Developing Capability Profile for the Three Dimensional Printing Process

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Well-established Layer Manufacturing (LM) technologies, such as Stereolithography (SLA) and Selective Laser Sintering (SLS) have over their years of existence become well defined by numerous researchers. Subsequently, the capabilities of these technologies are sufficiently documented and reliable for use. Several other emerging LM technologies still lack reliable information concerning their respective capabilities regarding accuracy, strength, surface finish, build time and cost. Many questions related to different factors influencing these characteristics need to be answered so that users are able to control their processes better, and designers to define their expectations and determine requirements. Applying appropriate statistical techniques, this paper reports on continued research towards developing the capability profile for the ZPrinter 310 System from Z Corporation. A matrix of different material combinations was developed and the effects on accuracy, surface roughness, build volume location and time for each combination were investigated.

Nomenclature

R_a	Roughness Average, [μm]
RP_{ij}	Rapid Prototyping process chain for powder material *i* and infiltrating agent *j*, [dimensionless]
P_{calc}	Calculated probability, [dimensionless]
P_{crit}	Critical probability, [dimensionless]
H_0	A null hypothesis, [dimensionless]
H_1	An alternative hypothesis, [dimensionless]

Keywords
Layer Manufacturing, Accuracy, 3D Printing, Capability Profiles.

1. Introduction

The Three Dimensional Printing (3DP) based on MIT's (Massachusetts Institute of Technology) ink jet technology and utilized by Z-Corporation in a variety of printers is considered to be one of the most future oriented rapid prototyping (RP) systems. It is classified as a typical "concept modeller", a low-end system, and represents the fastest RP-process. It is spreading rapidly worldwide and within only three years it has become the third most widely used Layer Manufacturing (LM) equipment[1].

With the resourceful use of different materials in combination with the high building speed and suitable post treatment techniques, the technology's classification as a concept modeller has expanded to include a wide variety of additional applications far beyond the original expectations of only generating design iterations. These applications include pattern making for investment and vacuum casting as well as for bridge tooling, design aids for tooling equipment, anatomical modelling and prototyping of human organs and implants, reconstructive surgery aids and others. With the colour capabilities of the new range 3DP machines, this process is able to satisfy further scientific and engineering needs such as molecular modelling, thermal, mould flow, and finite element analysis.

It is, however, remarkable how for example the question of accuracy, even in most successful case studies is carefully avoided. Some publications give only a superficial view on the matter without a proper scientifically founded in-depth analysis of the accuracy problem[2, 3]. Indeed, for a large variety of applications the question of accuracy is irrelevant - conceptual modelling, medical applications, design aids, anatomical modelling to mention a few. Still, for some of the most important applications such as fit and function tests or pattern making for a number of moulding and forming processes, the question of (guaranteed) accuracy is of prime importance.

For new endeavours that sprout from the growth of current technologies into new machines, processes and applications to be successful and fully exploited, it has become imperative to better understand what the capabilities of the technologies are. Once the capability of each process has been defined, a foundation is laid from which all role players can make informed decisions towards matching appropriate processes to their demands. Thereby the most suitable process chain can be selected to satisfy multi-criteria requirements.

This paper deals with current research towards the building of a full capability profile - accuracy, surface roughness, strength, elongation, build time and cost - of this important process. It is based on carefully selected benchmarking parts and procedures, and includes the tools for reliable data processing and

MATERIALS (i)	INFILTRATING AGENTS (j)							
	None (j=1)	Z-Bond10 (j=2)	Z-Max (j=3)	Wax (j=4)	Synair (j=5)	Z-Bond100 (j=6)	Z-Snap (j=7)	Zi580 (j=8)
zp14 (i=1)	X	X	X	X	-	-	-	X
Zp15e (i=2)	X	X	-	X	X	-	-	X
Zp102 (i=3)	X	-	X	X	-	X	-	X
Zp250 (i=4)	X	-	X	X	-	X	X	-
ZCast 500 (i=5)	X	-	-	-	-	-	-	-

Table 1: Materials compatibility matrix

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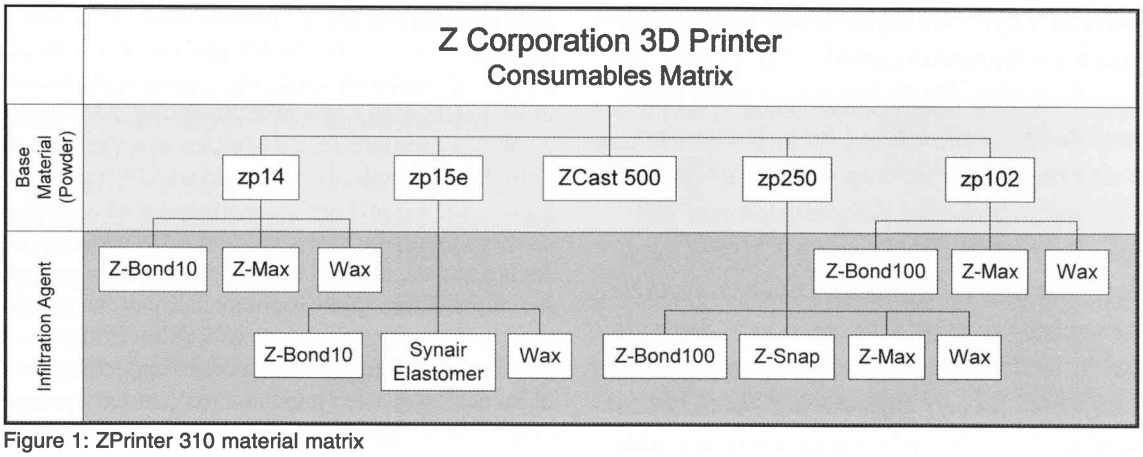


