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DIRECT MANUFACTURING

3D PRINTING & ADVANCED MANUFACTURING

FROM THE DESIGN LAB: AN INSIDER'S GUIDE TO LASER SINTERING

MASTERING SUCCESSFUL LS PARTS AT ANY 3D PRINTING EXPERIENCE LEVEL

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AN INSIDER'S GUIDE TO LASER SINTERING

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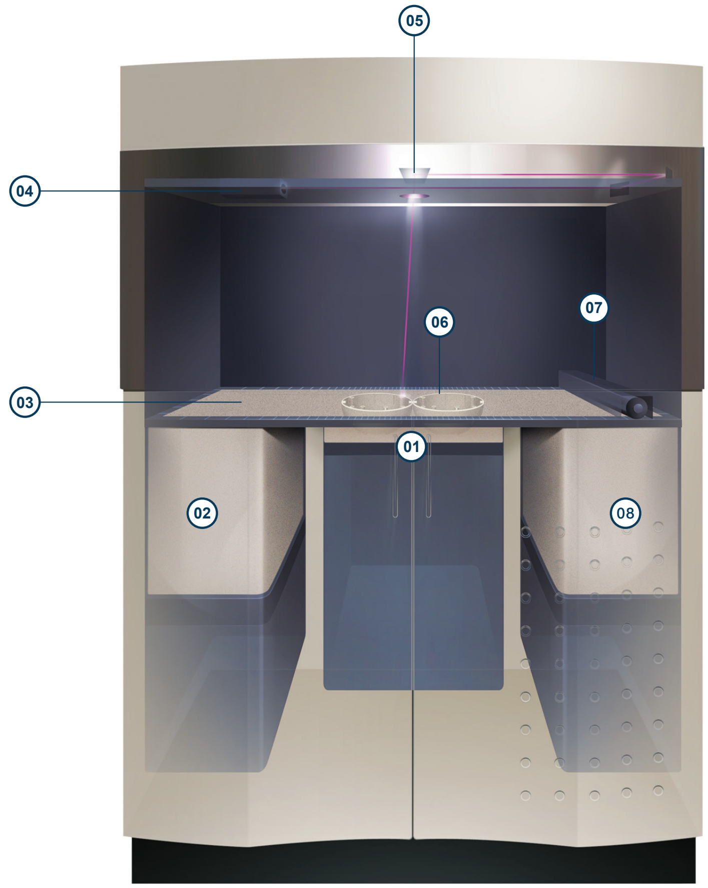
BRINGING THE DESIGN WISDOM OF LASER SINTERING ENGINEERS TO THE MASSES

While all additive manufacturing (AM) processes share the ability to create multifaceted parts with intricate features, each system has its own design guidelines to ensure accuracy and optimize part design for the build process and compatible materials. These design guidelines and trade knowledge are usually not shared externally, which can leave the average design engineer feeling adrift on a sea of 3D printing challenges. However, through years of experience, Stratasys Direct Manufacturing has gathered the most efficient design guidelines for one of the more popular 3D printing technologies: Laser Sintering. This article details a study undertaken by Stratasys Direct Manufacturing and the University of Texas (UT) at Austin which vetted tolerances for challenging LS design features such as minimum wall thickness, optimal build orientation for small to large features, and feature distances and areas in relation to part walls. Our goal is to make the information collected within the study well-known to the average design engineer and present working expectations for what LS can do, and therefore minimize errors and achieve consistently successful LS parts.



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For the first time, we're sharing industry secrets that solve everyday design challenges for parts made using Laser Sintering 3D printing.

Laser Sintering (also known as LS or SLS®) builds complex parts directly from 3D CAD data via a heat laser that fuses or sinters powdered thermoplastics. Similar to other 3D printing technologies, it enables part consolidation and complex geometries, however LS is unique in that it eliminates the need for support structures. Parts built with LS are printed in a bed of self-supporting powder; the excess powder is easily shaken out during post-processing. It is an affordable way to build durable production parts in low volumes. Common applications include ductwork, control surfaces, brackets, clips, clamps, fuel tanks and flight-certified parts.

The University of Texas set out to find solutions to common Laser Sintering design problems by conducting a series of experiments on parts containing test features of varying dimensions and build orientations. Build orientation—or the plane (X, Y, or Z) in which the part is built upon layer-by-layer — affects functionality and aesthetics of the final part. Because LS powders are heated to just below their melting point, factoring how the material may shrink and the angle upon which the CO_2 laser hits the design can significantly improve a product or alter how the design elements of the part withstand the process. Therefore, Stratasys Direct Manufacturing built the test parts within these studies in multiple orientations and sizes on a LS machine to best assess how orientation can be used to reinforce a design during printing. The beam offset used on these parts was 0.279 mm in both the X and Y direction. The machine uses a moving roller to re-distribute powder. The material used for all the tests was Nylon 12.

