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ESTIMATING THE UNCERTAINTY OF TENSILE STRENGTH MEASUREMENT FOR A PHOTOCURED MATERIAL PRODUCED BY ADDITIVE MANUFACTURING

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Abstract

The aim of this study was to estimate the measurement uncertainty for a material produced by additive manufacturing. The material investigated was FullCure 720 photocured resin, which was applied to fabricate tensile specimens with a Connex 350 3D printer based on PolyJet technology. The tensile strength of the specimens established through static tensile testing was used to determine the measurement uncertainty. There is a need for extensive research into the performance of model materials obtained via 3D printing as they have not been studied sufficiently like metal alloys or plastics, the most common structural materials. In this analysis, the measurement uncertainty was estimated using a larger number of samples than usual, i.e., thirty instead of typical ten. The results can be very useful to engineers who design models and finished products using this material. The investigations also show how wide the scatter of results is.

Keywords: static tensile test, measurement error, measurement uncertainty.

1. Introduction

Additive manufacturing, originally known as Rapid Prototyping, is becoming increasingly popular, with applications ranging from industry through design and architecture to medicine. The technology is now used to produce not only models and prototypes but also finished and semi-finished products. The present state of knowledge and future potential of additive manufacturing have been discussed, for instance, by Campbell [1]. He reports on the advancement of additive manufacturing materials, analyzes design possibilities and overviews industrial applications.

The advances in additive manufacturing processes and materials, being concurrent with the development of new materials characterized by better physical and mechanical properties, imply that extensive research is required to fully understand the behaviour of materials used for 3D printing. The key findings on the subject are presented in Ref. [2], which explains how environmental conditions, aging and build orientations, i.e., the arrangement of models on the build tray, affect the mechanical properties of type-1 specimens produced by stereolithography according to ASTM D638 [3]. The materials manufactured via stereolithography showed anisotropy and their mechanical properties decreased when they were exposed to environmental conditions. Another work on the mechanical properties of materials fabricated by stereolithography [4] is concerned with the effects of layer thickness. The paper suggests that the thinner the layer, the greater the maximum load to be carried by a specimen.

There are no papers reporting on the measurement uncertainty related to additive manufacturing materials. Even manufacturers' catalogues miss this information; they only

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provide the nominal value or range of parameters characterizing a material property, for example, tensile strength. Studies of the mechanical properties of polymers produced by additive manufacturing have been conducted using standards applicable to plastics. Most American companies and research institutes produce specimens and perform tensile testing in accordance with ASTM D638 [4]. In Europe, the ISO 527 standard is followed, with tensile specimens being produced in conformity with ISO 527-1 [5]. These standards recommend that results should be written as arithmetic means and, if necessary, as standard deviations. The estimation of measurement uncertainty for metallic materials is performed following Annex J to the ISO 6892-1 standard [6]. Section 23.3 of ISO 527-1 [5] concerning measurement results suggests that the evaluation of measurement uncertainty should not be combined with the evaluation of measurement results to determine the agreement with product specifications unless otherwise agreed with the buyer. In Section 23.1, however, we read that the analysis of measurement uncertainty is useful in order to identify the main sources of discrepancy between measurement results. More details on the evaluation of uncertainty of stress and strain measurement during a static tensile test can be found in [7].

This study attempts to estimate measurement uncertainty for a photocured resin, FullCure 720, taking into account the parameters established through static tensile tests. The specimen preparation, the static tensile testing and the analysis of results are described in the next sections.

2. Materials and methods

The specimens were made of photocured resin, FullCure 720, by means of an Objet Connex 350 3D printer based on PolyJet technology (http://objet.com/3d-printing-materials). The specimens were produced in accordance with ASTM D638, with dimensions being the same as those of type-I tensile bars used for testing plastics [3] width of the narrow section, 13 ±0.02 mm; length of the narrow section, 57 ±0.02 mm; overall width, 19 ±0.025 mm; overall length, 165 ± no max; gauge length, 50 ±0.01 mm; distance between the grips, 115 ±0.02 mm; fillet radius, 76 ±0.04 mm; and thickness, 4 ±0.4 mm.

