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Geometric Accuracy by 2-D Printing Model

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In order to improve the accuracy of three-dimensional printing (3DP), we carried out a set of experiments on two-dimensional (2-D) printed model. The combinations of three main processing factors were considered for every experiment: layer thickness, building orientation and infiltrant type. The results of experiments provided the appropriate anisotropic scale factor and proved the adequacy of anisotropic scaling. The analysis of results indicates that smaller layer thickness, infiltration with epoxy resin and sample orientation towards building direction of X axis provide better sample accuracy.

Keywords: rapid prototyping, three-dimensional printing, geometric accuraccy

0 INTRODUCTION

The models produced by three-dimensional printing (3DP) are not so accurate when compared to other Rapid Prototyping (RP) technologies. Several authors emphasized the problem of 3DP accuracy in their researches. Dimitrov et al. pointed out in their review of 3DP that the accuracy is a significant weakness when compared to other RP technologies [1]. Pilipović et al. noticed that 3DP test samples exceed tolerance limits for tensile testing and are less accurate than samples made with a hybrid Polyjet technique [2].

The researchers are constantly trying to improve 3DP accuracy which is evident in the number of published papers [3] to [8]. The effort for improvement is also reflected on a 3DP market - the manufacturers not only develop and deliver the new models of printers, but also new improved materials, device firmware, software and improved alternative spare parts for the existing models.

The primary objective of our paper was to determine the appropriate scale factors for the considered 3DP system in the selected combination of materials and processing parameters. The possible use of the appropriate scale factors for improving printer accuracy is also pointed out in [6] and it gave us the additional motivation to perform the experiments. The secondary objective was to determine the influence of 3DP processing factors on the accuracy and to determine the most accurate combination. Therefore, we carried out the experiments to improve the accuracy of the considered 3DP system.

1 3DP EQUIPMENT AND MATERIALS

The 3D printer, used for these experiments, was the model Z310, a product of Z Corporation. It is a low-cost monochrome 3D printer suitable for RP education or for small and medium sized companies. The printer firmware version was 10.158 and test samples were prepared in a printer software ZPrint version 7.5.23 [9] and [10].

The considered 3D printer combines a layered approach from RP technologies and a conventional ink-jet printing. It prints a binder fluid through the conventional ink-jet print head into a powder, one layer onto another, from the lowest model's cross-section to the highest (Fig. 1). After printing, the printed models are dried in a building box, then removed from the powder bed, de-powdered by compressed air, dried in the oven and infiltrated for maximum strength.

There are several base materials, i.e. powder types, available for the above mentioned 3D printer. For our experiment we used a plaster-based powder zp130 with an appropriate binder zb56. The powder zp130 is recommended for the accuracy and for delicate models. It is a mixture of plaster, vinyl polymer and sulfate salt [11].

All test samples were dried two times as recommended in [10] and [12]: first in the printer's building box for one hour and then, after de-powdering, in the oven for at least two hours at 55°C.

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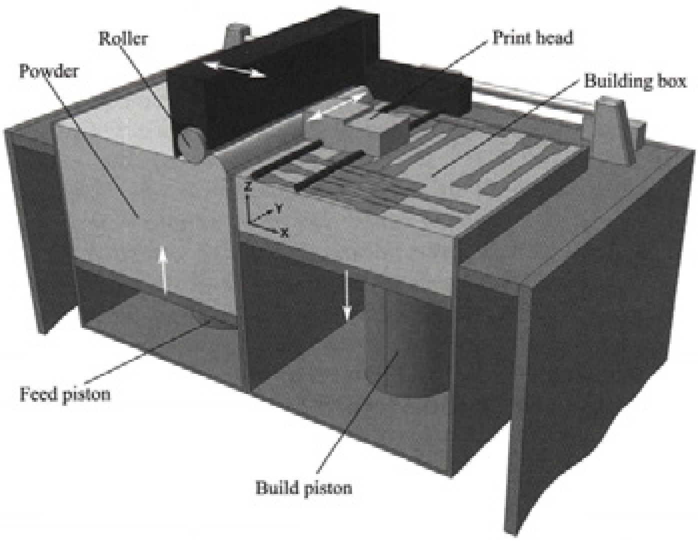

Fig. 1. *3D printer*

After drying, the samples were infiltrated with the appropriate infiltrant, regarding an appropriate combination of the experiment. The applied infiltrants were: cyanoacrylate based Loctite 406; epoxy resin based Loctite Hysol 9483 and normal wax Cera Alba.