The findings within this paper reinforce what the manufacturing engineers at Stratasys Direct Manufacturing have learned over two decades working with Laser Sintering technology and complement the *LS Design Guide* published by Stratasys Direct Manufacturing.

WALL THICKNESS

Wall thickness is a fundamental design feature which ensures stability, accuracy and tolerance for a part manufactured with Laser Sintering. As mentioned in the introduction, LS parts are exposed to very high temperatures throughout the build and are therefore susceptible to warp during the heating and cooling of each layer. Thinner walls are more likely to warp as they are subjected to heat and the weight of the powder with each consecutive layer. The team therefore designed a simple part to test fifteen varying wall thicknesses to determine how thin a wall could exist before degrading.

EXTERNAL WALL THICKNESS

This test vetted external wall thickness and tolerance. The part designed for this test, shown below in Figure 1, incorporated fifteen walls with thicknesses ranging from 0.2 mm to 3 mm. The objective was to uncover how thick or thin the walls of any given part can achieve before cracking or warping.

Figure 1 was built in two orientations to compare how orientation affected quality and feasibility of feature realization. The orientations were configured to result in walls which were vertical in relation to the surface of the build as well as horizontally located in respect to the surface of the build.

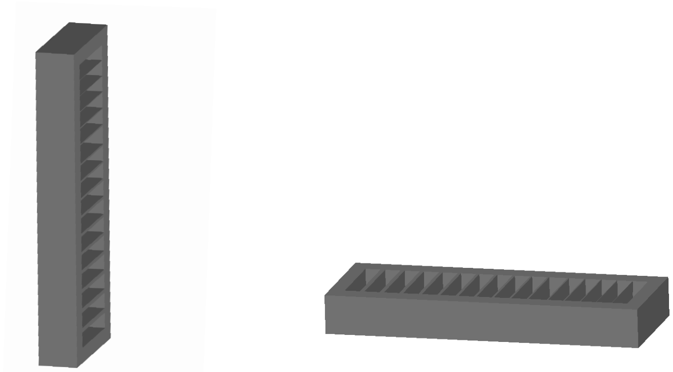


Figure 1: Via the left side orientation, the walls are horizontal with relation to the surface of the build where the build top is located at the uppermost surface; therefore this orientation will be referred to as the horizontal orientation. Via the orientation shown on the right, the internal walls are vertical in relation to the surface of the build therefore this orientation will be referred to as the vertical orientation.

When oriented vertically, the walls failed to form thinner than 0.5 mm while horizontally oriented walls at 0.5 mm thickness formed with significant warping. It was therefore determined that reliable walls thinner than 0.5 mm are not accurately feasible, regardless of orientation. The team then compared wall thicknesses from 1 mm to 1.6 mm. Based on their measurements of resolvability for walls within these dimensions, it was clear that horizontally built walls have a higher accuracy rate than vertically built walls. The pass/ fail criterion for walls can be seen in Figure 2.

THIN WALL

Fail	Neutral	Pass
Wall fails to form	Wall formation involves significant deformation	Wall formed and presents a rigid structure

Figure 2: Pass/ fail criterion for external wall thickness/ thinness.

The deviation in resolvability between vertical and horizontal wall orientations is due to two factors. The resolution of horizontal walls is limited by layer thickness while the resolution of vertical walls is limited by the laser spot size. Because the layer thickness (0.1 mm) is smaller than the laser spot size (0.47 mm diameter) the resolution is better at a horizontal orientation. However, typically, horizontally built walls have a higher potential to warp because they encompass more surface area across the horizontal plane and therefore higher powder density. Stratasys Direct Manufacturing may build parts at certain angles if their surface area warrants special consideration and warp is a large factor.

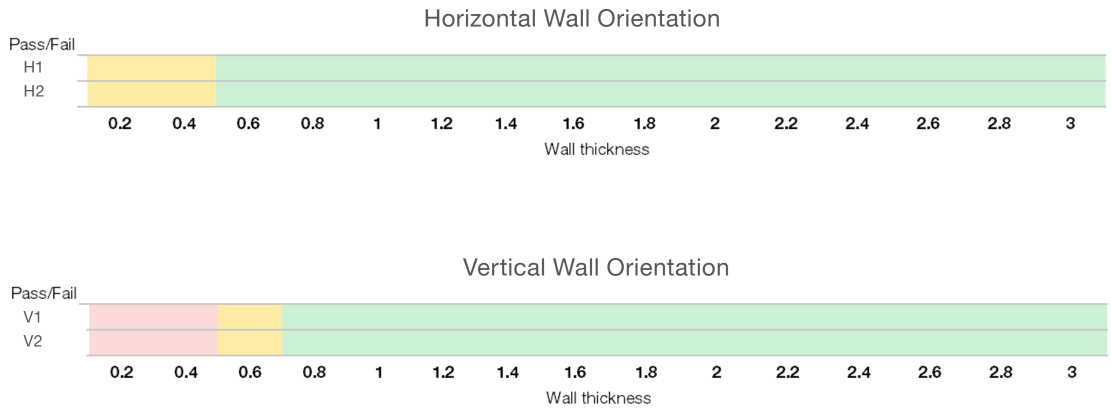


Table 1: Red designates a complete failure to build, yellow designates a passing build with significant inaccuracies, and green represents a complete build for each wall thickness.

