that with increasing exposure time in the range of 10-30 seconds, the strength increases from 34.1 MPa to 52.8 MPa. Additional processing in the ultraviolet chamber does not significantly affect the strength of the samples.

**Figure 4.** The dependence of tensile strength of samples with a layer thickness of 0.05 mm.
Figure 4 shows that the change in strength is similar in nature to Figure 3, where the layer thickness is 0.1 mm. The difference is the value of the maximum strength of the samples. Strength at 30 seconds of exposure is 55.2 MPa. The use of additional processing does not significantly increase the maximum strength to 55.4 MPa.

Figures 5-6 show the compressive strength of the specimens. The results are presented depending on the exposure time and the use of additional processing in an ultraviolet camera for 1 minute.

**Figure 5.** The dependence of the compressive strength of samples with a layer thickness of 0.1 mm.

**Figure 6.** The dependence of the compressive strength of samples with a layer thickness of 0.05 mm.

Figure 5 - 6 shows that the maximum strength indicators when changing the layer thickness from 0.1 mm to 0.05 mm are of a similar nature. Their values are approximately at the same level in the range from 230.53 MPa to 229.02 MPa. There is a significant decrease in compressive strength after additional processing in an ultraviolet chamber for 1 minute. The decrease in compressive strength reaches about 100 MPa.
4. Conclusions
The tensile strength of photopolymer samples is affected by the exposure time and the use of additional processing in an ultraviolet camera. The maximum tensile strengths are 55.25 MPa. Additional processing is not used. The exposure time of the layers with a thickness of 0.05 mm is 30 seconds. The use of additional processing in an ultraviolet chamber does not significantly increase the strength to 55.46 MPa. A similar level of change in strength values is observed for samples with a layer thickness of 0.1 mm. The maximum strength values are 52.89 MPa. Additional processing in the ultraviolet chamber increases the strength to 53.47 MPa. The exposure time of the layers is 30 seconds. The process of increasing strength is characterized by an increase in mechanical rigidity. In the polymer, longitudinal and transverse bonds are formed. Cross-links between molecules form a rigid framework and prevent the movement of longitudinal chains. The polymer structure is in a rigidly elastic state.

When conducting mechanical compression tests, the opposite picture is observed. The formation of additional bonds between the longitudinal chains of the polymer causes an increase in stiffness. The destruction of the samples occurs with a low value of strength in the range 109 - 143 MPa. The maximum values of compressive strength are achieved without additional processing in the ultraviolet chamber. Strength values are in the range of 209-230 MPa.

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