ADVANCES IN MANUFACTURING SCIENCE AND TECHNOLOGY Vol. 34, No. 4, 2010

DETERMINATION OF SYSTEMATIC ERRORS OF 3D PRINTER IN ORDER TO ENSURE MANUFACTURING CORRECTNESS OF THE PROTOTYPE

Piotr Zgórniak, Wojciech Stachurski

S u m m a r y

This paper presents the length measurement results for experimental cuboidal samples made by means of a 3D printing (3DP) method. A Z Corporation 310 Plus printer was employed to manufacture these samples. The main aim of this experimental research was to evaluate the accuracy of CAD model reproduction using printed samples. Experimental tests were performed to determine the systematic errors in the location of the printed samples within the building chamber of the 3D printer. Moreover, the influence of sample positioning relative to a Cartesian coordinate system on the systematic errors was investigated. In this article, an extensive statistical analysis of the experimental data is performed to evaluate the uncertainty of the statistical error estimation in the XYZ directions. Finally, this paper will provide many practical tips that can be employed to manufacture more advanced prototypes with the 3DP method, which has recently come to be regarded as less expensive and the fastest rapid prototyping method.

Keywords: rapid prototyping, 3D printing, dimensional accuracy, experimental tests

Określenie błędu systematycznego drukarki 3D w celu zapewnienia poprawności wykonania prototypu

S t r e s z c z e n i e

Przeprowadzono badania eksperymentalne dotyczące oceny dokładności wymiarowej próbek prostopadłościennych wykonanych za pomocą drukarki trójwymiarowej ZPrinter 310 Plus. Określono dokładność odwzorowania próbek w porównaniu z ich modelem zaprojektowanym w systemie CAD. Wyniki badań eksperymentalnych stanowiły podstawę do wykonania modelu funkcjonalnego przekładni planetarnej. Oszacowano wartości błędów systematycznych dla różnego położenia próbek względem kartezjańskiego układu współrzędnych, związanego z komorą budującą drukarki 3D. Sformułowano także wskazówki praktyczne do zastosowania w budowaniu zaawansowanych prototypów funkcjonalnych w technologii druku 3D.

Słowa kluczowe: szybkie prototypowanie, drukowanie 3D, dokładność wymiarowa, badania eksperymentalne

Address: Piotr ZGÓRNIAK, PhD Eng., Wojciech STACHURSKI, PhD Eng., Technical University of Łódź, Institute of Machine Tools and Production Engineering, Stefanowskiego 1/15, 90-924 Łódź, e-mail: piotr.zgorniak@p.lodz.pl

1. Introduction

In recent years, the continuous progress of rapid prototyping (RP) methods has been widely observed. A complete database now includes well over 7,000 US patents and published applications, covering the period from 1892 to the present [1]. However, while the development time for a new product has been dramatically speeded up, rapid prototyping and rapid manufacturing (RM) technologies are still expensive [2]. In many cases, small and middle-sized companies are unable to buy RP systems, making it difficult for their products to easily compete with of bigger companies. In this case, the management of a small or new business has to answer the difficult question of whether buying an RP system is economically justified. The demanding requirements in relation to the short development time for a new product might cause a greater number of errors during the design process. Consequently, giving up investments in RP technologies might put new and small companies at risk for experiencing considerable losses. Although there are many RP technologies such as stereolithography (SLA), selective laser sintering (SLS), and direct metal laser sintering (DMLS), determining which is most suitable for their needs might sometimes be very difficult [2-5]. According to ZCorporation, the ZPrinter 310 Plus is an affordable monochrome 3D printer that makes it possible to build parts at high speed (25 mm per hour) and with great accuracy. The vertical build speed is about 25 mm per hour with a resolution in the XY direction of 300 x 400 dpi. The layer thickness that can be applied depends on the type of powder and ranges from 0.089 to 0.203 mm [6, 7]. However, although the three dimensional printing (3DP) system used in this investigation is mainly classified as a typical "concept modeler" and more accurate RP methods have been developed [2, 9-10], the authors decided to find out if it is possible to manufacture a functional prototype by means of this equipment. Initially, many might find the idea of making functional prototypes by means of a 3DP system such as the ZPrinter 310 Plus ridiculous. However, the idea arose from many inquiries from industry. Despite the fact that the models made using zp131 are not as durable as plastic or resin models, the authors decided to carry out an investigation to determine whether it is possible to make a functional prototype of a planetary gear model using one of the most economical RP methods, 3D printing (3DP) [2, 6, 7]. The authors came to the conclusion that it would be better to have less accurate and less resistant prototypes than none. Hence, the authors decided to investigate how accurate this method is and then, based of obtained results, correct the settings of the 3D Printer in order to obtain parts that might be applicable to assemble a functional prototype of the planetary gear.

