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STUDY OF THE INFLUENCE OF TECHNOLOGICAL FEATURES OF LASER STEREOLITHOGRAPHY PROCESS ON FUNCTIONAL CHARACTERISTICS OF PARTS

V.V. Vnuk[1], E.V. Ippolitov[1*], S.V. Kamaev[1], M.A. Markov[1], A.A. Nikulenko[2], M.M. Novikov[1], S.A. Cherebylo[1]

[1]Institute on Laser and Information Technologies Branch of the Federal Scientific Research Centre "Crystallography and Photonics" of the Russian Academy of Sciences, Svyatoozerskaya 1,140700, Shatura, Moscow Region, Russia

[2]Central Aerohydrodynamic Institute "TsAGI", Zhukovsky St. 1, 140180, Zhukovsky, Moscow Region, Russia

*e-mail: ippevg@yandex.ru

Abstract. The article reports on the effect the building orientation of the part, produced by laser stereolithography technology, has on achieving its best functional characteristics. Based on the example of IPLIT-3 and IPLIT-4 resins, the study shows that in contrast to the literature data on other commercial photocurable resins (PCRs), there is no definite advantage of the vertical orientation of the test samples compared to their horizontal orientation for obtaining the best values of the manufactured part functional characteristics.

Keywords: additive technologies, laser stereolithography, photopolymerization, three-dimensional modeling, photocurable resin

1. Introduction

The additive technologies, which include laser stereolithography [1-3], are nowadays able to produce not only prototypes but also fully functional parts. The functionality of the parts is defined by both the properties of the photocurable resin (PCR) used and the parts building technology [4-8]. For structural materials, strength characteristics, such as tensile and bending strength, tensile modulus, hardness, etc., are usually specified. However, the technological features of manufacturing the tested samples are not specified. All materials intended for use in additive technologies allow obtaining parts in a simpler way – by filling the molding tooling with this material, followed by hardening, sintering, or fusion of the material. Although the samples obtained in this way will be made of the same material, their mechanical properties may differ from the parts obtained additively. It can be assumed that differences in the objects' properties made of the same material can also arise if changes are made to the additive building technology of the parts or their post-processing. Parts manufacturing parameters at laser stereolithography technology, which can potentially influence mechanical characteristics, include hatch type and pitch, layer thickness, product building orientation, as well as UV radiation dose received during the part post-processing in the additional polymerization chamber [1,3,9-11].

UV post-curing is a stage of the manufacturing process and its parameters are set by the developer of the PCR in order to achieve the best strength characteristics of the given PCR. Therefore, the user has only to follow the manufacturer's recommendations for UV curing of the parts. Layer hatching parameters (hatching pattern and pitch) are the most important

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technological characteristics and are determined by the resin developer in order to achieve the best part accuracy. In addition, these parameters are also tightly linked to the laser type and the optical system parameters of the machine used. Changing these parameters manually will result in a low-quality product. The thickness of the working layer will determine the distribution of absorbed laser energy along with the depth of the layer of liquid PCR, and, consequently, the parameters of the three-dimensional polymer mesh being formed, which will inevitably affect the strength characteristics of the final part. The same reason causes the effect of improvement of physical and mechanical properties after UV post-curing of the fabricated sample, the so-called "green part".

The effect the part orientation during building has on its mechanical characteristics is discussed in the literature both at the level of theoretical description [1,9] and experimental observation of this effect [10-11]. The authors of these articles consider the dependence of the mechanical properties of the part on the above-mentioned parameters of fabrication and post-processing. In the studies mentioned, a conclusion is made that the improvement of strength characteristics when decreasing the thickness of the working layer and at the vertical orientation of the part is a consequence of the fact that under these conditions the part is formed of a larger number of layers. Namely, according to the literature data, a zone with the best mechanical properties for this material is formed at the interface "lower layer – upper layer". Consequently, the more layers a part is formed of, the more such zones it will include and the stronger it will be.

