An Investigation of Dimensional Accuracy of Parts Produced by Three-Dimensional Printing

M. N. Islam, *Member, IAENG*, Brian Boswell and A. Pramanik

Abstract—**The three-dimensional (3D) printing process involves making parts by building paper-thin layers based on data directly from 3D CAD files. It is an extremely flexible process and is capable of creating parts of complex geometry with materials such as ceramics, metals, or polymers. In this paper we provide experimental results of a preliminary study of dimensional accuracy of parts produced by 3D printing. A general purpose coordinate measuring machine was used to determine the accuracy of each part. Typically, 3D-printed prismatic parts have two types of errors: variation in linear dimension and variation in hole diameter. We examined these two types of errors and their effects on the dimensional accuracy of a typical component part. The data showed inherent size errors associated with the 3D printing process, indicating that further investigation is needed.**

Index Terms—**Additive manufacturing, dimensional accuracy, international tolerance grade, rapid prototyping, 3D printing**

I. INTRODUCTION

THREE-dimensional (3D) printing is an additive manufacturing process invented and patented by the Massachusetts Institute of Technology in 1993 [1]. The process involves making parts layer by layer using data directly transferred from most 3D CAD programs. It is an extremely flexible system capable of creating working mechanisms and complex geometry using a variety of materials. Each layer begins with the distribution of a thin layer of the material powder from the feed bin. Using inkjet technology, a binder material selectively joins the particles where the cross-section of the object is formed. After a layer is printed, the build piston lowers itself slightly and a new layer of powder is spread over its surface. The process is repeated until the desired shape is achieved. Once the object is built, excess powder is removed and is recycled and reused for making the next object. 3D printing is a popular choice among additive manufacturing processes due to its faster production time, ease of use, and affordability.

Other available additive manufacturing processes include stereolithography, fused deposition modelling, selective laser sintering, electron beam melting, and laminated object manufacturing. Initially, additive manufacturing processes were applied for making models and prototype parts quickly; as a result the term rapid prototyping (RP) is often applied for characterising these processes. Today however, there is a much wider range of applications, such as: rapid tooling (RT), i.e., making tools for other manufacturing processes, such as patterns for the casting process, and direct digital manufacturing (DDM), i.e., making finished products directly from CAD files. Both RT and DDM require high-dimensional accuracy of parts.

Investigations of dimensional accuracy achievable by various RP processes have received notable attention in the literature [2-9]. However, 3D printing, being a relatively new technology, only has a limited number of published studies [10-12] related to dimensional accuracy achievable by the process. A few review papers [13-15] have compared various RP processes, including 3D printing.

RP parts for low-volume end use need to be robust and fit the designed functionality. This makes it essential that the dimensional accuracy of the parts meet the required standard. Previous researchers have mainly devoted their studies to fixing accuracy and the relationships between processing parameters and post-curing accuracy. To the best of our knowledge, there has been no investigation into the consistency and repeatability of different features of the sample part fabricated by a 3D printer. In this paper we investigated dimensional accuracy and repeatability of parts produced by 3D printing. We also identified trends in the accuracy or repetitive variation in linear dimensions and diameter errors of holes.

II. SCOPE

Dimensional accuracy of a component part represents the degree of agreement between the manufactured dimension and its designed specification. It is the most critical aspect for ensuring dimensional repeatability of manufactured component parts. The objective of this project is to investigate the dimensional accuracy characteristics of a typical component part produced by the 3D printing process.

According to current dimensioning and tolerancing standards [16,17], the dimensional accuracy of a component part is evaluated through its size (size tolerance) and shape (geometric tolerance, including form, orientation, and location). For the sake of simplicity, we only addressed size variations in length dimension and hole diameter. Size variation is especially important for component part fitting together as size directly influences the clearance conditions of the fit.

Manuscript received March 6, 2013; revised April 1, 2013.