Table 1 illustrates the pass/fail matrices for horizontal and vertical walls. These results are from visual inspection as well as careful measurements. While walls above 0.5 mm may build, to ensure walls resist stresses, we recommend a minimum thickness of 0.8 mm as walls at this feature possessed at least some rigidity.

EXTERNAL WALL THICKNESS: SUMMARY OF RESULTS

- Walls built in the horizontal direction are able to resolve at smaller dimensions
- Horizontally built walls can realize 0.6 mm while vertically produced walls are unable to achieve a minimum sturdy wall below 0.8 mm.
- While horizontal walls realize at dimensions thinner than 0.6 mm, walls this thin will lack significant rigidity to prevent warping

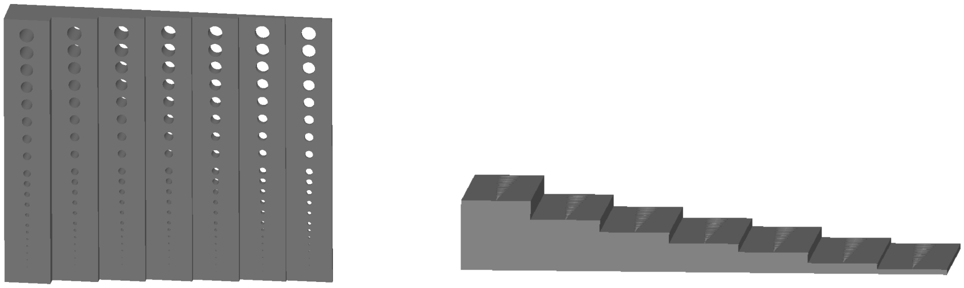


Figure 3: There are 21 holes per step with diameters ranging from 0.125 mm to 4 mm. In the orientation shown to the left, the hole features are horizontal with relation to each Z-axis cross-section therefore this orientation will be referred to as the horizontal orientation. The image on the right shows the hole features in a vertical orientation in relation to each Z-axis cross-section therefore this orientation will be referred to as the vertical orientation.

HOLES

When determining how a hole factors into a design for Laser Sintering, there are three key areas the team considered: Diameter versus thickness, diameter versus tolerance, and the relationship of the hole to the greater design (i.e. its proximity to other holes or similar design features).

DIAMETER

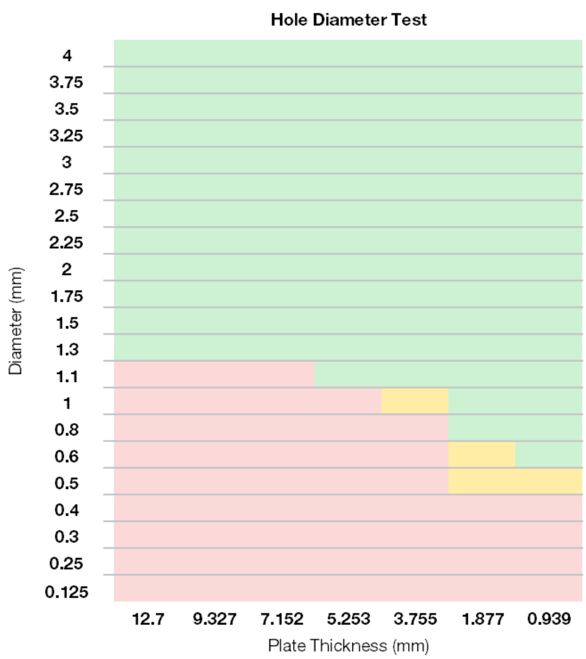
For this test, the team designed a part with varying wall thicknesses and hole diameters. The design, shown in Figure 3, consists of seven steps with wall thicknesses ranging from 0.939 mm to 12.7 mm thick. Each step incorporates multiple holes with diameters ranging from 0.125 mm to 4 mm, with the larger holes used primarily to gauge tolerance as compared to the CAD model. The model was built in vertical and horizontal orientations, where orientation is based on the holes themselves as vertical and horizontal, to determine how orientation factored into accuracy and resolvability for these design features.

Based on accuracy, repeatability and manufacturability, holes should be built larger than 1.5 mm when possible. Anything lower than a 1.5 mm hole diameter will be difficult to accurately fabricate using LS. Stratasys Direct Manufacturing builds features in a vertical orientation for smaller holes that require tighter tolerances in order to maximize resolution. Building holes in this manner lowers the minimum possible hole diameter to about 0.5 mm less than the horizontal value. As noted in the Stratasys Direct Manufacturing Laser Sintering Design Guide, keeping wall thickness around holes at 3.0 mm also helps ensure accurate holes.