Thus, in order to achieve the best mechanical properties without changing the PCR, the user has little choice but to decide in favour of a smaller layer thickness and/or the part building orientation on the platform to allow for the number of layers being as large as possible. Although modern PCRs allow fabricating parts with layer thickness ranging from tens to several hundred microns, there is a narrower range of layer thicknesses for each PCR that is optimal in the balance of the "precision – production time". Decreasing the layer thickness leads to an increase in the building time and, consequently, in the cost of the part fabrication. Changing the part orientation on the platform can also lead to an increase of the processing time, but to a lesser degree, because if the number of layers becomes larger in the Z coordinate, for example, then the size of each layer in the XY plane decrease.

It is worth noting that in each case the authors of the studies mentioned provide experimental data for one polymer material, reporting that by changing the part orientation during its fabrication they achieved a certain increase in the mechanical strength characteristics. The present article constitutes an attempt to test what effect the change of the platform orientation has when fabricating the part from different resins produced at ILIT RAS. The article further studies whether it is possible to achieve improvement of the part mechanical characteristics, resorting neither to modification of the PCR itself, nor to the significant correction of the manufacturing technology; resorting neither to making changes in the part for subsequent reinforcement, nor to other methods that complicate the technological chain and raise the cost of the parts.

2. Materials and equipment

In order to investigate the mechanical properties of cured PCR, 3D computer models of two types were manufactured. These represented standard samples for testing polymer materials according to the requirements of GOST 11262-80 (for tension) and GOST 4648-71 (for static bending). Figure 1 shows the respective sketches.

PCRs IPLIT-3 [12] and IPLIT-4 [13] were used for the fabrication of test samples. All fabrication processes were performed at ILIT RAS on stereolithographic machines SLA-250 (3D Systems) and LS-400e (ILIT RAS). Fabrication accuracy was 0.1 mm in each of the coordinates regardless of the part orientation, which is considered acceptable according to the requirements of the above-mentioned GOSTs for the study of such samples. The HeCd-laser with a wavelength of 325 nm was used as a UV beam source in the machines. Strength tests of the fabricated samples were carried out on the rupture machine I1185M-100-01-1 (100kN) at Prof. N.E. Zhukovsky Institute "TsAGI". Modeling of the samples was performed in SOLIDWORKS CAD.

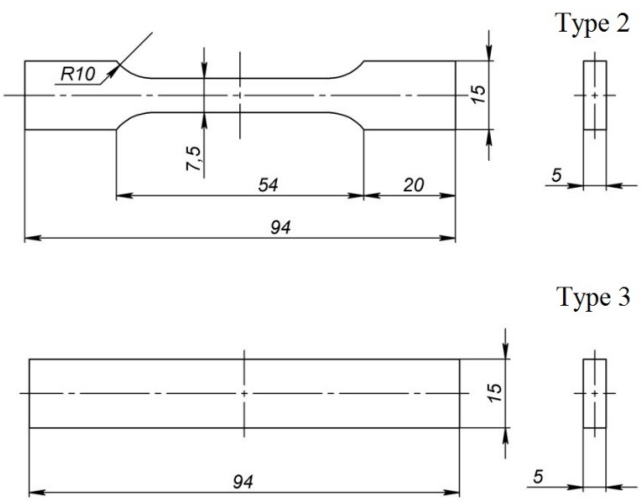

Fig. 1. Sketches of standard samples for testing polymer materials

The computer models were then converted to the STL format. During the transformation, the surface of the original model is approximated with a given accuracy by the faceted surface, formed by a set of flat triangular facets. The approximation accuracy, in this case, was 0.005 mm – linear and 1 degree – angular.

Magics software by Materialise was used to work with the STL files. Models converted to the STL format by means of Magics were placed on the building platform of the stereolithographic machines. Two-part building orientations were selected for fabrication. For each orientation, the necessary technological supports were formed. Figure 2 shows screenshots of the software interface with two-part orientations on the building platform.