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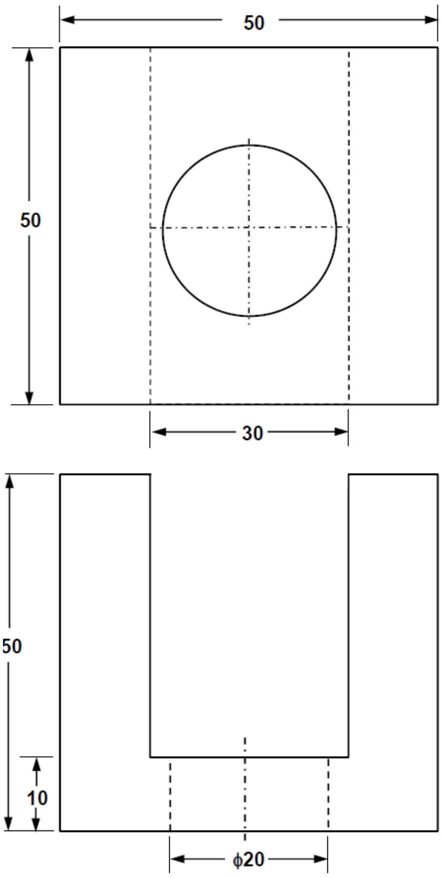
III. EXPERIMENTAL WORK

A simple U-shaped test part with a hole was designed for our experimental procedure (Fig. 1), which was to provide independent analysis of variations of both length dimensions and hole diameter. Length dimension was defined as the distance between two parallel planes. To differentiate among length dimensions, the terms length, width, and height were used according to their orientation on the printer bed during production: length (parallel to the *x*-axis), width (parallel to the *y*-axis), and height (parallel to the *z*-axis). We further differentiated the length dimension into two types: (i) external, i.e., the distance between two external planes, and (ii) internal, i.e., the distance between two internal planes (faces). In Fig. 1, the 50-mm dimension is an example of the external type whereas the 30-mm dimension is an example of the internal type.

Ten test parts were produced, each part individually, in a Z450 3D printer manufactured by Z Corporation (USA). It is a multicolour 3D printer specially designed for everyday use in a standard office environment. It is equipped with a number of useful features, such as automated setup and self-monitoring, automated powder loading, and automated powder recycling and removal. The printer has a specified resolution of 300×450 dpi and a 203×254×203 mm build size. The selected build layer thickness was 0.1016 mm, and the material used for the fabrication of the part was high-performance composite powder Z150 with clear binder solution zb63.



(All dimensions are in mm)

Fig. 1. Test part

The finished parts were measured using a Discovery Model D-8 coordinate measuring machine (CMM) manufactured by Sheffield (UK). The probe used was a spherical probe of 4 mm diameter manufactured by Renishaw Electrical Ltd (UK). It is a touch trigger probe which is the most popular probe used in today's CMMs. The linear dimensions and hole diameters were determined using the standard built-in software package of the CMM. For each feature, nine measurements were taken at a 1-mm height step. For determining hole diameters, eight points were probed at each height.

IV. RESULTS AND ANALYSIS

The variation of linear dimensions is given in Fig. 2 to Fig. 5, and it is interesting to note that all the dimensions in the xy plane, i.e., external length, internal length, and width, are undersized. On the other hand, the dimension in the z direction, i.e., height, was oversized. Also the average error for the height was about three to four times higher than the average error for each dimension on the xy plane. We believe the undersizing of length dimensions in the xy plane is inherent in the 3D printing building process as the binding fluid causes shrinkage when coming in contact with the building powder. The oversizing of height is thought to be caused by the incremental building error of the build table's vertical movement. The variation of the hole diameter is given in Fig. 6. This variation is a dimension measured in the *xy* plane and displayed a similar trend as in the length dimensions, i.e., the holes were undersized. Comparing Fig. 1 to Fig. 6 it appears that the variation of errors (±3σ) for the hole diameter is greater than the variations of all other dimensions.

A typical hole profile created by the 3D printing process is depicted in Fig. 7, where z=0 represents the bottom face of the test part. This type of error is commonly known as error in shape. Although variation of geometric error is not part of this study, this depiction will help us understand the inherent size error problem associated with 3D printing. Fig. 7 shows a bell mouth shape for the hole; that is, the minimum hole diameter is at the bottom and it increases with height. The maximum hole size is reached at the top, even though the hole is still undersized. We believe it is due to the layered printing process and the contraction due to the binding action between the build powder and the binding liquid. The first layer is free to contract, and as a result the maximum contraction occurs at this stage and produces the smallest hole diameter. When the next layer is printed, its contraction is restricted by a printed layer, resulting in less contraction. The process continues as further layers are printed. The last layer contracts by the least amount, resulting in the largest diameter but still slightly undersized.

