Evaluation of the rheological properties of photopolymers used in Polymer Jetting technology

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Abstract. The paper presents the results of tests related to relaxation of stresses in models of samples made using the technology of photo-curing of liquid polymer resins - polyjet modeling (PJM). The models of the samples were made using two types of materials: VeroWhite and FullCure 720. The tests were performed on samples in compliance with the PN-EN ISO 3384 standard. The technological parameter whose impact was analyzed was the orientation of the models on the virtual building platform, which was defined with three variability levels (0°, 45°, and 90°). The tests demonstrated that the position of the models on the building platform has a significant impact on the relaxation of compressive stresses. Moreover, the most advantageous positions of the models on the building platform from the standpoint of relaxation of stresses were determined.

Keywords: Additive Technology, PJM, Stress Relaxation, Maxwell model, Mechanical Properties

1 Introduction

Rapid prototyping (RP) technologies have been known since over 30 years ago when some of the first technologies, such as Stereolithography (SLA) [14], Selective Laser Sintering (SLS) [15], and Fused Deposition Modelling (FDM) [16] were developed and patented. Due to the layer nature of construction, manufactured elements have a number of anisotropic properties that largely depend on the orientation of the models in relation to the building platform. This problem has been described in a number of publications related to both the mechanical properties of models and the accuracy of dimensions and shapes [3, 4, 11, 17]. In the case of many additive technologies, such as SLS, PJM, and FDM, it is possible to build not only prototypes but also fully functional models, including the so-called overprints [1, 2, 5, 9-13].

Additive technologies can be divided according to many criteria. One of the most important criteria is the form of the starting material, which can be a solid, e.g. a rod (FDM), a liquid (SLA, PJM), or a powder (SLS, SLM). Another very common criterion is the type

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of bonding between layers, such as gluing (LOM), sintering (SLS), and chemical reactions (SLA, PJM). Those technologies use such materials as both plastics and selected groups of metals.

The study described in this paper consisted in tests of relaxation of stresses in polymer samples made using the PJM technology from two materials (FullCure 720 and VeroWhite) in accordance with the PN-EN ISO 3384 standard [7]. Moreover, during the tests, the Statistica software and the Origin software was used to conduct a basic statistical analysis of the results of the tests and to approximate the relaxation curves using selected mathematical models.

2 Research

The stress relaxation tests were performed using the Inspekt Mini 3kN machine made by Hegewald & Peschke [6]. The compression test was performed using two compression disks: a fixed upper disk and a swinging lower disk. The samples, designed in accordance with the standard [7], had the following dimensions: diameter – 13 mm and height – 6.3 mm. The samples were made of two polymer resins: VeroWhite (1-9) and FullCure 720 (10-18). During the tests, the samples were subject to deformation equal to 10% of their height, i.e. 0.63 mm. The set deformation was maintained for 90 minutes. After the test cycle was completed, relaxation of stresses was determined according to relationship 1 given in the PN-EN ISO 3384 standard [7]; Table 1 shows the results of the measurements according to the orientation of the models on the building platform (Fig. 1 and 2).

Fig. 1. Orientation of the models on the building platform: a) Connex 350 machine, b) Cartesian coordinate system

Fig. 2. Samples: a) VeroWhite (numbers 1-9), b) FullCure 720 (numbers 10-18)

3 Research results

The tests concerning relaxation of compressive stresses were conducted in accordance with the ISO 3384 standard. The individual relaxation tests were conducted for 60 minutes, after stabilization for 30 minutes indicated with the symbol $R(t)_{30-90}$ and the total relaxation was determined after 90 minutes $R(t)_c$. The determined parameters of the rheological model that was used are shown in Tables 2 and 3. The stress relaxation value was calculated in accordance with relation 1 given in the aforementioned standard.

$$R(t) = \frac{F_0 - F_t}{F_0} \quad (1)$$

where: F_0 – initial force [N], F_t – force after the time t , [N].

Table 1 shows the results of the experimental measurements and the calculated indicators of relaxation of compressive stresses after 60 and 90 minutes. The figures that follow show the actual measurement charts for the samples made from the VeroWhite material (resin) (Fig. 3-5, samples 1-9) and the FullCure 720 material (Fig. 7-9, samples 10-18). The experimental relaxation curves were approximated using the exponential functions in the 2 and 3 form [8].

$$y = y_0 + A_1 e^{-x/t_1} \quad (2)$$

$$y = y_0 + A_1 e^{-x/t_1} + A_2 e^{-x/t_2} \quad (3)$$

where: y – the stress function, y_0 , A_1 , A_2 , t_1 , t_2 – parameters of the stress functions.

Further in the description, functions (2) and (3) are referred to as relaxation functions. Approximations of the actual relaxation functions were performed in the Origin software using an implemented Levenberg-Marquardt algorithm. Figures 6 and 10 show examples of approximation with a five-parameter relaxation function (3) applied to the experimental results. Tables 2 and 3 show the parameter of the approximating functions (3) and the determined test indicators R^2 .