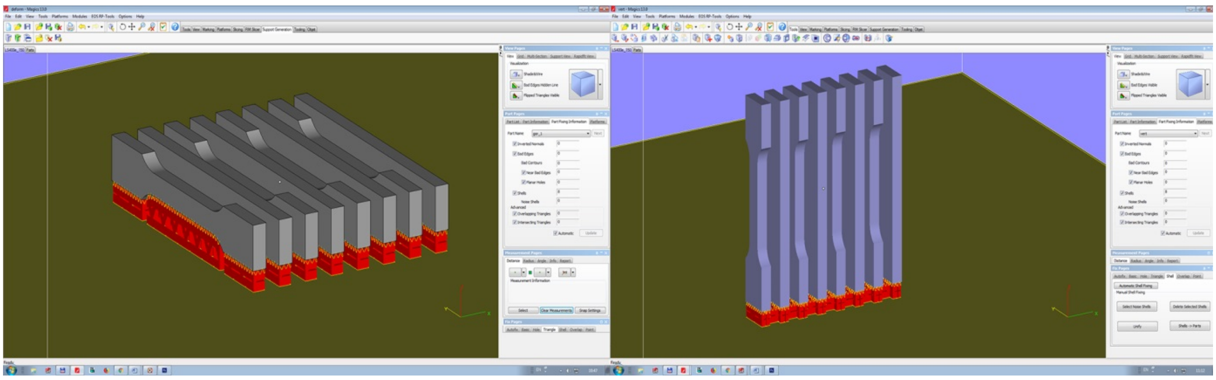

Fig. 2. Interface Magics with two variants of part orientation on a building platform

After the test samples were built and washed, they were placed in the UV post-curing chamber. Ultraviolet treatment of the parts helps to achieve the maximum degree of the polymer network cross-linking to reduce the content of methacrylic groups to the lowest possible values. The post-curing of the parts was performed in the UV post-curing chamber and lasted 0.5 hours. This is enough to achieve the minimum of a 95% conversion of unreacted methacrylic groups in the polymer. The Philips TLK 40W/05 lamps, used in the chamber, have a spectrum of the 315-460 nm range, with a maximum of 365 nm. Power consumption is 40W, UV-A power is 5W. During the post-curing process, the parts were rotated in order to achieve their uniform illumination.

Studies of the post-curing process of IPLIT-3 and IPLIT-4 resins were not carried out in this study. Earlier experiments using first versions of PCR developed at ILIT RAS, both multi-component and single-component in composition, as well as acrylic resins supplied by 3D Systems showed that the content of unreacted methacrylic groups in all examined samples after curing did not exceed 50 %, falling to the level of 5-10 % of the initial amount in the liquid resin after UV post-curing. The content of such groups was monitored using an FTIR spectrometer by the intensity of the absorption peak of the C=C bond in the acrylic group in the region of 1610-1650 cm^{-1} [14]. The post-curing process lasted for 30 minutes, as mentioned above. Longer irradiation resulted in the subsequent rapid aging of such parts. According to these studies, we developed technological recommendations for the post-curing process for acrylic oligomers and PCRs based on them, used in the LS series stereolithography machines. Our experimental data which have not been previously published but made available as technological recommendations to buyers of stereolithography machines and PCRs produced by ILIT RAS correlate well with the existing literature data [9-11].

The rupture machine (Fig. 3) was equipped with two screw drives and an AC digital frequency servo drive with encoder speed feedback. The machine was operated via PC. The limits of the permissible relative error of load measurement within the confidence range were not more than 1%.

a) b)

Fig. 3. Central Aerohydrodynamic Institute "TsAGI" experimental installations: a) tensile testing of samples; b) three-point bending tests

3. Experimental results

Below you can find the experimental data on mechanical testing of the test samples.

Table 1. Results of tensile testing of a series of the IPLIT-3 samples, vertical orientation

№ exp.	Max. load P_{max}, N	Elongation at break ε_M, %	Breaking load P_p, N	Breaking strength σ_p, MPa	Elastic modulus E, MPa	Line color in the figure (Fig. 4)
1	300	0.737	300	8	526.7	
2	401	-	401	10.69	493.3	
3	589	0.118	538	14.35	413.3	
average value	430	0.427	413	11.01	477.8	