2. Experimental procedure

During the tests, a ZCorporation ZPrint 310Plus 3D Printer was used. Samples were made of zp131 powder glued with the zb60 binder. To investigate the influence of different locations of the sample in the building chamber of the 3D printer on its dimensional accuracy, the following criteria were established. The building chamber was divided into 9 imaginary cells, as presented in Fig. 1b.

a) b)

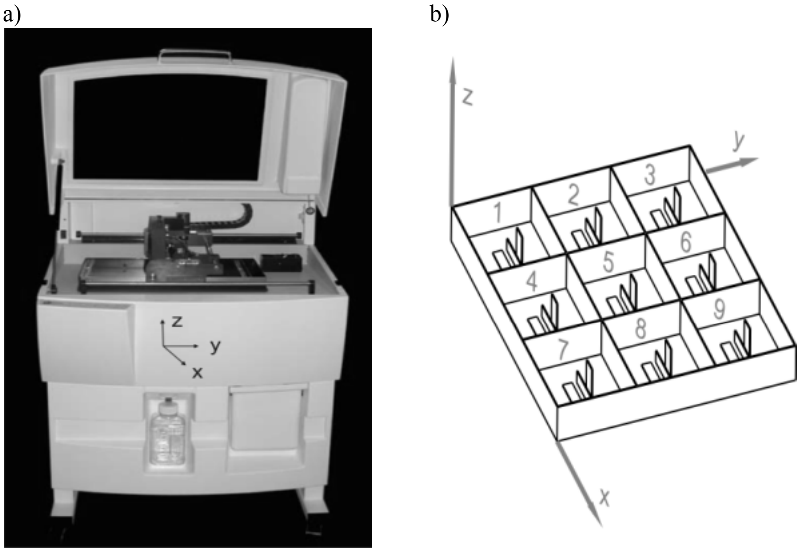

Fig. 1. ZCorporation 3D printer, type ZPrint 310 Plus [6] (a)
and building chamber cell position (b)

In each cell (numbered from 1 to 9), three samples were positioned at Locations A, B, and C. The positions of the samples in a cell are presented in Fig. 2a. In addition, a XYZ coordinate system was established for the 3D printer to evaluate the experimental results. Moreover, the set of samples presented in Fig. 1b was printed three times to evaluate the influence of the print variable on the dimensional accuracy of the sample.

The main aim of the experimental tests was to investigate the dimensional differences between the samples and CAD model. The length was 25 mm, the width was 10 mm, and the thickness of the sample was 1 mm. Numerous thickness, width, and length measurements were carried out, along with approximately three measurements of each variable. Measurements of the dimensions were carried out using a Mitutoyo digimatic micrometer. These dimensions are shown in Fig. 2b.

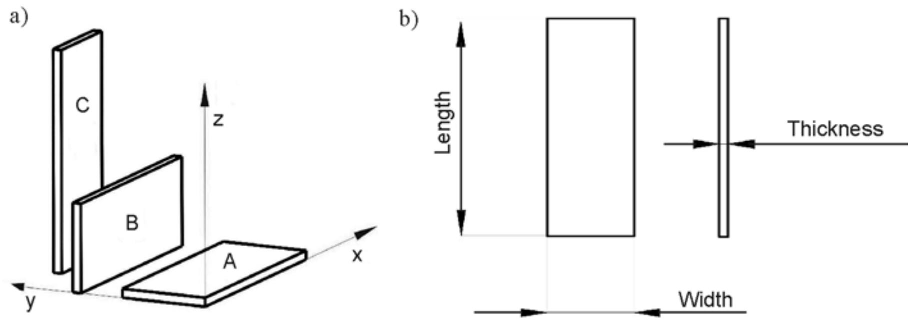

Fig. 2. Samples positions in each cell of building chamber of 3D printer (a), measured dimensions that were used for the statistical evaluation (b)