The international tolerance (IT) grade is often used as a measure to represent the precision of a machining process. Its value varies between 1 and 16. The higher the IT grade number is, the lower is the precision of a process. The following formula based on tolerance standards for cylindrical fits has been applied by a number of authors [18–20] to estimate the process capability tolerance achievable through various manufacturing processes:

$$PC = \left(0.45\sqrt[3]{X} + 0.001X\right)10^{\frac{IT-16}{5}} \qquad (1)$$

where PC is the process capability tolerance (mm), X is the manufactured dimension (mm), and IT is the IT grade number.

To consider 3D printing as a viable alternative for RT and DDM, it is imperative to compare the precision of the 3D printing process with other available manufacturing processes. In Table 1 a comparison of linear dimensional error results for three manufacturing processes—CNC end milling, wire-cut discharge machining (WEDM), and 3D printing—is given using published data [21,22]. The expected IT grades were calculated applying Eq. (1), where six times standard division values are used as process capability tolerances. The calculated values show that in terms of linear dimensional accuracy, 3D printing performed poorly compared to the CNC end milling process; however, the precision level of 3D printing is similar to WEDM.

V. CONCLUDING REMARKS

From our experimental work and the subsequent analysis, we observed some clear tendencies, which are listed as follows:

- Dimensions in the *xy* plane are always undersized whereas the dimension in the *z* direction is oversized;
- The holes are always undersized, and a bell mouth shape is present in all holes;
- The precision level of 3D printing is similar to WEDM, but the CNC end milling process has greater precision.

In summary, we have presented a preliminary study on the inherent size errors associated with the 3D printing process. A hypothesis was presented explaining this phenomenon. This hypothesis may be further tested by having each building layer assigned a separate colour, allowing individual layer measurements to be obtained.

ACKNOWLEDGMENT

The authors acknowledge the contribution of Mr. Prashant Barfiwala, a final year student at the Department of Mechanical Engineering, Curtin University, Australia.

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TABLE I
COMPARISON OF LINEAR DIMENSIONAL ERRORS

		End Milling [21]		WEDM [22]		3D Printing	
Input parameters	Unit	Length	Width	Length	Width	Length	Width
Design size	mm	200	75	20	10	50	50
Measured mean size	mm	199.966	74.963	19.787	9.902	49.847	49.861
Linear dimensional error	µm	-34	-37	-213	-98	-153	-139
Range of measurement	µm	36	35	97	193	104	101
6 x Standard deviation	µm	51	53	146	136	202	210
Calculated IT grade		7.277	8.146	11.352	11.713	11.365	11.365

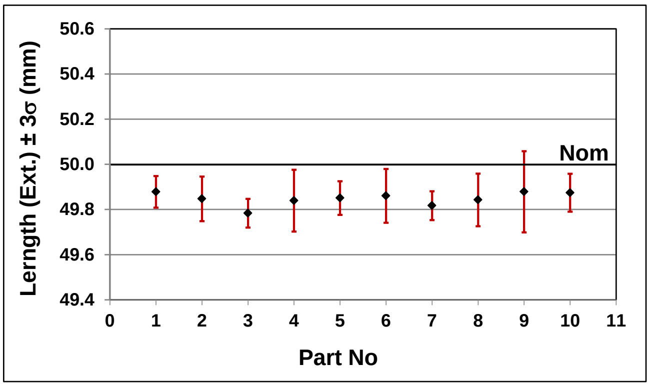

Fig. 2. Variations of length (external)

