A DESIGNER'S GUIDE FOR DIMENSIONING AND TOLERANCING SLS PARTS

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ABSTRACT

Because additive manufacturing (AM) is a relatively novel industry, with the first commercial machines introduced in the late 1980s, many designers are unaware of the capabilities of AM technologies. Many engineers also find it difficult to utilize AM because of a lack of "Design for AM" knowledge in the public domain. Reliable information on material properties, dimensions and tolerances, and other process-related specifications is often scattered throughout the literature, if it is publicly available at all. The objective of the research reported in this paper is to begin to create a designer's guide for dimensioning and tolerancing parts that are additively manufacturing using selective laser sintering (SLS) technology. The guide is based on a series of experiments designed to determine the limiting feature sizes for various types of features fabricated in commercially available SLS machines. The features include slits, holes, letters, mating gears, and shafts built in a preassembled state. The impact of part thickness, orientation, clearance, and dimensions on the resolvability of features is examined. Results are reported in a series of matrices that relate realizable feature sizes to other important variables such as part thickness.

Keywords: Additive Manufacturing, selective laser sintering, tolerancing, dimensioning, design for additive manufacturing

1. OVERVIEW OF A DESIGNER'S GUIDE FOR DIMENSIONING AND TOLERANCING SLS PARTS

AM is attractive to engineering designers because it offers unique capabilities that are not found in conventional subtractive or formative manufacturing processes [1]. Using selective laser sintering (SLS), designers have the opportunity to fabricate almost any shape or topology, including complex internal structures such as cellular or lattice structures. These capabilities can be used to consolidate components for lightweighting and ease of assembly, to tailor customized structures for form-fitting and multifunctional applications, to fabricate moving joints and mechanical assemblies *in situ*, and to create unique, one-of-a-kind products. Without the need for dedicated tooling, these products can be fabricated economically in lot sizes as small as one.

It can be difficult, however, for experienced or novice engineers to design for AM. The expansive capabilities of AM lift the design-for-manufacturing (DFM) constraints of conventional manufacturing processes, thereby expanding the design freedom of the designer, but they also leave the designer with new sets of process-specific design rules that are often poorly understood and quantified. Accuracy and resolution of different features can vary from AM process to process and also with part orientation, thickness, and other characteristics of the part and the build.

Without detailed, quantitative knowledge of the accuracy and resolution capabilities of a specific AM process, defects are common. For example, Figure 1 displays a selection of products fabricated in SLS by undergraduate and graduate students in an AM course at UT Austin. Defects include unreadable text, thin walls that lack integrity, and moving parts that either fuse together or fail to mate properly.

Figure 1. Examples of defects in SLS parts. L to R: unresolved walls, unreadable text, slipping gears

Although expert AM part designers may be able to avoid these defects by leveraging their extensive experience fabricating similar features, it is important for less experienced AM part designers to have access to publicly available information on the accuracy and resolution of AM processes with respect to common sets of features. It is also important for this information to be much more detailed and feature-specific than the accuracy and minimum feature size estimates that are typically available from manufacturers. Towards this goal, several authors have designed and fabricated benchmark parts and published comparative studies of prominent processes such as SLS, stereolithography (SLA), and fused deposition modeling (FDM) (e.g., [2-4]). These studies typically investigate the accuracy and repeatability of a variety of features, including cubes, cylinders, slots, holes, and overhanging beams, and also investigate warpage, curl, and surface finish under various conditions.

These benchmarking studies leave several unresolved questions that can be important for designers of mechanical parts for SLS. Those questions include: How much should mating gears be separated to prevent both fusion of the mating teeth and slipping between the moving teeth? How much clearance should be provided between a rotating shaft and a surrounding bore if the parts are fabricated in an assembled state? How does the answer differ with orientation and thickness of the surrounding part? How does the resolvability of holes and slots and thin walls vary with orientation and the thickness of the surrounding part? What types and sizes of fonts are appropriate for SLS and how does the answer change with orientation of the surface and the raised or indented nature of the font?