Figure 1: ZPrinter 310 material matrix

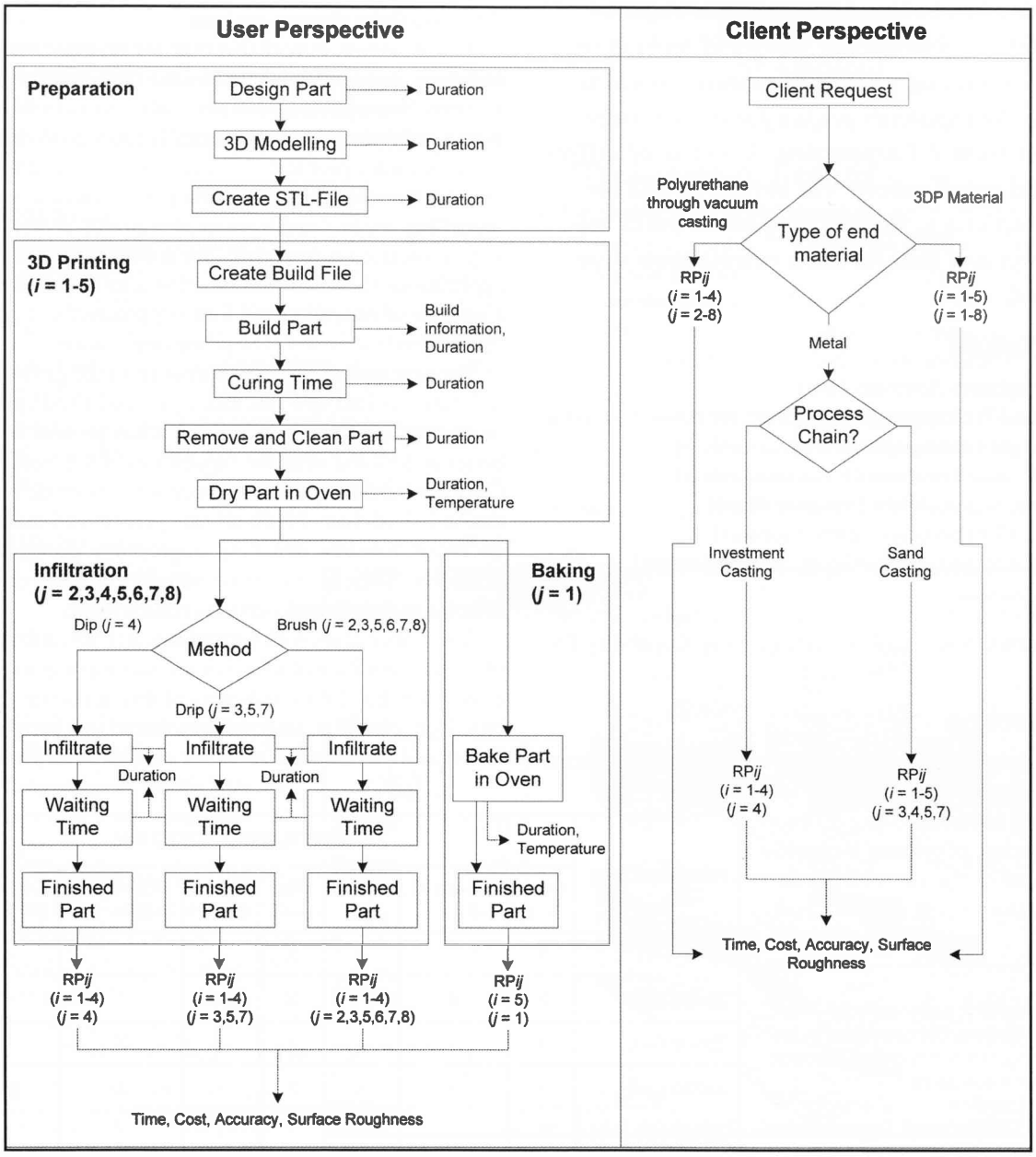


Figure 2: The ZPrinter 3DP process chains

interpretation. The study builds on previous work[4], and expands to include investigations on the ZPrinter 310 System, primarily focusing on the aspects of the capability profile that relate to accuracy, surface roughness, time and cost. The influencing factors taken into account are:

- ❑ Materials used (MU)
- ❑ Nominal Dimensions (ND)
- ❑ Build Orientation - in relation to the different axes (BO)
- ❑ Infiltrating agent (IA)

For the purpose of this study, testing was done on a single ZPrinter 310 machine available at the RPD Laboratory of Stellenbosch University. Figure 1 shows the different material combinations considered during the study.

2. Capability Profiles - Essentials

An important aspect of this study is to define the process chain for 3D-Printing more clearly. This process chain includes not only the fabrication of the part, but also the various processes that precede and follow it. The process chain is considered from two different points of view - from that of the user (service provider), as well as from that of the customer-designer, production planner, component manufacturer.

Table 1 shows the compatibility of each of the powder materials with the various infiltrating agents. The practical meaning hereby is the large variety of possible applications. Each cross (x) indicates a compatible combination. The matrix also shows the coding scheme for the materials and infiltrating agents used during this study. Powder materials have been denoted the letter *i*, while the infiltrating agents with the letter *j*. This coding scheme was used extensively to identify different benchmark parts.

