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A multi-factor correction matrix for SLA additive technology with the use of coordinate measuring technique

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ABSTRACT

The article presents issues related to SLA additive technology and the concept of 3D printing control by introducing corrections to the dimensions of objects at the design stage.

The research carried out in the Laboratory of Coordinate Metrology at the Cracow University of Technology was presented. The research included measurements with the use of selected coordinate systems. Replicas of gauge blocks (printed from Tough 2000 photocurable resin), a series of rings and a specially designed standard composed of basic geometric elements most commonly found in production (printed from three types of resins Grey, Tough 2000 and Clear) were measured. Based on the obtained measurement results, the first version of a special multi-factor correction matrix for SLA additive technology was developed and presented. The correction matrix enables the 3D printer operator to obtain the object in a way that is as consistent as possible with the expected values. The idea of the matrix is to provide practical guidelines on what correction should be done when entering the given input values at the design stage of the printing process, knowing the type of material, geometric shape and dimensions of the printed detail.

The concept was confirmed in the context of improving 3D printing accuracy. Possibilities of developing the concept were also proposed, with the idea of implementing the matrix into an expert system with the possible addition of elements of artificial intelligence.

1. Introduction

3D printing is one of the key production technologies of the last decade. That is related to the high accuracy and high smoothness of printed objects' surfaces. At the same time, it is also a relatively economical production way [1]. This technology is rapidly developing which is connected with the constant expansion of its application areas e.g. aerospace and defence, healthcare, food industry, automotive, architecture and construction, energy and fashion [2]. Nowadays with 3D printing technology, it is possible to produce objects with geometries that were difficult or even impossible to achieve using classical methods. In the future, it can completely revolutionize and change many industries.

There is an observed increase in interest, e.g. in pharmaceutical and medical applications [3] and also neuroscience [4]. The wide range of applications causes and explains the need to undertake work on the development of this technology. Various works are being carried out to improve 3D printing accuracy around the world [5–7]. In the Laboratory of Coordinate Metrology (LCM) at the Cracow University of Technology, thanks to the possibility of using highly precise measurement systems such works are also undertaken.

2. Regularities in maintaining the dimensions when SLA printing

As already mentioned, the area of application of SLA technology is constantly growing. One such area is developed at LCM the concept of printing standards, dedicated to calibration and coordinate measurements. This is intended to significantly improve the process of obtaining appropriate standards by laboratories.

Therefore, LCM decided to print a calibration sphere, gauge blocks (Fig. 1), rings (Figs. 4, 5) and a special standard (Fig. 9) and examine the obtained models for dimensional verification using selected coordinate systems. The objects were made using a Formlabs Form 3B+ 3D printer. Form Wash and Form Cure devices were also used to process the print. The Formlabs Form 3B + printer because of its high precision, is used mainly for dental and medical applications, although the area of application is much wider.

2.1. The quality of reproduction of gauge blocks using SLA technology

To print the gauge blocks, Tough 2000 photopolymer resin from Formlabs was used. This resin is characterized by high tensile strength and resistance to damage.

The printed models were processed and placed in the Form Wash washer. This process was intended to clean the elements of excess resin.

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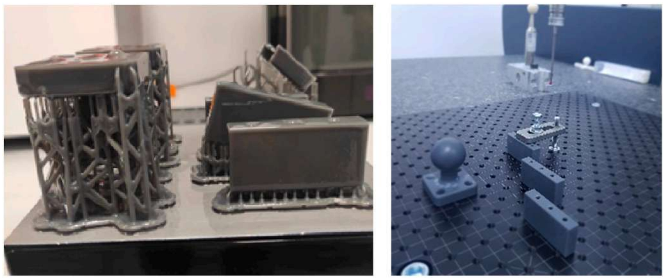


Fig. 1. On the left are models of gauge blocks before processing - SLA printing, on the right are models of the calibration sphere and gauge blocks - contact measurement with the use of Zeiss Eclipse coordinate measuring machine.

