Errors in different geometric aspects of common engineering parts during rapid prototyping using a Z Corp 3D printer

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Abstract The aim of this paper is to analyse dimensional errors and repeatability of commonly used engineering parts, including a metric bolt, a gear and a shaft, produced by rapid prototyping. The parts were designed by a SolidWorks software package and printed by a ZPrinter 450 from Z Corporation where ZP150 powder and ZBond 90 infiltration were used. In most cases, the dimensional errors on produced parts were within acceptable limits. However, the process was determined to be unsuitable for features requiring very high dimensional accuracy and good surface finish. The influence of the stacking effect on the parts became significant in the case of longer parts and was proportional to the z axis dimension of a part. The accuracy and repeatability of a produced part depended on the part's orientation. Dimensions in the z axis direction showed very good repeatability, but the accuracy decreased with the increase of length. On the other hand, the repeatability in the xy plane was not as good compared to the accuracy in the same plane.

Keywords Rapid prototyping · 3D printing · Dimensional error · Repeatability

1 Introduction

Rapid prototyping (RP) is defined as a generative manufacturing process where a part is built by adding material, instead of detracting material from an existing part [1]. The material is added layer by layer in the direction of the machine's z axis, until the part is completed [2–4]. Various RP processes were developed in the late 1980's [2]. Since then, there has been constant development in terms of build accuracy, speed, surface quality and mechanical properties [5]. Most frequently, the differences among various technologies is in the material used to build the part and the technology used to bind the materials together [6, 7]. Rapid prototyping offers an efficient solution to most of the problems encountered when conventional manufacturing methods [8, 9]. The time saving occurs not only in the manufacturing process but also in the design stage, where there is no need to adjust the design to make the part manufacturable with the least possible difficulty [2]. This means that RP provides the user with design freedom, where a part of any shape can be produced, without consideration of the manufacturing process. Thus, this method has the potential to produce parts in high volume in the future. However, the mechanical properties of the products are very difficult to define, as these depend on the individual RP technique and material used [7]. Selective laser sintering (SLS) and three-dimensional (3D) printing are rapid prototyping technologies which have lower costs and shorter manufacturing times than traditional stereolithography (SL) [10–12]. However, the quality and precision of different rapid prototyping (RP) systems have not yet been established [10, 13].

RP processes introduce errors in the parts which result in dimensional differences between the CAD model and the produced part. Masood and Rattanawong [14] studied the

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influence of part orientation on the volumetric error. A special algorithm was developed to determine the relationship between part orientation and minimum volumetric error. This has been verified analytically and experimentally for parts of different complexity. The algorithm is based on slicing the model into layers to determine the resulting complex contours. Then, the volumes of these contours are calculated for different orientation angles in the xyz coordinate system. A total volumetric error is calculated by adding the volumes of all the layers in the various individual orientations. The orientation angle with lowest total volumetric error is then chosen as the desired one.

Dimitrov et al. [15] studied the linear accuracy, precision, repeatability and obtainable dimensional tolerances in several case studies for the 3D printer of Z Corporation. The factors that influence the accuracy are the material used, nominal part dimensions, build orientation, geometric features and their topology, wall thickness, post-treatment, and infiltrating agents. It is possible to use scaling factors of unity on the machine itself for a specific material, process axis and magnitude of the nominal dimension. Only the accuracy of nominal dimensions of the parts was studied, but sufficient details of the accuracy variation across different features of individual parts were not included.

Pandey et al. [16] conducted studies on the part orientation in stereolithography and fused deposition modelling (FDM). It was found that a system that considers all possible orientations is necessary, unlike one that considers only a few preselected orientations of the parts where surface profile characteristics are used as a base.

Alexander et al. [17] studied the staircase effect which is present in all layered manufacturing processes. The relationship between the staircase effect and the shape of the part was proven to have a significant influence on the part's surface quality.

Tong et al. [18] applied a software compensation method to the SLA machine. The compensation process began by designing a special part composed of 169 cylinders at 13 height levels. By measuring the position of the top central point of each cylinder, it was possible to obtain the function of its nominal position and the error coefficient. Five hundred and seven independent equations were obtained, which are equivalent to 42 coefficients. These were used to compensate for machine error by making adjustments to the CAD model. The compensated parts showed improvement in the dimensional accuracy; however, the cylindrical or spherical features were improved by a very small amount. Furthermore, the compensated parts showed no improvement or worsened in the z axis dimension, due to the layer quantization, which signifies that a face of the part, which should have been on a single layer, was found to be on multiple layers.