Figure 2 shows a representation of the 3DP process chain depicted from the two different perspectives as mentioned above. Depending on the set of requirements such as material, time, cost, accuracy and model quality, it presents either the client or the user with the set of process steps involved to gain the desired results.

A particular client may want to have a part made from either plastic or metal. This condition will dictate which type of casting method (as secondary process) to use. This in turn will dictate which specific sets of material and infiltrating agent combinations will be best suited for the customer's specific needs. The client will also have certain requirements such as to cost, time, surface roughness and accuracy for his model, prototype or pattern.

In addition to showing the steps involved from a prototype production point of view, the different points of data accumulation for this study have also been indicated.

3. Research Approach

The steps undertaken to reach the stated objectives can be summarized as follows:

- ❑ Research the different process links, materials, infiltrating agents and post-treatment procedures associated with 3DP and its applications.
- ❑ Document the applicable process chains for 3DP.
- ❑ Design a suitable benchmark part to be used to obtain the necessary information for this study.
- ❑ Fabricate benchmark parts of the different powder materials and their corresponding infiltrating agents, using the appropriate processes.
- ❑ Apply experimental procedures to obtain measurement results.
- ❑ Analyse, interpret and compare the data obtained from the measurements.
- ❑ Make recommendations for future research.

3.1 Benchmark part development

The execution of benchmarking tests is a traditional practice and necessary for all kinds of high productive and capital-intensive equipment. The objective of the benchmarking can, however, differ substantially from application to application. In the case of this study, a benchmarking procedure was developed with the sole purpose to evaluate the performance capabilities regarding accuracy and surface roughness of the 3DP process as implemented by Z-Corporation.

Extensive literature review was performed during a previous study[4] and resulted in the development of a benchmark part (Figure 3), which compares same type features in equivalent quantities, but created in each of the three build axes. The main purpose of this benchmark part was the investigation of the achievable dimensional accuracy over the whole build volume. On this ground also the size of the benchmark part (190 x 190 x 190 mm) was chosen covering adequately the entire build space

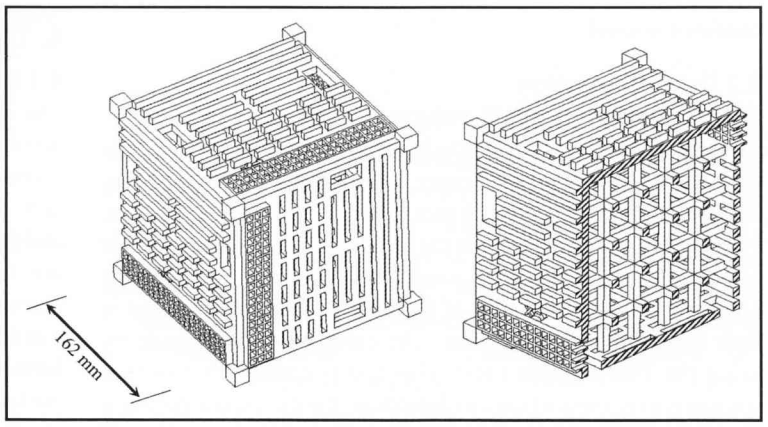


Figure 3: Benchmark part for dimensional accuracy studies[4]

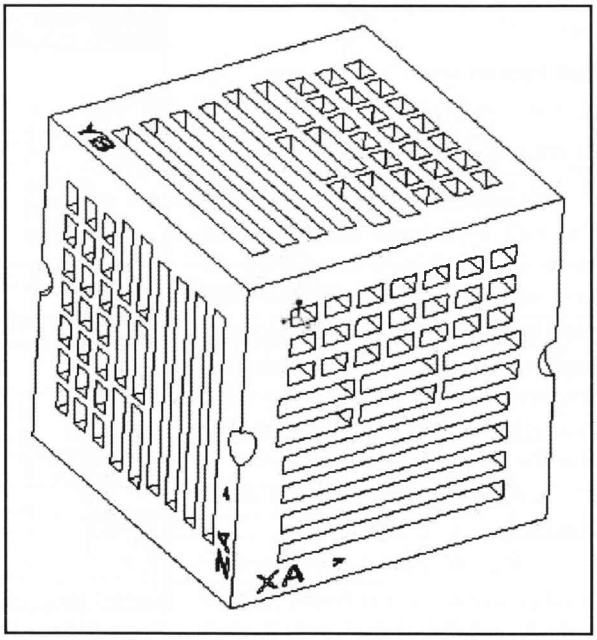


Figure 4: The bencahmark part used in this study

(200x250x200).

In line with the objectives of this study this benchmark design had to be modified accordingly (Figure 4). By decreasing its size, several parts can be produced simultaneously. In this way parts that are infiltrated differently still originate from the same build, which would allow comparisons to be made between the parts within one production batch, thereby minimising other possible influencing factors. In addition to this, the effect of the position within the build volume could now also be investigated.

In order to decrease the size of the part, the features with nominal dimensions of 162 mm were removed from the previous benchmark part design. The remaining nominal dimensions were chosen to represent small and medium lengths, and were set as 2, 6, 18 and 54 mm.

$$x_0 = 2$$
$$x_i = 3x_{i-1} \qquad i = 1,2,3 \qquad (1)$$

The new benchmark part also had sufficiently flat surfaces to allow for the surface roughness measurements to be taken directly on it, on each of the three build directions.

