

THE ACCURACY MYTH

Don't Make the Mistake of Confusing High Resolution With Accuracy

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As additive manufacturing is called on to produce parts that do more than look good, there's a growing emphasis on dimensional accuracy and repeatability over resolution.

INTRODUCTION

Most design and manufacturing engineers understand the concepts of accuracy, repeatability and resolution. They know that the term accuracy describes how closely a manufacturing system's output conforms to a tolerance within a specified dimensional range. They know repeatability captures the system's ability to produce consistent output, time after time. And resolution refers to the smallest measurement the system can reproduce.

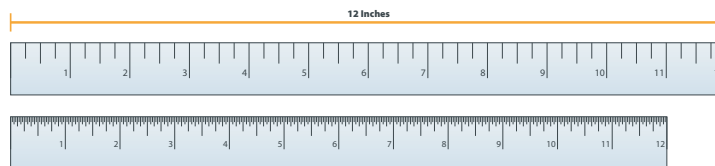
These three concepts are second nature to anyone who designs parts or controls manufacturing processes. Yet, there is a widely held misconception about these measurement concepts as they relate to additive manufacturing. Over the years, some engineers have slid into using resolution attributes – such as layer thickness or dots per inch – as a careless shorthand term for accuracy.



Resolution does not, in fact, translate directly to a system's overall accuracy. One simple way to visualize the real-world distinction between these two concepts is to imagine that two measuring sticks of differing length are both marked as 12 inches long, yet the second stick is actually 1 inch shorter. The first stick is divided into 1/16-inch increments, and its true length is verified at precisely 12 inches. Even though the shorter stick reads "12 inches," it is verified to be only 11 inches long. But this shorter measuring stick is divided into 1/32-inch increments, which is twice the resolution of the 12-inch measuring stick.

The 12-inch ruler with 1/16 inch increments exhibits lower resolution but high ultimate

accuracy. The 11-inch ruler with the finer increments does the opposite: It exhibits high resolution but low absolute accuracy.



Regardless of the build method, it's tempting to equate the height of the incremental layer and the width of the smallest feature with

system accuracy. The finer the resolution – the myth goes – the more accurate the part.

The same goes for additive manufacturing systems. Some make parts like the first ruler – with finely resolved features but lower overall dimensional accuracy. Others turn out parts with lower, but acceptable, resolution and excellent accuracy.

When additive manufacturing was in its infancy and was used primarily for model making, the distinction between accuracy and resolution did not matter much. It was enough for an early "rapid prototyping" machine to turn out models whose dimensions were approximate at best, as long as the model met the cosmetic goals. Users just needed a model to paint and show to their marketing department.

Today, though, much more is required of additive manufacturing systems. They routinely turn out functional prototypes, fixtures, or finished goods that must meet the same stringent accuracy and repeatability standards associated with traditional manufacturing

In some circumstances, there is limited truth to that reasoning. "In some applications, a fine resolution is important. In others, it doesn't matter," says Sheku Kamara, director of the rapid prototyping lab at the Milwaukee School of Engineering.

So when does resolution count? As it relates to accuracy, "resolution becomes critical only when part feature size becomes very small," says Kamara. If the application requires micro-scale feature sizes or wall thicknesses, then resolution can dictate a system's ability to accurately create the very small features. For example, Kamara points out, if the feature size is 0.002 in. (0.0508 mm) and the system's best Z-resolution is 0.005 in. (0.127 mm), then layer thickness can constrain part-feature accuracy.

This circumstance tends to arise in applications such as jewelry patterns and micro-fluidics components – applications requiring very fine detail, which benefit from very high resolution systems. Today, though, applications with micro-

scale features are a tiny fraction of all additive manufacturing jobs.

Most additive manufacturing systems are used to create parts that measure several inches or more across and have tolerance capabilities no tighter than several thousandths of an inch. At this scale, the size of the material deposits or the “spot size” of the UV light doesn’t control the overall accuracy of the part or the repeatability of the process.