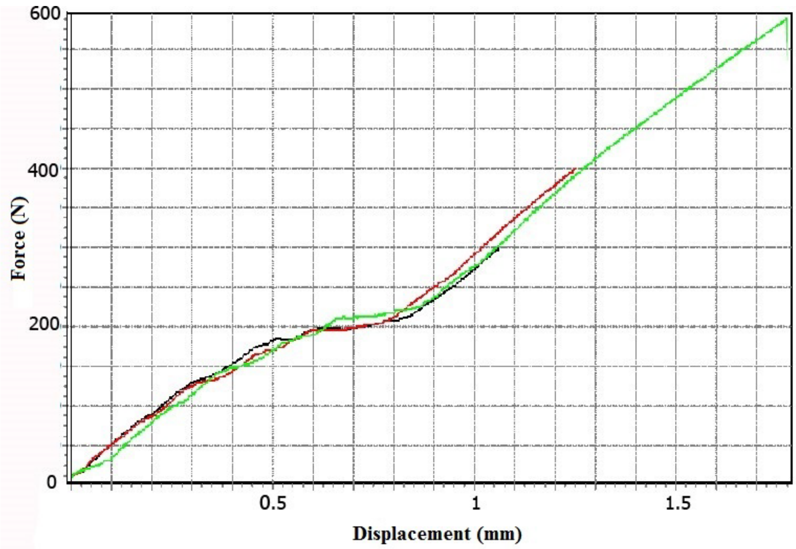

Fig. 4. Dependence of force (N) on the displacement of the crosshead of the unit during tensile testing of the IPLIT-3 samples manufactured with vertical orientation

Table 2. Results of tensile testing of the IPLIT-3 samples, horizontal orientation

№ exp.	Max. load P_{max}, N	Tensile strength σ_{max}, MPa	Elongation at break ε_M, %	Breaking load P_p, N	Breaking strength σ_p, MPa	Elastic modulus E, MPa	Line color in the figure (Fig. 5)
1	308	8.213	0.017	222	5.92	426.7	
2	349	9.307	0.071	321	8.56	400	
3	255	6.8	0.012	224	5.973	360	
average value	304	8.107	0.033	256	6.818	395.6	

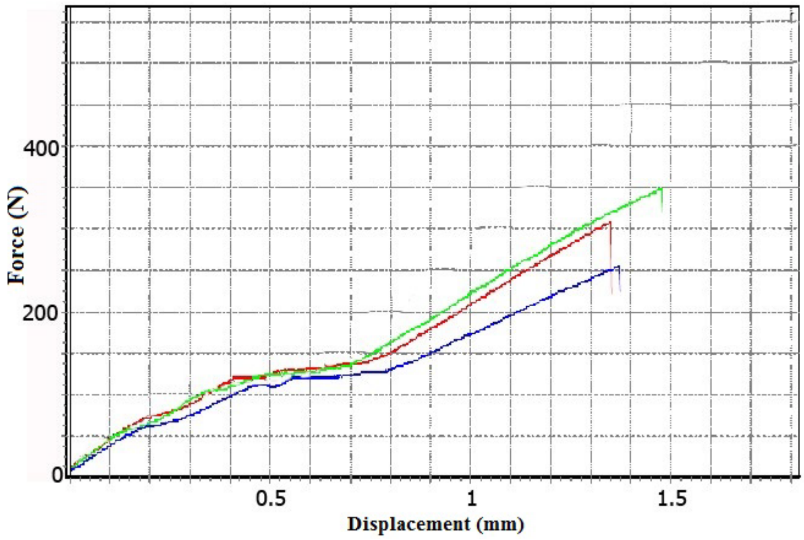

Fig. 5. Dependence of force (N) on the displacement of the crosshead of the machine during tensile testing of the IPLIT-3 samples manufactured with horizontal orientation

Table 3. Results of tensile testing of a series of the IPLIT-4 samples, vertical orientation

№ exp.	Max. load P_{max}, N	Tensile strength σ_{max}, MPa	Breaking load, P_p, N	Breaking strength σ_p, MPa	Elastic modulus E, MPa	Line color in the figure (Fig. 6)
1	672	19.44	649	18.78	528.1	black
2	603	16.75	538	14.94	347.2	green
3	744	20.67	619	17.19	569.4	blue
average value	673	18.95	602	16.97	481.6	