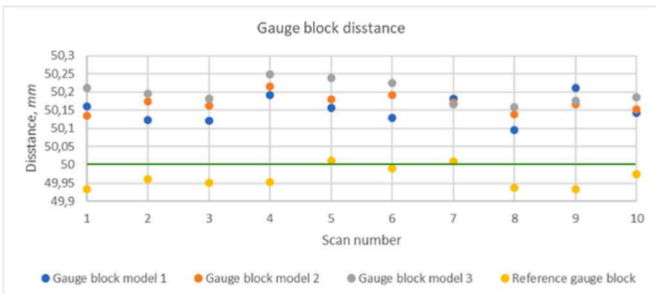
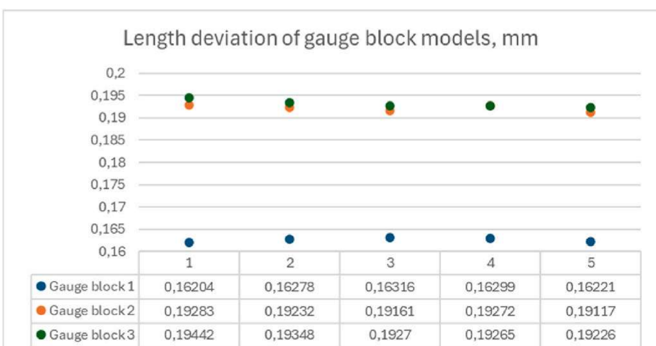


Fig. 2. Length measurement results on reference and printed gauge blocks - measurement with an Absolute Arm with a laser head.



	1	2	3	4	5
Gauge block 1	0,16204	0,16278	0,16316	0,16299	0,16221
Gauge block 2	0,19283	0,19232	0,19161	0,19272	0,19117
Gauge block 3	0,19442	0,19348	0,1927	0,19265	0,19226

Fig. 3. Length measurement results on reference and printed gauge blocks - measurement with Zeiss Eclipse contact CMM.

After cleaning, the model was placed in the Form Cure UV chamber, where the resin hardened for an hour at 70 °C.

The first stage of the research was carried out using optical coordinate technology - the Romer Absolute Arm 7320RI with a Scanner RS2 laser head with the accuracy of about 70μm. The measurements included 10x scans of all elements. The results were analyzed in Polyworks and GOM Inspect programs. The measurement procedure began with thermal stabilization of the objects and then both reference and printed gauge blocks were whitened to reduce reflection.

All measurement results of the length of printed gauge blocks are greater than the set value of 50 mm (Fig. 2). Because the measurement results of the reference gauge block are around 50 mm, it can be assumed that the larger dimension is more related to the printing technology than to the measurement technique. The observed regularities made it possible to develop a thesis that higher printing accuracy can be achieved by including dimension correction at the design stage of the printing process.

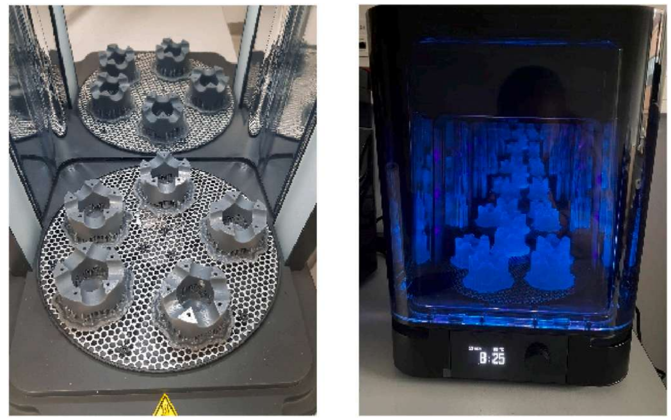


Fig. 4. On the left printing process, on the right hardening process.

Fig. 5. On the left measurement with the use of Zeiss Eclipse contact CMM, on the right rings from various resins.

To confirm the measurement results, it was decided to measure the gauge blocks again, this time using a Zeiss Eclipse contact coordinate measuring machine (CMM) with Calypso software. The MPE (Maximum Permissible Error) equation describing this machine is MPE $= 0.003 + 0.004/1000 * L$ mm. The results are shown in Fig. 3.