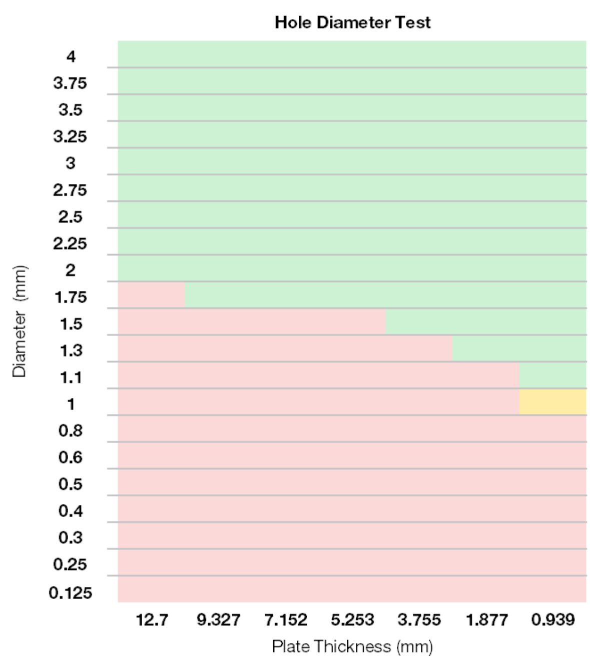
Table 2 demonstrate the pass fail matrices for both vertically and horizontally oriented holes where yellow designates a hole resolved but lost acceptable tolerance, red designates a hole that allowed zero light to pass through and is therefore a failed hole, and green designates a successful and accurate hole.

Table 2:

VERTICALLY ORIENTED HOLES PASS/FAIL RESULTS



HORIZONTALLY ORIENTED HOLES PASS/FAIL RESULTS



HOLE DIAMETER TEST: SUMMARY OF RESULTS

- The test plate (from Figure 3) with features built in the vertical orientation allowed a 0.6 mm minimum hole resolution at the smallest thickness of 0.939 mm
- The test plate (from Figure 3) with features built horizontally allowed for a 1.1 mm hole resolution at the smallest minimum thickness of 0.939 mm

PROXIMITY

Often, holes require some level of proximity to other features. When considering the proximity of a hole to another design opening or the edge of the design itself, a considerable distance is recommended. If a hole is too close to a wall it is possible that it will fail to form completely. The team experimented with a series of holes through the length of square shafts. The design, shown in Figure 4, incorporates holes with varying distances from the wall or edge of the part. The clearance between the wall and the hole at the smallest measure was 0.0 mm (i.e. on the wall itself) while the greatest distance from hole to wall was 1.05 mm. Hole diameters were also varied to understand how diameter affected resolvability. Hole diameters ranged from 2.5 mm to 10 mm.

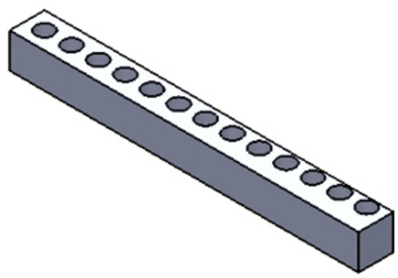
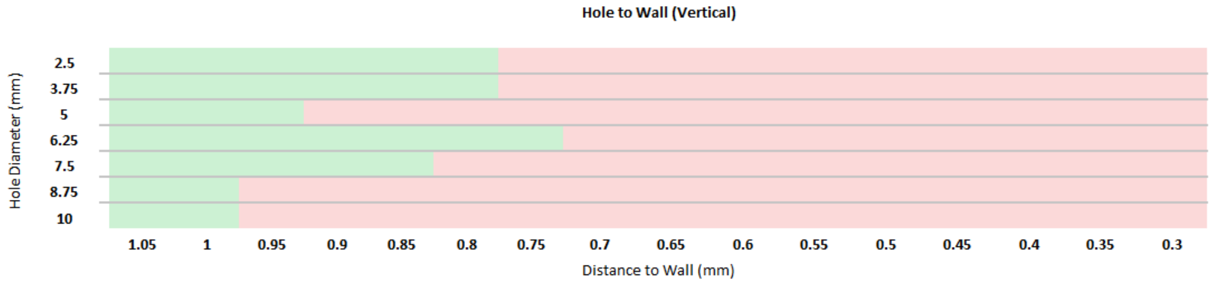


Figure 4: Hole proximity is tested.

As could be expected, the larger the hole diameter the greater the distance between another feature or edge was required while smaller holes could build closer to the edge of the wall. The largest diameter, 10 mm, needed 1.05 mm distance from the wall edge to fully build while the smallest diameter, 2.5 mm, required only 0.8 mm distance from the edge of the wall. Once again, the features were built in vertical and horizontal orientations with minimal differences in accuracy between the two orientations. The results in Table 3 include green, which indicates a resolved hole, and red, which indicates a failed hole build. In this case, there were no in-between results; either the hole was created or failed to build.