In this paper, a set of benchmark parts are designed, fabricated, and measured to answer these questions for the 3D Systems Vanguard series of SLS machines. A subset of benchmark parts are introduced in Section 2, along with a sampling of results in Section 3. A full description of the benchmark parts and results is available in a full-length report available on the first author's website [5].

2. BENCHMARK PARTS

Benchmark parts were designed to investigate feature resolution, font resolution, and clearance between moving mechanical parts. Most features were fabricated on parts of varying thickness and with different build orientations to investigate the effects of those factors on resolution and accuracy. Separate benchmark parts were designed for each type of feature to be investigated. Many of the designs (along with the graphical approach for presenting the resulting measurements) were inspired by the research of Dominik Sippel, as described on the Shapeways website [6]; however, his work investigated only EOS laser sintering machines, rather than 3D Systems Vanguard machines, and did not investigate the moving mechanical parts described here. A selection of the benchmark parts is described in this section, which is organized by benchmarking category.

2.1 Feature Resolution

Feature resolution experiments included the investigation of circular hole resolution versus part thickness, circular hole resolution versus proximity to the edge of a part, thin wall resolution, small diameter pin resolution, and square hole resolution versus part thickness. All feature resolution experiments were conducted in two orthogonal orientations in which the primary plane of the part was either parallel or orthogonal to the build plane.

Two example types of benchmark parts are pictured in Figures 2 and 3. In each figure, the z-axis is aligned with the height of the build chamber, and the paired pictures illustrate the two orientations in which the parts were fabricated. Figure 2 illustrates the benchmark part for investigating circular hole resolution versus part thickness. The circular holes ranged in diameter from 0.125 mm to 4.0 mm, and the part thickness ranged from 0.94 mm to 12.7 mm. As shown, identical parts were built in horizontal and vertical orientations in which the central axis of the holes was aligned with the height and width of the build chamber, respectively. Figure 3 illustrates the benchmark part for investigating thin wall resolution versus part thickness. The thin walls ranged in thickness from 0.2 mm to 3 mm. The part was build in two orientations, as shown, with the thin walls either coplanar with the build plane (horizontal orientation) or orthogonal to the build plane (vertical orientation). Two duplicate parts were fabricated in each orientation for each part.