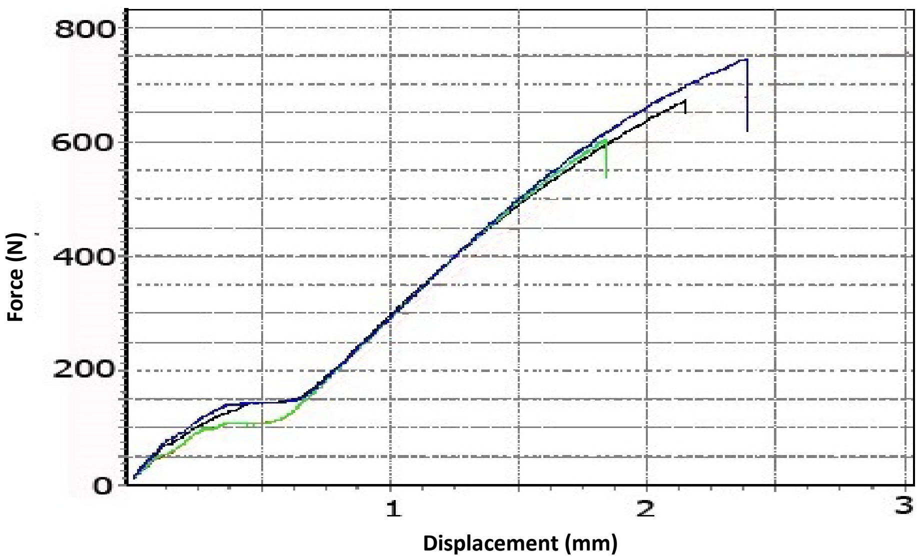

Fig. 6. Dependence of force (N) on the displacement of the crosshead of the machine during tensile testing of the IPLIT-4 samples manufactured with vertical orientation

Table 4. Results of tensile testing of the IPLIT-4 samples, horizontal orientation

№ exp.	Max. load P_{max}, N	Tensile strength σ_{max}, MPa	Convent. yield strength σ_y, MPa	Breaking load P_p, N	Breaking strength σ_p, MPa	Elastic modulus E, MPa	Line color in the figure (Fig. 7)
1	517	13.81	10.33	353	9.428	454.1	
2	400	10.68	6.43	199	5.315	454.1	
3	484	12.93	8.78	291	7.772	480.8	
average value	467	12.47	8.512	281	7.505	463	

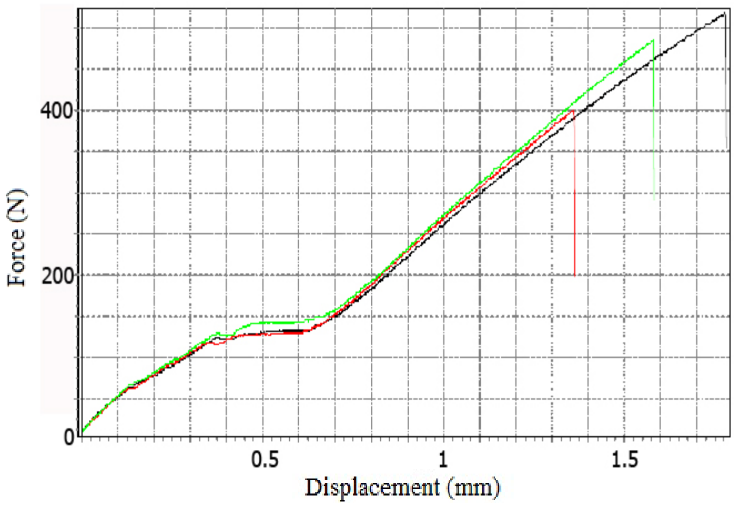

Fig. 7. Dependence of force (N) on the displacement of the crosshead of the unit (mm) during tensile testing of the IPLIT-4 samples manufactured with horizontal orientation

Table 5. Test results on bending of the IPLIT-3 samples, vertical orientation

№ exp.	Maximum load for cross-bending P_{max}, N	Transverse stress at max. load σ_{max}, MPa	Elastic modulus E, MPa	Line color in the figure (Fig. 8)
1	55	13.2	720	
2	60	14.4	600	
3	86	19.84	576.7	
average value	67	15.81	632.2	