The next step was to determine the quantity of slot features for each nominal dimension that would be required for statistical certainty. Using the *t*-distribution, combined with historical data from measures taken before[5], minimum sample quantities for each nominal dimension category were calculated for a 95% confidence level.

3.2 Data acquisition

3.2.1 Location in build volume

The first aim of this study was to investigate whether the location in the build volume of the printer would influence the resulting dimensional accuracy of the parts produced. For this purpose, 9 parts were spaced equally in the build volume (8 in each corner and one in the centre) and a comparison was made between the 18 mm nominal dimensions of the same build directions, but in their different build locations. The comparison was made by using the Two-Sample *t*-test. This test is commonly used for comparing two sets of data to determine the difference between the means of the two samples. The comparison is in the form of a hypothesis test and can be stated as follows:

Null hypothesis:

$$H_0 : \mu_1 - \mu_2 = \Delta \qquad (2)$$

Alternative hypothesis:

$$H_1 : \mu_1 - \mu_2 \neq \Delta \qquad (3)$$

The null hypothesis states that the mean of sample 2, subtracted from the mean of sample 1, will be a certain value denoted by Δ. Test statistics and degrees of freedom were calculated, from which *p*-values were obtained. A critical *p*-value (α) was selected at 5% significance. The test for the proposed hypothesis is:

- $P_{calc} < P_{crit}$: Reject H_0 in favour of the alternative H_1
- $P_{calc} > P_{crit}$: H_0 cannot be rejected

In other words, if it is found that for example, P_{calc}=0.001 while P_{crit}=0.05, it will have been established that the means of the populations of sample 1 and sample 2 differs from Δ at a level of significance of 5%.

3.2.2 Measurement procedures

The different combinations of appropriate infiltrants for each build material have been shown in Table 1. From this table it is evident, with the exception of ZCast500, that each material has 5 different possible combinations. Each benchmark part in a specific build was infiltrated with a different appropriate infiltrating material. The infiltrated benchmarks were measured on a Mitutoyo Bright 710 CMM (Coordinate Measuring Machine). The quoted accuracy of the CMM and probe system is ± 0.006 mm for the size of measurements. A program was written in order to speed up and standardise the required measurements. The measurements were processed into the subcategories for each nominal dimension per benchmark part. From these, average values and standard deviations for each nominal dimension were calculated.

3.2.3 Surface roughness measures

The surface roughness was calculated by taking 4 measurements of R_a on each side of each benchmark cube. The average of these 4 measurements was calculated to give the final reported surface roughness value. In all cases the cut off length for the calculation of R_a was 0.25mm.

4. Discussion of Results

4.1 Influence of build location on part accuracy

The investigation of the influence the build location has on part accuracy was performed using the Zp102 plaster based powder. To ensure that only the printing process would influence accuracy, all measurements were taken on parts directly after removal and depowdering from the printer, with no further post-processing. Figure 5 below indicates the position of each of the 9 cubes that were printed at the extremities of the build volume. Location 4 is referenced to the position at the bottom right-hand corner furthest away from the origin, while position 9 is in the centre of the build volume. On each cube, 36 dimensions (18 mm) were

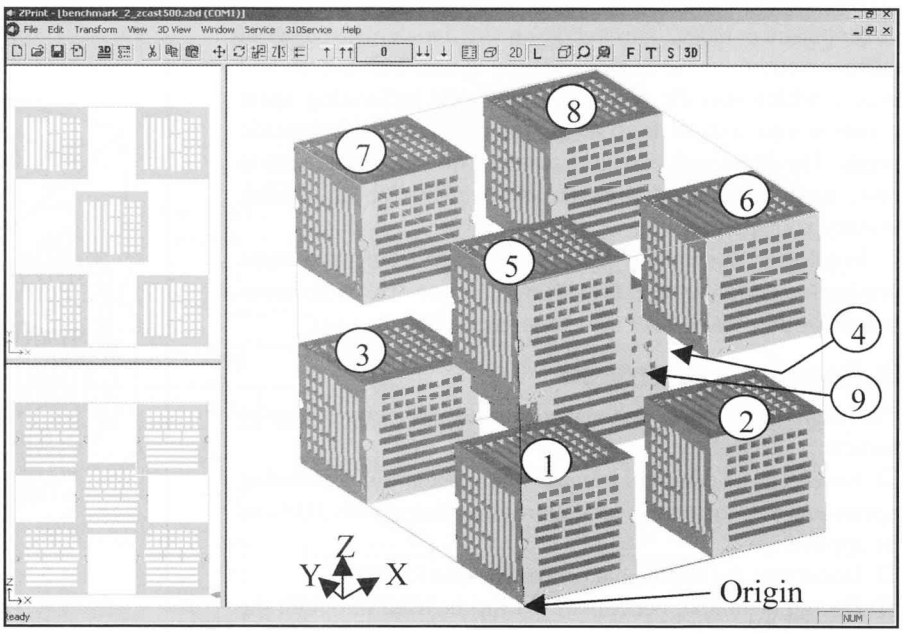


Figure 5: Parts location

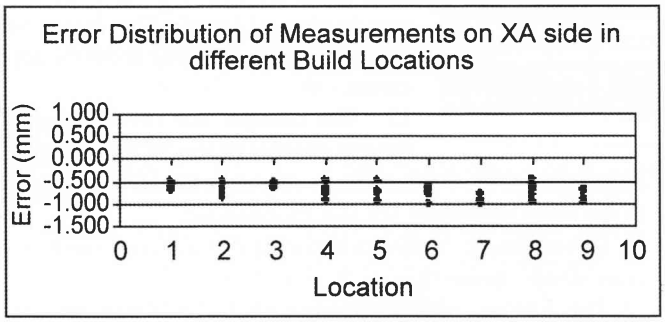
measured (12 per build axis). A total of 108 representative measurements for each build direction were investigated.