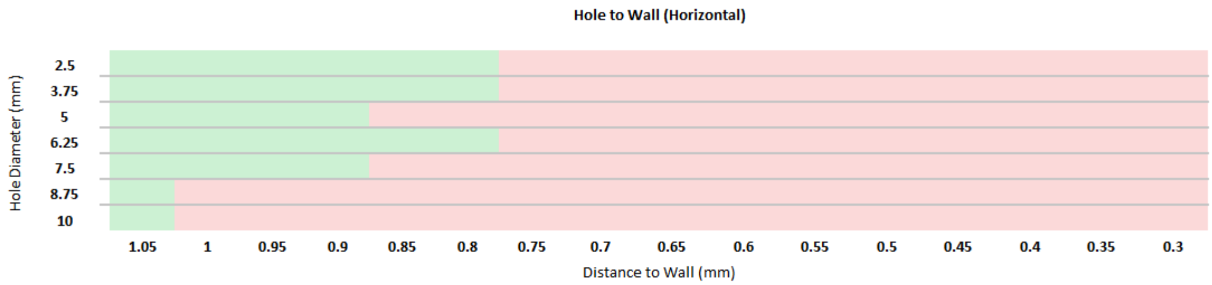


Table 3: Pass/fail matrices for hole diameters and distance from other features (in this case, the edge or wall of the part).

HOLE PROXIMITY: SUMMARY OF RESULTS

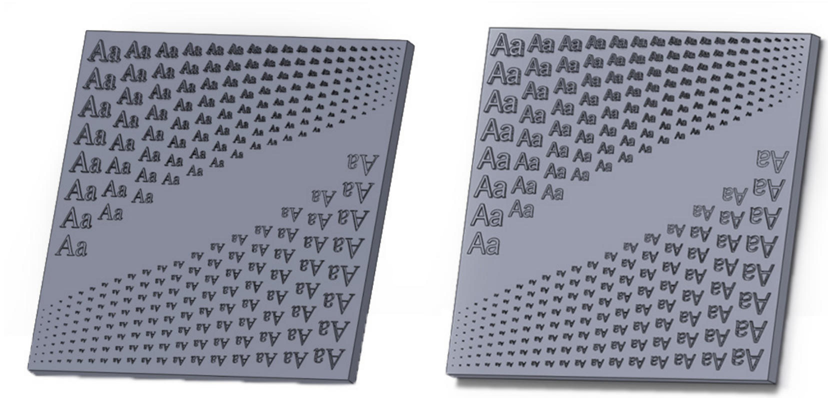
- The vertical features result shown in the Table 3 allowed for a minimum distance of 0.8 mm at the smallest hole diameter
- The largest hole diameter allowed for a distance of 1.05 mm.
- To ensure the wall will resolve, minimize hole diameter and orient the features vertically

TEXT

To understand how more aesthetic features resolve for LS, the team designed font plates with a range of font sizes in both serif and sans-serif which were tested both downskin and upskin, vertically and horizontally oriented. This test sought to prove that directly 3D printing serial numbers or labels into a part for design and brand purposes is feasible and can be preferable depending on the application or project timeline.

FONT SIZE

The design in Figure 5 incorporates a plate with font sizes ranging from 36 – 1 (defined by font point sizes within typical word processors). In addition to the font size itself, the fonts were raised and recessed from the plate by 0.25 mm to 2 mm, with height gradations occurring at 0.24 mm increments.



		Font Size [pt]																		
		36	28	24	20	18	16	14	12	11	10	9	8	7	6	5	4	3	2	1
Font Height/Depth [mm]	2	36/2	28/2	24/2	20/2	18/2	16/2	14/2	12/2	11/2	10/2	9/2	8/2	7/2	6/2	5/2	4/2	3/2	2/2	1/2
	1.75	36/1.75	28/1.75	24/1.75	20/1.75	18/1.75	16/1.75	14/1.75	12/1.75	11/1.75	10/1.75	9/1.75	8/1.75	7/1.75	6/1.75	5/1.75	4/1.75	3/1.75	2/1.75	1/1.75
	1.5	36/1.5	28/1.5	24/1.5	20/1.5	18/1.5	16/1.5	14/1.5	12/1.5	11/1.5	10/1.5	9/1.5	8/1.5	7/1.5	6/1.5	5/1.5	4/1.5	3/1.5	2/1.5	1/1.5
	1.25	36/1.25	28/1.25	24/1.25	20/1.25	18/1.25	16/1.25	14/1.25	12/1.25	11/1.25	10/1.25	9/1.25	8/1.25	7/1.25	6/1.25	5/1.25	4/1.25	3/1.25	2/1.25	1/1.25
	1	36/1	28/1	24/1	20/1	18/1	16/1	14/1	12/1	11/1	10/1	9/1	8/1	7/1	6/1	5/1	4/1	3/1	2/1	1/1
	0.75	36/0.75	28/0.75	24/0.75	20/0.75	18/0.75	16/0.75	14/0.75	12/0.75	11/0.75	10/0.75	9/0.75	8/0.75	7/0.75	6/0.75	5/0.75	4/0.75	3/0.75	2/0.75	1/0.75
	0.5	36/0.5	28/0.5	24/0.5	20/0.5	18/0.5	16/0.5	14/0.5	12/0.5	11/0.5	10/0.5	9/0.5	8/0.5	7/0.5	6/0.5	5/0.5	4/0.5	3/0.5	2/0.5	1/0.5
	0.25	36/0.25	28/0.25	24/0.25	20/0.25	18/0.25	16/0.25	14/0.25	12/0.25	11/0.25	10/0.25	9/0.25	8/0.25	7/0.25	6/0.25	5/0.25	4/0.25	3/0.25	2/0.25	1/0.25