2 DESIGN OF THE EXPERIMENT

In our experiments we used models for tensile tests defined in standard ISO 527:1993. Tensile test model is selected because it has sufficient different dimensions and the models can be used for additional tests of mechanical properties if needed. The measured dimensions on test samples were: total length (L), width at the end (W), neck width (W1) and height (H). The position of dimensions on the test sample and nominal values of dimensions are presented in Fig. 2. Since the tensile test model has the small hight regarding other dimensions, we considered it as a 2-D model.

Two sets of test samples were planned. For the first set we considered non-scaled samples, so called the base set. The samples of the second set will be scaled with appropriate scale factors obtained from the measuring of the base set.

In both sets, the test samples were printed in a combination of considered processing factors. We considered combinations of the following processing factors: layer thickness, building orientation and infiltrant type.

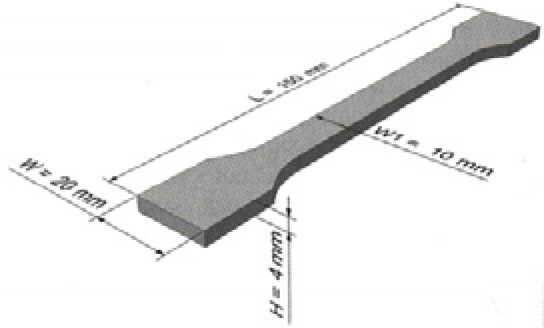

Fig. 2. *Measured dimensions of the test sample*

Layer thickness can be selected from two possible values – 0,1 mm and 0,0875 mm. The first thickness is default for the printer and it is therefore marked with number 1 in the beginning of the label for a particular combination of factors.

The model can be oriented in any possible direction inside the printer building box. We considered two directions: sample oriented with largest dimension L towards the building axis X and towards axis Y. Thereby, the samples were aligned at the bottom plane of the building box. In the experiment label of a particular combination of factors, sample orientation is marked on the second place of the label with letter X or Y respectively. The orientation towards the building axis Z was omitted since it considerably prolonged the printing time.

The type of the infiltrant is marked with letter at the end of the label for a particular combination of factors. The letters used for a particular infiltrant type are: W for wax, E for epoxy resin and C for cyanoacrylate.

For every particular experiment i.e. particular combination of factors in each set, 6 test samples were printed and measured (Fig. 3).

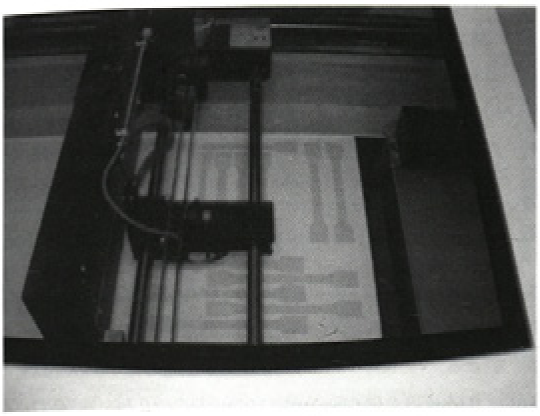

Fig. 3. *3D printing of test samples*

We measured dimensions of test samples with digital caliper Lux Profi model 572587, with the measurement range 0–150 mm and accuracy 0.01 mm.

3 RESULTS

The measurement results of the base set samples are presented in Table 1. Common statistical values are calculated and presented in table rows, grouped by the measured dimension and combinations. Calculated values are: arithmetic mean ($\overline{x}$); standard deviation (S); relative standard deviation (RSD); average error (Δx); relative error ($\Delta x/X$) and relative deviation ($\overline{x}/X$).

The relative standard deviation adequately expresses the precision of a particular experiment combination regarding the measured dimensions. It is the absolute value of the coefficient of variation, usually expressed as a percentage and calculated by:

$$RSD = \frac{S}{\overline{x}} \cdot 100 \qquad (1)$$

If average standard deviations for every measured dimension in the base set of samples are presented together in a single chart, it can be noticed that the standard deviation is higher for larger dimensions (Fig. 4).