Horizontal Orientation Vertical Orientation

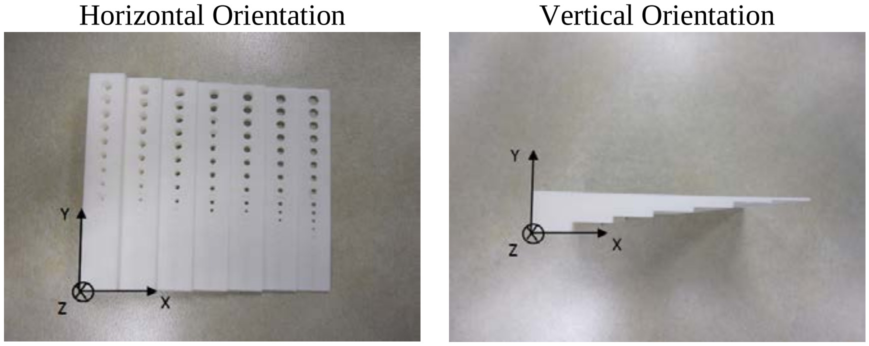


Figure 2. Benchmark Part for Circular Hole Resolution Versus Part Thickness

Horizontal Orientation Vertical Orientation

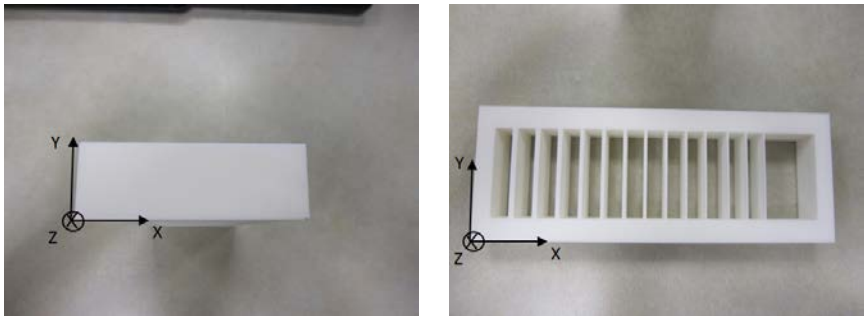


Figure 3. Benchmark Part for Thin Wall Resolution Versus Orientation

2.2 Font Resolution

Font resolution experiments included fabricating parts with different fonts in different orientations and with different font sizes and heights (if raised) or depths (if recessed). As shown in Figure 4, grids of letters were fabricated with different font sizes and heights/depths. On each surface, both raised and recessed letters were fabricated. Letters were fabricated on both sides of the plate, as well, to investigate upward and downward facing font resolution for the horizontal orientation shown in Figure 5. The vertical orientation in Figure 5 is used to investigate the resolution of side-facing font.

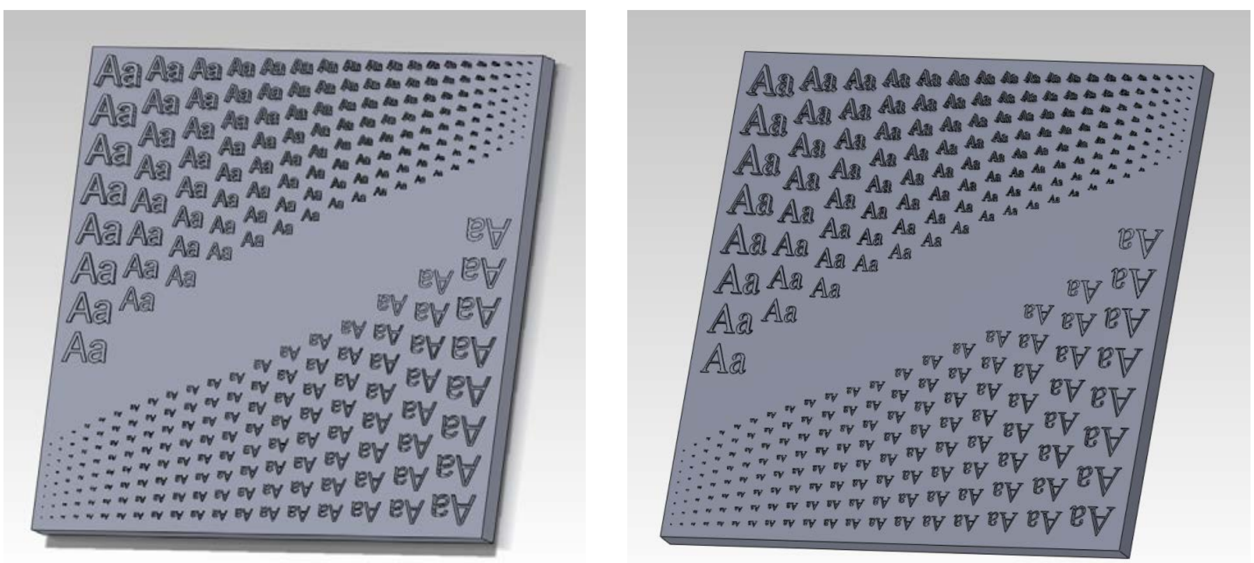


Figure 4. Benchmark Parts for Two Different Fonts (Sans Serif on the Left and Serif on the Right). Font sizes vary from Left to Right. Font Heights/Depths Vary from Top to Bottom. Raised Letters are Pictured on the Upper Left; Recessed Letters on the Lower Right.