Figure 5: The serif fonts plate (left) and sans serif font plate (right) incorporate a range of font sizes. The fonts are either extruded from the plate or de-bossed into the plate as well as located on upward (upskin) and downward (downskin) facing surfaces. Orientation is again determined by the Z-axis cross-section, where horizontal orientation refers to the part standing in a vertical orientation with features perpendicular to the Z-axis while vertical orientation refers to a lying flat part with parallel features to the Z-axis. Font sizes and depths tested are listed in the above chart.

Two separate parts were tested against the following parameters:

- Font height above the surface of the part and recession cut into the part's surface
- Font size
- Lettering facing downward or upward in the build envelope
- Font type

Results from both tests are below and demonstrated in Tables 4, 5, 6 and 7.

FONT SIZE: SUMMARY OF RESULTS

SANS-SERIF

- Optimum quality is lost around size 14 font built in vertical orientations and size 24 font built in the horizontal build orientation
- Fonts began to degrade in quality around size 20 font for letters built above the surface of the part
- Vertically orientated recessed text became illegible at roughly a size 14 font while vertically orientated raised text became illegible at a size 20 font. Quality remained similar for features built horizontally with a minimum font size of 24.
- Sans-serif fonts are recommended for raised lettering due to higher success rate of feature resolvability

SERIF

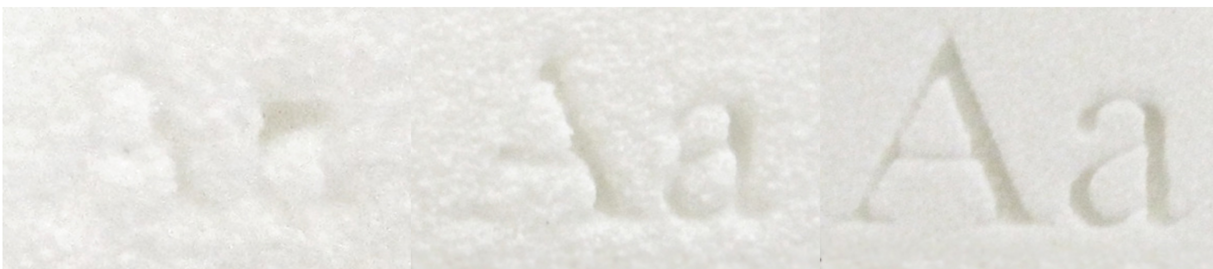
- Optimum quality is lost at around a font size of 12-14 for parts built in a vertical orientation in the build envelope and a font size of 28 for parts built in the horizontal orientation.
- Raised serif fonts are not recommended due to high levels of failure to resolve during testing
- Recessed serif fonts were noted to have better resolution at a font size of 14 or higher with a depth of 12 or higher

Fail	Neutral	Pass
Failed build: Major gap fusion and failure of feature resolution	Neutral Build: Font is legible, but contains defects such as partial wall fusion or small gaps in the wall	Pass build: Font is legible with the naked eye, and contains no defects such as fused or incomplete walls

Table 4: Pass/ fail criterion for raised sans-serif fonts

Fail	Neutral	Pass
Font is illegible due to defects such as major gap fusion and 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.

Table 5: Pass/ fail criterion for recessed sans-serif fonts



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.

Table 6: Pass/fail criterion for recessed serif fonts

In addition to testing fonts in both serif and sans-serif, vertical and horizontal orientations, font features were tested in both upskin and downskin orientations (which directly relates to their position in relation to the laser itself). The team tested these features through a series of multiple plates to land on the best conclusion.

FONTS: SUMMARY OF RESULTS

- Serif fonts should be recessed with an upskin orientation for best results
- Both serif and sans-serif fonts should be formatted vertically
- Both serif and sans-serif fonts produced better resolution when recessed as opposed to raised

MOVABLE COMPONENTS

3D printing enables you to create moveable features without the need for secondary assembly. Consolidating features into one part, however, involves new challenges when it comes to Laser Sintering. Considering space between features, openings to allow for the removal of excess powder, and overall tolerances for movable structures requires understanding a few key design requirements.