This paper investigates the dimensional error and repeatability in the RP process using a Z Corp 3D Printer. Geometric error is defined as the difference between the dimensions of the 3D CAD model and the corresponding dimensions of the part produced. This is directly related to the staircase effect, layer thickness and the part's shape. Improvement in the part's accuracy in RP has been reported by various authors for simple and more complex parts in numerical form. As a result of this approach, it is frequently impossible to declare the achieved accuracy to be satisfactory for engineering prototypes. Furthermore, the conducted studies mostly focus on fused deposition modelling, stereolithography, selective laser sintering or other processes [3, 14, 15]. There has been a significant and constant improvement in all aspects of quality in 3D printing in the past several years which is expected to continue in the future. The aim of this paper is, therefore, to study the achievable accuracy and repeatability of typical engineering parts. Those parts are chosen with respect to their frequent usage and standardization. Comparing the dimensions of printed parts with the tolerances designated by industrial standards creates the possibility to declare the parts accurate or not, instead of simply expressing the results in a numerical form. This project is focused on the parts which are at the end of the development process and require testing for fit and function, not for the parts produced for direct use.

2 Experimental work

Three parts were produced for this study. The first part is a specially designed shaft with various features. In general, it is similar to an automobile steering shaft, with a hollow inside to a certain length from the edge. The second part is a single $M20 \times 2.5$ bolt which has been chosen because of its cylindrical shape with the thread profile cut along a helix. The third part is a simple gear with high accuracy demands. This part features a hole for a shaft assembly with a specified tolerance range. The combination of the features of these three parts provides a solid indication of the achievable accuracy in engineering prototypes produced by the Z Corp 3D printer. Details of the design features of these three parts are given in the following subsections.

2.1 Shaft design

The shaft shown in Fig. 1 includes a number of cylindrical features and two pin holes. The three parameters measured in this study are shown in Table 1. The specified size of the small diameter (SD) is $\varnothing 20h11$, which creates a lower tolerance limit of 19.870 mm and upper tolerance limit of

Fig. 1 Details of the shaft

Table 1 Parameters of the shaft

Parameter	Original dimension (mm)	Tolerance range (μm)	Adjusted value (mm)
SD (small diameter) ^a	20.000	h11 (0/–130)	19.935
L (shaft length) ^a	190.000	–	190.000
PH (pin hole diameter)	10.000	–	10.000
PH (pin hole alignment) ^a		100	

^a Measured parameters

20.000 mm. The nominal value for the small diameter in the CAD model are set at the middle of the tolerance range, i.e., 19.935 mm. The nominal size of the shaft length (L) is 190 mm; considering this as a nonfunctional dimension, no tolerance was set for it. The alignment of the centre coordinates of the two pin holes with respect to x and z coordinates are also investigated, and a limit of 0.1 mm was set.

2.2 Design of the metric bolt

The diameter of this bolt is 20 mm with a 55 mm length and a 2.5 mm pitch (Fig. 2). The bolt was designed according to Standards Australia ISO metric hexagon bolt and screw standards, using product grades A and B. The shortened title of this standard is AS 1110.1-2000. Furthermore, tolerances were set by AS 5066-2002 which are tolerances for ISO metric bolts, screws, studs and nuts of production grades A, B and C. Afterwards, the thread profile was sketched and swept along a helix to cut the thread. The profile of the thread was made according to AS 1721-1985 which is designated for general purpose metric screws. A 2D drawing and a 3D model of the metric bolt are shown in Fig. 2. The measured parameters with additional parameters of interest are given in Table 2. The nominal length of the bolt

is 55 mm with a tolerance range of js17 (± 1.05 mm), which is the standard tolerance for bolts of this length used in industry. The js17 tolerance specification gives a lower tolerance limit of 53.950 mm and an upper tolerance limit of 56.050 mm for the bolt length.

The thread of the bolt is shown in detail in Fig. 2, where the basic parameter is the pitch (P), which is the nominal dimension of the basic triangle. After subtraction of $H/4$ and $H/8$ from the triangle's height, the final height of the thread was obtained. The distance between the two thread triangles is defined by $P/4$, as shown in Fig. 2. Dimensions of the parameters are given in Table 2. The width of the hex head (S) is the basic size of 30 mm with a tolerance range of h15 (0, –840 μm). The h15 tolerance specification gives the nominal value of 29.580 mm with a lower tolerance limit of 29.160 mm and an upper tolerance limit of 30.000 mm.