3. Experimental results

The first step in the statistical evaluation was to investigate the correlations between the independent variables (print, cell, and position) and the dependent ones (thickness, width, and length). To accomplish this, 152 samples were considered. Some data had to be excluded because of damage to the sample during the measurement process. Extremes values for the measured variables were used in the statistical evaluation without elimination. A correlation table based on this statistical evaluation is presented as follows (Table 1):

Table. 1. Correlation table for evaluated variables

Variable	**Correlations (Spreadsheet14) Marked correlations are significant at p < ,05000 N = 152 (casewise deletion of missing data)**					
	Print	Cell	Position	Thickness	Length	Width
Print	1.000000	0.012767	0.019629	-0.011595	0.216848	-0.001407
Cell	0.012767	1.000000	-0.076523	-0.028304	0.240894	-0.131171
Position	0.019629	-0.076523	1.000000	0.822832	-0.712077	0.271718
Thickness	-0.011595	-0.028304	0.822832	1.000000	-0.529142	-0.158298
Length	0.216848	0.240894	-0.712077	-0.529142	1.000000	-0.393385
Width	-0.001407	-0.131171	0.271718	-0.158298	-0.393385	1.000000

The results presented in this table show the highest correlation between position and thickness, with a value of 0.823. The results showing the mutual correlation between the thickness, position, and cell variables are presented in Fig. 3.

The experimental data presented in Fig. 4 show that the thickness values had the smallest difference from the CAD model at Position A, where the thickness value was established as 1 mm. The mean of the thickness

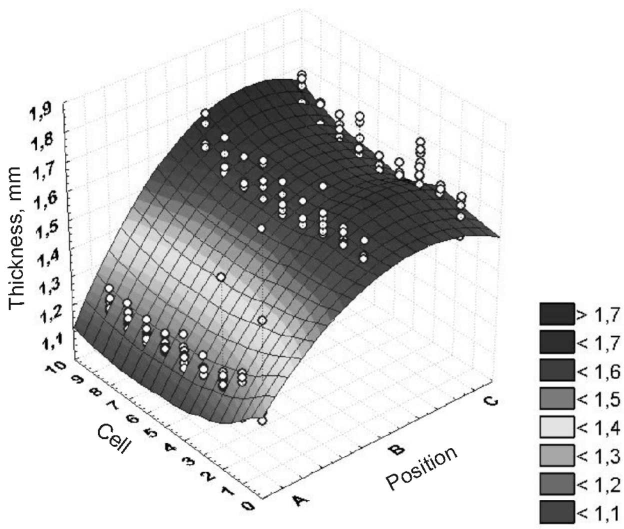

Fig. 3. 3D Surface plot of thickness against position and cell

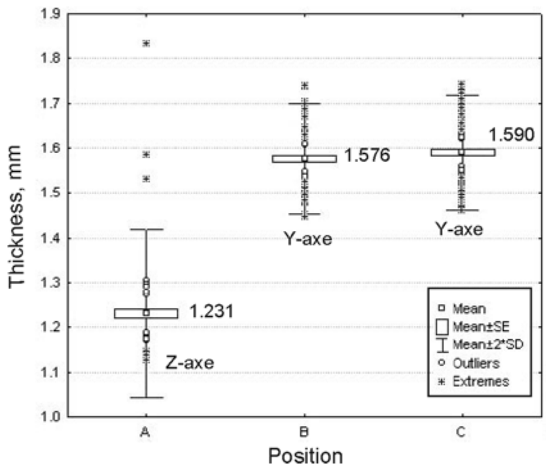

Fig. 4. Box plot of thickness grouped by position

in position A was equal to 1.231. The thickness means for positions B and C had values of 1.576 and 1.590, respectively. Between the cell and length we observe a significant correlation coefficient, but this parameter has a lower value. The results in Fig. 5 show mutual relations between the length, cell, and position variables. From this figure, we can come to the conclusion that the position of the sample in the building chamber had a great influence on the dimensional accuracy of the printed models. In this case, the thickness dimension in position

A was printed in the Z printing direction according to Fig. 2. Positions B and C were printed in the Y printing direction when using the 3D printer coordinate system presented in Fig. 1. The obtaining results show that the smallest statistical error in the Z printing direction had a value of 0.231 mm. The samples printed in the Y and Z directions had greater values of 0.576 and 0.590, respectively.