GEARS

The goal of this test was to uncover the workability of gears with varying sizes and clearances between center to center distances to ensure gears and pins mesh and move smoothly. The team made a center distance test device to test the performance of gear mates when changing the center distance between the gear shafts. Figure 6 shows the design the team developed while Figure 7 shows the gear part dimension values that were tested.

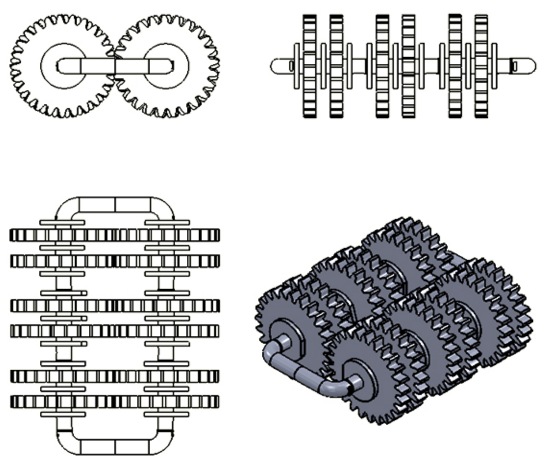


Figure 6: This gear was designed to test how much the center distance can be varied before fusing occurs and or before the gears fail to mesh during rotations. The three gear pieces test separate sizes with 15-20 teeth. Gear pairs run the length of the design. The center distance is gradually increased by 0.5 mm.

Gear Racks (Teeth Number)	15 x 15	20 x 20	25 x 25
Large End Shaft Distance (mm)	52.1	63.2	76.3
Small End Shaft Distance (mm)	50.6	61.7	74.8
Small Gap (mm)	1.39	0.54	0.67
Middle Gap (mm)	1.57	0.75	0.88
Large Gap (mm)	1.78	0.93	1.11

Figure 7: Gear Test specifications

The results followed some of the expected trends with loose shaft clearances and large shaft separation distances leading to gears that failed to mesh. However, small shaft clearances combined with small shaft separation distances did not lead to gears fusing. None of the smallest shaft clearances and separations failed while all of the larger ones did. Another interesting result is that medium sized gear teeth were superior to either larger or smaller gears. All gears with 20 teeth resolved and meshed well for the 1 mm shaft clearance. Table 7 shows the pass/ fail criterion for the gears as well as the orientation for this test.

Table 8 shows the pass/ fail matrices for the three different gear sizes along with their shaft clearances and separation distances where green is a pass and proper mesh and red is a failure to mesh. Yellow indicates a neutral clearance where accuracy was not ideal but resolved. These tests were performed multiple times and the most definitive results are included below.

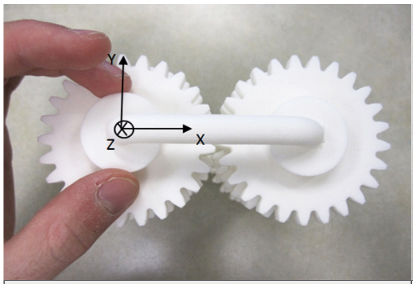
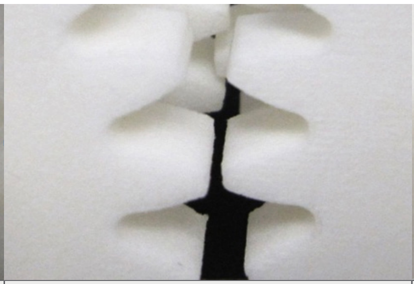
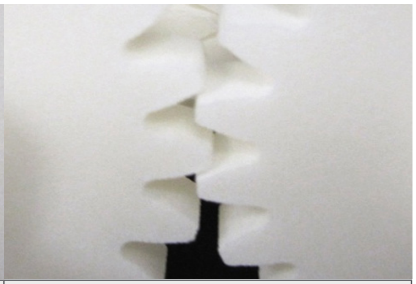
		
Orientation	**Fail**	**Pass**
Vertical Gear Test Orientation	Little to no gear teeth contact at maximum possible separation	Gears mesh at maximum possible separation, no slippage

Table 7: Pass/ fail criterion for gears manufactured in LS.

Gear teeth-15

shaft clearance (mm)	Separation distance		
	1.39	1.57	1.78
1			
1.5			

Gear teeth-20

shaft clearance (mm)	Separation distance		
	0.54	0.75	0.93
1			
1.5			

Gear teeth-25

shaft clearance (mm)	Separation distance		
	0.67	0.88	1.11
1			
1.5			

Table 8: Tests varied, however the ability of the gear teeth to meet clearance within LS manufacturing is definitively proven.