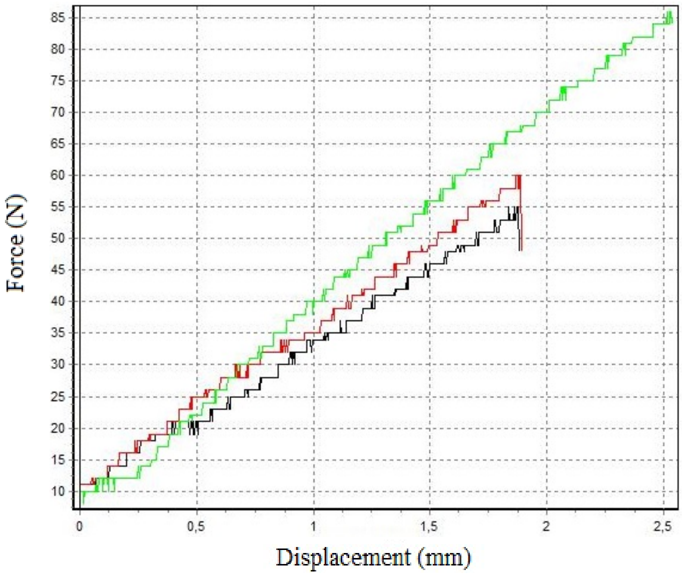

Fig. 8. Dependence of force (N) on the displacement of the crosshead of the unit (mm) during bend testing of the IPLIT-3 samples manufactured with vertical orientation

Table 6. Test results on bending of the IPLIT-3 samples, horizontal orientation

№ exp.	Maximum load for cross-bending P_{max}, N	Transverse stress at max. load σ_{max}, MPa	Elastic modulus E, MPa	Line color in the figure (Fig. 9)
1	40	9.166	458.3	
2	53	12.72	480	
3	46	10.97	476.8	
average value	46.3	10.95	571.7	

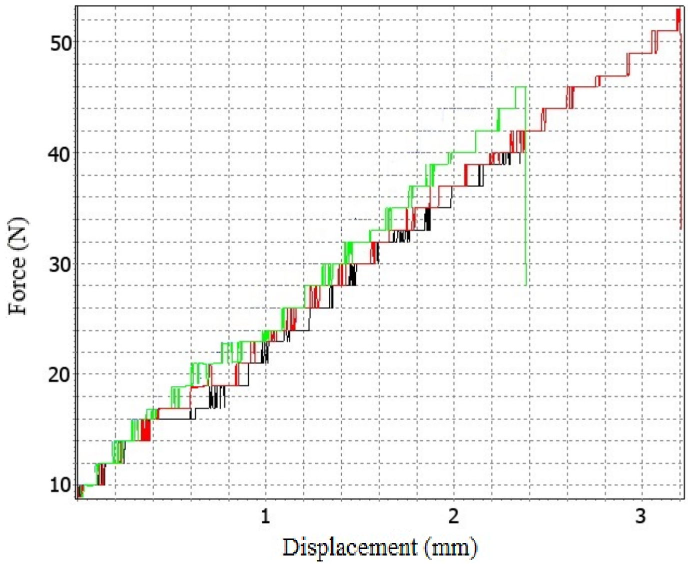

Fig. 9. Dependence of force (N) on the displacement of the crosshead of the unit (mm) during bend testing of the IPLIT-3 samples manufactured with horizontal orientation

Table 7. Test results on bending of the IPLIT-4 samples, vertical orientation

№ exp.	Maximum load for cross-bending P_{max}, N	Transverse stress at max. load σ_{max}, MPa	Elastic modulus E, MPa	Line color in the figure (Fig. 10)
2	147	35.28	720	
3	148	36	486.5	
4	147	35.52	845.6	
average value	147.3	35.6	684	