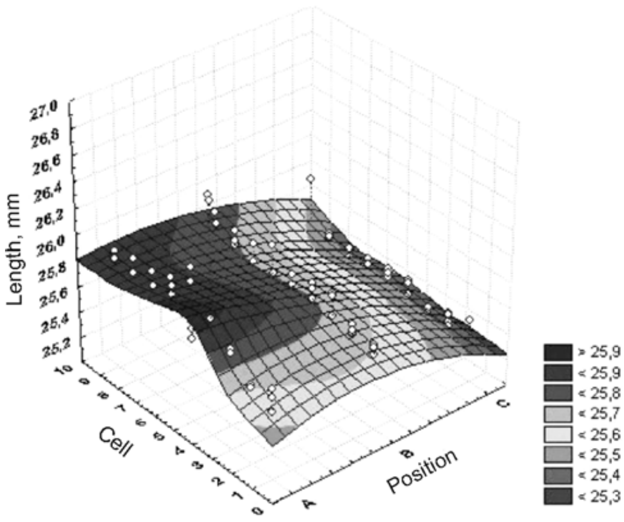

Fig. 5. 3D Surface plot of length against position and cell

According to Table 1, the correlation between the length and position variables is also significant. The correlation coefficient in this case is equal to –0.712. The results concerning the mutual relationships between the length, position and cell variables are presented in Fig. 5.

Figure 6 shows a better representation of the relationship between the length measurement results and the sample location in the building chamber of the 3D printer for the three different positions A, B and C. According to Fig. 6, the mean length measurement values for the three different positions in the building chamber of the 3D printer are as follows: position A = 25.81 mm, position B = 25.68 mm, and position C = 25.39 mm. From these results, we can come to the conclusion that the statistical errors in the different printing direction (X,Y,Z) have different values. The nominal value for the CAD model of the sample was 25 mm. The greatest difference was noticed in Position A (0.81 mm). According to Fig. 2, the printing direction for this 25-mm dimension in positions A and B was the X axis of the building chamber of the 3D printer, but in position C the length was printed in the Z direction. This phenomenon will be thoroughly discussed in the following parts of this article.

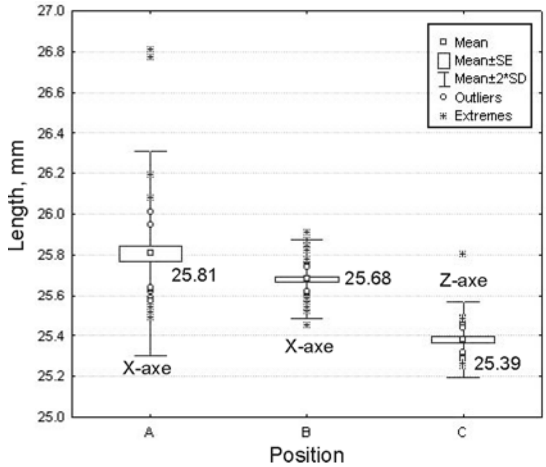

Fig. 6. Box plot of lengths grouped by position

As can be seen in Table 1 and the previous plots, the remaining results concerning the cell location in the building chamber of the printer are not statistically significant, with the exception of the length. Moreover, many of the prints showed poor correlation between the remaining variables.

For example results concerning the influence of the cell variable on the thickness of the samples are presented in Fig. 7. On the basis of the results

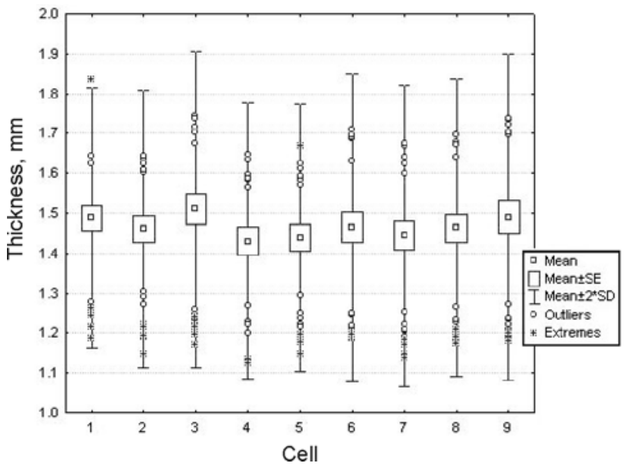

Fig. 7. Box plot of thickness values grouped by cell

presented in this plot, we can come to the conclusion that the fluctuations of the means in this case are not significant.