GEARS: SUMMARY OF RESULTS

- A shaft clearance of 1.5 mm on each side ultimately becomes too large for gears to mesh properly. Therefore, we recommend using a shaft clearance of 1 mm and a tooth separation distance between 0.5 mm and 1 mm.
- Choosing larger tooth separation distances could cause slippage in the gears.
- A tooth separation of less than 0.5 mm is possible but was not tested, so lowest amount of separation isn't clear.

PINS

At Stratasys Direct Manufacturing, we sometimes incorporate pins into a part as supports for delicate features which are removed in post-processing. Pins are also used as important staple features for designs. The team determined that it would be important to test pin diameters to land on a diameter that would withstand distortion or incompleteness during LS manufacturing. The pin test was performed using the design in Figure 8 where 15 pins are incorporated to test pin diameters ranging from 0.2 mm to 3 mm.

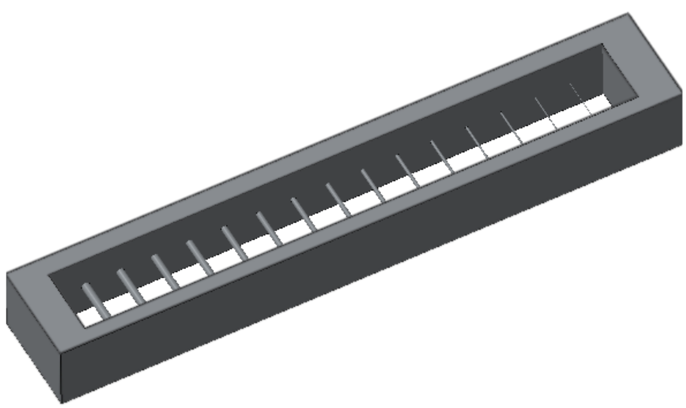


Figure 8: The pins within this design have varied diameters beginning as small as 0.2 mm and ending at the largest 3 mm in diameter.

Pin Diameter (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

Table 9: Pass/ fail matrices for pin diameters.

For this test, only horizontal orientation was observed where the pin features are horizontal to the surface of the build. The team hypothesizes that vertically oriented pins would experience ideal resolution, therefore it was determined that testing horizontally orientated pins and verifying resolvability for horizontal features would dictate success of similar features vertically orientated. The test revealed LS is capable of building a minimum pin diameter above 0.5 mm. We recommend designing pins larger than 0.8 mm in diameter as smaller pins result in uneven surfaces and are more susceptible to bending. Table 9 indicates green for pin diameters that passed, yellow for pin diameters that passed but experienced inaccurate surfaces and post warping, and red for pin diameters that failed to build. The test was performed twice with minimal results variations.

PIN DIAMETER: SUMMARY OF RESULTS

- The minimum size pins that can be resolved is 0.8 mm in the vertical and horizontal direction.
- Pins with a diameter of 0.6 mm do not form rigid structures but will resolve.
- Pin diameters below 0.6 mm did not form at all.

CONCLUSION: PUTTING THE GUIDELINES TO WORK

You can rely on Laser Sintering to deliver critical design features for production parts when the build process is well understood and you take into account design parameters.

Based on these extensive tests, we have gathered below the key design elements to keep in mind when beginning a new LS project:

- A minimum wall thickness of 0.8 mm (0.03 in) to ensure features possess rigid strength.
- Holes should be built larger than 1.5 mm (0.06 in) diameter.
- For circular holes, minimize wall thickness to achieve better hole resolution and tolerances.
- For small gaps, thinner walls are recommended for improved resolution.
- Smaller holes are better when in proximity to edges or walls whereas larger holes are recommended overall when tighter dimensional tolerances are required. If a hole is too close to a wall it is possible that it will fail to form completely.
- We do not recommend serif fonts, however de-bossed serif and sans serif text offers better resolution and legibility.
- We recommend larger holes for thin bearings for adequate shaft rotation and the smallest tested separation for gears.

If you have questions or need further assistance, the team at Stratasys Direct Manufacturing is here to offer support. If you have LS design tips of your own to share, please send them to us on Twitter (@StratasysDirect) or via email info@news.stratasysdirect.com so we can pass on your wisdom to others.

ADDITIONAL RESOURCES

- Stratasys Direct Manufacturing has a supplementary set of Laser Sintering Design Guidelines, offering engineering considerations that complement this report.
- In addition to Nylon 12 (the material used to produce the parts tested in this report), Stratasys Direct Manufacturing offers a wide variety of LS materials suitable for production applications. Detailed material specifications are available at stratasysdirect.com/materials/laser-sintering/.

ACKNOWLEDGEMENTS

The design guidelines and test results contained herein were commissioned by Stratasys Direct Manufacturing and developed by Tyler Govett, Kevin Kim, Michael Lundin and Daniel Pinero as part of the Mechanical Engineering Design Projects Program at The University of Texas at Austin, under the director of Dr. Carolyn Seepersad.

It's important to note that LS machines from different companies have unique manufacturing processes that affect the resolution of manufactured parts.

Harvest Technologies (now Stratasys Direct Manufacturing) was a sponsor of the UT project.

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