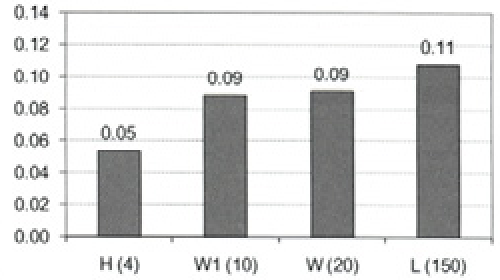

Fig. 4. *Average stand. deviations in the base set*

However, if relative standard deviations for each measured dimension are considered, it can be noticed that the relative standard deviation is higher for smaller dimensions (Fig. 5). Furthermore, average relative errors are higher for larger dimensions (Fig. 6).

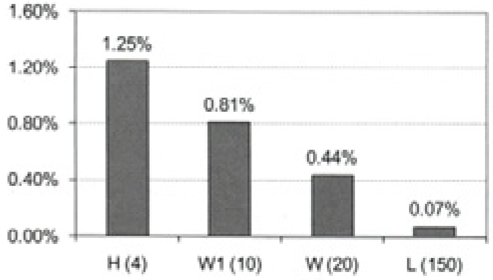

Fig. 5. *Average relative standard deviations in the base set*

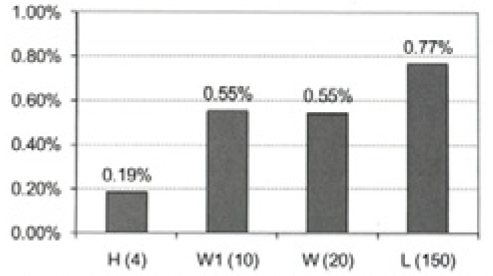

Fig. 6. *Average relative errors in the base set*

Relative errors and relative standard deviations show significant differences between measured dimensions. Such significant differences justify the anisotropic scaling of every particular dimension instead of the common overall scale factor.

Table 1. *Summary of base set measurements for* L, W, H *and* W1 *dimensions*

Layer thickness	0.1 mm						0.0875 mm					
Infiltrant	Wax		Epoxy resin		Cyanoacrylate		Wax		Epoxy resin		Cyanoacrylate	
Orientation	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*
Experiment label	1XW	1YW	1XE	1YE	1XC	1YC	2XW	2YW	2XE	2YE	2XC	2YC
Dimension L (Length), mm												
$\bar{x}$	151.03	150.81	151.09	150.90	151.09	150.89	151.37	151.25	151.36	151.22	151.51	151.27
S	0.10	0.17	0.07	0.13	0.09	0.12	0.05	0.18	0.13	0.06	0.09	0.12
RSD, %	0.07	0.11	0.04	0.09	0.06	0.08	0.03	0.12	0.08	0.04	0.06	0.08
Δx	1.03	0.81	1.09	0.90	1.09	0.89	1.37	1.25	1.36	1.22	1.51	1.27
Δx/X, %	0.69	0.54	0.72	0.60	0.73	0.59	0.91	0.83	0.90	0.81	1.01	0.85
$\bar{x}/X$	1.0069	1.0054	1.0072	1.0060	1.0073	1.0059	1.0091	1.0083	1.0090	1.0081	1.0101	1.0085
Dimension W (Width), mm												
$\bar{x}$	20.57	20.57	20.60	20.73	20.59	20.62	20.99	20.96	20.99	20.94	21.13	21.15
S	0.06	0.10	0.08	0.10	0.13	0.08	0.06	0.13	0.09	0.06	0.11	0.09
RSD, %	0.31	0.46	0.38	0.47	0.65	0.40	0.27	0.62	0.44	0.28	0.54	0.43
Δx	0.57	0.57	0.59	0.73	0.59	0.62	0.98	0.96	0.98	0.93	1.13	1.15
Δx/X, %	0.38	0.38	0.40	0.49	0.39	0.41	0.66	0.64	0.66	0.62	0.76	0.77
$\bar{x}/X$	1.0283	1.0283	1.0298	1.0366	1.0294	1.0308	1.0493	1.0479	1.0493	1.0468	1.0567	1.0575
Dimension H (Height), mm												
$\bar{x}$	4.22	4.19	4.28	4.25	4.38	4.40	4.21	4.15	4.18	4.18	4.43	4.48
S	0.06	0.04	0.05	0.05	0.08	0.07	0.08	0.03	0.03	0.01	0.09	0.08
RSD, %	1.44	0.85	1.05	1.06	1.75	1.49	1.87	0.68	0.78	0.28	1.94	1.76
Δx	0.22	0.19	0.27	0.25	0.38	0.40	0.21	0.15	0.18	0.18	0.43	0.48
Δx/X, %	0.15	0.12	0.18	0.17	0.25	0.26	0.14	0.10	0.12	0.12	0.28	0.32
$\bar{x}/X$	1.0550	1.0463	1.0688	1.0633	1.0954	1.0992	1.0521	1.0367	1.0458	1.0446	1.1067	1.1192
Dimension W1 (Neck width), mm												
$\bar{x}$	10.53	10.48	10.61	10.61	10.60	10.61	11.08	11.04	11.02	10.86	11.27	11.27
S	0.04	0.03	0.06	0.11	0.10	0.07	0.11	0.17	0.05	0.04	0.16	0.12
RSD, %	0.41	0.31	0.59	1.04	0.91	0.65	1.01	1.58	0.42	0.40	1.38	1.03
Δx	0.53	0.48	0.61	0.61	0.60	0.61	1.08	1.04	1.02	0.86	1.27	1.27
Δx/X, %	0.35	0.32	0.41	0.40	0.40	0.41	0.72	0.69	0.68	0.57	0.84	0.85
$\bar{x}/X$	1.0532	1.0475	1.0608	1.0607	1.0603	1.0613	1.1075	1.1035	1.1015	1.0857	1.1267	1.1270