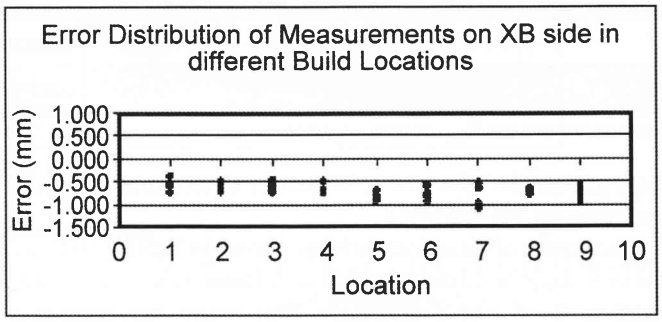
The results of the measurements are shown in Figure 6 below. The graphs on the left (XA, YA, and ZA) refer to the sides of the cubes that are closest to the axes that meet at the origin. The opposite sides of each cube are then denoted XB, YB, and ZB respectively. The averages and standard deviations given in the table below the graph combine both the A and B sides of the respective X, Y and Z build directions. Initial inspection reveals that the measured errors in the X and Y direction of each build position are roughly centred around -0.5 mm. This value seems quite large, but the errors mostly have narrow distributions, thus enabling this error to be compensated for in future. Measured values in the Y-build direction are the most stable. The reason for this is not yet clear, but may be associated with the fact that the action of spreading the powder takes place in the X-direction. The Y-build direction may not be affected by this action.

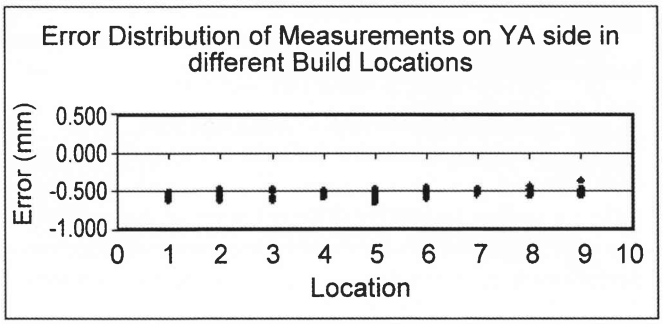
A more concerning observation, however, is seen in the disparities between measured values in the Z build direction. The encircled points in the bottom two graphs refer to measures taken on the cubes that were on the top layer (including location 9 in the middle of the build volume). Their values are distinctly different in magnitude from cubes built in the bottom layer of the build volume. The bottom cubes (1 to 4) display much higher accuracy with low dispersion.

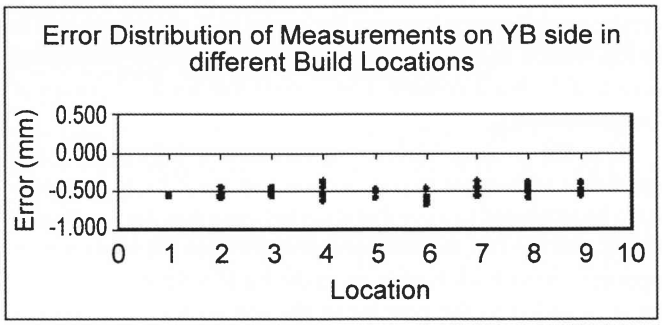
In order to draw final statistical conclusions to determine how the build location influences part accuracy, the Two-Sample *t*-test defined above was applied to only the data from the cubes

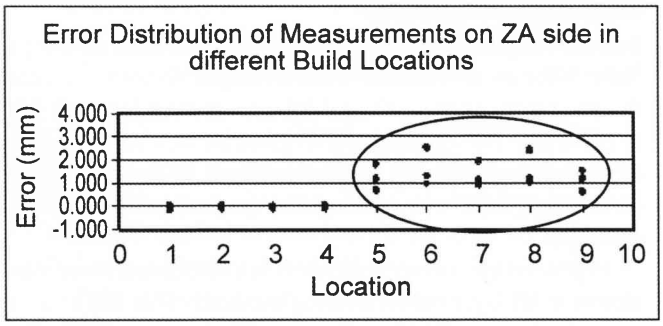
Location 1: XA, YA, ZA	Location 2: XA, YA, ZB
Location 3: XB, YA, ZA	Location 5: XA, YB, ZA

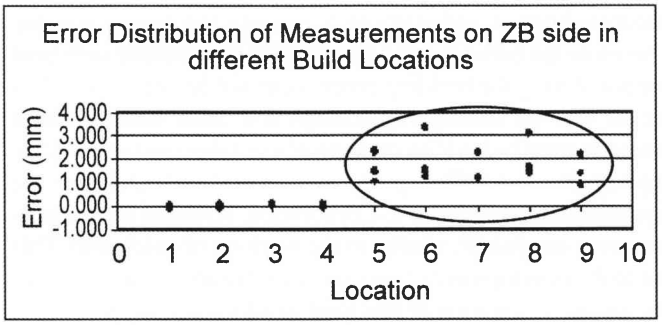












		Build Location								
		1	2	3	4	5	6	7	8	9
X	Avg	-0.564	-0.633	-0.594	-0.689	-0.832	-0.748	-0.823	-0.702	-0.763
	Std Dev	0.111	0.112	0.081	0.118	0.148	0.137	0.188	0.133	0.118
Y	Avg	-0.554	-0.540	-0.521	-0.528	-0.547	-0.566	-0.501	-0.491	-0.502
	Std Dev	0.026	0.054	0.051	0.068	0.058	0.070	0.055	0.055	0.064
Z	Avg	-0.045	-0.016	-0.024	0.015	1.401	1.802	1.413	1.791	1.290
	Std Dev	0.083	0.069	0.074	0.086	0.560	0.881	0.521	0.767	0.519