Horizontal Orientation Vertical Orientation

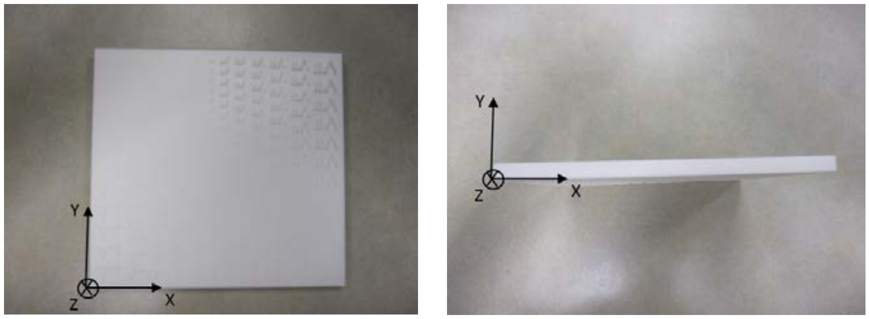


Figure 5. Build Orientations of Benchmark Parts for Font.

2.3 Clearances for Moving Mechanical Parts

Clearance experiments included shafts with varying bore diameters and gear assemblies with varying clearances. Figure 6 illustrates the benchmark part for investigating shaft clearance. Part thickness decreases from 25.4 mm to 1.27 mm along the y-axis, and bore diameter decreases incrementally from 13.6 mm to 10 mm along the x-axis. Shafts are identically dimensioned with 4 mm lengths and 10 mm diameters. The part was fabricated in only one orientation, as shown in Figure 6, with the central axis of each shaft aligned with the height of the build chamber (the z-axis).

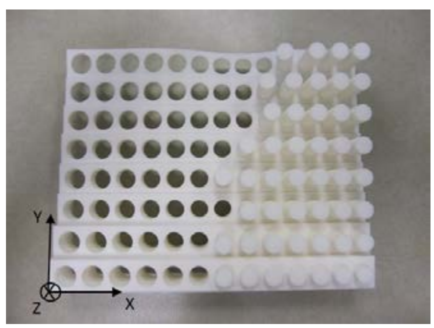


Figure 6. Benchmark Part for Shaft Clearance.

Gear clearances were investigated with the benchmark part in Figure 7. As shown in the figure, six pairs of gears were fabricated on each test part. Shaft/bore clearances of either 1 or 1.5 mm were tested, together with gear tooth clearances of 0.5, 1, or 1.5 mm. Three different versions of the test part were created with 15, 20, and 25 gear teeth per gear. The part was always aligned as shown in the figure, with the z-axis aligned with the height of the build chamber, and two identical copies of each part were fabricated for repeatability.

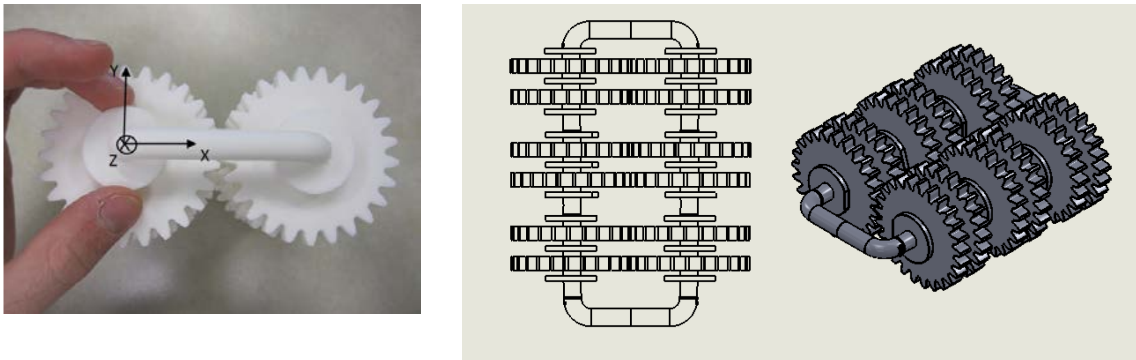


Figure 7. Benchmark Part for Investigating Gear Clearances

3. REPRESENTATIVE RESULTS

All of the benchmark parts were fabricated on a 3D Systems Vanguard SLS machine by Harvest Technologies. Harvest Technologies used production machine settings and Nylon 12 powder. Metrology was conducted on each fabricated part. Pass/fail criteria for each feature were compiled to determine whether the feature was adequately resolved. Tolerances were also quantified by measuring the parts with calipers for larger features or an optical microscope for smaller features. Each measurement was repeated by four members of the team, and results were averaged to improve accuracy and reduce bias from individual measurements. A representative sampling of the results is provided in this section, with full results available in the original report [5].