During the investigation, another aspect was discovered. The authors wanted to determine the kind of relationship that existed between the statistical errors in the XYZ directions of the 3D printer and the dimensional values of the measured samples. The XYZ coordinate system established for the 3D printer was previously presented in Fig. 1. The results concerning this case are shown in Fig. 8-10.

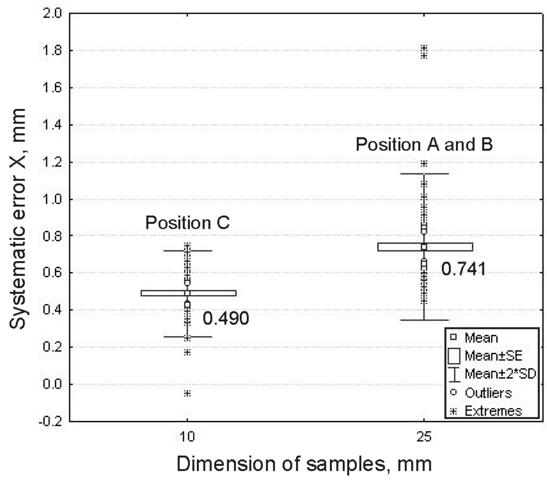

Fig. 8. Box plot of systematic error in X direction of the 3D printer coordinate system

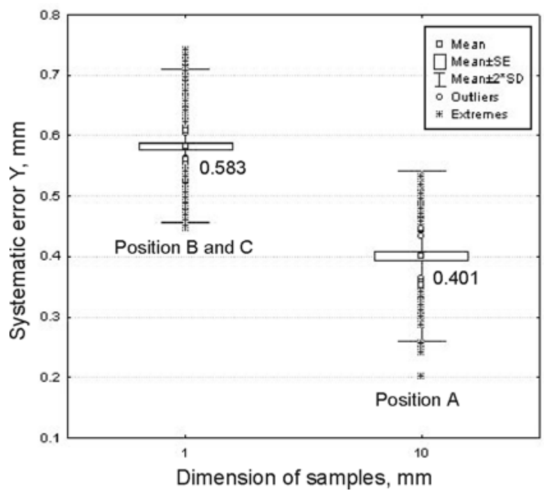

Fig. 9. Box plot of systematic error in Y direction of the 3D printer coordinate system

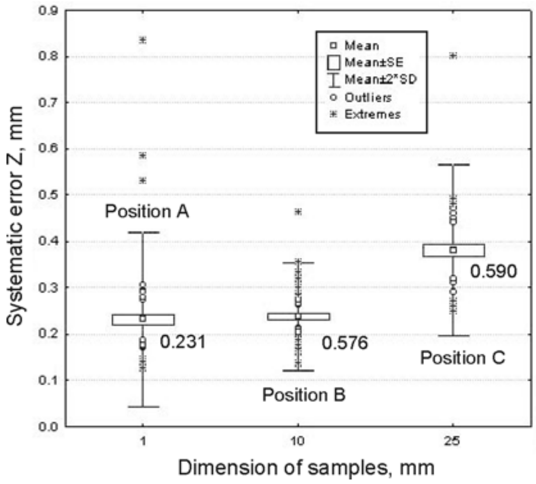

Fig. 10. Box Plot of systematic error in Z direction of the 3D printer coordinate system

In Figure 8, we can compare only two parameters: the width, which has a nominal value of 10 mm, and the length, with a nominal value of 25 mm. The systematic error in the X direction increases when the dimension of the sample increases.

Based on Fig. 9, the value of the systematic error in the Y direction decreases when dimension of the sample increases. Here, the thickness and width dimensions of the samples are presented.