Figure 6: Error distributions of 18mm nominal dimensions at different build locations

Build Direction Being Investigated	Sides being Compared					P_{calc}	P_{crit}	Difference at 95% significance
	Group 1		vs.	Group 2				
	Location	Side		Location	Side			
X	1	XA	vs.	2	XA	0.3810	0.05	NO
X	1	YA	vs.	2	YA	0.5868	0.05	NO
X	1	ZA	vs.	2	ZB	0.1406	0.05	NO
Y	1	XA	vs.	3	XB	0.3041	0.05	NO
Y	1	YA	vs.	3	YA	0.3576	0.05	NO
Y	1	ZA	vs.	3	ZA	0.7154	0.05	NO
Z	1	XA	vs.	5	XA	0.0242	0.05	**YES**
Z	1	YA	vs.	5	YB	0.3326	0.05	NO
Z	1	ZA	vs.	5	ZA	0.0003	0.05	**YES**

Table 2: Values for P_{calc} at 95% significance

at the extremities of the build volume. The locations that were compared are the following:

The results of these comparisons, shown in Table 2, indicate that only the Z build direction has an influence on the measurements in the X and Z directions. This means that there is a significant difference between the group of X measurements in the top section and the group of X measurements in the bottom section of the build volume. The same is true for the 2 groups of Z measurements.

From these observations the conclusion follows that the significant influences to part accuracy in the Z build direction has to be attributed to a combination between powder and binder weight, and the fact that unbound powder does not lend enough support to parts built higher up in the build volume. As binder liquid is added to the powder in the top section, the powder becomes heavier and starts to 'sink' into the excess powder. Therefore the belief that the free powder will provide sufficient support during the building process can not be confirmed. This means that for example overhangs and other delicate shape elements must be build by creating of a suitable (and removable) support structure. This problem was realised lately by the equipment manufacturer Z-Corporation, referring to this phenomenon as *squash*[6], similar to the working of quicksand. This led to the development of specialised software features providing an aid for creation of this kind of additional support.

4.2 Accuracy

The measured errors for all 17 cubes are presented in Figure 7. The number 17 constitutes the different combinations of powder materials and infiltrants as shown in Table 1, but with the exclusion of Zp14 due to its discontinuation; furthermore accuracy studies had already been performed on this material[5]. The figure indicates the measured deviation in each of the build axes per combination of build powder and post processing infiltrant. The reported error values in this figure are average values of measurements taken - each according to the following sample:

- 2mm - 43 measures per build direction
- 6mm - 42 measures per build direction
- 18mm - 12 measures per build direction
- 54mm - 8 measures per build direction

There are a total of 8 infiltration agents which are sequentially numbered as columns at the top of each graph. The absence of X, Y, or Z deviations at certain places on the graphs signify that these build materials were not processed with a specific infiltrant material - thus no measures were taken.

Some observations that can be made from this figure include the following:

- The Zp102 powder is the most accurate of the four powders (mostly within ±0.3mm and better), with the ZCast500 displaying the largest magnitude of errors (within ±1.0mm). This fact is very important when deciding about the application.
- The changes that occur during the baking process of the ZCast material to dimensions in the Y direction are very significant, while changes in the other directions are less pronounced.
- Deviations in Y-direction for Zp250 material seem to be consistently worse than its X- and Z-directions.
- The infiltrant material to use with the build powders are as follows:
  - Zp15e - Synair Elastomer
  - Zp102 - Wax, Z-Bond 100, and Z-Max
  - Zp250 - Z-Bond 100, Z-Snap, and Wax
- The percentage errors for different nominal dimensions for each material are not the same. This suggests the need for different scaling factors for different nominal dimensions - i.e. dynamic scaling factors are required to compensate for expected deviations in each build direction for different dimensions.

4.3 Surface roughness

Surface roughness measures were taken on each of the parts built. Four measurements were averaged to give the results shown in Table 3 below. The measured values range from 1.93 µm to 18.72 µm. The Zp102 material gives the best surfaces, due to its fine grained powder. And as expected, in general the worst surface roughness was measured across the layers in the Z build direction.

In general the surface roughness is a substantial issue related almost to all layer manufacturing methods. This lies to a large extent in the specific of the process. The layer type of building an object by adding materials as opposed to the subtractive methods characterised by removing material creates already the conditions for certain roughness. Obviously, the bigger the layer is the lower the surface roughness will be. This is why the manufacturers of layer devices don't usually give a quantitative characteristic of the surface roughness of their process. The best surface roughness is achieved by the Solidscape machines due to the very fine layer thickness of 13 µm. Hereby a surface roughness of 0.8-0.16 µm is achieved. This is however in big controversy with the building speed of the machine. The layer thickness of the here discussed 3D printer Z310 depends on the material used and can be set down up to 80 µm with a still high