The obtained deviation values are analogous to those obtained from measurement with the Articulated Arm. Based on both measurement cycles, shifts from 0.15 mm to 0.20 mm can be expected, with the concentration of results for two gauge blocks around 0.19 mm. It can therefore be concluded that the printed gauge blocks are consistently larger than the expected value. Similar results from two different measurement systems additionally confirmed the usefulness of the coordinate technique in the evaluation of 3D printing.

2.2. Repeatability of SLA technology – measurement of the inner and outer diameters of ring models made of various resins

To continue the considerations and avoid generalizations, it was decided to examine the repeatability of SLA printing using different types of resins. In the next stage of work, a series of rings with an internal diameter of 25 mm, an external diameter of 45 mm and a height of 20 mm were designed and printed. The rings were made of three types of photocurable resins: Grey, Tough 2000 and Clear. The selected materials differ in colour and surface structure after printing, as well as properties such as stretchability, elastic modulus and reflectivity. The ring printing process and hardening process are presented in Fig. 4.

The measurements were carried out in the same way as in point 2.1,

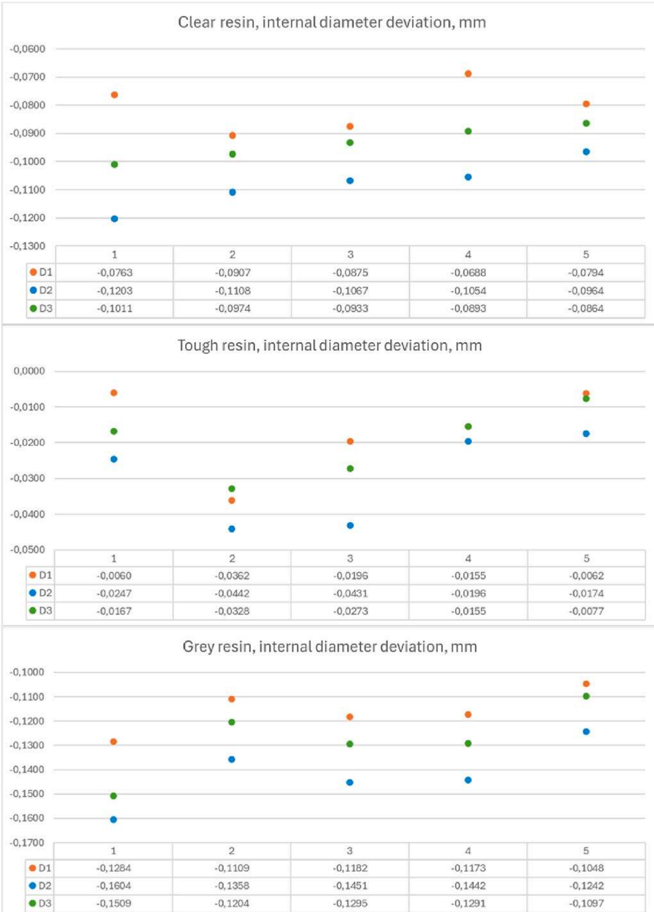


Fig. 6. Internal diameter deviations of five rings made of three resins - the measurement repeated at three heights D1, D2, D3.

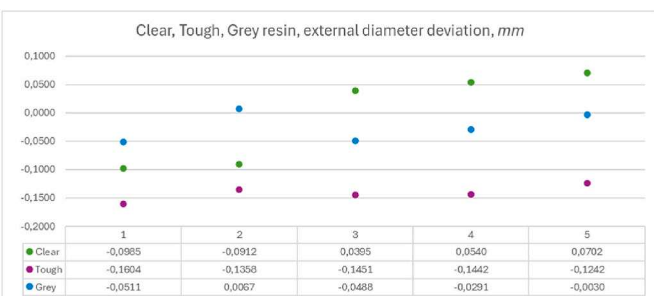


Fig. 7. External diameter deviations of five rings made of three resins.

so they included measurements using an Articulated Arm with an optical head and measurements on a Zeiss Eclipse contact CMM presented in Fig. 5.

To extend the research, it was decided to additionally measure the inner diameter of rings at three heights. The results are presented in Fig. 6.