3.1 Feature Resolution

The pass/fail criteria for circular holes are described in Figure 8. Results for a vertically oriented part and a horizontally oriented part are illustrated in Figure 9, with the orientations corresponding to Figure 2. As shown in Figure 9, hole resolution is better for parts oriented in the vertical orientation; as shown in Figure 2, vertically oriented parts include holes with their central axes aligned with the build plane. For those parts, the thickness of the build layer has a stronger influence on the resolvable hole size than the beam width. Since the layer thickness for these builds was approximately 0.1 mm, while the beam width was approximately 0.28 mm, it is not surprising that smaller holes are resolved for the vertically oriented parts. Part thickness also has an influence on hole resolution, with smaller holes resolvable in thinner parts. Thicker parts require more laser scanning in the region of the hole, likely resulting in small amounts of oversintering and coarser hole resolution. In addition to these charts of hole resolution, hole diameters were measured repeatedly, and resulting statistics are documented in the full report [5].

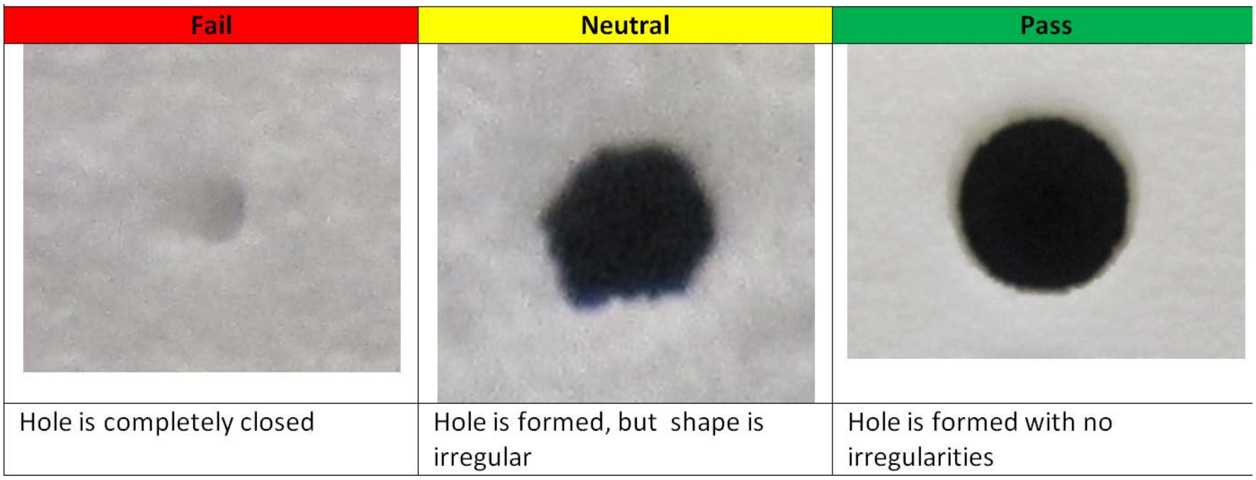


Figure 8. Pass/Fail Criteria for Circular Holes.