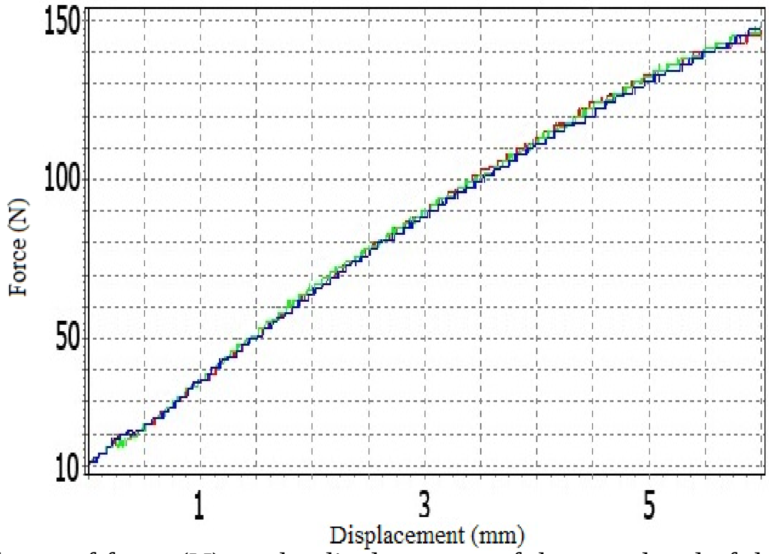

Fig. 10. Dependence of force (N) on the displacement of the crosshead of the unit (mm) in bend testing of the IPLIT-4 samples manufactured with vertical orientation

Table 8. Results of bend testing of the IPLIT-4 samples, horizontal orientation

№ exp.	Maximum load for cross-bending Pmax, N	Transverse stress at max. load σmax, MPa	Elastic modulus E, MPa	Line color in the figure (Fig. 11)
1	124	31.66	893.6	
2	85	21.7	765.9	
3	120	30.24	504	
average value	109	27.9	721	

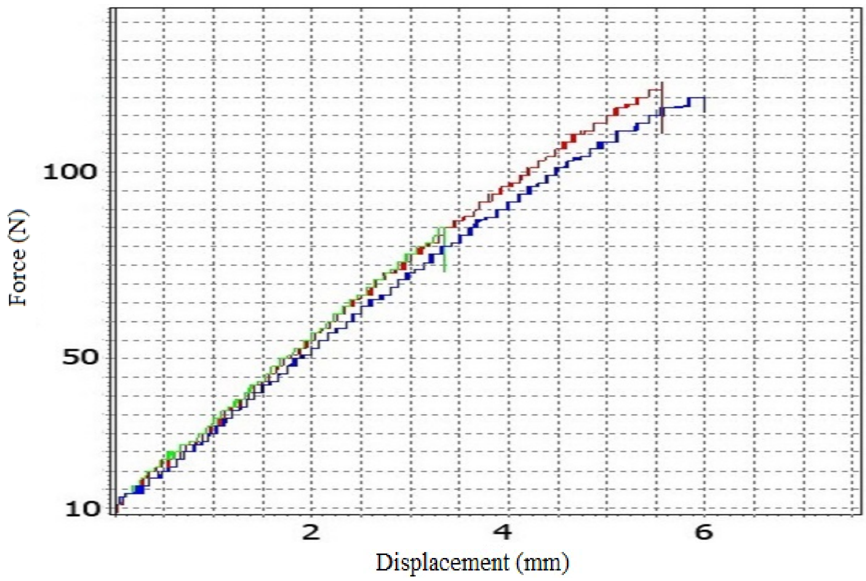

Fig. 11. Dependence of force (N) on the displacement of the crosshead of the unit (mm) during bend testing of the IPLIT-4 samples manufactured with horizontal orientation

The results of tensile and flexural testing of the samples made of IPLIT-3 and IPLIT-4 materials with different orientations on the platform (vertical and horizontal) are presented in table 9. As would be expected, the PCR IPLIT-4, as a more modern development, has better tensile strength characteristics and is more flexible to bending than the PCR IPLIT-3.