Analyzing the obtained results, a consistent deviation in diameter values towards minus values can be observed.

As in the case of internal diameters, in the case of external diameters (except for Tough resin) (Fig. 7), the values are also smaller, but not as significantly.

In practice, it can be stated that the printed rings are smaller than the set values. Due to their repeatability, the obtained results can be used as the first data for the correction matrix.

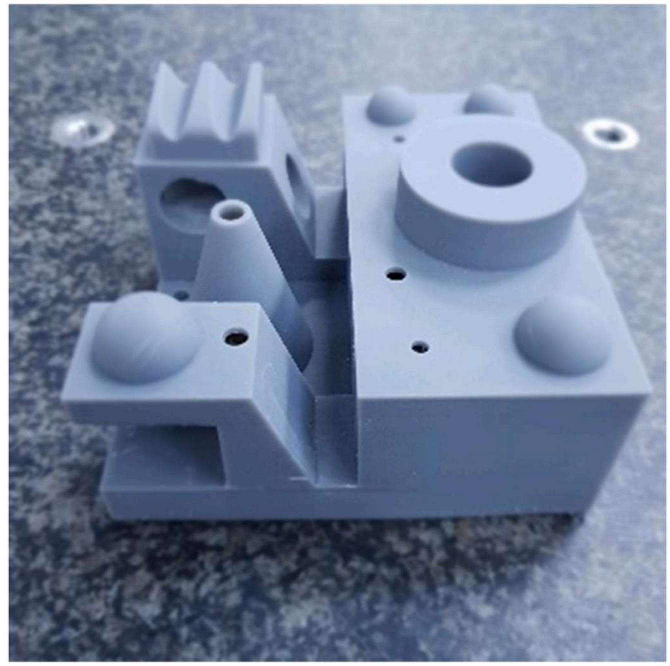
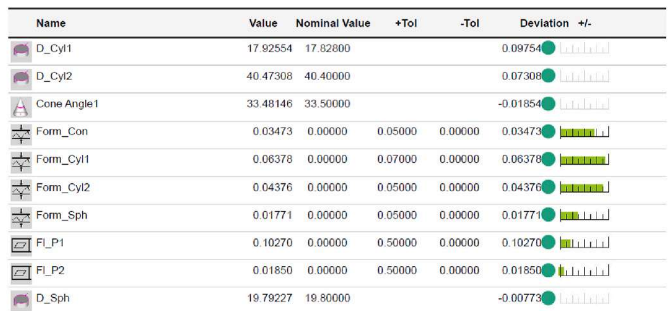


Fig. 8. A special standard for testing the regularities of SLA printing.



Name	Value	Nominal Value	+Tol	-Tol	Deviation +/-
D_Cyl1	17.92554	17.82800			0.09754
D_Cyl2	40.47308	40.40000			0.07308
Cone Angle1	33.48146	33.50000			-0.01854
Form_Con	0.03473	0.00000	0.05000	0.00000	0.03473
Form_Cyl1	0.06378	0.00000	0.07000	0.00000	0.06378
Form_Cyl2	0.04376	0.00000	0.05000	0.00000	0.04376
Form_Sph	0.01771	0.00000	0.05000	0.00000	0.01771
Fl_P1	0.10270	0.00000	0.50000	0.00000	0.10270
Fl_P2	0.01850	0.00000	0.50000	0.00000	0.01850
D_Sph	19.79227	19.80000			-0.00773

Fig. 9. A Report of the measurement results of selected characteristics of the developed standard.

2.3. Special standard concept – pilot measurement

The next stage of work consisted of designing, printing and measuring a special standard (Fig. 8) composed of basic geometric elements most often found in production. The standard was made as before from three types of photocurable resins and duplicated three times. Zeiss Eclipse CMM was used for measurements. As a result of the measurements, further regularities coming from the printing process were observed e.g. (Fig. 9), but before they are included in the matrix, the authors planned to perform an additional series of measurements.