The study was conducted according to the procedure presented in Fig. 1.

A solid 3D model of a specimen was created in a CAD program and saved as an *.stl* file. The triangulation parameters to be exported include: resolution – adjusted, deviation – 0.016 mm tolerance, and angle – 5° tolerance. It is important that the values of the triangulation parameters should not be too low to ensure rounded edges (in this case, the fillet radius, R); they should not be too high, either, so as not to increase the volume of the file (*.stl*). Subsequently, the specimen models were virtually placed on the build tray of the Connex350 printer using the Objet Studio program. The specimens were produced in the Glossy mode to ensure a smooth surface. Figure 2 shows the virtual arrangement of the specimen models over the build tray in the Objet Studio program.

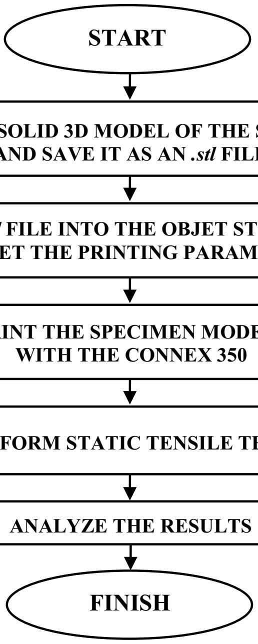

Fig. 1. Test procedure.

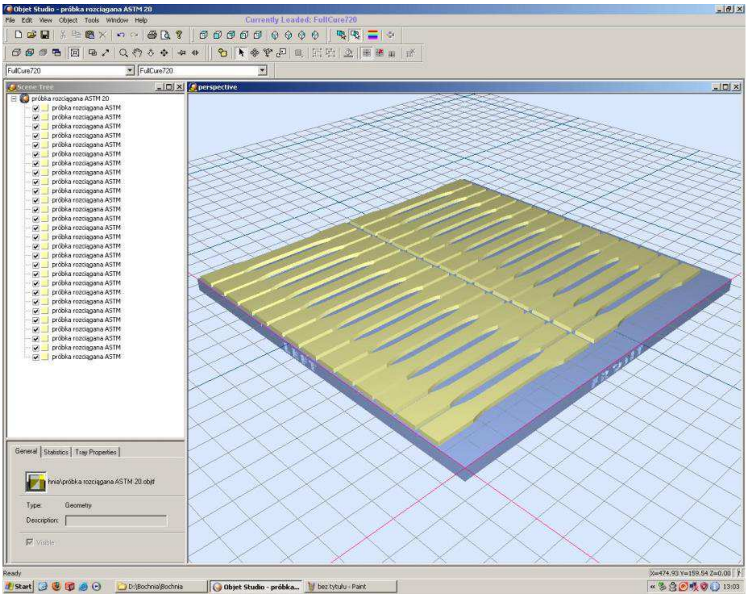

Fig. 2. Specimen models on the build tray in the Objet Studio program.

After the printed specimens and the support material were removed off the build tray, the specimens were prepared for static tensile tests. The testing was performed using an Ispekt mini universal testing machine [8]. The test speed was set at 5 mm/min in the LabMaster program [9] that the Inspekt mini universal testing machine is equipped with.

3. Results and discussion

The example cumulative plot in Fig. 3 shows changes in the load acting on the specimens in the function of displacement drawn by the computer connected to the universal testing machine.

