Dimensional accuracy of 3D printed parts

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Introduction

The aim of this article is to provide engineers and designers with a method for comparing the expected dimensional accuracy that can be obtained from 3D Printing technologies. While all technologies have strengths and weaknesses, the 2 most governing factors on whether a part will print to specifications are:

Design - The accuracy of printed a part depends heavily on the design. Variations in cooling and curing result in internal stresses that can lead to warping or shrinkage. 3D printing is not suited for flat surfaces or long thin unsupported features.

Accuracy will also decrease as part sizes become larger. Specific design recommendations for each of the technologies discussed in this article can be found in Chapter 5 of the Knowledge Base.

Materials - Like design, accuracy also depends upon material. Often the accuracy of a part is sacrificed for the enhancement of a specific material property. For example, a standard SLA resin will produce more dimensionally accurate parts than flexible resin. For parts where high accuracy is critical, standard printing materials are recommended.

Accuracy variables

In order to help quantify the accuracy of a 3D printed part the following parameters will be used.

- ***Dimensional accuracy*** - quantitative values from machine manufacturers and material suppliers that state the expected accuracy of parts. All tolerances stated are with respect to well designed parts on a well calibrated machines.
- ***Warping or shrinkage*** - the likelihood a part will warp or shrink during the printing stage. This depends heavily on design however some processes produce parts that are inherently more at risk of warping or shrinking.
- ***Support requirements*** - for many 3D printing technologies, the amount of support used will govern how accurately a surface or feature is printed. The downside to this is that support affects the surface finish of a part as it must be removed.

For information on the minimum feature size and details that each 3D printing technology is able to achieve refer here. The impact layer height has on a 3D printed part is discussed in this article.

FDM

Fused deposition modeling (FDM) is best suited for low-cost prototyping, where form and fit are more important than function.FDM produces parts one layer at a time by extruding a thermoplastic onto a build plate.

For large parts, this can lead to big variations in temperature across the build platform. As different areas of the part cool at different rates internal stress cause the print to deform, leading to warping or shrinkage. Solutions like printing rafts, heated beds, and radii at sharp edges and corners can help to reduce this.

Differnet materials are more prone to warping than others. For example, ABS is known to be more susceptible to warping than PLA.

Dimensional tolerance	± 0.5% (lower limit: ± 0.5 mm) - desktop± 0.15% (lower limit: ± 0.2 mm) - industrial
Shrinkage/warping	Thermoplastics that require a higher print temperature are more at risk. Adding a radius on the bottom edge in contact with the build plate or a brim is recommended. Shrinkage usually occurs in the 0.2 - 1% range depending on material.
Support requirements	Essential to achieve an accurate part. Required for overhangs greater than 45^{o} degrees.

SLA

SLA (stereolithography) printers use a laser to UV cure specific areas of a resin tank to form a solid part one cross-section at a time. These cured areas, however, are not at full strength until post-processing with UV. Because of this and the angle and orientations that SLA parts are typically printed at, sagging of unsupported spans can occur.

As one layer is built up at a time, this effect becomes cumulative leading to the dimensional discrepancies sometimes seen in tall SLA parts. Dimensional discrepancies can also occur because of the peeling process used by some SLA printers. The pulling force during the peeling process can cause the soft print to bend which again can accumulate as each layer is built up.

Resins that have higher flexural properties (less stiff) are at a greater risk of warping and may not be suitable for high accuracy applications.

Dimensional tolerance	± 0.5% (lower limit: ± 0.10 mm) - desktop± 0.15% (lower limit: ± 0.01 mm) - industrial
Shrinkage/warping	Likely for unsupported spans.
Support requirements	Essential to achieve an accurate part.

SLS

Selective laser sintering (SLS) produces parts with high accuracy and can print designs with complex geometry. A laser selectively sinters powder one layer at a time to form a solid part.

To restrict the likelihood of parts warping or shrinking during printing, SLS printers use heated build chambers that heat up the powder to just below the sintering temperature. This does still, however, result in temperature gradients in large SLS parts where the bottom of the part has cooled while the recently printed top layers remain at an elevated temperature. To further mitigate the likelihood of warping occurring parts are left in the powder to cool slowly (often for 50% of the total build time).

Dimensional tolerance	± 0.3% (lower limit: ± 0.3 mm)
Shrinkage/warping	Shrinkage usually occurs in the 2 - 3% range however most SLS print providers allow for this in the design.
Support requirements	Not required.

Material Jetting

Material jetting is considered the most accurate form of 3D printing. Because there is no heat involved in the printing process warping and shrinkage rarely occur.

Most dimensional accuracy issues related to features and thin walls that are printed below printer specifications. Material jetting prints support as a solid structure from a soft secondary material that is removed after printing. The solid nature of the support results in surfaces in contact with the support being printed to a high level of accuracy. Care must be taken when handling parts produced via material jetting as they can warp and dimensionally change as a result of exposure to ambient heat, humidity, or sunlight.

Dimensional tolerance	± 0.1% (lower limit: ± 0.05 mm)
Shrinkage/warping	Not an issue for material jetting.
Support requirements	Essential to achieve an accurate part.

Metal 3D printing

Metal printing (specifically DMLS and SLM) use a laser to selectively sinter or melt metal powder to produce metal parts. Much like SLS, metal printing produces parts one layer at a time in a controlled, heated environment on industrial-sized machines. This layer-by-layer construction coupled with the very high temperatures involved in the process creates extreme thermal gradients, and the net effect is that stresses are built into the part.

As a result, metal printed parts are at a high risk of distorting or warping, meaning good design practices and part orientation are critical to achieving an accurate part. Unlike SLS, support structures are vital to minimize distortion of the part during production. Parts are also generally built upon a solid metal plate and need to be removed once the print process is complete. A sound understanding of the process is required along with solid and lattice support structures to keep the part securely attached to the print bed and stop it from detaching. Most parts are also stress relieved (via a heat treatment process) after they're built and before removal from the build plate (doing so allows the crystalline structure to relax, preventing failure later).

Since the cost of metal 3D printed parts is high, simulations are often used to validate the accuracy of a design, before starting the print job.

Dimensional tolerance	± 0.1 mm
Shrinkage/warping	Parts at a high risk of shrinkage or warping. Bracing and support are used to help reduce the likelihood of this occurring.
Support requirements	Essential to achieve an accurate part.

Rules of thumb

- For the highest accuracy (and when budget is not a constraint), Material Jetting is the optimal solution.
- For high accuracy, SLA is recommended for parts smaller than 1000 cm^3 (10 x 10 x 10 cm), and SLS for parts with dimensions greater than 1000 cm^3 (10 x 10 x 10 cm).
- Quick, cost-effective prototyping FDM is the best solution.