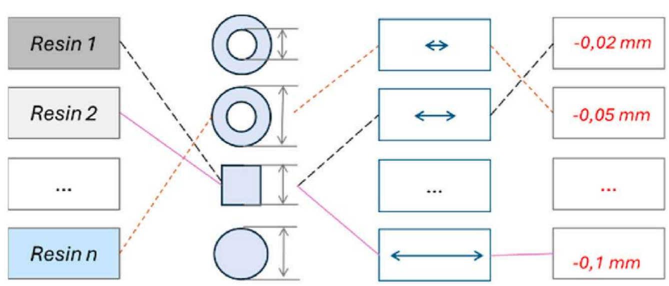


Fig. 10. The matrix operation diagram.

Table 1
Multi-factor Correction Matrix for SLA additive technology – first version.

No.	Resin			Characteristic			Correction Value, mm
	Clear	Tough	Grey	Length (gauge block)	Internal diameter (ring)	External diameter (ring)	
1	x				x		0,09
2		x			x		0,02
3			x		x		0,13
4		x		x			0,19
5	x					x	0,01
6		x				x	−0,02
7			x			x	0,03

Table 2
Results of ring measurements with correction.

Resin type	Internal diameter value, mm		Difference value, mm	
	out of correction	with correction	out of correction	with correction
Clear	24,90602	24,98375	−0,09398	**−0,01625**
Tough	24,97785	25,00091	−0,02215	**0,00091**
Grey	24,87141	24,99809	−0,12859	**−0,00191**
	External diameter value, mm			
	out of correction	with correction		
Clear	44,98970	44,98946	−0,01030	**−0,01054**
Tough	45,01714	45,00316	0,01714	**0,00316**
Grey	44,97494	45,00367	−0,02506	**0,00367**

3. A multi-factor correction matrix for SLA additive technology

3.1. SLA print correction matrix concept

The analysis of the measurement results and the conclusions from the research confirmed the existence of certain regularities in the SLA technology in terms of reproducing the dimensions. This allowed the development of the first version of a special multi-factor correction matrix enabling the printer operator to obtain the object in a way that is as consistent as possible with the expected values. The idea of the matrix is to provide practical guidelines on what correction should be done when entering the given input values at the design stage of the printing process, knowing the type of material, geometric shape and dimensions of the printed detail. The matrix operation diagram is presented in Fig. 10.

The diagram (Fig. 10) can also be described by the formula (1)

$$v_{out} = v_{in} + k \tag{1}$$

v_{out} – obtained real value of given characteristic,
v_{in} – entered value of given characteristic,
k – value of correction,

where:

$$k \approx f\left(x_r, x_{ch}, x_{d....,} x_n\right) \tag{2}$$

x_r – influence of used resin type,
x_{ch} – influence of measured characteristics,
x_d – influence of dimensions.

3.2. Verification of multi-factor correction matrix

To prove the thesis, the rings were reprinted including the corrections from Table 1 when entering the values of dimensions. After carrying out analogous measurements as before, the obtained results are presented in Table 2. The results clearly show that much smaller differences are obtained when the operator includes the proposed corrections. This emphasizes the validity of the assumptions made.

4. Conclusions

The research and analyzes confirmed a high level of accuracy in reproducing dimensions when printing with SLA additive technology, sufficient for selected engineering tasks. The measurements carried out using a precise coordinate technique, preceded by the design and printing of numerous objects using SLA printing, allowed us to establish the regularities of the dimensions realization in 3D printing. This enabled the development of the first version of a special multi-factor correction matrix, which allows the printer operator to obtain a detail as close as possible to the set values.

The matrix is based on the relations between input values to the printing process in the form of resin type, geometric shape and dimensions of the printed object, and output values in the form of objects with established dimensions. It has been proven that it is possible to determine the value of corrections that can be used at the data entry stage, thus achieving more accurate printings.

With the necessary development work, the presented solution can significantly improve the accuracy of 3D printing. In a further stage of work, it is proposed to extend the analyses with new combinations of input data and, noting that the proposed solution is an expert system, the authors consider developing a simple application enabling the user to receive corrections after entering basic data about a given print task. The authors additionally see the potential to develop the idea of such an application with artificial intelligence elements that would simulate corrections for paths for which analyzes have not yet been performed.

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