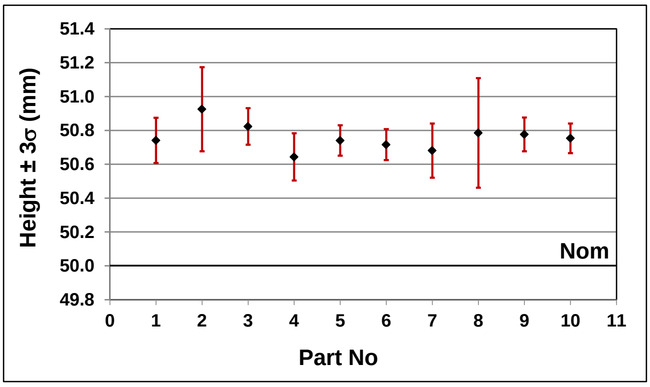

Fig. 5. Variations of height

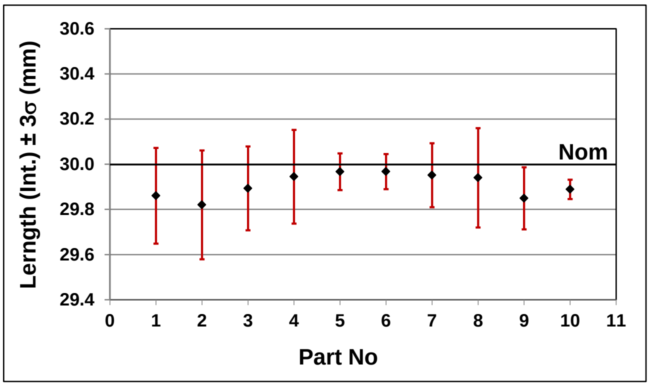

Fig. 3. Variations of length (internal)

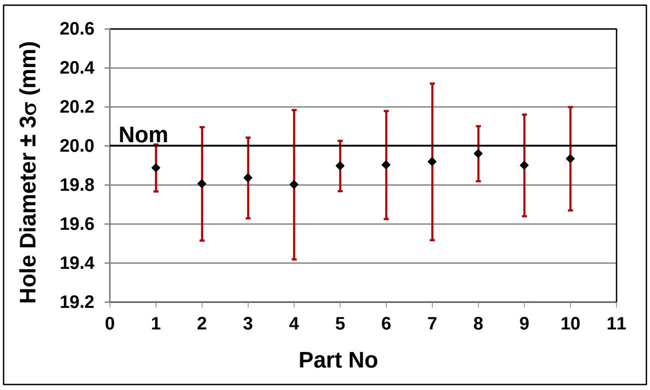

Fig. 6. Variations of hole diameter

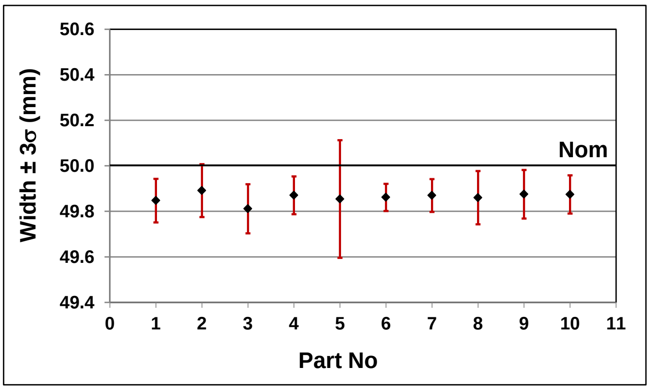

Fig. 4. Variations of width

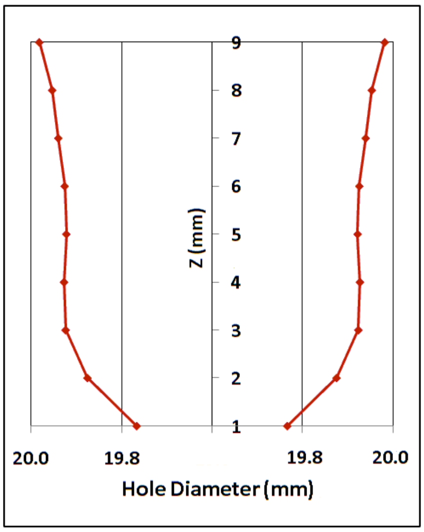

Fig. 7. A typical hole profile created by 3D printing