High-end Fused Deposition Modeling (FDM) systems can produce parts with layer resolutions down to 0.005 in. (0.127 mm), delivering a part that isn’t as smooth as an injection molded part. However, they have an overall accuracy or tolerance of +/- 0.0035 in. or +/- 0.0015 in./in. (+/- 0.089 mm or +/- 0.0015 mm per mm), whichever is greater. This falls easily within the average tolerance for an injection molding job, which is typically 0.005 in. (0.127 mm).

If the additive manufacturing machine’s most important requirement is to produce a part with a class-A surface finish or sharp edges, then you may need a system whose forte is high resolution. But smooth surface finish or sharp edges do not mean you have an accurate part. Consider the following image. Part one was built on a 3D printer with a very high layer resolution of 0.0015 in. (0.0381 mm). Part two was built on an FDM 3D printer using a lower-resolution setting of 0.010 in. (0.25 mm).

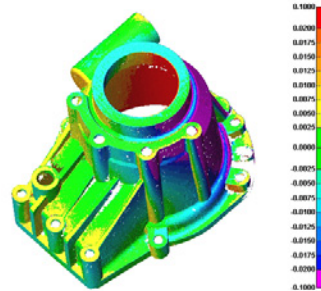


Figure 1

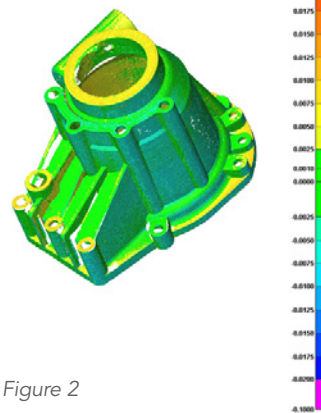


Figure 2

Photo Courtesy of T. A. Grimm & Associates Inc.

Figures 1 and 2: High Resolution vs. High Accuracy: Color maps reveal that part one – built on a very high-resolution 3D printer – is not as accurate as part two, built using a lower-resolution setting on an FDM system. Purples and reds reveal that the very high-res printer produced deviations of +/- 0.020 in. (0.51 mm) or more. Greens reveal the FDM-built part is mostly in the +/- 0.005 in. (0.13 mm) range.

As figures 1 and 2 show, accuracy is a function of the system’s ability to control the motion of the material deposition or curing mechanism across the entire build envelope.

THE GROWING NEED FOR ACCURACY

While additive manufacturing got its start as a way to produce mostly cosmetic models, the field has evolved into full-fledged manufacturing. Today, additive systems turn out not just models for show and functional prototypes for physical testing, but finished goods, too.

FDM systems, for example, are increasingly employed as a cost-effective way to make manufacturing jigs, fixtures, and other tools. FDM systems also make low-volume production parts that in the past would have been injection molded or machined. Overall dimensional accuracy is paramount if these manufacturing aids and finished goods are to function properly.

As additive parts move into applications with more challenging functional requirements, their accuracy tolerances are specified in the same manner as those of traditional manufacturing methods.

These tolerances are cited in thousandths of an inch (or hundredths of a millimeter) over given part dimensions, not dots per inch or slice height.

However, in manufacturing applications, the accuracy of a single part as it comes out of the system is just one of three critical considerations. The other two are the repeatability of that accuracy over many parts and the stability of their dimensions over time.

Repeatability

According to Kamara, repeatability can make or break an additive system in functional prototyping and direct manufacturing applications, where multiple versions of parts must be made within acceptable part-to-part dimensional tolerances. “Just as resolution does not translate into accuracy, accuracy does not translate into repeatability. Some systems have good accuracy but poor repeatability,” he says.

Kamara cites three repeatability considerations:

1. From part to part in a single build on a single machine
2. From part to part in multiple builds on a single machine
3. From part to part in multiple builds on multiple machines

Consistency across the build envelope, from build to build, and machine to machine is critical when manufacturing finished goods. Without process control, dimensional variance will yield unacceptable parts.

To scrutinize the repeatability of the FDM process, two exhaustive studies analyzed thousands of dimensions over hundreds of parts manufactured on multiple systems. One study showed that the large-format, production-oriented FDM machine had a standard deviation of just 0.0017 in. (0.043 mm), which means that 99.5% of all dimensions were within +/- 0.005 in. (0.13 mm). The other study showed that the multi-purpose – prototyping and production – systems studied produced 95.4% of all dimensions within +/- 0.005 in. (0.13 mm), for a standard deviation of 0.0027 in. (0.069 mm).