For the particular combination in scaled set of samples, anisotropic scale factor (AS) of particular dimension is a multiplicative inverse of the matching relative deviation from the same combination in the base set:

$$AS_D = \left(\frac{\bar{x}}{X}\right)^{-1} \quad (2),$$

where index D denotes anisotropic scaling direction and could be either X, Y or Z.

For example, the anisotropic scale factor in building direction X of the experimental combination 1XW is:

$$AS_X(1XW) = \left(\frac{151.03}{150}\right)^{-1} = 1.0069^{-1} = 0.99318 \quad (3).$$

But for the combination 1YW, in which the largest dimension of the sample (L) is oriented in building direction Y, the width (W) of the sample is oriented along building direction X, therefore:

$$AS_X(1YW)=\left(\frac{20.57}{20}\right)^{-1}=1.0283^{-1}=0.97245 \quad (4).$$

Such an exchange of length and width values in the calculation of anisotropic scale factor must be done for every experiment combination with samples oriented along the building direction Y.

The complete list of applied anisotropic scale factors for each experiment combination of scaled set is given in Table 2.

Table 2. *Anisotropic scale factors*

Label	1XW	1YW	1XE	1YE	1XC	1YC	2XW	2YW	2XE	2YE	2XC	2YC
AS_X	0.9932	0.9725	0.9928	0.9647	0.9928	0.9701	0.9910	0.9543	0.9910	0.9553	0.9900	0.9450
AS_Y	0.9725	0.9946	0.9711	0.9940	0.9714	0.9941	0.9531	0.9918	0.9531	0.9919	0.9464	0.9923
AS_Z	0.9479	0.9558	0.9357	0.9404	0.9129	0.9098	0.9505	0.9646	0.9562	0.9573	0.9036	0.8882

Appropriate anisotropic scale factors were entered in ZPrint software regarding printed samples and combination. Table 3. shows measurement results of scaled set samples.