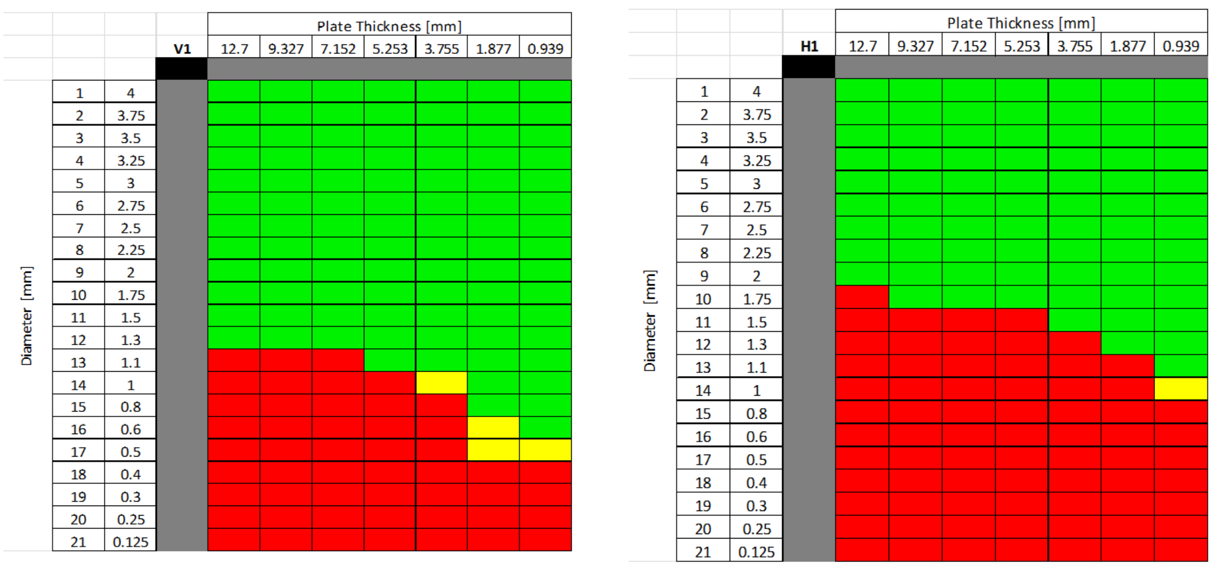


Figure 9. Circular Hole Resolution Versus Plate Thicknesses for Vertical Part Orientation (Left) and Horizontal Part Orientation (Right). See Figure 2 for Orientation Description. Color coding matches Figure 8.

The pass/fail criteria for thin walls are described in Figure 10. Results for a vertically oriented part and a horizontally oriented part are illustrated in Figure 11, with the orientations corresponding to Figure 3. As shown in Figure 11, thin wall resolution is better for parts oriented in the vertical orientation, in which the walls are coplanar with the build plane. For parts in the preferred orientation, it is possible to build walls as thin as 0.2 mm (less than twice the layer thickness), although those walls are very thin—so thin that they buckle under the residual stresses associated with the cool-down of the build. In either orientation, it is possible to resolve walls as thin as 0.8 mm.

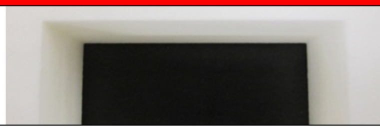
Fail	Neutral	Pass
		
No wall formation	Wall formation occurs, but wall is fragile	Wall formed as a rigid structure

Figure 10. Pass/Fail Criteria for Thin Walls.

Wall Test (Horizontal wall)								Wall thickness [mm]							
	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3
V1															
V2															

Wall Test (Vertical Wall)								Wall thickness [mm]							
	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3
H1															
H2															

Figure 11. Thin Wall Resolution Versus Wall Thickness for Vertical Part Orientation (Top) and Horizontal Part Orientation (Bottom). See Figure 3 for Orientation Description. Color Coding Matches Figure 10.

3.2 Font Resolution

The pass/fail criteria for fonts are described in Figure 12. Results for a horizontally oriented part are illustrated in Figure 13, with the orientation corresponding to Figure 5. As shown in Figure 13, font resolution is much better for upward facing surfaces than for downward facing surfaces. The downward-facing letters may suffer from oversintering associated with building thick parts around and on top of the letters.

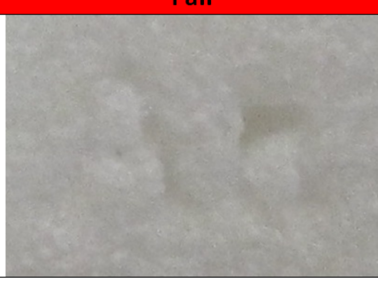
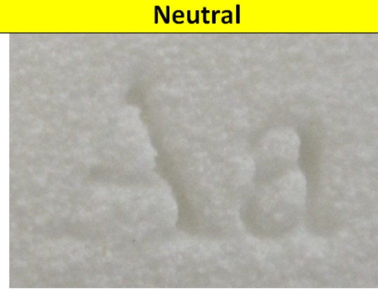
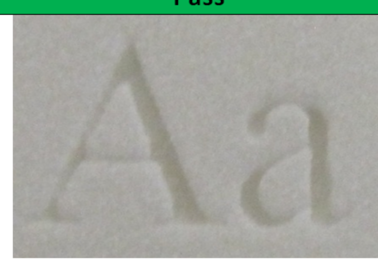
Fail	Neutral	Pass
		