2.3 Gear design

The toothing of the gear was constructed in SolidWorks by an involute line and contains 15 teeth with the pitch of 18.840 mm. A two-dimensional drawing with the dimensions is shown in Fig. 3. All the calculated parameters and other dimensions are shown in Table 3. The gear has been

Fig. 2 Details of the M20x55 metric bolt

Table 2 Parameters of the M20 x 2.5 metric bolt

Parameter	Original dimension (mm)	Tolerance range (μm)	Adjusted value (mm)
D (major diameter)	20.000	6 g (−42/−377)	19.790
P (pitch distance)	2.500	–	2.500
P/8	0.312	–	0.312
l (length of the bolt) ^a	55.000	js 17 (± 1.05)	55.000
S (width of the head) ^a	30.000	h15 (0/−840)	29.580
k (height of the head)	12.290	js15 (± 420)	12.290
d_3 (minor basic diameter)	16.624	0/670	17.080

^a Measured parameters

constructed according to ISO 21771: 2007. The hole at the centre is 20 mm with H11 and has a 0–0.130 mm tolerance range, which gives a lower tolerance limit of 20.000 mm and an upper tolerance limit of 20.130 mm.

2.4 Equipment

The parts were produced by a Z Printer 450 3D printer manufactured by Z Corporation (USA). It is a printer with a single tri-colour head especially designed for everyday use in a standard office environment. The printer has a 203 mm $\times$ 254 mm $\times$ 203 mm build size and a print resolution of 300 dpi $\times$ 450 dpi with a capability of printing 2–4 layers/min. The layer thickness can be selected to be between 0.089 and 0.102 mm; for this study the default setting of 0.102 mm was selected. Specifications of the 3D printer used in this study are available at [19].

Fig. 3 Details of the gear

Table 3 Parameters of the gear

Parameter	Formula	Dimension (mm)
HD (hole diameter) ^a		Ø20H11 (20.065 mm)
m (gear module)		6
p (pitch)	$p = \pi m$	18.84
d (pitch diameter)	$d = z \cdot m$	90
d_f (minor diameter)	$d_f = d - 2h_f$	75
h_f (tooth height)	$h_f = 1.25 m$	7.5
d_b (basic diameter)	$d_b = d \times \cos \alpha$ ($\alpha = 20^\circ$)	84.57
d_a (major diameter)	$d_a = d + 2 m$	102
z (number of teeth)		15
s (tooth width)	$s = \pi m / 2$	9.42

^a Measured parameters

High-performance composite material ZP150 was employed for the fabrication of the parts. Z150 is a commercially available powder made of calcium sulfate hemihydrate, better known as plaster of Paris [20]. It is curable by a fine mist of water mixed with salt. To gain further strength, the parts can be infiltrated and cured by epoxy resin. However, application of the epoxy resin was avoided due to the unpredictable and non-uniform layer thickness on the parts' surfaces. ZBond 90 (80–100 % ethyl-2-cyanoacrylate [21]) was used to infiltrate the part to within 4 mm of the surface and create a reasonably strong and hard shell.

2.5 Printing process

After the creation of the 3D models in SolidWorks, they were saved in STL format and opened using software supplied by the printer manufacturer, ZPrint with an add-on named ZEdit, which allows the user to add support structures, orient the part around any axis or edit its colour. The orientations of parts during their production are shown in Fig. 4. All three parts, and three pieces per part, were added to the same printout. This was repeated three times. At the third printout, four pieces of each part were made to obtain a total number of ten pieces of each part. For the 190 mm long shaft printed in the orientation shown in Fig. 4 at the highest speed (4 layers/min) with the largest layer thickness (0.102 mm), the estimated time of printing is 7 h and 46 min. Hence, it is a slow process, but, despite that, the printer works autonomously and quietly with little need of human assistance during the process.

After the printing, the printer heated up to the appropriate temperature to allow the parts to dry while they were still in the powder bed. After the parts were dried, the device automatically removed excess powder from the bed and returned it to the feeder for reuse. The parts were then placed into the integrated fine powder removal chamber

Fig. 4 Orientation of the parts in the printer

where the remaining powder was cleared off by compressed air. Subsequently, the parts were taken out of the printer, infiltrated by ZBond 90 and then dried. The dried parts were then measured for their dimensional accuracy and repeatability.