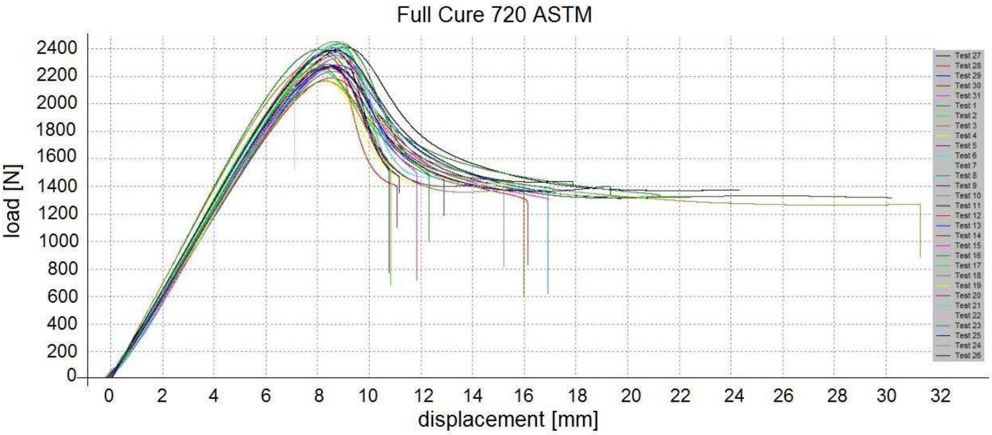

Fig. 3. Load vs displacement for FullCure 720.

Table 1 shows values of the maximum tensile load obtained for each test.

Table 1. Values of the maximum tensile load.

Test/specimen number	Maximum load F_{mi} [N]	$(F_{mi}-\overline{F}_m)^2$ [N^2]	Test/specimen number	Maximum load F_{mi} [N]	$(F_{mi}-\overline{F}_m)^2$ [N^2]
Test 1	2396	4542	Test 16	2438	11883
Test 2	2253	5716	Test 17	2428	9818
Test 3	2292	1340	Test 18	2166	26373
Test 4	2165	26810	Test 19	2331	6
Test 5	2406	6045	Test 20	2262	4466
Test 6	2335	41	Test 21	2413	7188
Test 7	2453	15406	Test 23	2373	1959
Test 8	2237	8301	Test 25	2276	2809
Test 9	2274	3003	Test 24	2333	19
Test 10	2452	15203	Test 26	2391	3942
Test 11	2391	3890	Test 27	2411	6864
Test 12	2356	747	Test 28	2189	19577
Test 13	2384	3106	Test 29	2281	2306
Test 14	2288	1684	Test 30	2271	3346
Test 15	2354	645	Test 31	2260	4704
			$\overline{X}$	**2329**	
			Σ		**201741**

Specimen No 22 was excluded from the calculations, because it failed before the maximum tensile load was reached.

The measurement uncertainty was determined for each quantity using the following formulae [10]:

- type-B evaluation was applied to calculate the standard uncertainty

$$u_B = \frac{a}{\sqrt{n}}\,, \tag{1}$$

where: a – half of the width of the interval containing a boundary error,
n – number of measurements;

- type-A evaluation was applied to establish the standard uncertainty

$$u_A = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(x_i - \bar{x})^2}\,, \tag{2}$$

where: n – number of measurements,
$\bar{x}$ – arithmetic mean of all the quantities measured,

- the combined standard uncertainty was estimated on the basis of a series of measurement results obtained for each quantity

$$u_{\bar{y}} = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial y}{\partial \bar{x}_i}\right)^2 u_i^2}\,, \tag{3}$$

where: u_i – standard measurement uncertainty obtained for the input data calculated using the type-A or type-B evaluation.

The width of the specimens, b_0, was measured with an accuracy of 0.05 mm, whereas the thickness, a_0, was established with an accuracy of 0.01 mm, as recommended by the ISO 527-1 2012 standard. The average thickness and width were:

- $\bar{a}_0$ = 3,97 mm and
- $\bar{b}_0$ = 13 mm, respectively.