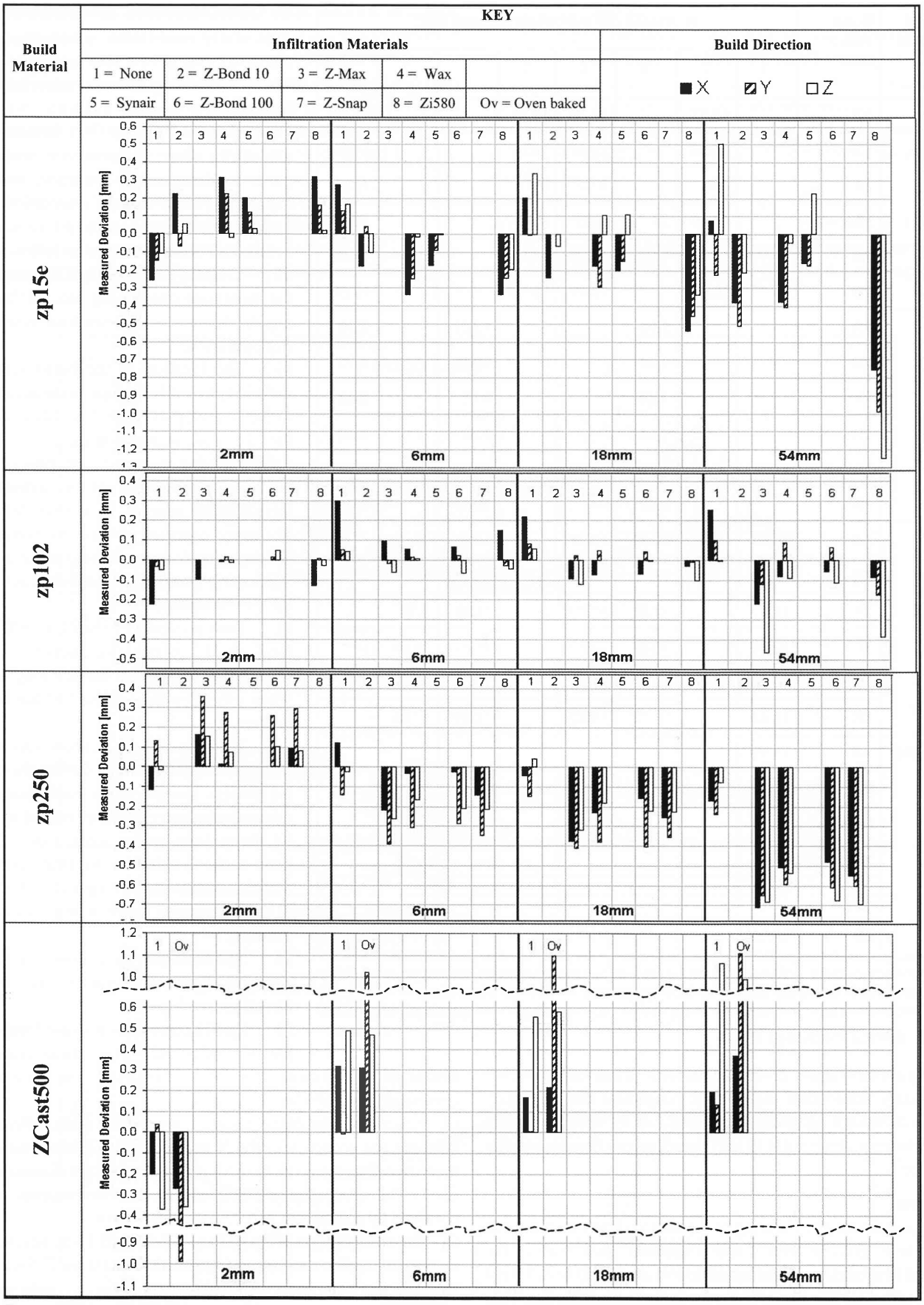


Figure 7: Measured deviations of 3DP material-infiltrant combinations per build axis

Build Material	Build Axis / Side	R_a Values per Infiltration Material [µm]							
		1	2	3	4	5	6	7	8
zp15e	XA	1	13.87		12.19	13.04			12.40
	XB		15.54		12.67	14.67			14.85
	YA		8.61		9.42	9.91			11.85
	YB		10.49		9.93	9.88			10.14
	ZA		16.72		16.40	14.69			17.66
	ZB		16.43		12.37	19.15			17.00
zp102	XA	2		2.09	3		13.07		6.20
	XB			6.30			12.63		4.73
	YA			4.05			8.20		3.62
	YB			1.93			7.37		9.63
	ZA			3.13			14.13		5.84
	ZB			2.53			16.15		10.41
zp250	XA	10.89		12.22	13.37		14.07	12.19	
	XB	11.06		12.71	3.18		12.33	12.54	
	YA	11.47		12.06	10.00		11.29	9.93	
	YB	10.70		10.34	10.39		11.84	10.85	
	ZA	13.17		14.99	14.93		13.65	18.39	
	ZB	12.68		18.72	15.83		16.49	17.96	
ZCast500	XA	13.19							
	XB	12.71							
	YA	12.11							
	YB	11.89							
	ZA	15.04							
	ZB	16.10							

[1] The benchmark cube unfortunately broke before surface roughness measures were taken
[2] The parts were infiltrated before surface roughness measures were taken
[3] The benchmark cube unfortunately broke before surface roughness measures were taken

Table 3: Surface roughness results

building speed of about 25-30 mm per hour. It has to be however also clearly stated that the surface roughness can be easily improved through additional treatment, i.e. by sanding. In this way surface roughness of 0.15 µm (almost mirror finish) could be achieved[7].