2.6 Measurement procedure

Measurements were taken by a general purpose coordinate measuring machine (CMM), Discovery model D-8, Sheffield, UK. It has 0.1 micron position resolution with axial repeatability of measurement of $\pm 2.5 \mu\text{m}$ within its full travel area. It is a programmable CMM, and the code for measurement of each part was written prior to the measurement. Subsequently, all 10 pieces of each part were measured. For the shaft shown in Fig. 1, the small diameter ($\text{Ø}20\text{h}11$) was measured to monitor its deviation from the

nominal value and its ability to fit with the gear hole ($\varnothing 20H11$). The length of the shaft was measured to investigate the effect of layer thickness stacking. The alignment of pin holes was measured exactly, and a 0.1 mm tolerance limit was set. For the bolt shown in Fig. 2, the length and width were measured. It was not possible to measure the minor diameter (d_3) with the CMM machine; therefore, it was left out of the measuring procedure. For the gear shown in Fig. 3, the hole diameter ($\varnothing 20H11$) was measured to investigate its deviation from the nominal value and its ability to fit with the shaft ($\varnothing 20h11$).

3 Results and discussion

3.1 Shaft measurement

Figure 5a shows the measurement results for the small diameter of each sample, which varies between 19.888 and 19.951 mm, with an average value of 19.923 mm. The measured values of the small diameter are well within the specified tolerance limit. It is worth noting that most of the measured data is below the nominal value. This indicates the tendency of the Z Corp 3D Printer to build cylindrical features with a diameter lower than the nominal. There are also four points where the measured value and the nominal value are very close. The part orientation shown in Fig. 4 produces good dimensional accuracy of the features investigated here. As most of the data points are below the nominal level, it is recommended to set the nominal level higher inside the tolerance range. This would result in the data points being present more uniformly around the middle of the tolerance range.

Figure 5b shows the measurement results for shaft length for each sample, which vary from 192.041 to 192.817 mm, with an average value of 192.390 mm. It is a significant off-set from nominal value. This was caused by an inaccuracy of the material volume deposited from the printer's head into a single layer. The result of a high number of layers in

the shaft is the stacking of this volumetric error, which causes an off-set of the resulting dimension from the nominal value. This is an issue of repeatability, the machine's ability to produce dimensionally consistent parts. Certain differences between the measured and nominal values result in the parts being made by the stacking of many layers, depending on the length of a part. This is a natural phenomenon of 3D printing in the build direction of the z axis, as reported by previous studies [20, 22]. This problem can be resolved by software compensation of the 3D model. For example, in this case, a reduction of the nominal value of the part length by an average deviation (2.390 mm) in the CAD model would result in a shaft length of much smaller deviation from the designed one. In practice, this approach would require prediction of length variation. The orientation of the shaft is such that it takes more layers to get the total length. Less error might be introduced if the shaft were to be placed horizontally.

The alignment of pin hole centres with respect to x and z coordinates was investigated. Figure 6a shows the difference between the x coordinates of the two pin holes. The figure shows that most of the data points are within the limit of 0.1 mm; therefore, the alignment accuracy has been met in most cases. There is only a single data point which shows a significantly higher deviation from the trend set by all the other data points. Figure 6b shows the difference of the z coordinate between two pin holes which is similar to that shown in Fig. 6a, where most of the points are within the set limit of 0.1 mm. The alignment of holes was in most cases within the limit. However, the consistency and reliability of results are not satisfactory considering the inaccuracy in the hole diameter. Software compensation will be not suitable in this case. To improve the results, the pin holes have to be oriented with their axis parallel with the z axis of the 3D printer.

3.2 Bolt measurement

Figure 7a shows the measurement results for length of the bolt for each sample, which vary between 55.348 and

Fig. 5 Shaft measurement results: **a** small diameter and **b** length

Fig. 6 Difference between the pair of pin holes in
a x coordinate and
b z coordinate

Fig. 7 Bolt measurement results: a length, b head width

55.652 mm, with an average value of 55.485 mm. The measured length lies well within the tolerance range. However, there is certain off-set of the measured values from the nominal. This is caused by the stacking of layers in the z axis build direction which was also an issue in the length measurement of the shaft. The range of the measured values is 0.304 mm, which could satisfy smaller tolerance ranges. However, this would only be possible with an application of software compensation of the nominal value. The design criteria of the resulting length being within the tolerance range of js17 has been met; thus, the length of the bolt is accurate. The length of the bolt is shorter than that of the shaft, and the length of the bolt was more accurately produced. Therefore, the magnitude of the length affects the accuracy when it is oriented along the z axis.