Font is illegible due to defects such as major gap fusion and large portions of incomplete font structures	Font is legible, but contains defects such as partial wall filling or small gaps in the wall	Font is legible with the naked eye, and contains no defects such as fused or incomplete walls.

Figure 12. Pass/Fail Criteria for Fonts.

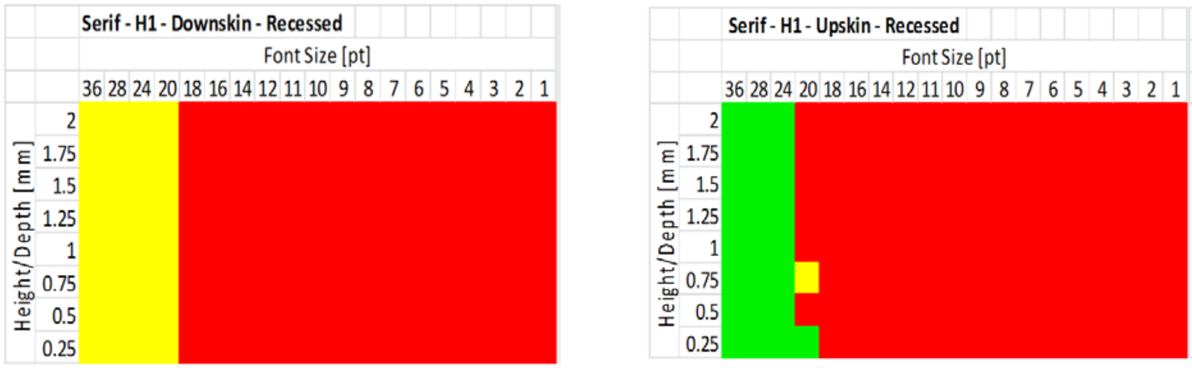


Figure 13. Font Resolution for Serif Font, Recessed Letters, and Horizontal Part Orientation. Font Size is Charted on the Horizontal Axis Versus the Depth of the Recessed Letter on the Vertical Axis. Downward Facing Letters are Depicted on the Left; Upward Facing on the Right. Color Coding Matches Figure 12.

3.3 Clearances for Moving Mechanical Parts

The pass/fail criteria for gears are described in Figure 14. The acceptability of the mesh between the gears is illustrated in Figure 15. In Figure 15, failures (color-coded in red) indicate that the gear teeth are too far apart to maintain reliable contact; none of the gears fused together in this experiment. Based on these results, it is reasonable to recommend a shaft clearance of 1 mm (but no larger) and a gear tooth separation of 0.5 to 1.0 mm.

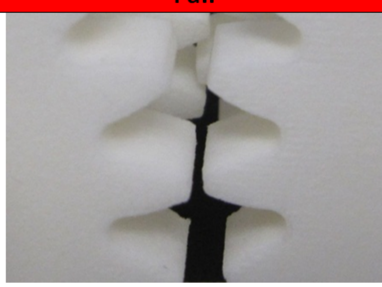
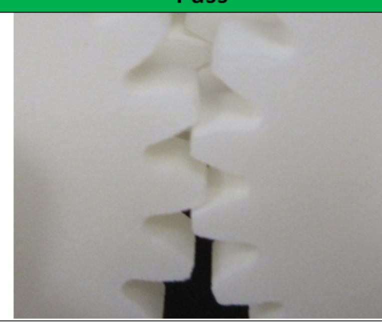
Fail	Neutral	Pass
	Cannot be directly observed	
Little to no gear teeth contact at maximum possible separation	Gears mesh at maximum possible separation, but slippage occasionally occurs	Gears mesh at maximum possible separation, no slippage

Figure 14. Pass/Fail Criteria for Gears.