4.4 Time

The required time for building of a part on a LM machine will always be of great interest. Table 4 shows a breakdown of the time (infiltration time not included) associated with the different aspects of the 3D Printing process for each of the materials. This is in accordance with the process chain as shown earlier in Figure 2. The times relate to the 3D printing of 5 benchmark cubes per material (70 mm nominal side dimension), which constitutes a total printed volume of 681.1cm^3 per print session.

5. Conclusions and outlook

This study contributes substantially to the development of a 3DP capability profile by combining different materials and infiltrating agents suitable for Z-Corporation's ZPrinter 310 System and evaluating these combinations with regards to dimensional accuracy, surface roughness, build volume orientation and building time. Some of the experimental results can be summarised as follows[8]:

- ❑ Creating parts with Zp102 material is the most time-consuming process; building Zp15e parts is the least time-consuming operation.
- ❑ The location in the build volume definitely has an influence on the accuracy of the created parts. The Z-build direction has the most significant influence. It is recommended that parts are printed directly on the printing platform so that they have a stable support. Parts with delicate geometry, especially with cantilever-type overhanging features, should make use of supporting geometries (provided now by the ZPrint software).
- ❑ Parts printed with the ZCast500 material display better characteristics with regard to accuracy and surface roughness when placed in the left half of the build volume.
- ❑ The ZCast500 parts show very little change in measurements during the baking process, except in the Y-build direction where the measurements increased in size by about 1mm in the worst cases. This leads to the conclusion that important dimensions must be placed in either the X or Z build direction when using ZCast500 material.
- ❑ Zp250 displays the most consistent accuracy characteristics across the 3 build directions.
- ❑ Zp102 is the most unbiased and display very accurate average measurements across all 3 build directions. This is the case for all the Zp102 combinations with the infiltrant agents.
- ❑ Apart from the ZCast material, there is not a big difference between the accuracy of the X and Y build direction, making these two directions the best for placing important dimensions.
- ❑ The most accurate and unbiased measurements were obtained by combining Zp102 with Z-Bond100.
- ❑ The combination of Zp102 and Z-Max yields the best result in terms of surface roughness, followed by Zp102 and Zi580. The worst surface roughness for Zp102 was obtained in combination with Z-Bond100.
- ❑ Zp15e material yields the best surface roughness in combination with Wax. The worst surface roughness for Zp15e was measured in combination with Zi580.
- ❑ Zp250 material also yields the best surface roughness in

Activity	Time for Activity (in minutes) per Material				
	zp14	zp15e	zp102	zp250	ZCast500
Build	210	163	308	264	266
Curing	30	36	63	121	39
Remove/Clean	47	60	75	55	65
Totals	**287**	**259**	**446**	**440**	**370**

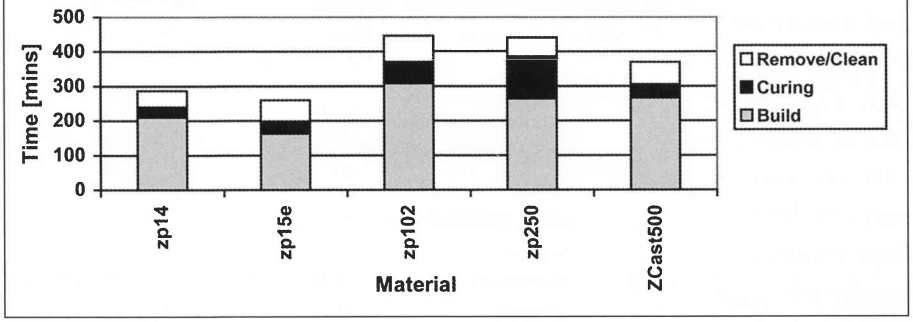


Table 4: Build and post-processing times associated for each material

combination with Wax, and its worst with Z-Snap.

❑ ZCast500 shows the best surface roughness results in the left side of the build volume (locations 1 and 2), while the back, right corner of the build volume yields the worst results in this regard.

The results of this study has gone far in establishing the capability profile for the ZPrinter 310 System and will be used as a platform for further studies in this direction. The following issues are envisaged for future research:

i The influence of the location in the build volume needs further attention. This study did, however, prove that a more in-depth study will yield very valuable information for scaling and part design requirements. The question of dynamic scaling factors in different build axes becomes an interesting and challenging avenue of future software research.

ii The influence of the different environmental factors on the created parts' characteristics is also not yet fully known and understood. A proper process model will enhance the capability profile when using different materials and infiltrating agents.

iii More research must be done to verify the predicted accuracy of part dimensions according to derived equations that are discussed by Louw[8]. There might be other equations or functions that will deliver a better prediction for the data, and these should be more thoroughly investigated. The results of accurately being able to predict dimensional error in each build direction will be an important aspect for developing dynamic scaling factors as suggested above.

iv The influence of the bleed compensation on the parts' characteristics needs also further investigation. Bleed occurs when a liquid is poured onto a porous material, such as when binder is laid down onto the powder during printing. The spreading action of the liquid is defined as "bleed". The printer's software estimates the edge of the part and arranges laying drops of binder in the middle of the edge. When bleed compensation is used, the printer compensates where it lays the binder so that the bleed is at the edge of the part. This results in a sharper and more accurate model. The effects of this compensation on accuracy need to be investigated.

v Future research should look at the entire process chain using 3DP as core technology, involving also the appropriate secondary processes such as casting and forming.

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