Click the links below to read the full studies:

[Fortus 360mc/400mc Accuracy Study](#)
[Fortus 900mc Accuracy Study](#)

The high repeatability of these FDM systems is paired with long-term dimensional stability.

Long-Term Stability

Whether a part has a service life of weeks or years, the repeatable accuracy of an additive manufacturing machine is only half the equation. Just as critical is the material stability, which is responsible for part accuracy over time. Environmental conditions, such as heat, moisture and ultra-violet exposure, as well as residual stresses from some additive processes may cause parts to shrink, expand or warp.



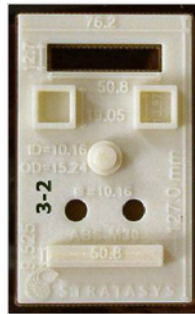
The features in these test patterns appear to be high quality due to a nice surface finish, crisp edges and fine detail, yet they exhibit warping, showing an inability to hold the desired tolerance.

Some processes use materials, such as photopolymers, that are less dimensionally stable over time than thermoplastics. “They experience changes in dimensions and mechanical properties, even after the part has been removed from the machine,” explains Kamara. However, additive parts made from industrial thermoplastics, such as ABS or polycarbonate, do not exhibit these post-build changes.

The best way to assess the ultimate accuracy of an additive manufacturing process is to measure parts over time. If you need parts that maintain their tolerance for months or years, don’t accept the measurements of newly produced parts. Plan a series of checks over an appropriate period to verify the material is stable.

For example, three random parts from the previously mentioned FDM repeatability studies were re-evaluated for this white paper. The parts had been haphazardly stored for well over a year, with no concern for environmental conditions. Yet the samples were virtually unchanged. There is no warping, and the

dimensions fall within the range of the original study. The lengths are within +/- 0.002 in. (0.05 mm) of the 5.000 in. (127.00 mm) nominal dimension, as was true in the study. Likewise, the 3.000 in. (76.20 mm) widths are within the same range of -0.003 in. (-0.08 mm) to +0.004 in. (0.10 mm).



One of many identical parts produced for the repeatability study.

The test results in tables 1 and 2 show that FDM meets the accuracy, repeatability and stability demands of manufacturing. And separate studies by Loughborough University proved that FDM's thermoplastics are just as stable in terms of mechanical properties.

Click the links below to read the full studies:

- [ABS-M30 Material Property Study](#)
- [Polycarbonate Material Property Study](#)

CONCLUSION

When additive manufacturing systems turned out models only for show, resolution may have been an acceptable way to describe the system's capabilities. However, those days are over.

Resolution does have some significance when describing a system's capacity to replicate very small features or very thin wall sections. Yet the vast majority of additive manufacturing applications today have feature size requirements that fall within the reach of most systems, making these systems' resolution more than sufficient for most applications. Resolution does not translate to a system's ability to produce parts with accurate dimensions – and to do so over and over again.

Given additive manufacturing's push into demanding functional applications, it's important to consider whether an additive machine can produce parts that hold a tolerance and can do so repeatedly. This is the hallmark of any capable manufacturing system, additive or not.

Width Nominal (3.000", 76.2 mm)	Apr-2008 Actual	Aug-2011 Actual	Change over time
Sample 1	2.997"	2.997"	0.000" (0.00 mm)
Sample 2	3.001"	3.000"	-0.001" (0.03 mm)
Sample 3	2.999"	2.998"	-0.001" (0.03 mm)
Average	2.999"	2.998"	-0.001" (0.03 mm)

Length Nominal (5.000", 127 mm)	Apr-2008 Actual	Aug-2011 Actual	Change over time
Sample 1	4.999"	4.998"	-0.001" (0.03 mm)
Sample 2	4.998"	4.998"	-0.000" (0.00 mm)
Sample 3	4.998"	4.996"	-0.002" (0.05 mm)
Average	4.998"	4.997"	-0.001" (0.03 mm)

Tables 1 and 2: FDM parts retain their accuracy over time, as shown by measurement of accuracy study samples that were measured more than one year after they were produced.

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