Table 1. Research results

Material	Samples number	Pd, °	F _{max}	F ₀ , N	F _t , N	R(t) ₃₀₋₉₀	R(t) _c
VeroWhite	1	0°	1409.19	1364.94	1355.24	0.007	0.038
	2		1264.95	1185.58	1151.57	0.029	0.09
	3		1390.5	1331.45	1312.71	0.014	0.056
	$\bar{x}$		1354.88	1293.99	1273.17	0.017	0.061
	S		78.44	95.36	107.43	0.011	0.026
	4	45°	1300.69	1235.19	1220.04	0.012	0.062
	5		1259.51	1176.5	1146.12	0.026	0.09
	6		1354.22	1304.54	1285.79	0.014	0.05
	$\bar{x}$		1304.81	1238.74	1217.32	0.017	0.067
	S		47.49	64.09	69.87	0.007	0.02
	7	90°	1295.86	1253.54	1244.15	0.007	0.04
	8		1283.09	1214.55	1190.96	0.019	0.072
	9		1235.64	1147.66	1116.25	0.027	0.097
	$\bar{x}$		1271.53	1205.25	1183.79	0.018	0.069
	S		31.73	53.55	64.25	0.01	0.028
FullCure 720	10	0°	1292.17	1176.61	1133.66	0.037	0.122
	11		1331.53	1243.96	1207.46	0.029	0.093
	12		1381.42	1308.97	1280.88	0.021	0.073
	$\bar{x}$		1335.04	1243.18	1207.33	0.029	0.096
	S		44.73	66.18	73.61	0.007	0.025
	13	45°	1366.08	1290.24	1250.23	0.031	0.084
	14		1302.11	1184.88	1128.21	0.047	0.133
	15		1294.01	1167.46	1107.35	0.051	0.144
	$\bar{x}$		1320.73	1214.19	1161.93	0.043	0.121
	S		39.48	66.43	77.17	0.011	0.032
	16	90°	1369.50	1301.65	1277	0.019	0.068
	17		1290.62	1197.16	1162.97	0.028	0.099
	18		1374.69	1293.72	1263.47	0.023	0.081
	$\bar{x}$		1344.94	1264.18	1234.48	0.024	0.082
	S		47.11	58.17	62.29	0.005	0.016

Fig. 3. Exemplary diagram for $Pd - 0^\circ$, VeroWhite

Fig. 4. Exemplary diagram for $Pd - 45^\circ$, VeroWhite

Fig. 5. Exemplary diagram for $Pd = 90^\circ$, VeroWhite

a)

b)

c)

Fig. 6. Figures from Origin software: a) 0° , b) 45° , c) 90° , VeroWhite

Table 2. Exemplary results for above-mentioned diagram 3-5

Pd°	y_0	A_1	A_2	t_1	t_2	Chi^2	R^2
0	1353.945	22.709	29.57	161.706	1893.284	0.099	0.998
45	1217.271	35.414	42.569	184.351	2188.143	0.333	0.998

Fig. 7. Exemplary diagram for $Pd - 0^\circ$, FullCure 720

Fig. 8. Exemplary diagram for $Pd - 45^\circ$, FullCure 720

Fig. 9. Exemplary diagram for $Pd - 90^\circ$, FullCure 720

Fig. 10. Figures from Origin software: a) 0°, b) 45°, c) 90°, FullCure 720

Table 3. Exemplary results for above-mentioned diagram 7-9

Pd°	y_0	A_1	A_2	t_1	t_2	Chi^2	R^2
0	1112.911	58.247	114.422	222.382	3290.344	0.729	0.999
45	1245.866	37.972	76.05	207.745	3487.365	0.348	0.999
90	1264.674	34.707	64.199	196.101	3407.333	0.296	0.999

A quantitative analysis of the results of the tests leads to the conclusion that in the case of sample modules made using the PJM technology and using the VeroWhite resin, relaxation of stresses is on a similar level. In all three orientation options (0°, 45°, and 90°), the value of relaxation did not exceed 0.07 (respectively $R(t)_{30-90}$ - 0.017, 0.017, and 0.018, and $R(t)_c$ - 0.061, 0.067, and 0.069). In the case of the samples made of the transparent FullCure 720 material, relaxation $R(t)_{30-90}$, depending on the orientation, was equal to 0.029, 0.043, and 0.024 for the three respective angles of 0°, 45°, and 90°. An overall analysis of the test cycle also indicates similar trends for three sample orientation options, i.e.: 0° - 0.096, 45° - 0.121, and 90° - 0.082. It is clear that the second option, i.e. 45°, is the least advantageous option and demonstrates a nearly two times higher value of stress relaxation.

4 Conclusion

Based on the results of the tests of relaxation of stresses in samples made using the PJM technology, the following general conclusions can be drawn.

The five-parameter relaxation function approximates very well the experimental results determined in the course of the compressive stress relaxation. This function may be represents by the general Maxwell model of the rheological properties of the tested materials.

In the case of models made of the VeroWhite material, there is no visible impact of orientation of the models on the building platform on stress relaxation. If the FullCure 720 transparent resin is used to build the models, the value of relaxation for the 45° angle is nearly two times larger than in the other two cases.

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