The standard uncertainty obtained by type-B evaluation using formula (1) was:

- u_{aB} = 0.0009 mm for the thickness of the specimens tested,
- u_{bB} = 0.0046 mm for the width of the specimens tested.

The standard uncertainty calculated by means of formula (2) using type-A evaluation was:

- u_{aA} = 0.0021 mm for the thickness of the specimens tested,
- u_{bA} = 0.02 mm for the width of the specimens tested.

When thickness and width were measured, the predominant uncertainty was calculated using type-A evaluation. Further calculations were based on these values.

The uncertainty for the average maximum load measured $\bar{F}_m$ was calculated from formula (2) and the data included in Table 1 as u_{F_m} = 15.2 N.

The uncertainty for the indirectly measured tensile strength R_m was calculated from formula (3) using the following transformation:

$$u_{R_m} = \sqrt{\left(\frac{\partial \bar{R}_m}{\partial \bar{F}_m}\right)^2 u_{F_m}^2 + \left(\frac{\partial \bar{R}_m}{\partial \bar{a}_0}\right)^2 u_{aA}^2 + \left(\frac{\partial \bar{R}_m}{\partial \bar{b}_0}\right)^2 u_{bA}^2}\,, \tag{4}$$

and after more transformations, we had:

$$u_{R_m} = \sqrt{\left(\frac{1}{\bar{a}_0\bar{b}_0}\right)^2 u_{F_m}^2 + \left(\frac{-\bar{F}_m}{\bar{a}_0^2\bar{b}_0}\right)^2 u_{aA}^2 + \left(\frac{-\bar{F}_m}{\bar{a}_0\bar{b}_0^2}\right)^2 u_{bA}^2}\,, \tag{5}$$

where: $\bar{F}_m$ = 2329 N – average maximum tensile load on the basis of Table 1,
u_{F_m} = 15.2 N – uncertainty of the average maximum tensile load,

$\bar{a}_0$ = 3.97 mm – average thickness of the specimens,
u_{aA} = 0.0021 mm – uncertainty of the average thickness of the specimens,
$\bar{b}_0$ = 13 mm – average width of the specimens,
u_{bA} = 0.02 mm – uncertainty of the average width of the specimens.

Substituting the calculated values into formula (5), we obtain the uncertainty of tensile strength measurement performed for thirty samples u_{R_m} = 0.295 MPa. Tensile strength was calculated from the formula:

$$\bar{R}_m = \frac{\bar{F}_m}{\bar{a}_0 \bar{b}_0} . \tag{6}$$

The data from Table 1 and the calculated values of the average thickness and width of the specimens tested were substituted into formula (6) to calculate tensile strength R_m = 45.1 MPa. The final result was written as: R_m = 45.1 ±0.295 MPa.

The standard deviation is the parameter that is most commonly calculated by computer programs of universal testing machines. The parameter is determined from the formula:

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2} . \tag{7}$$

Table 2 shows data obtained with the LabMaster software operating the universal testing machine.

Table 2. Data used to calculate the standard deviation.

Test/specimen number	Tensile strength R_{mi} [MPa]	$(R_{mi} - \bar{R}_m)^2$ [MPa^2]	Test/specimen number	Tensile strength R_{mi} [MPa]	$(R_{mi} - \bar{R}_m)^2$ [MPa^2]
Test 1	46.54	2.16	Test 16	47.23	4.66
Test 2	43.65	2.01	Test 17	47.10	4.12
Test 3	43.91	1.36	Test 18	42.13	8.64
Test 4	41.74	11.14	Test 19	44.88	0.04
Test 5	46.21	1.30	Test 20	43.94	1.30
Test 6	45.42	0.12	Test 21	46.64	2.47
Test 7	47.40	5.44	Test 23	45.75	0.45
Test 8	43.24	3.34	Test 25	43.98	1.19
Test 9	44.17	0.82	Test 24	45.32	0.06
Test 10	47.33	5.08	Test 26	46.34	1.59
Test 11	46.44	1.88	Test 27	46.72	2.73
Test 12	45.76	0.48	Test 28	42.57	6.26
Test 13	45.85	0.61	Test 29	44.08	0.99
Test 14	44.32	0.56	Test 30	44.11	0.93
Test 15	45.61	0.29	Test 31	43.79	1.65
			$\bar{X}$	**45.07**	
			Σ		**73.63**