Table 3. *Summary of scaled set measurements*

Experiment Label	1XW	1YW	1XE	1YE	1XC	1YC	2XW	2YW	2XE	2YE	2XC	2YC
Dimension L (Length), mm												
$\overline{X}$	150.09	150.11	149.92	149.96	150.19	150.26	150.05	150.26	150.13	150.22	150.23	150.20
S	0.12	0.08	0.05	0.04	0.07	0.20	0.11	0.07	0.10	0.03	0.19	0.13
RSD, %	0.08	0.05	0.04	0.03	0.05	0.14	0.08	0.04	0.07	0.02	0.13	0.09
Δx	0.09	0.11	-0.08	-0.04	0.19	0.26	0.04	0.25	0.13	0.22	0.23	0.20
$\overline{x}/X$	1.0006	1.0007	0.9994	0.9997	1.0013	1.0017	1.0003	1.0017	1.0009	1.0015	1.0016	1.0013
Dimension W (Width), mm												
$\overline{X}$	20.17	20.14	19.96	19.90	20.27	20.32	20.16	20.10	20.10	20.19	20.15	20.00
S	0.03	0.07	0.02	0.05	0.11	0.09	0.13	0.05	0.08	0.08	0.07	0.23
RSD, %	0.14	0.36	0.12	0.26	0.54	0.42	0.63	0.26	0.40	0.40	0.35	1.13
Δx	0.17	0.14	-0.04	-0.11	0.27	0.32	0.16	0.10	0.10	0.19	0.15	0.00
$\overline{x}/X$	1.0083	1.0068	0.9980	0.9948	1.0136	1.0158	1.0082	1.0052	1.0049	1.0093	1.0074	0.9998
Dimension H (Height), mm												
$\overline{X}$	3.98	4.09	4.03	4.02	4.09	4.11	4.02	4.10	4.02	4.13	4.04	4.10
S	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.01	0.03	0.02	0.08	0.05
RSD, %	0.59	0.74	0.78	0.75	0.77	0.68	0.53	0.22	0.69	0.55	2.03	1.10
Δx	-0.02	0.09	0.03	0.01	0.09	0.11	0.02	0.10	0.02	0.11	0.04	0.10
$\overline{x}/X$	0.9958	1.0217	1.0075	1.0038	1.0225	1.0283	1.0046	1.0250	1.0054	1.0317	1.0096	1.0242
Dimension W1 (Neck width), mm												
$\overline{X}$	10.51	10.39	10.37	10.26	10.64	10.47	10.75	10.68	10.64	10.42	10.88	10.89
S	0.14	0.04	0.06	0.05	0.11	0.11	0.10	0.12	0.06	0.02	0.06	0.10
RSD, %	1.31	0.36	0.59	0.44	1.03	1.07	0.93	1.09	0.55	0.19	0.57	0.95
Δx	0.51	0.39	0.37	0.26	0.64	0.47	0.75	0.68	0.64	0.42	0.88	0.89
$\overline{x}/X$	1.0513	1.0392	1.0370	1.0262	1.0640	1.0468	1.0753	1.0683	1.0635	1.0417	1.0877	1.0887

4 ANALYSIS AND DISCUSSION

In order to determine whether the measured results are significantly affected by surface roughness, standard deviations of measured dimensions are compared with the average roughness of samples. The level of roughness for 3D printed samples is N10, and respectively average roughness is 12.5 μm [2]. Standard deviations for both base and scaled set are several times higher than average roughness, therefore surface roughness did not have any significant influence on the measured results.

The overall effect of anisotropic scaling could be assessed if the results of both base and scaled set are compared (Fig. 7). A comparison of average errors between the sets reveals a considerable reduction of errors for all scaled dimensions in the scaled set of samples. A smaller error reduction is obtained for the neck width (W1) which is not scaled by own scale factor but indirectly by the anisotropic scale factor of width (W).

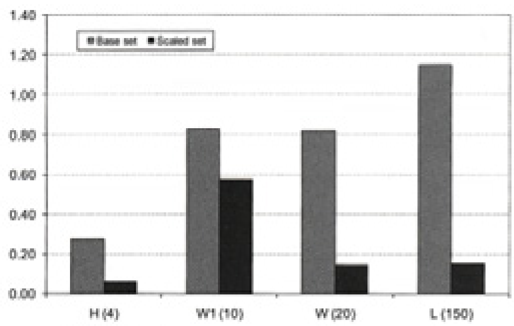

Fig. 7. *Average errors between sets*

A comparison of average relative standard deviations between the sets shows that there is no significant difference in deviations before and after scaling, except for the height of samples (Fig. 8).

The analysis of relative deviations for each experiment factor in the scaled set, reveals active relations within the considered factor. For dimensions: largest dimension – length (*L*) - has the lowest average relative deviation (1.000889), while the smallest – height (*H*) - has the highest relative deviation (1.015000). When comparing infiltrants: the samples infiltrated with the epoxy resin have the lowest average relative deviation (1.004735), while the samples infiltrated with the cyanoacrylate have the highest values (1.010592). The samples oriented along the building direction X have smaller deviations (1.004993) than those oriented along Y direction (1.009605). Finally, the samples printed with layer thickness 0,1 mm do not show any significant difference in relative deviation compared to those printed with layer thickness 0.0875 mm: 1.006682 to 1.007915.