Table 9. Consolidated results of tensile and bending tests (mean values)

Parameter	IPLIT-3, vertically	IPLIT-3, horizontally	IPLIT-4, vertically	IPLIT-4, horizontally
Tensile Strength σ_{max}, MPa	11	8.107	18.95	12.47
Max.load (tensile) P_{max},N	430	304	673	467
Tensile modulus E, MPa	477.8	395.6	481.6	463
Voltage at max. load (bending) σ_p, MPa	15.81	10.95	35.6	27.9
Max. bending load, P_{max},N	67	46.3	147.3	109
Elastic modulus (bending) E, MPa	632.2	471.7	684	721

The measurement results indicate that having used both studied resins we obtained the parts whose mechanical properties depend on the part orientation in the process of layer-by-layer manufacturing. As mentioned earlier all the parts were subjected to UV post-curing, after which no presence of microzones with a weak degree of three-dimensional cross-linking was detected. Both the PCRs and the respective technologies have much in common: curing by radiation of 325 nm, the same photoinitiator, both consisting of methacrylic oligomers.

The main similarity though remains the fact that both PCRs present a mixture of oligomers, with none of its components being basic in percentage.

4. Discussion of results

Polymeric materials are characterized by the results of strength test experiments [15] and, if possible, it is recommended to use statistical processing of such data. Samples may contain inhomogeneities and microdefects, which will affect the experimental results. We excluded the least reliable series that significantly differ from the rest of the results.

The 2018 study [16], examining some technological features of the use of multicomponent PCR, describes situations when during the formation of supports or layers containing small area sections, the cured polymer contained the original oligomers in a ratio different from that of the original PCR. This was due to the different reactivity of the oligomers and monomers that made up the PCR. Each of the oligomers or monomers is characterized by its own rate constant of chain growth, the rate constant of oxygen addition, which inhibits polymerization, and the rate constant of radical recombination [5]. The "slowest" components are pushed out of the polymerization zone by the "faster" components. So the initially formed polymer network contains the PCR components in a ratio that is different from the original resin. As mentioned above, the 2018 study [16] proposed a mechanism for the separation of this PCR during the curing of thin layers by displacing the "slow" components in the horizontal direction. Due to this, in the usual mode of curing the IPLIT-4 PCR layer, thin-walled elements and auxiliary supporting structures are formed mainly from the urethane component of this PCR. If the area of the hardened layer is large, the displacement of the "slow" components of the composition occurs vertically, with movement into the depth of the layer. The result of this phenomenon is the "quasi-layering" of the obtained part when horizontal layers differing in the composition are independently formed inside the apparatus-formed layer due to the separation of fast and slow polymerization zones.

PCR IPLIT-3 [12] contains three oligomers, two of which, according to their weight fraction (40% each) in the composition, can be considered as a principle. These components are very different in molecular weight, and the formation of a three-dimensional network from the "fastest" component saves enough space for the "slower" component with a smaller molecule size. Thus, IPLIT-3 polymerizes more uniformly, without vertical or horizontal delamination. As a result, when the orientation of the samples changes during building, we see the effect arising from an increase in the number of layers only, similar to the literature data [9-11]. In PCR IPLIT-4 [13], there are four such oligomers and monomers, and there is no significant difference in the mass or size of the molecules. The multicomponent nature of this PCR is attributed to a combination of technological and economic requirements for modern stereolithographic materials.

The performance of samples made from IPLIT-4 is somewhat unconventional for all the cases described in the literature. The tensile and breaking strength has improved, as for other resins described in the literature. But bending tests show that parts grown from this material will have more elasticity when oriented vertically. This can also be considered to be a confirmation of the assumption of "quasi-layering" of vertically oriented parts due to the formation of horizontal zones with different stoichiometric ratios of the original PCR components.

5. Conclusion

The experimental data obtained by us allow us to conclude that there is no unambiguous improvement in the mechanical characteristics of parts manufactured using laser stereolithography technology with the vertical orientation for the two investigated materials.

While the tensile and breaking strength does increase for vertically oriented parts, elastic characteristics of the parts can demonstrate both increasing and decreasing elasticity. Unlike other studies on this topic, according to our results, the final choice of the part orientation depends on the specific PCR used and on the parameters that the user deems most important when using the part. Technological recommendations provided by the developers and/or manufacturers of the used PCR, based on the results of similar studies, should constitute the basis for such a choice.

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