Substituting the data from Table 2 into formula (7) gives the value of the standard deviation, s = 1.59 MPa. Knowing the expected value and the standard deviation, we can represent the result in the form of normal distribution using the formula:

$$f(x) = \frac{1}{s\sqrt{2\pi}} e^{\frac{-(x-\bar{R}m)^2}{2s^2}} , \tag{8}$$

where: *f(x)* – the probability density function.

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Figure 4 shows the probability density function of the normal distribution of tensile strength.

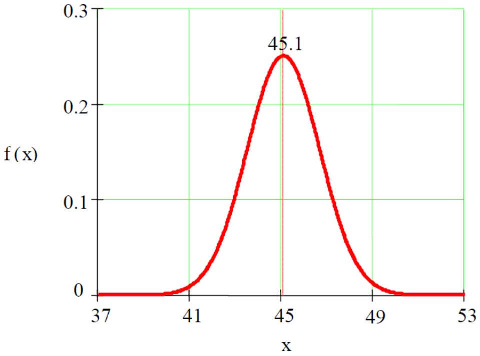

Fig. 4. Probability density function of the normal distribution of tensile strength.

If we divide the value of the standard deviation by $\sqrt{n}$, we obtain the value of measurement uncertainty u'_{R_m} = 0.291 MPa, which differs by 0.004 from the uncertainty calculated from formula (5).

4. Innovation-related risk vs measurement uncertainty

Additive manufacturing is an innovative approach to production of machine elements and other finished products. This technology can be used to fabricate small batches or one-of-a-kind items. However, it would be difficult to determine the actual properties of finished products, i.e., strength properties, for every manufacturing process. To reduce innovation-related risk, it is vital to calculate measurement uncertainty on the basis of tensile test data. Determining measurement uncertainty is a certain solution. The calculations take into consideration changes in the properties of each piece measured.

Tensile tests are destructive tests and their results can be used for an entire population of samples, i.e., items produced. In the case considered here, the problem of uncertainty refers to the geometrical dimensions of the specimen cross-section and the maximum tensile load causing failure. That is why it was necessary to estimate combined standard uncertainty. The assessment was based on one parameter, i.e. the indirectly measured tensile strength, Rm. We took into account the changes in the specimen dimensions and their material structure, with the latter affecting the load transfer capacity. Determining the measurement uncertainty for this type of innovative manufacturing techniques is essential as it provides design engineers with a tool to support decision-making on how to practically use additive manufacturing. Similarly to the application of other modern measurement methods described in elaborations [11, 12], extends the applicability of different manufacturing techniques.

5. Conclusion

This analysis has confirmed good repeatability of results at the maximum tensile load, as shown in the cumulative plot in Fig. 3. After the maximum tensile load was exceeded, i.e., in the plastic region, the specimens failed at different elongations.

Model materials used in additive manufacturing have not been studied as extensively as the most common structural material, i.e. metal alloys and plastics. Hence, the necessity to better understand them. In this study, the performance of FullCure 720 was analyzed using a larger number of samples, i.e., thirty, whereas a typical number is ten.

The results will be useful to engineers designing models made of FullCure 720. The measurement uncertainty determined on the basis of the tensile test data testifies to a high repeatability of results. The standards concerning the testing of composites, which were adopted for the material used in additive manufacturing, do not include requirements for the evaluation of measurement uncertainty. They include, however, requirements for the calculation of the standard deviation. Evaluation of measurement uncertainty of new, not commonly known, materials seems absolutely justified.

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