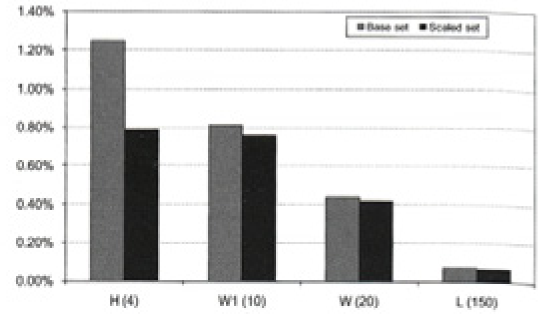

Fig. 8. *Average relative standard deviations compared between sets*

Considering particular combination and dimension, combinations 1YE and 2XW had the least average relative deviation of specimen's length (1.0003). For width, combinations 2YC (0.9998) had minimum and closest to it was 1XE (0.998), while for height it was combination 1YE (1.0038).

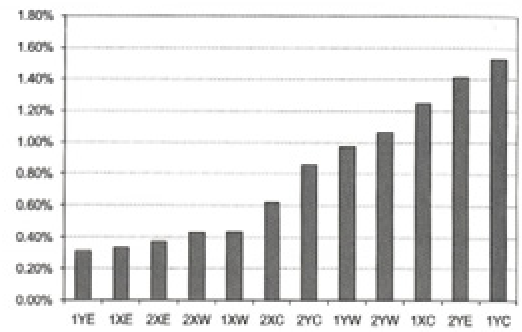

Fig. 9. *Sorted average relative errors of scaled set combinations*

A comparison of average relative errors for combinations of the scaled set reveals that the combination with the lowest relative error is 1YE (Fig. 9). The combination 1YC had the highest relative error. It is interesting to notice that the most accurate combination and as the second most inaccurate - 2YE share the same infiltrant type and building orientation. Also confusing could be the fact that the most accurate combination is printed with higher layer thickness as the second most inaccurate combination. Most likely the reason for this is that the accuracy of combination 2YE is significantly influenced by the operator's skills either during the cleaning of samples or while applying the epoxy resin. Relative errors of other combinations are equally distributed regarding the particular factor.

In order to understand completely the effect of factors on relative deviation and printing accuracy, we performed a factorial analysis of variance (ANOVA). Since there is a significant difference in relative deviations between the measured dimensions, a dimension is considered as an additional factor for ANOVA calculations. It is considered with 3 levels – length, width and height. Other factors and their levels are considered according to the experiment design. ANOVA of relative deviations is presented in Table 4. The abbreviations used for factors are: D - dimension; LT - layer thickness; O - orientation; I - infiltrant.

The ANOVA calculation reveals that the dimension of printed sample was the most influential factor on the relative deviation. Beside the dimension, sample orientation and infiltrant type also showed a significant influence on the relative deviation. However, the analysis did not prove any influence of layer thickness variations.

Despite the lack of influence when considered alone, the layer thickness variations had a significant influence in the interaction with the infiltrant type. The interaction of dimension and sample orientation is also strongly emphasized according to the analysis of variance. Other interactions of factors have either smaller or insignificant influence when compared to the critical value of Fischer's distribution with the probability of 0.95 and respective degrees of freedom (1; 180).

To avoid an oversight of the possible significant interaction of particular variants within a particular experiment combination, we also performed a differential analysis of the influence of particular factor variants within the other factor.

Table 4. *Anova of relative deviations in scaled set*

Factors	Sum of squares	Degrees of freedom	Mean square	Variance	Probability	F(0.95)
D	0.0073	2	0.0037	103	0.0000	3.89
LT	0.0001	1	0.0001	2	0.1306	3.89
O	0.0011	1	0.0011	32	0.0000	3.89
I	0.0013	2	0.0006	18	0.0000	3.89
D*LT	0.0001	2	0.0001	2	0.1335	3.89
D*O	0.0029	2	0.0014	40	0.0000	3.89
LT*O	0.0002	1	0.0002	4	0.0373	3.89
D*I	0.0008	4	0.0002	6	0.0003	3.89
LT*I	0.0020	2	0.0010	29	0.0000	3.89
O*I	0.0002	2	0.0001	3	0.0609	3.89
D*LT*O	0.0004	2	0.0002	6	0.0040	3.89
D*LT*I	0.0009	4	0.0002	6	0.0002	3.89
D*O*I	0.0005	4	0.0001	3	0.0145	3.89
LT*O*I	0.0006	2	0.0003	8	0.0004	3.89
D*LT*O*I	0.0006	4	0.0002	4	0.0027	3.89
Error	0.0064	180	0.0000			

For that purpose, a thorough reading of results for each combination and reading of appropriate multifactor charts were performed (Fig. 10 and Fig. 11).