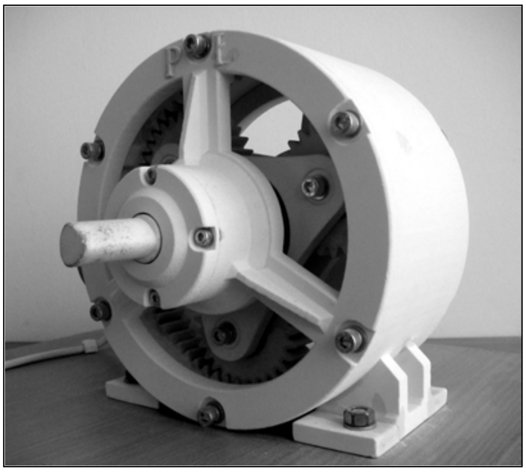

Fig. 11. Isometric view of planetary gear prototype made by 3D Printing method

According to Fig. 10, the value of the systematic error in the Z direction increases when the dimension of the sample increases. Here, the thickness, width, and length dimensions of the samples are presented. For better accuracy in evaluating the systematic error phenomena, more levels of dimensions and greater numbers of samples are planned for a future investigation of this subject.

On the basis of the obtained results, a functional prototype for a planetary gear was made. Figure 11 shows an isometric view of the prototype made by the ZPrinter 310 Plus. To build the parts of the planetary gear model, zp131 powder and zb60 binder were used. To obtain better durability for the prototype, selected parts were infiltrated by Z-Bond 101 resin [6, 7].

Conclusions

Based on the results of the experiment, the following conclusions were formulated:

- The dimensional accuracy of a sample was unrelated to its position in the building chamber of the 3D Printer. The location of a sample in the different imaginary cells (from 1 to 9) did not have any correlation to its dimensional accuracy.
- The position of a sample in the XYZ coordinate system of the building chamber (positions A, B, C) had a significant influence on its dimensional accuracy. In this case, the smallest value of systematic error was observed in Position A for its thickness. The remaining positions (B and C) in the same case were characterized as having greater systematic errors approximately on the same level.
- The position had a great influence on all of the dimensions of a sample, but the highest influence could be observed in the case of the Thickness.
- As can be seen in Figure 10, the smallest value of systematic error was in the Z direction. In addition, an increase in statistical error in relation to an increase in dimension was observed in the Z and X directions but not in the Y direction.
- To obtain more reliable results concerning the systematic errors in the XYZ printing directions, more positions should be taken into consideration. To compare the same numbers of sample dimensions we need to have at least five positions.

References

[1] http://www.additive3d.com/pat_db.htm

[2] D.T. PHAM, R.S. GAULT: A comparison of rapid prototyping technologies. *Journal of Machine Tools & Manufacture*, **38**(1998), 1257-1287.

[3] E. CHLEBUS: Innowacyjne technologie Rapid Prototyping – Rapid Tooling w rozwoju produktu. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2003.
[4] E. CHLEBUS: Techniki komputerowe Cax w inżynierii produkcji. Wydawnictwa Naukowo-Techniczne, Warszawa 2000.
[5] K.E. OCZOŚ: Stan obecny i perspektywy rozwoju rapid – technologii. *Mechanik* (2009)2, 81-107.
[6] ZPrinter 310 User Manual – Part Number 09508 Rev F, 2004.
[7] http://www.zcorp.com
[8] D. DIMITROV, W. van WIJCK, K. SCHREVE, N. de BEER, J. MELJER: An investigation of the capability profile of three dimensional printing process with an emphasis on achievable accuracy. *CIRP Annals – Manufacturing Technology*, **52**(2003)1, 189-192.
[9] E. SACHS, M. CIMA, J. CORNIE: Three-Dimensional Printing: The physics and implications of additive manufacturing. *CIRP Annals – Manufacturing Technology*, **42**(1993)1, 257-260.
[10] D.N. SILVA, M. GERHARDT de OLIVEIRA, E. MEURER: Dimensional error in selective laser sintering and 3D-printing of models for craniomaxillary anatomy reconstruction. *Journal of Cranio-Maxillofacial Surgery*, **36**(2008), 443-449.

Received in June 2010