Figure 7b shows the measurement results for width of the bolt head for each sample, which vary between 29.461 and 29.749 mm, with an average value of 29.654 mm. The range of the measured values is 0.288 mm. The designed tolerance criteria of h15 has been met; therefore, the S dimension of the bolt has been produced accurately. Tolerance of h15 is commonly used in the industry to define this parameter. The part orientation shows a positive influence on the accuracy of the investigated parameter and is

recommended for any similar features where similar results are expected.

3.3 Gear measurement

Figure 8a shows the measurement results for hole diameter (HD) for each sample, which vary between 19.868 and 20.057 mm, with an average value of 19.891 mm. It is noted that most of the measured values are under the minimum limit and all the values are under the nominal value. The measured results can be considered unacceptable, as most of the points lie out of the tolerance range. This can be partially solved by software compensation. However, this might not be sufficient. Therefore, in this case, the accuracy of the Ø20H11 is not satisfactory. This should be considered in the design stage of future research. The hole in the gear and the shaft were designed for a fit function.

Figure 8b shows the variation of shaft and gear diameters, which is intended to describe the shaft and gear fitting scenarios. In the fitting of these two parts, the worst case scenario is the shaft with the maximum size (19.951 mm) and the hole with the minimum size (19.868 mm). This will produce an interference fit with a -0.083 mm clearance. If the interchange assembly principle is applied, it is

Fig. 8 **a** Hole diameter and corresponding tolerance range, **b** fit of the shaft and gear

Fig. 9 **a** A fit of printed gear and shaft, **b** a fit of printed bolt with a standard nut M20

likely that some fittings will not be possible. However, a practical fit test conducted in this study, where gear and shaft were selected randomly, all fits were made successfully. A gear mounted on the shaft is displayed in Fig. 9a.

Characteristic parameters of the bolt's thread, such as the pitch, major and minor diameter were not measured by the CMM machine, as it would result in the questionable reliability of the measured values. Hence, another testing method was used where a standard commercially available nut was screwed on the printed bolt. Since the printed bolt had been designed as a lower grade bolt with a 6 g tolerance range for the major diameter, as indicated in Table 1, the nut used was of a lower grade 6 g tolerance range. All the printed $M20 \times 2.5$ bolts were screwed together with an $M20$ nut successfully, which is illustrated in Fig. 9b. All the printed bolts worked well with the standard nuts; therefore, the accuracy of the printed bolts was satisfactory and designed tolerance ranges were met. The accuracy of higher grade bolts and nuts is, however, questionable as the tolerance ranges are lower. Usually, two grades of nuts and bolts are commercially available: higher and lower (6 g and 6 h tolerance ranges). Furthermore, bolts and nuts of smaller diameters may not meet the tolerances. This should therefore be investigated experimentally.

Post-processing also has a great influence on the resulting accuracy, since each part has to be infiltrated to gain acceptable strength. Applying a layer of epoxy is not recommended in a case where accuracy is desired. The most beneficial post-processing procedures are those which infiltrate the surface of a part and do not therefore affect the accuracy. The 3D ZPrinter 450 is primarily used for modelling purposes. However, it is proven in this paper that it can be used for a range of engineering prototypes. The range of applications of this machine is very wide and includes many different ranges. By improving characteristics, such as the surface roughness and stacking effect, the range of applications might become significantly higher. The material properties are not considered here.

4 Conclusions

The 3D printing method can produce almost every feature of any part, but the accuracy and repeatability of those features are affected by various factors, such as the part's orientation and size. The accuracy of the parts manufactured in this study was acceptable in most cases, based on data analysis and practical tests. The results confirm higher accuracy of the machine in the z axis and show that it can

be used for building accurate engineering prototypes when the length along the z axis is within certain limits. The accuracy and repeatability of the diameter of the shaft were very good. The 3D printer could not build the 190 mm long shaft accurately though excellent repeatability was obtained. It appears that software compensation will be able fix the problem. The alignment of two pin holes in the shaft was mostly inside the limit, though a few points were beyond the limit in both the x and z coordinates. The diameters of both holes were significantly below the nominal value, and even though both followed the same trend of repeatability, this was not particularly good. Similar to the shaft, the bolt (55 mm long) produced was a little bit longer (55.485 mm) and had very good repeatability. Although the manufactured bolts were well inside the tolerance limits, the accuracy can be further improved by software compensation. The thread of all the bolts was properly fit with the corresponding type of nut. The hex head widths of the bolt were within the tolerance limit and showed very good repeatability. The repeatability and accuracy of the gear hole were not that good, as only a few measurements were inside the tolerance limit, despite the fact that all the gears fit perfectly with the shafts in most of the cases.

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