Differential analysis reveals one particular effect in the interaction of dimensions and building orientation. Although the interaction of those factors appears significant for the experiment, it is mainly caused by big variances of height. Other dimensions did not show any significant variances regarding the building orientation.

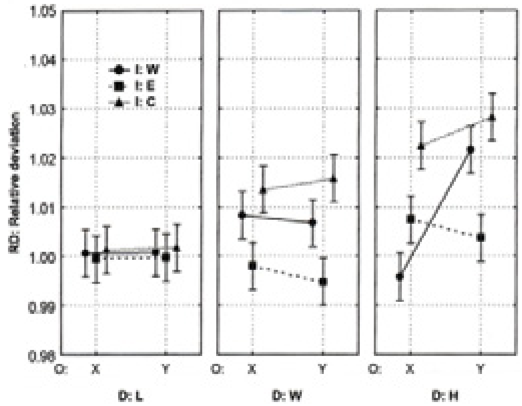

Fig. 10. *Average relative deviations for layer thickness 1*

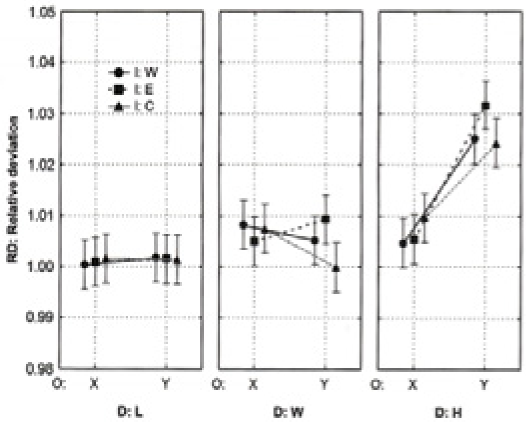

Fig.11. *Average relative deviations for layer thickness 2*

Multifactor charts show that relative deviations of samples printed with smaller layer thickness 2, are grouped in narrower clusters than relative deviations of larger layer thickness 1. Therefore, smaller layer thickness 2 provided a better overall precision of samples.

5 CONCLUSION

The obtained experiment results clearly show that the scaling of 3D printed samples provides a better dimensional precision of samples. Furthermore, the significant differences in relative errors and relative standard deviations between measured dimensions prove the adequacy of anisotropic scaling for samples with significant differences between the main dimensions. A limitation of the anisotropic scaling exists for dimensions that are not scaled directly with their own scale factor, as it was presented in this paper for dimension of neck width (W1).

Although a comparison of average relative errors reveals the combinations with minor errors, from the factorial analysis of variance it can be concluded that an appropriate combination of 3DP processing factors should be selected regarding the significant dimension of the printed sample. For the accuracy of the largest dimension, i.e. length, the sample should be printed with default layer thickness 0,1 mm, oriented toward building direction X and infiltrated with the epoxy resin. Since there is a significant interaction of factors, i.e. layer thickness and the infiltrant type, from differential analysis it could be concluded that a combination of the default layer thickness and infiltration with the wax is also the appropriate selection for both considered building orientations. The accuracy of the medium dimension (width) could be improved if the printed sample is infiltrated with the epoxy resin, while other processing factors did not show any significant influence. The accuracy of the smallest dimension (height) could be improved if the printed sample is infiltrated with wax or epoxy resin and the sample is oriented towards building direction X.

From the overall analysis the following could be concluded for the particular processing factor:

- The layer thickness: smaller layer thickness provides better overall precision of samples.
- The infiltrants: the most accurate are samples infiltrated with epoxy resin and

the least accurate are samples infiltrated with cyanoacrylate.

- The building orientation: the samples oriented towards direction X are more accurate than samples oriented towards direction Y.

Further researches could also be performed to improve the accuracy of the considered 3DP system like the experimental measurement of test sample behaviour and a finite-element based simulation using a non-linear visco-elastic constitutive model similar to the one published in [13].

Although it is possible that some of the presented conclusions are valid for similar machines or even rapid prototyping techniques, all conclusions should be considered only for the selected 3D printer and selected materials. New materials and new equipment for 3D printing are developed constantly and could demand new analyses.

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