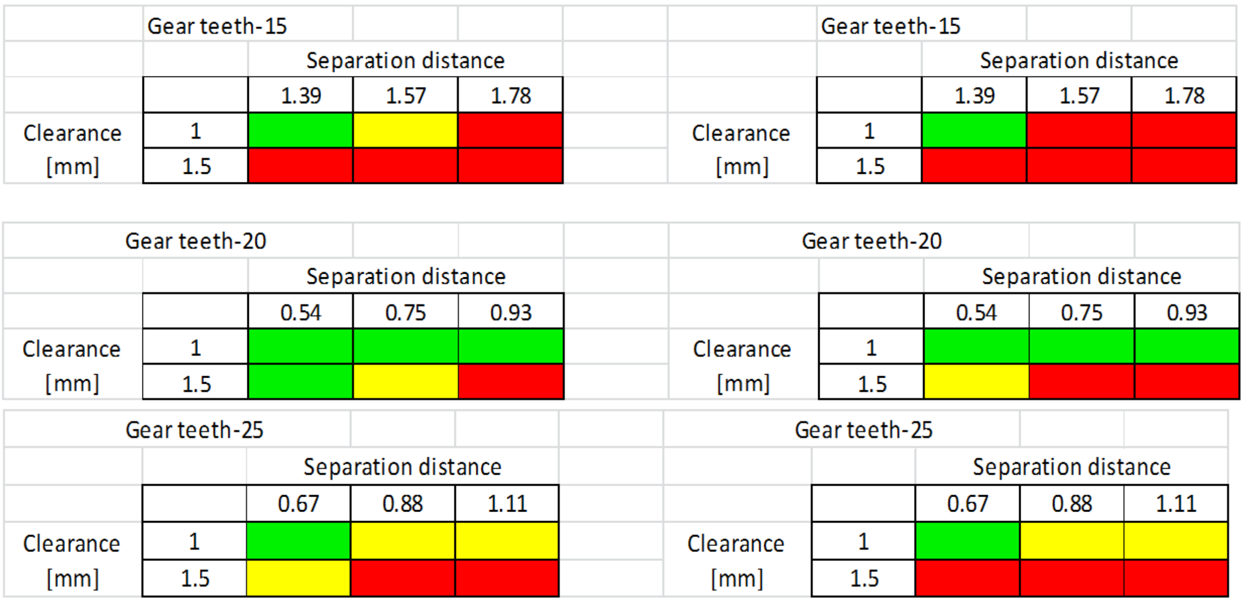


Figure 15. Acceptability of Meshing Gears as a Function of Separation Distance Between Gear Teeth, Clearance Between Gear Inner Diameter and Shaft, and Number of Gear Teeth. Gears are Oriented as Shown in Figure 7.

4. Closure

This paper offers a snapshot of the of the results of a series of experiments designed to determine the limiting resolution of a selection of features fabricated in commercial SLS machines. The matrices provided in this paper relate feature resolution to other important parameters such as part thickness, clearances, and build orientations.

The complete designer's guide offers additional matrices for features including shafts preassembled within a bore, holes in proximity to the edge of a part, slits, and many different permutations of the results reported here, such as additional build orientations. The complete designer's guide also includes quantitative analysis of the accuracy of specific features based on repeated measurements of that feature in multiple parts and multiple build orientations.

The results are certainly limited in several ways. First and foremost, the results are specific to the 3D Systems Vanguard HiQ+HiS machine and Nylon 12 powder. Other machines and/or materials could yield different results. Secondly, many features remain unexplored, such as springs, fasteners, and knobs, along with geometric characteristics such as warping and concentricity.

Acknowledgements

The authors gratefully acknowledge Harvest Technologies for sponsoring the project and fabricating all of the test parts. Thanks also to the Senior Design Projects program in UT Austin's Mechanical Engineering Department for making the project possible.

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